ELECTRICITY PRODUCTION FROM BIOGAS IN SERBIA
Assessment of Emissions Reduction

by

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Original scientific paper
DOI: 10.2298/TSCI150812189C

Biogas represents a promising source for the production of clean energy. The objective of this paper was to quantify the potential for the reduction of emissions to the environment during the production of electricity from biogas in comparison with environmental effects of the production of the same amount of electricity from fossil resources (coal from Kolubara basin and natural gas). Basis for comparison of environmental impacts in this work was the annual production of electricity in biogas plants of the total capacity of 80 MW. This study has shown that the annual production of electricity from biogas power plants of 80 MW results in: substitution of up to 840 kt of coal from Kolubara basin and 123.2 million m^3 of natural gas; reduction of greenhouse gases emissions in the range of 491.16 kt to 604.97 kt CO_{2eq}, depending on the energy efficiency of the process of electricity production from biogas; reduction of greenhouse gases emissions up to 92.37 kt CO_{2eq} compared to the use of natural gas for electricity generation.

Key words: *biogas, emission, lignite, natural gas, greenhouse gas, Serbia, energy efficiency*

Introduction

Security of energy supply, environmental protection in energy sector as well as mitigating the effects of climate change represent current major challenges of the world community. The activities that promote the use of renewable energy sources and increase energy efficiency were launched at global and regional levels (UN, EU) in order to achieve the aforementioned objectives. Serbia joined the global efforts through adoption of various policies promoting the use of renewable energy sources and increase of energy efficiency in energy production and consumption.

Electricity production and environment pollution in Serbia

The total installed capacity for the production of electric energy in Serbia amounts to 8.355 MW, out of which 5.171 MW is in thermal power plants, and 2.831 MW is installed in hydro power plants. The installed capacity of gas power plants is 353 MW [1]. Emissions from energy sector represent the dominant source of environmental pollution in Serbia. Ther-

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mal power plants in the country use solid fuel (lignite) for electricity generation. During this process, over 5.5 million tons of ash is generated per year [2], causing uncontrolled secondary emissions. Emissions of nitrogen and sulfur oxides from thermal power plants represent a major air pollution source. The reduction of these emissions is very important because of their adverse effect on the health of the population, their impact on creating photochemical smog and acid rains as well as the harmful effect they have on the ozone layer in the lower atmosphere. The reduction of CO_2 and N_2O is also very significant as they belong to the group of greenhouse gasses (GHG). Particulate matter emissions reduction is important because of their negative impact on health, especially of the respiratory organs. The importance of solving these problems is also mentioned in the strategic document in the field of environmental protection, national program for the environmental protection, which was adopted by the Government of the Republic of Serbia [2].

The Republic of Serbia has signed and ratified the UN Framework Convention on Climate Change (UNFCCC). As a developing country, Serbia is not obliged to quantify its GHG emissions reductions, but is obliged to develop a GHG inventory as well as to define and report the measures for GHG emissions reduction [3].

Biogas and electricity production in Serbia

In the process of accession to the EU, the energy sector of Serbia will be faced with the obligation of investments in CO_2 emissions reduction. In order to achieve these commitments the diversification of natural resources as well as the increase in energy production from renewable sources will have to be achieved [4]. Biogas represents a renewable energy source that can significantly contribute to this obligation. The amount of energy produced from biogas in Serbia in 2012 amounted to 0.001 Mton of oil equivalents (Mtoe), which represented 0.11% of energy produced from renewable sources [5].

After the stimulus measures adopted by the Government of the Republic of Serbia in the period 2009-2013 [6, 7], the investments in the construction of biogas plants started. The action plan for renewable energy sources by 2020 [8] was adopted, assuming the construction of biogas plants with total power up to 30 MW of electricity by 2020. According to this action plan, the 19 ktoe of electricity generation from biogas was assumed, as well as another 10 ktoe in heating and cooling using biogas. According to Cvetkovic *et al.* [9] there were 4.5 MW of installed capacities for biogas production in Serbia in 2014, while the assumed values for 2025 and 2030 are 60 and 80 MW, respectively [10].

The most abundant resource for the production of biogas in Serbia is biomass from agriculture, municipal waste and waste flows from food and meat industry [9]. According to the action plan for renewable energy sources by 2020 [8], the potential for the production of biogas on medium to large farms is estimated to be 42 ktoe. Cvetkovic *et al.* [9] explored the potentials of biogas production from different sources in Serbia. The total potential in this research amounted to 1007 ktoe. The calculated potential for biogas production from agricultural crops directly cultivated for energy is 0.85 Mtoe thereof potential from livestock residues amounts to 94.13 ktoe, potential from municipal solid waste 49.72 ktoe, potential from slaughterhouse waste 9.94 ktoe, and potential from milk processing industry 3.21 ktoe.

Aim of the research

By the review of the previous research on the biogas use in Serbia, it can be concluded that there was no quantitative analysis of the benefits of the electricity production from biogas plants, which are related to the effects of reducing emissions into the environment and climate change mitigation through the reduction of GHG emissions. The emissions from biogas power plants were the subject of many studies. In some papers [11-13], the emissions of CH_4 and CO_2 from biogas power plants were analyzed, while the life-cycle analysis of GHG emissions from raw materials provision to energy production was carried out in [14]. In the papers [15-17] the comparison was made between emissions from biogas power plants with the plants using fossil resources (coal and natural gas). The papers [18-21] analyze the potential contribution of biogas power plants to GHG emissions reduction.

The aim of this study was to quantify the benefits which would arise from the production of up to 80 MW of electricity in biogas power plants, which is the aim of Serbia by 2030. The benefits are analyzed in relation to the production of electricity from lignite as a referent system. The comparative analysis of emissions from power plants using biogas (first scenario), Kolubara lignite (second scenario), and natural gas (third scenario), was performed. The biogas scenario was further developed by analyzing the influences of using different technologies in the electricity production from biogas, as well as the use of different substrates for biogas production. The analysis was performed on the following substrates used for biogas production: agriculture biomass, communal waste and waste waters from dairy, and meat industry. These substrates were determined to have the largest potentials for biogas production, as was determined in our previous research [9]. The technologies analyzed included gas motors and fuel cells, which are likely to be the most important technologies for electricity production using biogas by 2030.

Materials

This section describes non-renewable and renewable resources for electricity generation which are considered in the production of electricity in this paper, as well as the calculation methods used in the paper.

Kolubara lignite – Kolubara mining basin is located in the central part of Serbia. Lignite from this basin represents the most important resource for electricity production in Serbia. The total thermal power and thermal energy power plants that use lignite from Kolubara basin exceed 3000 MW [22]. The characteristics of Kolubara lignite are shown in tab. 1.

Table 1. Properties of Kolubara lignite [23]

Moisture	44-56%
Total sulfur	0.4-0.6%
Ash content	9.8-16.55%
Lower heating value	7.3-9.4 MJ/kg

Low heating value and high ash content contribute to the emission of pollutants into the environment from power plants using Kolubara lignite as energy sources. Energy efficiency in electricity production from coal ranges from 0.3-0.4 [17, 24]. The energy efficiency of electricity production, μ_e, was assumed to be 0.33 in this study.

Table 2. Typical chemical composition of natural gas [25]

CH_4	70-90%
C_3H_8	0-20%
CO_2	0-8%
O_2	0-0.2%
N_2	0-5%
H_2S	0-5%

Natural gas – 4% of installed capacity for electricity production in Serbia uses natural gas. Serbia consumes about 2.5 billion cubic meters of gas per year, mainly for the production of thermal energy. About 80% of the consumed natural gas is imported, contributing to the high current account deficit. A typical composition of natural gas is given in tab. 2. Natural gas can be converted into electricity using gas turbines or in combined cycle gas turbine processes (CCGT) in which the waste gases from the gas turbines are used in electricity production process [24]. The level of energy efficiency in the production of electricity from natural gas is from 0.25 to 0.58 [24, 26]. The energy efficiency in electricity production, μ_e, in this work was assumed to be 0.5. The Energy Development Strategy until 2025 with projections to 2030 [10] assumes the construction of new gas power plants and their connection to the electric power system of Serbia.

Biogas – Biogas can efficiently be used as source of energy in electricity generation. Biogas composition is dominated by CH_4 (50-75 vol. %) and CO_2 (25-45 vol. %). The typical composition of biogas is presented in tab. 3.

Table 3. The typical composition of biogas [27]

Substances	%
CH_4	50-75
CO_2	25-45
H_2O	2-7
O_2	< 2
NH_3	< 1
H_2S	20-20,000 ppm
N_2	< 2
H_2	< 1

There are several technologies suitable for electricity production using biogas: gas engines [28], gas turbines [29], micro turbines [30], and fuel cells [31]. The choice of technology for a particular application depends on the source of biogas, the type of industry, the level of contamination of the biogas, the price of equipment, and the incentives for the use of biogas at national and local level. The energy efficiency in the electricity generation from biogas is 19-34% for gas turbines, 26-30% for micro turbines, while it is 36-50% in fuel cells [32]. At present, the most widespread technology for the production of electricity from biogas are gas engines because of their low initial costs and greater energy efficiency (30-40%) compared to the other available technologies [17, 24]. In this investigation, it was assumed that gas engines will remain the dominant technology for the production of electricity from biogas by 2030. But, the efficiency of electricity production is assumed to grow in the following period, up to 45%. It was also assumed that the fuel cells will have wider use in practice by 2030, because of their high efficiency.

Calculations

The electricity produced from biogas, E_e, was calculated:

$$E_e = P_i T \tag{1}$$

where P_i [kW] is the installed capacity of biogas plants (assumed to be 80 MW in this paper), and T – the number of working hours per year of biogas plants. The volume of biogas, V_{BG}, required to generate this amount of electricity and was calculated using the formula:

$$V_{BG} = \frac{P_i T}{\mu_e LHV_{BG}} \tag{2}$$

The lower heating value of biogas, LHV_{BG} (60% CH_4) was assumed to be 6 kWh/m^3 according to the recommendation of the European Biomass Association given in Biogas Road Map for Europe [33]. The operating hours for gas engine biogas power plants are between 5000 and 8000 hours per year [15, 34]. In this work, the assumed number of operating hours, T, was 7700 hours. The number of operating hours of gas turbines is 8,300-8,500 [32], 7,450-7,900 hours of micro turbines [32], and about 7,900-8,300 hours of fuel cells [32], given the continuous biogas supply. As the biogas supply depends on different factors, such as hydraulic retention time, substrate type and many others, the assumed value of 7700 hours per year can be applied to other technologies also.

The amount of Kolubara lignite required to produce the calculated amount of electricity, M_L, and is determined according to:

$$M_L = \frac{E_e}{\mu_e \; LHV_C} \tag{3}$$

where LHV_C is lower heating value of Kolubara lignite (8 MJ/kg of lignite).

The volume of natural gas, required for the system whose output is equal to the electricity produced from biogas power plants of the total power of 80 MW was determined:

$$V_{NG} = \frac{E_e}{\mu_e \; LHV_{NG}} \tag{4}$$

where LHV_{NG} is lower heating value of natural gas (10 kWh/m^3_N of natural gas). During the process of anaerobic digestion (S1), the amount of 1-10% of biogas is lost [18], mainly during storage [11], causing CH_4 emissions into the environment. In this work, bearing in mind that the average loss of biogas is 1-3% [11, 18], the assumed value of biogas losses amounted to 2%. The V_{BG} represents 98% of the total quantity of the biogas produced in the process of anaerobic digestion. The volume of biogas released into the environment during anaerobic digestion, $V_{BG,losses}$ is calculated:

$$V_{BG,losses} = V_{BG}\left(\frac{100}{98} - 1\right) \tag{5}$$

The mass of CH_4 released into the environment from biogas during the anaerobic digestion process, M_{L,CH_4}, was calculated:

$$M_{LCH_4} = 0.6 \; V_{BG,losses} \, \rho_{CH_4} \tag{6}$$

where ρ_{CH_4} [kgm^{-3}] is the CH_4 density (0.71 kg/m^3). The emission factors used for the calculations are shown in tab. 4.

Table 4. Emission factors for different energy sources

Pollutant	Emission factors for biogas	Emission factors for Kolubara lignite	Emission factors for natural gas
CO_2	18.7 g/MJ of biogas [35]	1.2 kg/kWh [37]	1.92 kg/m^3 of natural gas [41]
N_2O	1.1 mg/ MJ of biogas [35]	25.3 mg/kg [38]	0.01024 g/m^3 of natural gas [41]
NOx	12 mg/MJ of biogas [36]	173g/GJ [39]	0.0024 kg/m^3 of natural gas [42]
Particles	3.8 mg/MJ of biogas [36]	0.8 g/kWh [40]	0.12 g/m^3 of natural gas [41]
SO_2	5.5 mg/MJ of biogas [35]	700 g/GJ [39]	0.0096 g/m^3 of natural gas [41]
CH_4	1.9 mg/MJ of biogas [36]	172 mg/kg [38]	0.0368 g/m^3 of natural gas [41]

The emissions of the following GHG were considered in this paper: CO_2, CH_4, and nitrogen (I) oxide (N_2O).

Methodology

In this paper, the environmental issues of the three scenarios in which the same amount of electricity is produced from biogas, Kolubara lignite, and natural gas are discussed. The emissions to the environment in each of the scenarios were analyzed and compared to each other.

The following scenarios were considered.

Scenario S1: electricity is produced from biogas generated in anaerobic digestion plants of the total power of 80 MW. In this scenario, emissions into the environment come from the process of anaerobic digestion (loss and CH_4 emissions) and the production of electricity from biogas. In this scenario, the assumed minimal energy efficiency was 0.25, while the maximum value of energy efficiency was 0.45, the value expected for gas engines by 2030. This way, the range of emissions reduction was obtained as in Cuelar and Webber methodology [17].

The development of the technology of the electricity generation from biogas as well as market development in this field is very dynamic. In this paper, in subscenario S1(a) the analysis of the development of the technologies for electricity generation and their efficiencies was performed according to the assumption of the percentage of their use by 2030. In this scenario, it was assumed that by 2030 80% (64 MW) will be installed in gas motors with efficiencies of 0.45, 10% (8MW) in fuel cells with efficiencies of 0.55, and remaining 10% in other technologies with mean efficiency of 0.40.

Different substrates can be used for biogas production, giving the biogas of different composition, which can significantly influence the later electricity generation. According to the research of Cvetkovic *et al.* [9], in subscenario S1(b) it was assumed that 70% (56 MW) of the installed biogas plants will be using agricultural biomass as substrate, 20% (16 MW) communal waste, and 10% (8 MW) waste water from food industry. The following CH_4 share in biogas produced from different substrates was assumed: 52% in biogas from agricultural biomass [14], 60% in biogas from communal waste [43], and 65% in biogas from food industry waste water [44]. Lower heating value of methane was 35.8 MJ/m^3.

Scenario S2: the same amount of electricity produced in scenario S1 is produced in thermal power plant using lignite from Kolubara. The emissions to the environment in this scenario were generated in the process of electricity production from Kolubara lignite.

Scenario S3: the same amount of electricity that was produced in scenario S1 is generated in power plants which use natural gas in CCGT process. The emissions into the environment in this scenario are the result of electricity production from natural gas.

Methodology for GHG emissions calculation

The system borders for the calculation of GHG emissions in S1 included biogas production process and electricity generation from the obtained biogas, while in the cases of S2 and S3, the process of electricity generation from these resources was considered. The total CH_4 emissions in scenario S1 are equal to the sum of the emissions during anaerobic digestion (loss of CH_4) and emissions generated in the electricity generation process. The equivalent emissions of CO_2, CH_4, and N_2O were calculated based on total emissions of these gases multiplied by the conversion factors. In accordance with the recommendations of the Intergovernmental Panel on Climate Change [45], the following conversion factors were applied: 1 kg CO_2 = 1 kg CO_{2eq}, 1 kg CH_4 = 25 kg CO_{2eq}, and 1 kg N_2O = 298 kg CO_{2eq}.

The reduction of the GHG emissions was compared to the first scenario:

$$Z_{\mathrm{I,II,III}} = Z_{\mathrm{CO_2}} + Z_{\mathrm{CH_4}} + Z_{\mathrm{N_2O}} \tag{7}$$

where $Z_{\mathrm{I,II,III}}$ [kg CO_{2eq}] represent the equivalent GHG emissions in the appropriate scenarios. Net GHG emissions in appropriate scenarios were determined by the eqs. (8a)-(8c):

$$\Delta Z_{\mathrm{GHG,I-II}} = Z_{\mathrm{I}} - Z_{\mathrm{II}}, \quad \Delta Z_{\mathrm{GHG,\,I-III}} = Z_{\mathrm{I}} - Z_{\mathrm{III}}, \quad \Delta Z_{\mathrm{GHG,II-III}} = Z_{\mathrm{II}} - Z_{\mathrm{III}} \qquad \text{(8a,b,c)}$$

where Z_{I} is the total equivalent GHG emissions in S1, Z_{II} – the total equivalent GHG emissions in S2, and Z_{III} – the total equivalent GHG emissions in S3.

Results and discussion

The total amount of electricity generated in all of the scenarios was obtained from eq. (1) and it amounted to 616 million kWh per year. The mass of Kolubara lignite necessary for the production of 616 million kWh of electricity in (S2) was determined according to eq. (3), while the volumes of biogas and natural gas required for the generation of the same amount of electricity were calculated from eqs. (2) and (4). The obtained mass of Kolubara lignite was 840 kt per year and the volumes of biogas and natural gas were from 229.1 million m^3_N to 410.6 million m^3_N of biogas (depending on energy efficiency), and 123.2 million m^3 of natural gas per year. Having in mind that 30 million tons of lignite is produced per year in the mines of Kolubara basin [23], the results show that the use of biogas as a renewable energy source can save about 2% of lignite production from the Kolubara basin. The use of biogas would contribute to a greater diversification of resources for energy production and increased energy independence from imported energy. Assuming the range of investments of 3,300 $/kW-5,000 $/kW [46], in order to reach 80 MW of installed power from biogas, the rough calculation can be made that this will require the investment between 264 and 400 million dollars by 2030, which depends on technology development, incentives for biogas projects and other factors.

Using eqs. (1) and (2), the calculated values of the amounts and energy content of the biogas needed for electricity generation in different technologies in subscenario S1(a) was calculated: 94.1 ktoe for gas motors, 13.2 ktoe for fuel cells, and 9.6 ktoe for other technologies. The obtained data indicate that the total of 117.0 ktoe of biogas potential is used for electricity generation, which amounts to 11.5% of the total biogas production potential in the Republic of Serbia [9].

Using the same equations, the results for the subscenario S1(b) were: 82.4 ktoe for agricultural biomass as substrate, 23.54 ktoe for communal waste, and 11.8 ktoe for food industry waste water as substrate.

The obtained data indicate that the total of 117.7 ktoe of biogas potential is used for electricity generation, which amounts to 11.7% of the total biogas production potential in the Republic of Serbia [9].

The values determined for the emissions in each of the scenarios are shown in tab. 5.

The data from tab. 5 show that the emission of CO_2 is dominant in all the scenarios. The emissions of CO_2 from Kolubara lignite combustion (S2) are the largest. They are 502.7 kt larger than the emissions of CO_2 in S3 and 4.5-8 times larger than the emissions in S1 (depending on the energy efficiency of the electricity production from biogas). By comparing the emissions in S1 and S3 it can be concluded that the CO_2 emissions from the plant using natural gas are 1.43-2.55 times larger than the emissions from plants using biogas. The analysis of these emissions is very important because CO_2 is GHG and contributes to global warming.

Table 5. Emissions per scenarios

Pollutant	S1		S2	S3
	$\mu_e = 0.25$	$\mu_e = 0.45$		
CO_2	165.86 kt	92.55 kt	739.2 kt	236.54 kt
NO_x	106.43 t	59.39 t	383.64 t	295.68 t
N_2O	9.756 t	5.44 t	21.25 t	1.26 t
SO_2	48.78 t	27.22 t	1.77 kt	1.18 t
Particles	33.70 t	18.8 t	492.8 t	14.98 t
CH_4	3,570 t	2,000 t	144.4 t	4.53 t

The total emissions of NO_x are also the largest in S2 (tab. 5). The emissions in this scenario are 3.66-6.45 times greater than the emissions of NO_x from plants which use biogas as a fuel. Emissions of NO_x in S3 are smaller than the emissions from the plant using Kolubara lignite S2 by 87.96 t.

The emissions of N_2O (tab. 5) are 5.54% of the total emissions of NO_x in S2 when using lignite as an energy source. The emissions of N_2O in the case when biogas is used as an energy source (S1) are 4.32-7.73 times greater than the emissions of N_2O in the case when natural gas is used as an energy sources (S3).

Based on the results of the calculation of the emissions of SO_2 (tab. 5) in the considered scenarios, it can be concluded that the largest emissions of SO_2 were in S2. They are 36.3-65 times greater than the emissions in the case biogas is used as an energy source (S1). Emissions of SO_2 in S1 were 23.1-41.34 times greater than in the case the natural gas is used as energy source. This fact is the consequence of the higher concentrations of sulfur in the form of hydrogen sulfide in biogas which generates SO_2 during combustion process.

The emissions of particulate matter (tab. 5) are the largest in S2. The value of these emissions in S2 is 14.62-26.21 times larger than the emissions of particulates in S1. By comparing the emissions of particles in S1 and S3, it can be concluded that the emissions are very similar. The differences may arise from different combustion technologies of biogas or natural gas and installation of more efficient devices which reduce the emission of particulate matter.

The equivalent GHG emissions (CO_2, CH_4, and N_2O) in each of the scenarios are shown in tab. 6.

Table 6. The equivalent GHG emissions per scenarios

GHG	I scenario ($\mu_e = 0.25$) [kt CO_{2eq}]	I scenario ($\mu_e = 0.45$) [kt CO_{2eq}]	II scenario [kt CO_{2eq}]	III scenario [kt CO_{2eq}]
CO_2	165.86	92.55	739.2	236.54
CH_4	89.25	50	3.61	0.113
N_2O	2.9	1.62	6.33	0.375
Total GHG	**258.01**	**144.17**	**749.14**	**237.028**

The total GHG emissions in S1 amounted to 258 kt CO_{2eq} and 144.17 kt CO_{2eq} for $\mu_e = 0.25$ and 0.45, respectively. The total emissions of GHG in S2 and S3 were to 749.14 kt CO_{2eq} and 237 kt CO_{2eq}, respectively. In scenario S1, GHG emissions from N_2O are negligible compared to the two other GHG (CO_2 and CH_4). In scenarios S2 and S3, the emission of CO_2 is dominant, while GHG emissions related to CH_4 and N_2O are minimal.

The net GHG emissions have the maximum value in the case when S1 with $\mu_e = 0.45$ and S2 are compared, and it amounts to –604.97 kt CO_{2eq}. The negative sign indicates that these are savings in emissions of GHG into the environment. Annual GHG emissions from power sector in 2010 were 28.96 Mt CO_{2eq} [22]. The use of biogas for electricity production would lead to savings of 1.7%-2.1% of the total emissions from power sector.

The results from tab. 6 also show the large difference in the savings of GHG when S1 and S2 are compared for different values of energy efficiency ($\mu_e = 0.25$ and $\mu_e = 0.45$). The difference was 113.84 kt CO_{2eq} in this study.

Specific net savings of GHG emissions, expressed as kg CO_{2eq}/kWh of produced electricity in the present study was 791 g/kWh for S1 with $\mu_e = 0.25$ *vs.* S2, 982 g/kWh for S1 with $\mu_e = 0.45$ *vs.* S2, 150g/kWh for S1 with $\mu_e = 0.45$ *vs.* S3, and 831.3 g/kWh for S2 *vs.* S3. The obtained values are in good agreement with the results of Bachmaier *et al.* [21] (573-910 g CO_{2eq}/kWh_{el}), and Cuellar and Webber [17] (366-685 g/kWh).

It can be observed that the loss of CH_4 (tab. 6) in the process of anaerobic digestion (S1) substantially participates in the emissions of GHG. The assumed loss of CH_4 in this paper of 2% means the emission from 2.75 to 4.93 million m^3 of biogas to the environment, depending on μ_e. Losses of biogas into the environment during anaerobic digestion go sometimes up to 10% [18]. This indicates that the management and prevention of loss of bio-methane in the process of storage in anaerobic digestion is of key importance when comparing GHG emissions from facilities that use biogas and natural gas. From eqs. (2), (5)-(7), and (8b) and the values of equivalent GHG emissions in S1 and S3 (tab. 6), $\Delta Z_{GHG,\ I–III}$ as a function of loss of CH_4 during (X) anaerobic digestion ($\mu_e = 0.45$) can be presented in fig. 1.

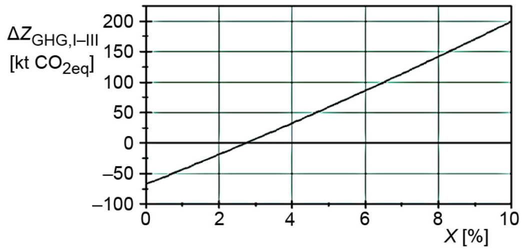

Figure 1. The $\Delta Z_{GHG,\ I–III}$ as a function of loss of methane during anaerobic digestion ($\mu_e = 0.45$)

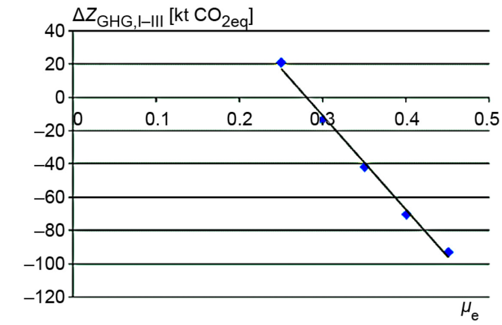

Figure 2. The $\Delta Z_{GHG,\ I–III}$ as a function of energy efficiency in electricity production from biogas (2% loss of CH_4 during anaerobic digestion)

Figure 1 shows the comparison of S1 ($\mu_e = 0.45$) and S3 where loss of more than 2.8% of biogas leads to the loss of net GHG emissions savings. These data indicate the importance of using the technology of biogas production which would lead to minimal losses from the system. Losses of biogas can grow with the years of use of biogas plants, but good maintenance and management can minimize the growth.

Using different values of energy efficiencies in the range from 0.25 to 0.45, eqs. (2), (5)-(7), and (8b) and the values of equivalent GHG emissions in S1 and S3 from tab. 6,

$\Delta Z_{GHG, I-III}$ as a function of energy efficiency can be obtained (fig. 2). It can be calculated that for the efficiency of electricity production from biogas greater than 0.28, there is the reduction in the GHG emissions comparing S1 ($\mu_e = 0.45$) and S3.

The calculations performed in this paper may involve a degree of uncertainty in the choice of data and the equations used. These uncertainties are primarily related to the composition of biogas, the degree of efficiency in energy transformation, the assumption of average emissions from biogas plant, estimate of the emissions from power plants, as well as the development of new technologies for more efficient use of biogas, coal and natural gas that could occur. The present results represent only the modeling and optimization of the possible environmental benefits in biogas production, but reaching these values will largely depend on the development of biogas sector in Serbia until 2030.

Conclusions

The results of this paper quantify the potential reduction in emissions in the process of production of electricity from biogas obtained by anaerobic digestion in comparison to the production of the same amount of electricity from fossil resources (Kolubara lignite and natural gas). Through the analysis of different scenarios this study suggests that in the case of annual production of electricity from biogas power plants of 80 MW (S1) it would result in:

- up to 840 kt substitution of Kolubara lignite (S2) or 123.2 million m^3 of natural gas (S3)
- the reduction of CO_2 emissions 4.5-8 times as well as the reduction NO_x 3.6-6.46 times in comparison to use of Kolubara lignite (S2)
- the savings of GHG emissions between 491.13 kt CO_{2eq} and 604.97 kt CO_{2eq} in comparison to use of Kolubara lignite (S2)
- to reduction of emissions of GHG up to 92.37 kt CO_{2eq} in relation to the use of natural gas (S3)

The analysis performed in this paper has shown that the required electricity generation can be obtained using 11.5% of the total biogas potential. Also, it has shown that 80 MW of biogas power plants can be supplied by biogas produced from substrates which amount to 11.7% of the total biogas potential.

The most significant benefits that could be expected from the production of energy in new power plants in the Republic of Serbia are production of energy from clean sources and the reduction of emissions of gases with greenhouse effect. The results of this study show that the production of electricity from new biogas plant meets the mentioned criteria.

Nomenclature

E_e – electricity produced from biogas, [kWh]
LHV_{BG} – lower heating value of biogas, [kWhm^{-3}]
LHV_C – lower heating value of Kolubara lignite, [MJkg^{-1}]
LHV_{NG} – lower heating value of natural gas, [kWhm$^{-3}_N$]
M_L – mass of Kolubara lignite, [kg]
M_{L,CH_4} – mass of methane released into the environment from biogas during the anaerobic digestion, [kg]
P_i – the installed capacity of biogas plants, [kW]
T – number of working hours per year of biogas plants, [h]
V_{BG} – volume of biogas, [m^3]
$V_{BG,losses}$ – volume of biogas released into the environment during anaerobic digestion, [m^3]
V_{NG} – volume of natural gas, [m^3]
X – loss of methane in process of anaerobic digestion, [%]
Z_I – total equivalent GHG emissions in S1, [kg CO_{2eq}]
$Z_{I,II,III}$ – equivalent GHG emissions in the appropriate scenarios, [kg CO_{2eq}]
Z_{II} – total equivalent GHG emissions in S2, [kg CO_{2eq}]

Z_{III} – total equivalent GHG emissions in S3, [kg CO_{2eq}]

Greek symbols

μ_e – energy efficiency of the electricity production, [–]
ρ_{CH_4} – methane density, [kgm^{-3}]

References

[1] ***, Second Environmental Performance Review for Republic of Serbia, Unece, 2007, available at http://www.unece.org/fileadmin/DAM/env/epr/epr_studies/native/Serbia%20II.pdf
[2] ***, National Program of Environment Protection up to 2020 (in Serbian), available at http://www.zzps.rs/novo/kontent/stranicy/propisi_strategije/Nacionalni_program_zastite_%20zs.pdf
[3] ***, First (Initial) National Communication of the Republic of Serbia under the United Nations Framework Convention on Climate Changes, published by Ministry of Environment and Spatial Planning, 2010, Belgrade
[4] ***, Directive 2009/28/EC of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources
[5] ***, Report on the environmental situation in the Republic of Serbia for 2012 year (in Serbian), Serbian Environment Protection Agency, Belgrade, 2013, available at http://www.sepa.gov.rs/download/Izvestaj_2012.pdf
[6] ***, Regulation on Requirements for Obtaining the Status of the Privileged Electric Power Producer (in Serbian), Official Gazette of the Republic of Serbia, No. 8/13, 2013, available at http://www.mre.gov.rs/doc/efikasnostizvori/Uredba%20o%20uslovima%20i%20postupku%20sticanja%20statusa%20povlascenog%20proizvodjaca03.07.pdf
[7] ***, Regulation on Incentive Measures for the Production of Electricity by Using Renewable Energy Sources and Combined Heat and Power (in Serbian), Official Gazette of the Republic of Serbia, No. 8/13, 2013, available at http://www.mre.gov.rs/doc/efikasnostizvori/B02%20Uredba%20o%20merama%20podsticaja%20za%20povlascene%20proizvodjace05.02.15.pdf
[8] ***, Serbian National Renewable Energy Action Plan (NREAP) up to 2020 (in Serbian), Official Gazette of the Republic of Serbia, No. 53/13, 2013, available at http://www.mre.gov.rs/doc/efikasnostizvori/nreap%20of%20republic%20of%20serbia%2028_june_2013.pdf?uri=celex:32009L0028
[9] Cvetković, S., *et al.*, Potentials and Status of Biogas as Energy Source in the Republic of Serbia, *Renewable and Sustainable Energy Reviews, 31* (2014), Mar., pp. 407-416
[10] ***, Strategy of Energy Development in the Republic of Serbia until 2025 with projections up to 2030, available at http://www.srbija.gov.rs/vesti/dokumenti_sekcija.php?id=45678
[11] Liebetrau, J.,*et al.*, Methane Emissions from Biogas-Producing Facilities within the Agricultural Sector, *Engineering in Life Sciences*, *6* (2010), 10, pp. 595-599
[12] Capponi, S., *et al.*, CO_2 Savings Affect the Break-Even Distance of Feedstock Supply and Digestate Placement in Biogas Production, *Renewable Energy*, *37* (2012), 1, pp. 45-52
[13] Laramee, J., Davis J., Economic and Environmental Impacts of Domestic Bio-Digesters: Evidence from Arusha Tanzania, *Energy for Sustainable Development, 17* (2013), 3, pp. 296-304
[14] Pucker, J., *et al.*, Anaerobic Digestion of Agricultural and other Substrates – Implications for Greenhouse Gas Emissions, *Animal*, *7* (2013), June, pp. 283-291
[15] Brynolf, S., *et al.*, Environmental Assessment of Marine Fuels: Liquefied Natural Gas, Liquefied Biogas, Methanol and Bio-Methanol, *Journal of Cleaner Production*, *74* (2014), May, pp. 86-95
[16] Akhgari, P. A., Kamalan, H., Economical – Environmental Evaluation of Natural Gas and Renewable Energy Systems, *International Journal of Energy Research, 37* (2013), 12, pp. 1550-1561
[17] Cuelar, A. D., Webber, M. E., Cow Power: The Energy and Emissions Benefits of Converting Manure to Biogas, *Environmental Research Letters, 3* (2008), 3, pp. 1-8
[18] Scholz, L. *et al.*, Greenhouse Gas Mitigation Potential and Mitigation Costs of Biogas Production in Brandenburg Germany, *AgBioForum*, *14* (2011), 3, pp. 133-141
[19] Kaparaju, P., Rintala, J., Mitigation of Greenhouse Gas Emissions by Adopting Anaerobic Digestion Technology on Dairy, Sow and Pig Farms in Finland, *Renewable Energy*, *36* (2011), 1, pp. 31-41
[20] Aurich, M.A., *et al.*, Impact of Uncertainties on Greenhouse Gas Mitigation Potential of Biogas Production from Agricultural Resources, *Renewable Energy*, *37* (2012), 1, pp. 277-284
[21] Bachmaier, J., *et al.*, Greenhouse Gas Balance and Resource Demand of Biogas Plants in Agriculture, *Engineering in Life Sciences*, *10* (2010), 6, pp. 560-569

[22] ***, Aspect of Climate Change on Development of the Energy Sector in Serbia, IPA EU SuDES Project, Belgrade, 2012
[23] Milisavljević, V., *et al.,* Consumption of Coal in Serbia and CO_2 Emissions Related to its Combustion, *Proceedings,* XIV SIMTERM 2009, 14th Symposium of Thermal Science and Engineering of Serbia, Sokobanja, Serbia, 2009
[24] ***, Efficiency in Electricity Generation, EURELECTRIC, July 2003. available at http://www.eurelectric.org/Download/Download.aspx?DocumentID=13549
[25] ***, Natural gas, Fuel Chemistry Division, Public Education and Outreach, available at http.www.ems.psu.edu/~pisupati/ACSOutreach/Natural_Gas.html
[26] Mancarella, P. Chicco, C., Assessment of the Greenhouse Gas Emissions from Cogeneration and Trigeneration Systems, Part II: Analysis Techniques and Application Cases, *Energy*, *33* (2008), 3, pp. 418-430
[27] Martinov, M., *et al., Biogas Technology,* Faculty of Technical Science, Novi Sad, Serbia, 2012
[28] Lantz, M., The Economic Performance of Combined Heat and Power from Biogas Produce from Manure in Sweden – A Comparison of Different CHP Technologies, *Applied Energy, 98* (2012), Oct., pp. 502-511
[29] ***, EPA Combined Heat and Power Partnership, Biomass CHP Catalogue of Technologies, EPA, 2007
[30] Somehsaraei, H. N., *et al.*, Performance Analysis of a Biogas-Fueled Micro Gas Turbine Using a Validated Thermodynamic Model, *Applied Thermal Engineering, 66* (2014), Feb., pp. 181-190
[31] Trogisch, S., *et al.*, Operation of Molten Carbonate Fuel Cells with Different Biogas Sources: a Challenging Approach for Field Trials, *Journal of Power Sources*, *145* (2005), 2, pp. 632-638
[32] Trendewicz, A., Braun, R. J., Techno-Economic Analysis of Solid Oxide Fuel Cell Based Combined Heat and Power Systems for Biogas Utilization at Waste Water Treatment Facilities, *Journal of Power Sources*, *233* (2013), July, pp. 380-393
[33] ***, Road Map for Europe, AEBIOM, 2007, available at http://www.4biomass.eu/document/news news/AEBIOM_Biogas_Roadmap.pdf
[34] Hennig, C., Gawor, M., Bioenergy Production and Use: Comparative Analysis of the Economic and Environmental Effects, *Energy Conversion and Management*, *63* (2012), Nov., pp. 130-137
[35] Spielman, M., *et al.,* Lifecycle Inventories of Bioenergy, Report No. 17, Swiss Centre for Lifecycle Inventories, Dubendorf, Switzerland, 2007
[36] Berglund, M., Borjesson, P., Assessment of Energy Performance in the Life-Cycle of Biogas Production, *Biomass and Bioenergy*, *30* (2006), 3, pp. 254-266
[37] Erić, M., *et al.,* Carbon Dioxide Emission from Thermal Power Plant Nikola Tesla A, *Proceedings,* International Conference on Power Plants, Power Plants 2012, Zlatibor, Serbia, 2012, pp. 1303-1312
[38] ***, http://www.epa.gov/climateleadership/documents/emission-factors.pdf
[39] Jovanovic, V. V., Komatina, M. S., NOx and SO_2 Emission Factors for Serbian Lignite Kolubara, *Thermal Science, 16* (2012), 4, pp. 1213-1228
[40] ***, Green Book of the Electric Power Industry of Serbia, Belgrade, 2009
[41] ***, EPA − Emission Factor Documentation for ap-42 Section 1.4 Natural Gas Combustion, available at http://www.epa.gov/ttnchie1/ap42/ch01/final/c01s04.pdf
[42] ***, Lectures (in Serbian), Faculty of Mining and Geology, University of Belgrade, available at http://www.rgf.bg.ac.rs/predmet/RO/VII%20semestar/Sagorevanje/Predavanja/12Ekologija%20sagorevanja.pdf
[43] Frankiewicz, T., Summary and Status of NAMAs in Solid Waste Sector, Global Methane Initiative, Florianopolis, Brazil, 2014
[44] ***, Biogas Renewable Energy, Information Website on Biogas, available at http://www.biogas-renewable-energy.info/biogas_composition.html
[45] ***, IPCC Guidelines for National Greenhouse Gas Inventories 2006, available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/
[46] ***, Biomass for Heat and Power, IEA ETSAP – Technology Brief E05 – May 2010 available at www.etsap.org

Paper submitted: August 12, 2015
Paper revised: November 10, 2015
Paper accepted: November 15, 2015