Techno-Economic Analysis of Biogas Powered Cogeneration

Rade M. Ciric and Zoran Kuzmanovic
Higher Education Technical School of Professional Studies Skolska 1, 21000 Novi Sad, SERBIA
Email: rciric@aol.com

***Abstract*—Climate change, mainly caused by increased greenhouse gases, and reduced fossil fuel reserves, has launched a more intensive use of renewable energy on a global scale. One example of application of the renewable energy is the use of biogas which is produced from livestock manure at the farmyards. The most important goal of building a biogas plant is the environment protection. In addition, it is possible to realize the positive socio-economic effects, promote rural development and make better use of human and material resources at the local level. However, the construction of cogeneration heat and power plant is a complex technical, organizational and investment venture. The objective of this paper is to present a feasibility analysis of biogas power plants for combined heat and power generation including different aspects such as available biomass resources, heat and electricity producing, verification of the requirements for connecting power plant to the grid, as well as analysis of the economic viability.**

***Index Terms*—livestock manure, biogas, distributed generators, cogeneration, techno-economic analysis**

I. Introduction

Climate change, mainly caused by increased greenhouse gases, and reduce fossil fuel reserves, have launched a more intensive use of renewable energy on a global scale. One of them is the use of biogas which is produced from livestock manure at the farmyards and/or energy crops. The special significance of the production and use of biogas is preventing methane gas that increases the greenhouse effect. Also, the use of biogas as a fuel, usually produces heat and electricity, and thereby contributes to achieving objectives. In addition, it is possible to realize the positive socio-economic effects, promote rural development and make better use of human and material resources at the local level.

The Autonomous Province of Vojvodina is an agricultural region in Serbia, with a high potential of biomass as a fuel for use in cogeneration [1]-[4]. Despite, the number of cogeneration plants using biomass of animal origin in Serbia is negligible. There are more reasons for that situation but two are the most important. Firstly, the investors in Serbia do not recognize the potential benefits of such facilities in the energetic, ecological, social and financial terms. The second reason is the lack of systematic incentives for the investment in the renewable energy field from the state.

In order to exploit existing potential of eco-energy, decision makers need an instrument which makes the effects of application of renewable energy solutions measurable in their energetic and cost dimensions but also regarding their ecological impact. The first step in every investment venture is the feasibility study and the techno-economic analysis.

The objective of this paper is to present several aspects of techno-economic analysis of future biogas power plants for combined heat and power (CHP) in a small village in the Autonomous Province of Vojvodina. The verification of the requirements for connection of the CHP plant to the grid is also presented.

II. Biogas Technology

Biogas occurs in anaerobic microbial process conditions (without oxygen). Anaerobic bacteria break down organic matter, and as a product of this process biogas, heat and the rest of the fermentation are produced. Biogas is a mixture of gases, the volume of which makes up about two-thirds of methane (CH_4) and one-thirds of carbon dioxide (CO_2). Methane is a combustible gas, and the goal is its production and use of its energy [5].

During the biogas production, it is important to ensure stability of anaerobic fermentation process. From the technical point, stability implies uniform yields of biogas of approximately equal composition. When considering a potential substrate for biogas production, their characteristics which determine the potential for biogas production, are analyzed. From the standpoint of cost, the most favorable substrate is farmyard manure, solid or liquid, since it is most often obtained from its own farm and is free of charge. Exceptionally, when livestock manure is obtained from another farm, the transportation cost should be predicted.

Liquid farmyard manure is made from animal excrement and transported by pumps and pipelines, Fig. 1. The dry matter content is up to 10%. If a mat is used, we get the solid manure, which has a dry matter content of 40%. The water content of manure is very high (68-93%), which is convenient when manure is combined with other substrates with higher shares of dry weight, and this is, for example, corn silage. The nnutrients, except for a

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portion of nitrogen, after fermentation can be found in the rest of the process, and can be used as fertilizer [5].

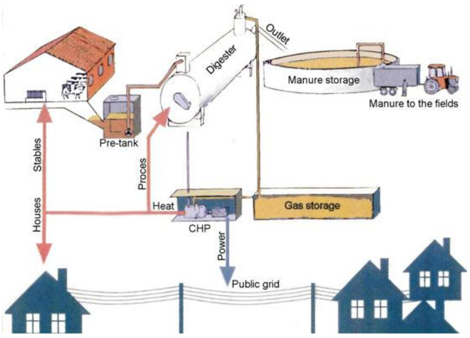

Figure 1. Concept of biogas plant

Figure 2. Fermentors

The facility in the biogas plant makes the equipment for storage, handling and preparation of the substrate, the production and storage of biogas, as well as storage of fermentation residue, Fig. 2. Electric power part of the plant consists of gas engines, power generators, heat exchangers, exhaust system and noise limiter [5], [6].

Mechanical energy produced at the motor shaft is transmitted to the synchronous generator (for rated power larger than 100 kW). One third of the input energy is transformed into mechanical energy, one-third into the heat, which is transferred to the engine coolant, while one-third of the energy used include products of combustion. Efficiency of electricity production (engine + generator) is in the range of 30% to 40%. In the same range is the efficiency of heat production. The combined production of electricity and thermal energy enables achieving the utilization factor of 75% to 78% [6].

III. Technical Feasibility

The first step in the development of the idea of building a biogas plant is to determine the location of the installation. A given location should has enough space for all the components of the plant and there should be posible to use the existing infrastructure. Besides, substrate transport costs should be as low as possible and there should be significant demand of thermal energy. Finally, the biogas plant should have the least impact on the environment. Power plant to be built is in the village Voganj in Vojvodina, covering an area of 7000 ha.

There is a pig farm at the edge of the village, which is about 4 km from the future biogas plant with capacity of 10000 head per year. There are pools at the farm for storing 20000 m^3 of liquid manure, which reduces the cost of building the plant. There are ten small family farms for fattening pigs in the village, with the annual capacity of 2000 to 2500 animals.

The total number of animals at the farms near the future power plant, from which it is possible to buy and transport the liquid manure, is in the range of 30000 to 35000 pigs per annum. Considering that each animal produces about 3.3 m^3 of liquid manure, we can calculate with the amount of 100000 m^3 of substrate potential. The size and power of biogas plants primarily depends on the availability of substrate. One head of cattle provides liquid manure enough for producing 0.1 kW of electricity [3]. Since in the radius of 20 km from the future plant there are 30000 pigs, the potential power of the biogas plant is 3 MW.

Thermal energy is a byproduct during the production of electricity. In the future plant, 1000 kW/hour of electricity and 1000 kW/hour of heat will be producing. With efficiency of CHP plant 0.78 [6], it is necessary to provide nearly 2700 kW/h of primary energy input.

In the immediate vicinity of the future plant there are large consumers of heat such as asphalt plant and silos for the grain storage. There is also the possibility of launching greenhouse food production. If we use the thermal energy from the biogas plant, the cost of greenhouse vegetable production would be reduced by about 30%.

Since there is a possibility that the customers will not spend the entire thermal energy produced, it must be ensured the way to drain the excess energy. This is achieved using the system of channels which are in the immediate vicinity of the CHP plant.

IV. Connection to the Grid

In general there are four conditions that are tested when connecting distributed generators (DG) to the distribution system, including: short-circuit power, voltage increase, flickers and higher harmonics [7]. The last two conditions are related primarily to the DG which uses the sun and wind as primary fuel energy. On the other side, when examining the conditions for connecting the biogas powered DG to the grid, basically we check the conditions of maximum generator power, in terms of short circuit in the grid and voltage increase at the connecting point.

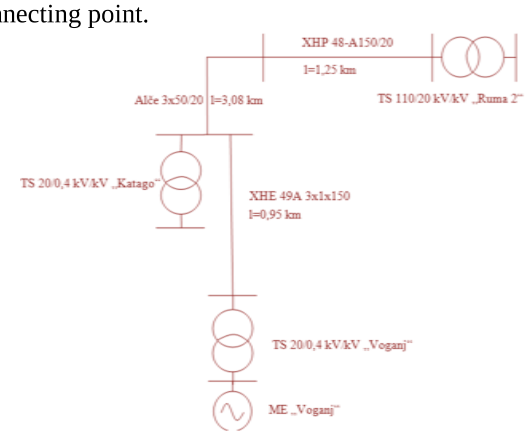

Figure 3. Connecting DG ME "Voganj" to the grid

There is no existing distribution network to the site where the new biogas plant is planned to be built. As the connection point to the distribution network, the existing TS 20/0.4 kV "Katago", which is supplied from the 110/20 kV "Ruma 2" has been selected, Fig. 3.

The verification of fulfilling conditions for connecting the considered power plant to the 20 kV network will be performed.

A. Short Circuit Power

The input data for short circuit calculation are given in the following:

- Subtransient three phase short circuit current of the transmission network, $I_{KS}^{//} = 5.84$ kA;
- The parameters of the power transformer in TS 110/20 kV „Ruma 2":
- transmission ratio 110/21 kV/kV,
- indicated apparent power $S_n = 31.5$ MVA,
- short-circuit voltage $u_k = 15.385$ %, and
- indicated copper loss $P_{CU} = 184.1$ kW.

The equivalent circuit of the fault loop reduced to 20 kV voltage level, for calculating short-circuit currents, is presented on Fig. 4. The impedance of the elements reduced to the 20 kV voltage level are:

Z_{KP20} is impedance of the 110 kV network,

Z_{KTA20} is impedance of the transformer 110/20 kV/ kV in the TS „Ruma 2",

Z_{VB20} is impedance of the 20 kV feeder supplying TS 20/0.4 kV „Katago",

$I_{KSU}^{//}$ is initial symmetrical fault current, and

U_n is rated voltage of the grid.

Based on the standards IEC 781 and IEC 909, the impedance of the transmission network is calculated using expression (1):

$$Z_{KP110} = \frac{cU_n}{\sqrt{3}I_{KS}^{//}} = \frac{1{,}1 \cdot 110}{\sqrt{3} \cdot 5{,}84} = 11{,}96\Omega \tag{1}$$

Reducing the impedance of the transmission network at 20 kV voltage level is performed by the expression (2):

$$Z_{KP20} = \frac{U_{n20}^2}{U_{n110}^2} \cdot Z_{KP110} = \frac{21^2}{110^2} \cdot 11{,}96 = 0{,}43598\Omega \tag{2}$$

The reactance and resistance of the transmission network are:

$$\begin{aligned} X_{KP20} &= 0{,}955 Z_{KP20} = 0{,}416\Omega \\ R_{KP20} &= 0{,}1 X_{KP10} = 0{,}0416\Omega \end{aligned} \tag{3}$$

Calculation of the impedance, resistance and reactance of the power transformer in the 110/20 kV/kV "Ruma 2" to 20 kV side is done according to the following expressions (4):

$$\begin{aligned} Z_{KTA20} &= \frac{u_k U_{n20}^2}{100 \cdot S_n} = \frac{15{,}385 \cdot 21^2}{100 \cdot 31{,}5} = 2{,}1539\Omega \\ R_{KTA20} &= \frac{P_{CU} U_{n20}^2}{S_n^2} = \frac{184{,}082 \cdot 10^3 \cdot 21^2 \cdot 10^6}{31{,}5^2 \cdot 10^{12}} = 0{,}082\Omega \\ X_{KTA20} &= \sqrt{Z_{KTA20}^2 - R_{KTA20}^2} = \sqrt{2{,}1539^2 - 0{,}082^2} = 2.152\Omega \end{aligned} \tag{4}$$

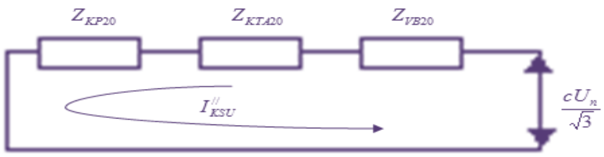

Figure 4. Eequivalent circuit of fault loop

The resistance and reactance of the 20 kV line are:

$$\begin{aligned} R_{VB20} &= 3.983\Omega \\ X_{VB20} &= 2.334\Omega \end{aligned}$$

The total fault loop impedance at TS 20/0.42 kV/kV "Katago", according to the equivalent scheme on Fig. 4 is given by the expressions (5):

$$\begin{aligned} R_{KU20} &= R_{KP20} + R_{KTA20} + R_{VB20} = 0{,}0416 + 0{,}082 + 3.983 = 4{,}106\Omega \\ X_{KU20} &= X_{KP20} + X_{KTA20} + X_{VB20} = 0{,}416 + 2{,}152 + 2{,}334 = 4{,}902\Omega \\ Z_{KU20} &= \sqrt{X_{KU20}^2 + R_{KU20}^2} = \sqrt{4{,}902^2 + 4{,}106^2} = 6{,}39\,\Omega \end{aligned} \tag{5}$$

Initial symmetrical fault current and the three-phase short circuit power at the 20 kV bus-bar of the transformer station 20/0.42 kV/kV "Katago" are calculated according to the standards IEC 781 and IEC 909, using the following expressions:

$$\begin{aligned} I_{KSU}^{//} &= \frac{cU_n}{\sqrt{3} \cdot Z_{KU10}} = \frac{1{,}1 \cdot 20}{\sqrt{3} \cdot 6{,}39} = 1{,}99kA \\ S_{KSU} &= \sqrt{3} U_n I_{KSU}^{//} = \sqrt{3} \cdot 20 \cdot 10^3 \cdot 1{,}99 \cdot 10^3 = 68{,}81MVA \end{aligned} \tag{6}$$

B. Criteria of Allowed DG Power

Checking the criteria of allowed DG apparent power at the connection point of the grid is performed according to the expression (7) [7]:

$$S_{DG} \le \frac{S_{KSU}}{50k} = \frac{68{,}81}{50 \cdot 1} = 1{,}38MVA \tag{7}$$

where k=1 for synchronous generators.

Maximum apparent power of DG that can be connected to the 20 kV bus in TS 20/0.42 kV/kV "Katago", is 1.38 MVA, which is more than the rated electric power of the future CHP plant. It can be concluded that there is a possibility of connecting considered DG to the 20 kV grid without the harmful effects in the network.

C. Criteria of Voltage Increase

Now let us check the voltage in the connection point of DG. Voltage increase at 20 kV bus-bar in TS "Katago" after connecting DG is calculated using expression (8), [8]:

$$\Delta u(\%) = 100 \cdot \frac{S_{DG}}{S_{KSU}} \cdot \cos(\psi_K + \varphi_{DG}) \le 2\% \tag{8}$$

where:

$\Delta u(\%)$ is voltage increase in the DG connection point (%),

S_{DG} is indicated apparent power of DG,

ψ_K is argument of the network impedance, measured from the connection point, and

φ_{DG} is argument of DG loading.

Voltage increase in the connection point must not exceed 2% of the rated voltage.

Given that the maximum value of the cosine function is equal to 1, and respecting the apparent power of DG S_{ME} = 1MVA and short circuit power S_{KSU} = 68.81 MVA, we obtain, from the graph on Figure 5, the amount of 1% of corresponding voltage increase. Accordingly the voltage increase condition (8) after connecting considered DG to the grid is satisfied.

D. DG Connection to the Grid

Since the considered generator produces electricity on the voltage 0.42 kV, it is necessary to build new TS 20/0.42 kV/kV, 1000 kVA, which will raise the voltage to 20 kV level. New TS 20/0.42 kV/kV "Voganj" will plug into the output cell 20 kV at the TS 20/0.42 kV/kV "Katago" by cable XHE 49A 3x1x150 mm2, 950 m, Fig. 3 .

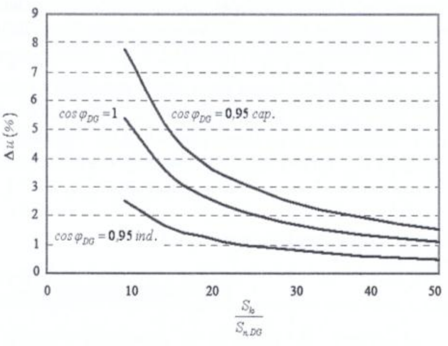

Figure 5. Voltage increase after connecting DG to the grid

V. PROFITABILITY

The value of investment has a great influence on the financial evaluation of the project. The value of investment per kW of the installed power decreases with increasing size of the cogeneration plant. Price of cogeneration plant based on "turn key" scheme for 1000 kW CHP unit is 500.000 € [4], [5]. Before starting the construction of CHP plant, there are additional costs related to obtaining permits, as well as the cost of consultancy service amounting to about 90.000 € [4].

Further, there are additional costs that must be taken into account, such as the procurement and construction of the TS 20/0.42 kV/kV and the 20 kV cable line, and its value is around 200.000 €. Finally, the total investment cost of considered CHP plant is about 1.29 million €.

It is necessary to hire two workers to keep the production process, whose gross salary per year is about 20.000 €. Furthermore, there is maintenance cost of the CHP plant about 60.000 € per annum. However, the largest costs after the CHP construction relating to the procurement of farmyard manure. Price of the manure per year is around 300.000 €, including the cost of transport. The total annual cost of maintenance and electricity production of the CHP plant amounts to 380.000 €. In the following two case studies regarding different financing scheme will be presented.

Case study 1

In this case the biogas plant is financed from the investors own funds. This type of financing is currently the best option in Serbia, since the interest rate is very high, around 15-20% annually.

The CHP plant will operate eleven months of the year. One month per year is required for insertion of fresh substrate in silos, as well as for regular annual maintenance of the CHP. The CHP plant will operate 4000 h/year, producing around 4 GWh of electricity per year and the same amount of heat.

In accordance with the Directives of the Government of the Republic of Serbia, the price of electricity from this type of the renewable energy sources, accounts for 0.16 €/kWh and it is guaranteed in 12 years period,. That would make the gross income of 640.000 € per year. By Ssubtracting tax (20 %) and the cost of maintenance and procurement of fuel, the net earnings annually will amount to 132.000 €. If the income is realized only by selling electricity to the Electric Power Industry of Serbia, the return on investment would come in about 9.8 years.

However, there is an opportunity to earn significant revenue by selling heat produced in the CHP. To make large iindustrial customers be interested in purchasing the thermal energy from the CHP unit, it is necessary to offer a price that is lower by about 20% from the current price of district heat, which is 0.05 € / kWh.

By selling all produced heat energy, the CHP plant owner would realize gross income of 200.000 €/year, or net 160.000 €/year (regular annual expenses are deducted from income on the sale of electricity). The rrevenue that would be realized by selling thermal energy reduces the repayment period of the CHP plant to 4.4 years. The total annual revenue that would be realized by selling electricity and heat would amount to around 300.000 €.

Case study 2

In this case the CHP plant is financed using 15 years loan with the annually interest rate 7 %. Factor of capital return CRF for a period of *n* years and the interest rate *i* is calculated according to the expression (9) [6]:

$$CRF(i,n)=\frac{i(1+i)^n}{(1+i)^n-1}=\frac{0.07(1+0.07)^{15}}{(1+0.07)^{15}-1}=0{,}1098\ 1\!\!\diagup_{year} \qquad (9)$$

The annual loan repayment A of a capital base K is calculated according to expression (10):

$$A=K\cdot CRF(0{,}07,\ 15)=1.290.000\cdot 0{,}1098=141.642\ {}^{Euro}\!\!\diagup_{year} \qquad (10)$$

The annual operating and maintenance costs of the CHP plant are therefore:

141.642+380.000 = 521.642 €/year.

The average costs of producing kWh of electricity from the CHP plant are:

$$CkWh=\frac{annual\ \ costs}{annual\ \ energy}=\frac{521.642}{4.000.000}=0.13\frac{Euro}{kWh} \qquad (11)$$

Since the guaranteed price of kWh of electricity is 0.16 €/kWh, the project is cost-effective. Under these conditions the CHP unit pays back in 4.6 years if both heat and power are delivered, or in 11 years if only the electricity is delivered.

VI. CONCLUSION

The production and use of biogas have multiple positive effects from the point of view of environmental protection, the use of renewable energy, support the national economy and the development of rural areas.

This paper analyzes bio-energy resources, the conditions of connecting DG to the grid and the economic viability of development of biogas CHP in a small village in Vojvodina, Serbia. Presented methodology can be a part of the tool which makes the energetic, ecologic and economic effects of application of biogas powered cogeneration, measurable.

The cost-benefit analysis has shown that with reasonable interest rate such a plant pays back in less than five years if both heat and electricity are delivered, or in eleven years if it delivers only the electricity. Obviously, the producing and selling both electricity and heat from the CHP plant is the most cost effective.

It is expected that the state and provincial gouverments in Serbia remove all the bariers in the renewables sector and strongly encourage the development of biogas technology and the construction of new biogas plants in Serbia [9], [10]. It is essential that the tariffs for electricity delivered are in line with the actual costs of production in order to deliver long-term profitable operation of the biogas plant. Further, it is necessary to introduce certain incentives which would encourage energy efficiency improvement, such as greater use of waste heat energy, and bonuses for the employment in the renewable energy sector [11], [12].

REFERENCES

[1] D. Gvozdenac, R. Ciric, and M. Tesic, "Prospects of energy efficiency improvement and development of the renewable energy sources in province of vojvodina," in *Proc.20th World Energy Congress*, Rome, Italy, November 2007, pp. 12-15.

[2] *The Main Directions of Technological Development of Vojvodina*, Provincial Secretariat for Science and Technological Development, Novi Sad, 2007.

[3] *Study on the Evaluation of the Total Potential and Possibilities of Production and Use of Biogas in Ap Vojvodina*, Faculty of Technical Sciences, Novi Sad, 2011.

[4] B. Lepotic, D. Kovacevic, D. Stojiljkovic, and B. Lazarevic "The construction of electricity/heat generation from biomass in serbia-guide for investors, ministry of mines and energy of the republic of serbia," Belgrade, 2010.

[5] T. Al Seadi, D. Rutz, H. Prassl, M. Kottner, T. Finsterwalder, Volk S., and R.: Janssen, *Biogas Handbook*, University of Southern Denmark, Esbjerg, 2008.

[6] G. M. Masters, *Renewable and Efficient Electric Power Systems*, John Wiley & Sons, Inc, 2004.

[7] "Directorate for development of electric power industry of Serbia," *Technical Recommendation*, no. 16, Belgrade, 2011

[8] V. Mijailovic, *Distributed Energy Resources*, Akademska Misao, Belgrade, 2011.

[9] J. Petrovic, D. Gvozdenac, and R. Ciric, "Biomass potential and barriers for its use for energy purposes in vojvodina," in *Proc. 5th PSU-UNS International Conference on Engineering and Technology (ICET 2011)*, Phuket, Thailand, 2-3 May, 2011, pp. 252-255.

[10] *The Energy Law*, Official Herald of the Republic of Serbia, no. 84, 2004.

[11] *Energy Development Strategy of the Republic of Serbia until 2015*, Official Herald of the Republic of Serbia, 2005, no 44.

[12] D. Gvozdenac, R. Ciric, and J. Petrovic, "Energy efficiency and renewable energy sources in province of vojvodina-strategy implementation program," in *Proc. 6th MedPower2008*, Thessaloniki, Greece, 2-5 November, 2008, paper no. 226.

Rade Ciric gained Dipl.- Ing diploma from the University of Novi Sad in 1987, Master of Science degree from the University of Belgrade in 1992, and Doctor of technical science degree (PhD) from the University of Novi Sad - Serbia in 2000, all in electrical engineering. From 1987 to 2003 Dr Ciric was with EPS- Elektrovojvodina Novi Sad. Dr Ciric was Post-Doctoral Research Fellow at the UNESP Ilha Solteira-SP, Brazil in 2001/2002 and the Visiting Professor in Power Systems and Electronics Research Group, University of the West of England (UWE), Bristol, UK in 2004/2005, through The Leverhulme Trust scheme. Dr Ciric was with the Secretariat for Science and Technological Development in the Government of AP Vojvodina, Serbia from 2005 to 2012. Dr Ciric is now Professor at the Higher Education Technical School of Professional Studies in Novi Sad and the Associated Professor at the Faculty of Electrical Engineering, University of Belgrade, Serbia.

Zoran Kuzmanovic graduated at the Higher Education Technical School of Professional Studies in Novi Sad in 2013.