INTERNATIONAL CONFERENCE

MEĐUNARODNA KONFERENCIJA

MEETING POINT OF THE SCIENCE AND PRACTICE IN THE FIELDS OF CORROSION, MATERIALS AND ENVIRONMENTAL PROTECTION

STECIŠTE NAUKE I PRAKSE U OBLASTIMA KOROZIJE, ZAŠTITE MATERIJALA I ŽIVOTNE SREDINE

PROCEEDINGS

KNJIGA RADOVA

Under the auspicies of the MINISTRY OF EDUCATION, SCIENCE AND TECHNOLOGICAL DEVELOPMENT OF THE REPUBLIC OF SERBIA

Pod pokroviteljstvom MINISTARSTVO PROSVETE, NAUKE I TEHNOLOŠKOG RAZVOJA REPUBLIKE SRBIJE

May 16-19, 2022 : : Divčibare, Serbia

CIP - Каталогизација у публикацији
Народна библиотека Србије, Београд

620.193/.197(082)(0.034.2)
621.793/.795(082)(0.034.2)
667.6(082)(0.034.2)
502/504(082)(0.034.2)
66.017/.018(082)(0.034.2)

INTERNATIONAL Conference YUCORR (23 ; 2022 ; Divčibare)
Meeting point of the science and practice in the fields of corrosion, materials and environmental protection [Elektronski izvor] : proceedings = Stecište nauke i prakse u oblastima korozije, zaštite materijala i životne sredine : knjiga radova / XXIII YuCorr International Conference = XXIII YuCorr [Jugoslovenska korozija] Međunarodna konferencija, May 16-19, 2022, Divčibare, Serbia = [organized by] Serbian Society of Corrosion and Materials Protection ... [et al.]] ; [organizatori Udruženje inženjera Srbije za koroziju i zaštitu materijala ... [et al.] ; [editors, urednici Miroslav Pavlović, Marijana Pantović Pavlović, Miomir Pavlović]. - Beograd : Serbian Society of Corrosion and Materials Protection UISKOZAM : Udruženje inženjera Srbije za koroziju i zaštitu materijala UISKOZAM, 2022 (Beograd : Serbian Society of Corrosion and Materials Protection UISKOZAM : Udruženje inženjera Srbije za koroziju i zaštitu materijala UISKOZAM). - 1 elektronski optički disk (CD-ROM) ; 12 cm
Sistemski zahtevi: Nisu navedeni. - Nasl. sa naslovne strane dokumenta. - Radovi na engl. i srp. jeziku. - Tiraž 200. - Bibliografija uz većinu radova. - Abstracts.
ISBN 978-86-82343-29-5
а) Премази, антикорозиони -- Зборници б) Превлаке, антикорозионе -- Зборници в) Антикорозиона заштита -- Зборници г) Животна средина -- Заштита -- Зборници д) Наука о материјалима -- Зборници
COBISS.SR-ID 68624905

XXIII YUCORR – International Conference | *Međunarodna konferencija*

PUBLISHED AND CD BURNED BY | *IZDAVAČ I NAREZIVANJE CD*
SERBIAN SOCIETY OF CORROSION AND MATERIALS PROTECTION (UISKOZAM)
UDRUŽENJE INŽENJERA SRBIJE ZA KORZIJU I ZAŠTITU MATERIJALA (UISKOZAM),
Kneza Miloša 7a/II, 11000 Beograd, Srbija, tel/fax: +381 11 3230 028, office@sitzam.org.rs; www.sitzam.org.rs

FOR PUBLISHER | *ZA IZDAVAČA* *Prof. dr MIOMIR PAVLOVIĆ, predsednik UISKOZAM*

EDITORS | *UREDNICI:* *Dr Miroslav Pavlović, Dr Marijana Pantović Pavlović, Prof. dr Miomir Pavlović*

SCIENTIFIC AREA | *OBLAST:* CORROSION AND MATERIALS PROTECTION **|** *KOROZIJA I ZAŠTITA MATERIJALA*

PAGE LAYOUT | *KOMPJUTERSKA OBRADA I SLOG:* *Dr Marijana Pantović Pavlović*

CIRCULATION | *TIRAŽ:* 200 copies **|** *primeraka*
PUBLICATION YEAR | *GODINA IZDANJA:* 2022
ISBN 978-86-82343-29-5

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Consideration of Energy Flows in the Life Cycle of Energy Production from Biogas

Razmatranje energetskih tokova u životnom ciklusu proizvodnje energije iz biogasa

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Abstract

The aim of this paper is to present the energy flows in the life cycle of the biogas cogeneration system, as well as their mutual relations, starting from providing of feedstock materials(corn silage and cow manure), anaerobic digestion, cogeneration up to the digestate as fertilizer on agricultural land. The cogeneration process has been considered according to the performance of the biogas plant located on the Mirotin dairy farm in Vrbas (Serbia). For evaluation of energy flows in this work were used four energy indicators. According to the Life Cycle Energy Assessment approach, results obtained in this study have shown that the biogas cogeneration process has positive energy balances and this process is energy sustainable. The applied approach in this research can be adjusted to any biogas power plant since it complies with the main material and energy balances.
Keywords*: Life Cycle Energy Analysis; Biogas; Cogeneration; Energy balance; Energy efficiency*

Izvod

Cilj ovog rada je da prikaže tokove energije u životnom ciklusu biogas kogeneracionog sistema, kao i njihove međusobne odnose, počev od obezbeđivanja sirovine (kukuruzna silaža i kravlji stajnjak), anaerobne digestije, kogeneracije, pa do digestata. kao đubrivo na poljoprivrednom zemljištu. Proces kogeneracije je razmatran prema performansama biogas postrojenja koje se nalazi na farmi mleka Mirotin u Vrbasu (Srbija). Za evaluaciju energetskih tokova u ovom radu korišćena su četiri energetska indikatora. Prema LCEA pristupu, rezultati dobijeni u ovoj studiji su pokazali da proces kogeneracije biogasa ima pozitivan energetski bilans i da je ovaj proces energetski održiv. Primenjeni pristup u ovom istraživanju može se prilagoditi bilo kojoj elektrani na biogas jer je u skladu sa osnovnim materijalnim i energetskim bilansima.
Ključne reči: *Energetska analiza životnog ciklusa; Biogas; Kogeneracija; Energetski bilans; Energetska efikasnost*

Introduction

Nowadays, coal, crude oil, and natural gas are the most important resources for energy supply. It was estimated that about 85% of the total world's primary energy consumption has been provided by fossil fuels in 2018[1]. Environmental protection, global warming, and the reduction of greenhouse gas (GHG) emissions are located on many political agendas (United Nations, European Union, etc). Greater use of biogas as renewable energy sources could be one of the solutions for the mitigation of these problems. The most important sources of biogas production include agriculture and food waste; organic waste from the industry; municipal solid waste in form of fermentable fractions and sludge from municipal wastewater treatment plants. The major components in biogas as a gas mixture are CH_4, CO_2, and impurities (such as O_2, H_2S, N_2, siloxanes, and water). The biogas can be used as a source for heat and electricity production, in the natural gas grid, as well as a fuel for traffic.

The Republic of Serbia is a region rich in biomass that can be used for biogas production. According to Energy Treaty with European Union, Serbia introduced feed-in tariffs as a supporting measure for electricity produced from biogas. The primary energy production from biogas in Serbia in the period 2015-2020 is presented in Figure 1[2].

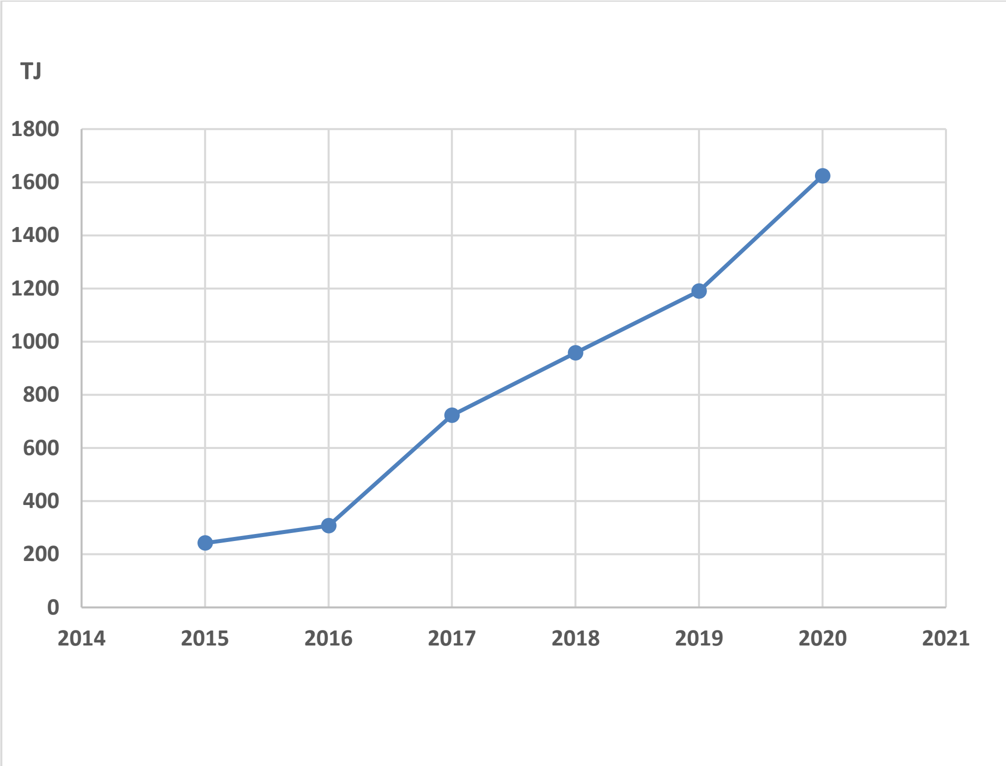

Figure 1. *Primary energy production from biogas in Serbia in the period 2015 to 2020[2]*

Energy analysis of biogas systems according to the Life Cycle Assessment (LCA) approach has been a focus of scientific research over the past two decades. Analyzing materials and energy flows, LCA estimates the influence of biogas processes on the environment. The phases of LCA (Figure 2) involve:

- Definition of the objective and the scope of the study;
- Inventory, in which the inputs of the life cycle are collected and the outputs determined and presented;
- Environmental impact assessment of the life cycle, where the impact is evaluated and quantified;
- Interpretation of the results, where the implications on the environment are described and the recommendations for decision-makers are provided.

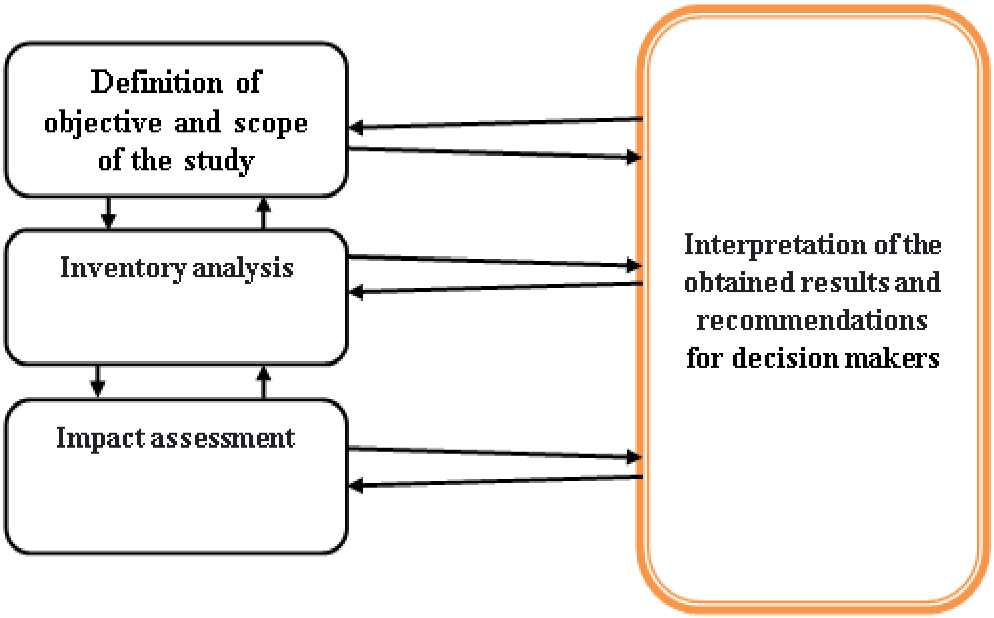

Figure 2. *The phases of LCA*

This approach involves feedstock supply, production process, transport, distribution, utilization, recycling, and product disposal or end of the biogas production process. The objectives of the biogas LCA studies are diverse. These studies were considered various resources for anaerobic digestion and biogas production [3,4] or the specific biogas technologies [5-7]. In studies [8,9], biogas was compared with other energy sources in the LCA analysis. LCA methodology is the base for conducting the life cycle energy assessment (LCEA) for different biogas utilization pathways. LCEA in an environmental context is implemented for consideration of fossil fuel needs or energy efficiency and characterization of biogas renewability. Scientific methodology for estimating the energy performance of biogas plants in LCEA has not yet been established. The production of biogas and the other types of energy that can be produced from biogas covers various energy flows: (i) from the production of materials for anaerobic digestion, (ii) via the process of anaerobic digestion (iii) to the use of the produced energy, and (iiii) the utilization of the produced digestate. The objective of this study is an analysis of the energy flows in the life cycle of the biogas cogeneration system, as well as their mutual relation, starting from the supply of the resources necessary for anaerobic digestion, heat, and electricity production up to the digestate on the agricultural soil as fertilizer. The analysis was performed using the data from the biogas plant Mirotin in Serbia.

Materials and Methods

In this work, the methodology of LCEA analysis was conducted according to ISO 14000 series standards [10,11].

Description of the system for LCEA

In this study, the Mirotin biogas plant was analyzed. The biogas power plant was built in 2011 and is situated in Vrbas (Serbia).On this farm, corn silage and cow manure are used as a substrate for anaerobic digestion. Cultivation of corn silage includes different operations such as soil preparation, sowing, plant protection, harvesting, and ensilage which use material and energy resources. The cow manure is stored in tanks and transferred to the digester by an electric pump. During the process of anaerobic digestion, it is necessary to provide a constant temperature in the range of 37- 40 °C. Produced biogas contains 50-55% of methane. The cogeneration unit (CHP unit) has an installed capacity of 1 MW_e. In this unit, biogas energy is converted into heat and electricity using gas motors.

The heat from the cogeneration unit is used for heating digesters and buildings. The produced electricity is delivered to the national electric grid and the company is a part feed-in tariff system in Serbia. After the process of separation, a digestate is obtained as a solid and a liquid phase. The digestate is further used as fertilizer on agricultural land for corn silage production.

System boundaries in LCEA

In this study system boundary for the biogas cogeneration process was defined for LCEA which is given in Figure 3. The biogas cogeneration system was analyzed using the data of the Mirotin biogas plant. The system boundary in Figure 3, is as follows: corn silage production using digestate as fertilizer, all electricity is imported, heat energy for the anaerobic digestion unit is used from the cogeneration unit, electricity and the remaining part of the heat from the CHP unit is exported (PC1 process).

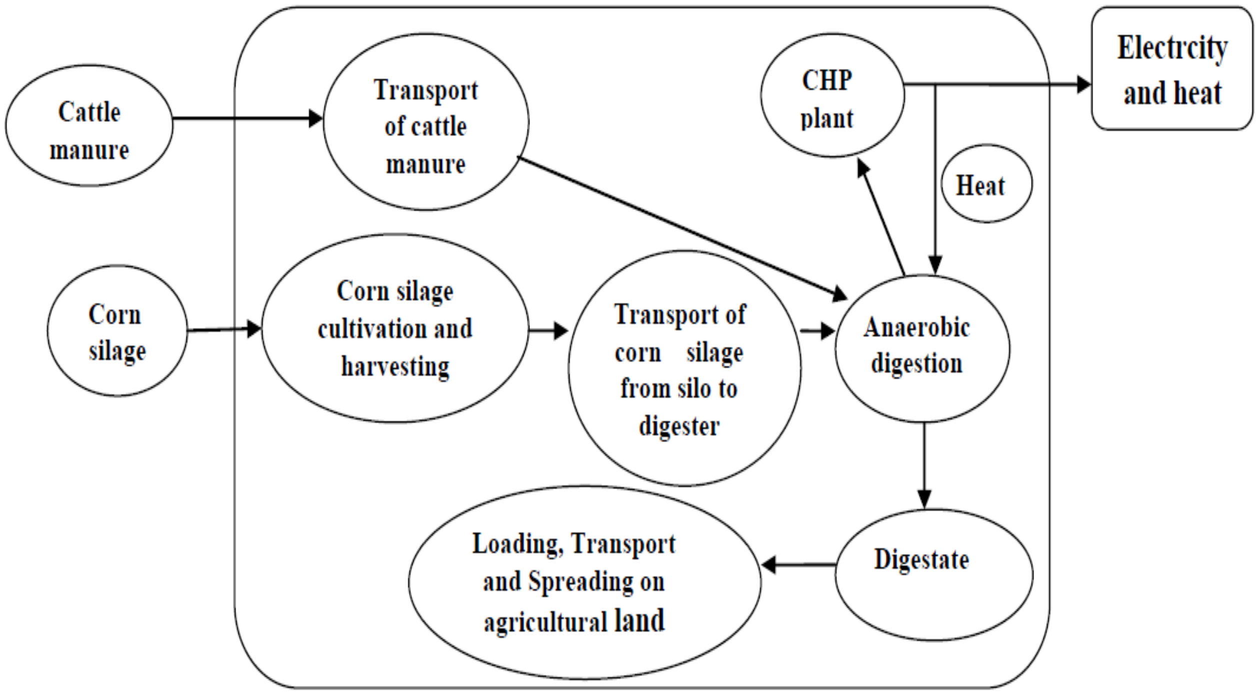

Figure 3*. System boundary in Life Cycle Energy Assessment for PC1 process on a farm in Serbia*

Mass flows in a biogas plant

Mass flows in Mirotin biogas plant were determined as as follows : MF_1 - Cow manure flow (26,800 t/year); MF_2 - Corn silage flow (10,363 t/ year); MF_3 - Total digestate flow (30,930 t/ year); MF_4 - Liquid digestate flow (24,470 t/year); MF_5 - Solid digestate flow (6,434 t/year) and MF_6 - Biogas flow (3,903,163 m^3_N/year).

Based on on-site data, dry matter (DM) in corn silage was 32% with volatile matter 93% of DM in corn silage, while DM in cow manure was 22%, with 80% of volatile matter in DM of cow manure.

The content of methane in biogas was 53.5% (average value). In the PC1 process was assumed that the mineral fertilizer for the corn silage cultivation process was replaced by the solid digestate. The yield of corn silage of 40 t/ha was assumed.

Calculation of energy input

The energy performance of the PC1 process was considered by the following indicators [12,13]

- The difference between energy output and total primary energy input (energy balance), where energy output was heat and electricity produced in the CHP unit, while energy input was the sum of primary energy input inside the boundary of the system for the LCEA.
- Energy output/energy input ratio (energy efficiency)
- The ratio of energy output and the sum of parasitic electricity and parasitic heat energy used for biogas production (μ_p). Parasitic electricity and parasitic heat energy represent energy that was provided out of the boundary of the biogas system in LCA.
- Ratio ($E_{F/TS}$) of energy balance and the dry matter (DM) mass of feedstock material (corn silage and cow manure).
- Energy inputs that were analyzed in this study are*:*
- The energy input for corn silage production, (*Fc)*, in GJ. The mineral fertilizer in corn silage cultivation is replaced by solid digestate and based on this fact, the energy input for corn production per hectare was adopted by the value of 8.3 GJ/ha [14].
- The energy input for the transport of corn silage, (*Ftransil*), in MJ. The distance for transport of corn silage in this study was 200 m.
- The energy input for transport of cow manure, (*Ftranman)*, to the digester and according to on-site measurements, *Ftranman,* was 3500 kWh/year.
- The energy input for anaerobic digestion, (*Fd)*, in MJ according to on-site data measurements
- The energy input for the CHP unit,*(Fcog)*, was used 207 MWh/year of heat and 244.5 MWh/year of electricity (on-site data measurement).
- The energy input for digestate separation, (*Fdsep)*, in MJ
- The energy input for using liquid digestate, (*Fldig)*, in MJ (loading, transport, spreading). The distance for transportation of liquid digestate was 7 km in this work.
- The energy input for using solid digestate, (*Fsdig)*, in MJ (loading, transport spreading). The distance for the transport of solid digestate was assumed as 3 km in this study.

Energy inputs were determined according to mass balance in the Mirotin biogas plant, on-site data, and specific energy inputs which are given in Table 1.

Table 1. Specific energy inputs are used for the determination of different energy inputs in the biogas cogeneration system [12,13]

Specific energy input	Value	References
SE_1	8.3 GJ/ha	[14]
SE_2	12.6 MJ/t·km	[15,16]
SE_3	78.6 MJ/t	[17,18]
SE_4	0.63 MJ/t	[16,19]
SE_5	2.84 MJ/t·km	[16,19]
SE_6	20.16 MJ/t	[20]
SE_7	3.78 MJ/t	[20]
SE_8	3.15 MJ/t·km	[20]
SE_9	25.83 MJ/t	[20]

Where is: SE_1 is the specific energy input for corn production (GJ/ha); SE_2 is the specific energy input for transport of corn silage (MJ/t·km); SE_3 is the specific energy input for digestate separation (MJ/t);

SE_4 is the specific energy input for liquid digestate loading (MJ/t); SE_5 is the specific energy input for liquid digestate transport (MJ/t·km); SE_6 is the specific energy input for liquid digestate spreading (MJ/t); SE_7 is the specific energy input for solid digestate loading (MJ/t); SE_8 is the specific energy input for solid digestate transport (MJ/t·km); SE_9 is the specific energy input for solid digestate spreading (MJ/t);

Calculation of energy performance of PC1 process

All equations necessary for the determination of energy indicators used in this work are summarized below:

The energy balance for PC1, E_{b2}, was calculated as:

$E_{b2} = E_{out2} - E_{in2}$ (1)

$E_{in2} = Fc + Ftransil + Ftranman + Fd + Fdsep + Fldig + Fsdig + Fchp$ (2)

E_{out2}= 8,839 MWh/year (heat energy) + 8,149.5 MWh/year (electricity) = 16,998.5 MWh/year (3)

In this process the efficiency of the electric energy generation (µCHP, el) and heat generation (µCHP, H) in cogeneration were calculated according to the equations (4-6) proposed by the Eastern Research Group [21]:

$\mu_{CHP, el.} = E_{el.\ prod} / E_{bg,,biogas}$ (4)

$\mu_{CHP,H} = E_{H,prod} ./E_{bg,,biogas}$ (5)

$E_{bg,,biogas} = 0.535 \cdot MF_6 \cdot HV_{CH4}$ (6)

where $E_{el.\ prod}$ and $E_{H,prod.}$ are the electricity and heat generated in the CHP unit (see equation 3); $E_{bg,\ biogas}$ is the energy content of biogas input to the CHP; HV_{CH4} is the lower heating value of methane (35.8 MJ/m^3_N).

μ_p was obtained in this process as:

$\mu_p = E_{out2}/(Framman + Fd + Fdsep + Fchp\ electricity)$ (7)

CHP electricity was 244.5 MWh/year.

$E_{F/TS}$ was obtained in this process as:

$E_{F/TS} = E_{b2}/M_{FTS}$ (8)

Results and Discussion

The obtained energy inputs for the PC1 process are given in Table 2.

Table 2. The energy inputs for the PC1 process

Energy input	Value
Fc	2,149.7 GJ
Ftransil	26.1 GJ (on-site data)
Ftranman	3,500 kWh/year (on-site data)
Fd	1,587.6 GJ/year (on-site data)
Fcog	207 MWh/year of heat and 244.5 MWh/year of electricity (on-site data)
Fdsep	2,431.1 GJ
Fldig	995.2 GJ
Fsdig	251.3 GJ

The calculated total energy input for the PC1 process was 9,081.1 GJ. In this process, the thermal energy for the digester is provided from a CHP unit in the amount of 1,356 MWh per year. The dominant energy inputs in this process are the energy inputs required for digestate separation (26.76%) and corn silage production (23.67%).

The energy balance in the PC1 process was 52,114 GJ(surplus energy), while the energy efficiency *(μ)* amounted to 6.74 (Table 3).

Table 3. Energy efficiency in a life cycle of biogas cogeneration in different studies

[20,21]	[22]	[23]	[24]	This study
3-7.5	2.5-7	3.5-8.2	5.5-6.8	6.74

The results in this study were in good agreement with the values (Table 3) for the energy efficiency (3.-7.5) determined in the studies of Eastern Research Group [21] and Pöschl et al. (2010) [20], as well as, the values of 2.5-8.2 calculated by Berglund and Börjesen (2006) [22], Seppälä et al.(2008) [23], and Navickas et al., (2012) [24].

The values of the energy efficiencies of electricity and heat generation in the cogeneration unit calculated for the system investigated in this paper were $\mu_{CHP, el.}$=0.39 and $\mu_{CHP, H}$=0.42. These results are in good agreement with the values obtained for modern CHP units [25-27]. The total energy efficiency in the CHP unit obtained as the sum of $\mu_{CHP, el.,}$ and $\mu_{CHP, H}$ was 0.81. This value for total energy efficiency was higher than the value of 0.6 obtained by Blengini et al. (2011) [28] and also it was higher than the value of 0.66 obtained by Havukainen et al. (2014) [29].

The parasitic energy in this process involved energy input for the transport of cow manure, the **e**nergy input for anaerobic digestion, the energy input for digestate separation, and energy input for CHP unit in the form of electricity. In the PC1 process, μ_p was calculated as 10.81 and parasitic energy represented 9.25% of energy output. The determined result was in good agreement with the values of the parasitic energy reported by Gropgen (2007) of 8.5% [30]. The energy input for digestate separation contributed the most to the parasitic energy input. This is electricity necessary for motors in the process of digestate separation. Implementation of the measures for rational use of electricity in the process of digestate separation (adjustable-speed drive equipment, voltage optimization, etc) can contribute significantly to the reduction of parasitic energy in this process.

$E_{F/TS}$ in the PC1 process amounted to 7.23 MJ/kg DM of input substrate. This result means that processing of 138.31 g DM of input substrate under the conditions in this process can achieve up to 1 MJ of positive energy balance.

According to Arodudu et al. (2014) [31], the bioenergy systems whose energy efficiency is below 3 are not sustainable and represent potential hazards to the environment primarily in land degradation, water pollution, and loss of biodiversity. According to that indicator, the system investigated in this paper is sustainable.

Determination of energy outputs according to the agricultural practice in Serbia, assumed distance of transport for the liquid and solid digestate to agricultural areas, technology for biogas production, and assumed lower calorific value of biogas may involve uncertainties in the estimation of energy output in biogas cogeneration process.

Conclusions

The objective of this study was energy analysis and determination of energy characteristics in the biogas cogeneration process (heat and electricity production) during the life cycle. Evaluation of energy flows was carried out according to the performances of the Mirotin biogas plant in Serbia and literature data. Four energy indicators were used to determine energy flows in this work. The obtained results show that the biogas gas cogeneration process has a positive energy balance ((52,114 GJ) and an energy efficiency of 6.74 in the life cycle and it is sustainable from an energy point of view. The obtained results can serve to the improvement of energy management on biogas power plants in Serbia. Also, this paper is conducted on data obtained in the real biogas system and it provides an extension of the existing database for further environmental and energy analysis of the other biogas energy systems.

Acknowledgments

This work was financially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Grant No. 451-03-68/2022-14/200026. The authors would like to thank the Mirotin Company, Vrbas, Republic of Serbia, for the help in the realization of this study.

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