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The SOFC in the Hybrid Power Supply System of a Livestock Enterprise

Abstract. *The paper is devoted to selecting the optimal capacity of solid oxide fuel cells (SOFC) which operate on biogas. A hybrid power supply system of a livestock enterprise has been considered. The livestock enterprise is supplied from the SOFC and the centralized electrical network. A methodology for the SOFC's capacity optimization has been developed according to the criteria of economic and environmental efficiency of SOFC. The effectiveness research of the SOFC use in a hybrid power supply system of a livestock enterprise has been carried out.*

Streszczenie. *Artykuł poświęcony jest doborowi optymalnej wydajności ogniw paliwowych ze stałym tlenkiem (SOFC) pracujących na biogazie. Rozważano hybrydowy system zasilania przedsiębiorstwa hodowlanego. Przedsiębiorstwo hodowlane jest zasilane z SOFC i scentralizowanej sieci elektrycznej. Opracowano metodologię optymalizacji wydajności SOFC zgodnie z kryteriami efektywności ekonomicznej i środowiskowej SOFC. Przeprowadzono badania efektywności wykorzystania SOFC w hybrydowym systemie zasilania przedsiębiorstwa hodowlanego.* (**SOFC w hybrydowym systemie zasilania przedsiębiorstwa hodowlanego**)

Keywords: SOFC, biogas, livestock enterprise, methodology for optimization.
Słowa kluczowe: przedsiębiorstwo hodowlane, SOFC, optymalizacja.

Introduction

Decarbonization and decentralization of electricity generation are the most important directions in the development of the global energy industry [1]. Fuel cells are considered as the most promising low carbon distributed generation technologies.

Compared to other distributed generation (DG) sources, the advantages of fuel cells are higher energy efficiency, no polluting impact on the environment, no noise and reliability [2]. Fuel cells are already widely used in the transport industry and for power supply of stationary objects of various capacities [3]. Power supply systems of agricultural enterprises are a promising area of fuel cells application.

The comparative analysis of fuel cells showed that high-temperature fuel cells, such as solid oxide fuel cells (SOFC), are the most effective for integration into power supply systems of agricultural enterprises [4]. Due to the high operating temperature, the SOFC can use biogas produced by processing agricultural waste as a fuel. The use of the SOFC on biogas will improve the quality of agricultural enterprises power supply and increase the efficiency of agricultural waste disposal.

For the effective integration of a DG source into the power supply system it is important to choose the optimal source power for the given conditions. For many types of DG sources, approaches to the selection of their capacity have been developed and scientifically substantiated. They are based on finding the extremum of the capacity function according to one or several criteria. To optimize the capacity of hybrid generation systems based on renewable energy sources (RES), the following methods are used:

- linear programming [5],
- heuristic search algorithms [6],
- numerical optimization [7], etc.

There are very few studies devoted to the optimization of a hybrid systems with SOFC. The combined operation of the SOFC and the centralized electrical network is considered in [8, 9]. The main tasks of research are related to ensuring the stable system operation and high quality of electricity. In [10] the results of modeling a hybrid system based on the SOFC and a Gas MicroTurbine are presented, but the sources parameters were set initially. The problem of optimizing the parameters of the Solar PV-Fuel cell system was solved in [11, 12]. the HOMER software was used for techno economic optimization of hybrid generation system. The optimal source parameters were selected based on the optimized cost of electricity [COE] and the global net present value cost (NPC), but hydrogen was used to operate the fuel cells. Also, the possibility of issuing surplus generation to the centralized electrical network was not considered.

There are some conflicting criteria when the SOFC are integrated into a power supply system with changing load schedules. The SOFC have a high unit cost of 1 kW of capacity, but the greater the SOFC's capacity is, the more electric energy the enterprise can get from its own eco-friendly source. Therefore, the criterion of economic efficiency when choosing the SOFC capacity is not enough.

The proposed approach to the SOFC capacity choice is the development of the research [13] and is based on the multi-criteria optimization methods. The goal of our research was to develop a methodology for optimization the SOFC's capacity in the hybrid power supply system of a livestock enterprise, to implement the methodology in a computer program and a database, and to investigate the effectiveness of the SOFC use for the power supply of a livestock enterprise.

The paper is organized as follows: Section 2 describes the structure and principles operation of the hybrid power supply system with the SOFC. Section 3 presents a methodology for the SOFC capacity optimization. Section 4 shows the results of the research on the effectiveness of the SOFC on biogas use in a livestock enterprise's hybrid power supply system.

Hybrid power supply system of a livestock enterprise

The object of the research is the power supply system of a livestock enterprise. The sources of electrical energy are the SOFC power plant operating on biogas from recycled waste and the centralized electrical network (Fig. 1).

The converter of current distribution is a device that connects sources and consumers with different parameters [14]. The electric power balance equation can be as follows:

$$P_N(t) = P_{SOFC}(t) - \Delta P(t) - P_L(t) \tag{1}$$

where: P_N – is the power from the centralized electrical network (kW); P_{SOFC} – is the power generated by the SOFC (kW); ΔP – is the power loss in the distribution electrical network of the enterprise (kW); P_L – is the power of the enterprise load (kW); t – is the current moment of time.

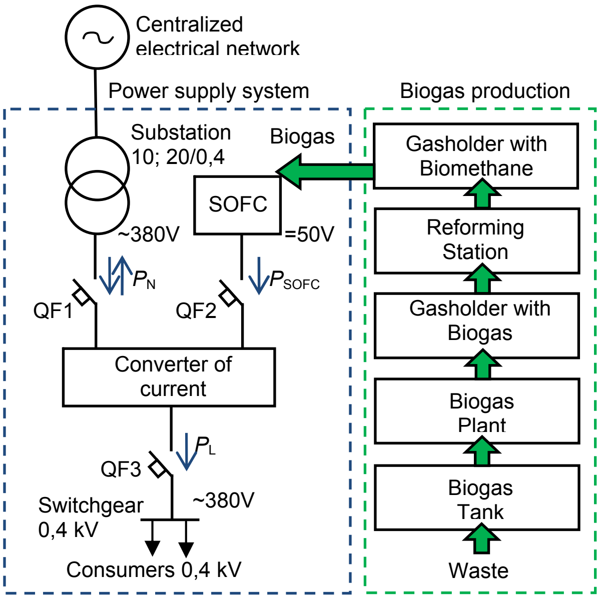

Fig.1. The block diagram of a livestock enterprise power supply with SOFC on biogas

The SOFC is the main source of electrical energy. P_{SOFC} can be defined as the average power that the SOFC can generate over a long period of time based on biogas production at a livestock enterprise:

$$P_{SOFC}(t) = \frac{V_{BIO}(t)}{24 \times F_{SOFC}} \tag{2}$$

where: V_{BIO} – is the volume of biogas daily production at the enterprise t (m^3); F_{SOFC} – is the average specific consumption of the primary gaseous SOFC's fuel per the generation of 1 kW·h (m^3/kW·h).

The V_{BIO} value must meet the condition:

$$V_{BIO} \leq V_{\text{MAX}} \tag{3}$$

$$V_{\text{MAX}} = \frac{N_A \times M_A \times K_1 \times K_2 \times N_B \times R_1 \times R_2 \times R_3 \times (100 - M_B)}{10^8} \tag{4}$$

where: V_{MAX} – is the maximum daily biogas production (m^3); N_A – is number of cattle (units); M_A – is the mass of the bio-waste from each animal per day (kg); K_1 – is the coefficient taking into account impurities in biomass (units); K_2 – is the biomass utilization rate (units); N_B – is the specific yield of biogas per kilogram of dry matter (m^3); R_1 – is the organic matter content in dry biomass (%); R_2 – is the level of biomass fermentation (%); R_3 – is the methane content in biogas (%); M_B – is the initial moisture content of biomass (%) [15].

ΔP takes into account electrical power loss in the medium and low voltage power lines and transformer substations, which are parts of the livestock enterprise's power supply system:

$$\Delta P(t) = \Delta P_{PL10}(t) + \Delta P_{PL0.4}(t) + \Delta P_{TR}(t) \tag{5}$$

where: ΔP_{PL10} and $\Delta P_{PL0.4}$ – are the electrical power losses in the medium and low voltage power lines; ΔP_{TR} – is the electrical power loss in the transformer substation.

The $P_L(t)$ values are specified using daily electrical load curves with a sampling rate equal to one hour. The $P_N(t)$ is an alternating function. If $P_N(t) > 0$, therefore, the SOFC generated power is sufficient to supply the enterprise's electrical load and surplus generation is transferred to the centralized electrical network:

$$P_N(t)^+ = P_{SN}(t) = P_N(t);\ P_{SOFC}(t) > \Delta P(t) + P_L(t) \tag{6}$$
$$P_N(t)^+ = P_{SN}(t) = 0;\ P_{SOFC}(t) \leq \Delta P(t) + P_L(t)$$

where: $P_{SN}(t)$ – is the power generated by the SOFC and transmitted to the centralized electrical network (kW).

If $P_N(t) < 0$, therefore, the SOFC generated power is not enough to supply the enterprise's electrical load and it receives the missing power from the centralized electrical network:

$$P_N(t)^- = P_{NL}(t) = P_N(t); P_{SOFT}(t) < \Delta P(t) + P_L(t) \tag{7}$$
$$P_N(t)^- = P_{NL}(t) = 0; P_{SOFT}(t) \geq \Delta P(t) + P_L(t)$$

where: $P_{NL}(t)$ – is the power from the centralized electrical network consumed by the livestock enterprise's load (kW).

The rules for distributing the electrical load of an enterprise between the power sources in the hybrid power supply system, expressed as logical conditions for the current moment of time, are shown in Fig. 2.

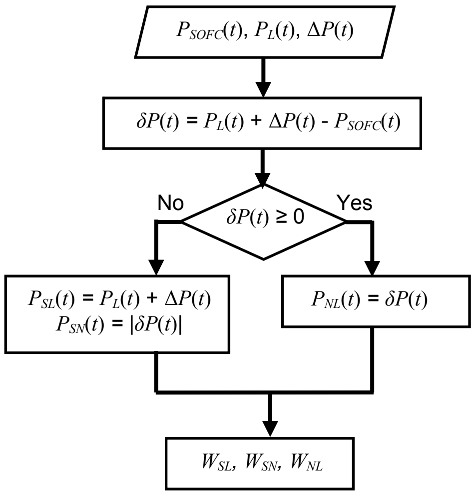

Fig.2. Distribution of electrical load between power sources in the hybrid power supply system

The generated and consumed electrical energy for the estimated period is determined as follows:

$$W_{SL} = \sum_0^T [P_{SL}(t) \times \Delta t] \tag{8}$$

$$W_{SN} = \sum_0^T [P_{SN}(t) \times \Delta t] \tag{9}$$

$$W_{NL} = \sum_0^T [P_{NL}(t) \times \Delta t] \tag{10}$$

$$W_{SOFC} = W_{SL} + W_{SN} \tag{11}$$

where W_{SL} – is the electricity generated by the SOFC and consumed by the enterprise's load (kWh); W_{SN} – is the electricity generated by the SOFC and transferred to the centralized electrical network (kWh); W_{NL} – is the electricity from the centralized electrical network consumed by the enterprise (kWh); W_{SOFC} – is the total electricity generated by the SOFC (kWh); $\Delta(t)$ – is the estimated period interval.

On the basis of the presented equation, a computer program based on Microsoft Excel which allows to calculate the performance indicators of the power supply system over the given estimated period, has been developed. The entire period is divided into small equal time intervals (Δt). During each time interval, the load of consumers, the composition of the operating sources and the power production are considered unchanged. The problem of electrical power distribution between the sources of the power supply system is solved for each time interval.

Methodology of SOFC's capacity optimization

A methodology of the SOFC's capacity optimization has been developed (Fig. 3).

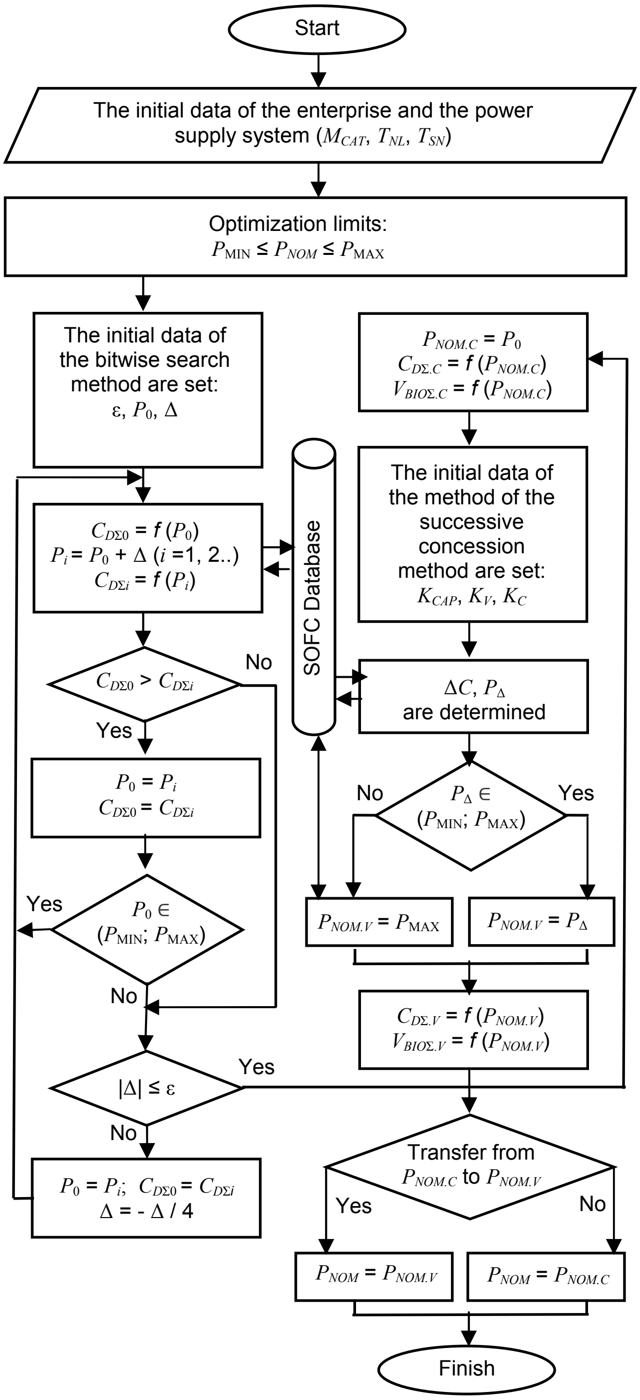

Fig.3. Block diagram of the algorithm for the SOFC's capacity optimization

The SOFC's capacity (P_{NOM}) is an optimization parameter. The methodology is based on the modified successive concessions method, the bitwise search method, and the SOFC database [16].

Using the bitwise search method and the SOFC database the optimal P_{NOM} value in terms of economic efficiency is determined. The criterion of economic efficiency is the discounted total costs of the enterprise power supply for the estimated period:

$$C_{D\Sigma} = \sum_{0}^{T}\left[C_\Sigma \times (1+r)^{-t}\right] \qquad (12)$$

$$C_\Sigma = \sum_{0}^{T}\left[C_{CAP} + C_{TEC} + C_{SP} + C_{NL} - C_{SN}\right] \qquad (13)$$

where: C_{CAP} – is the capital cost of the SOFC; C_{TEC} – is the maintenance costs; C_{SP} – is the personnel costs; C_{NL} – is the costs for electricity purchased from the centralized electrical network; C_{SN} – is the profit from the sale of surplus SOFC generation to the centralized electrical network; r – is the discount rate for the year t.

Further, the permissible deviation from the optimal P_{NOM} value is determined using the modified successive concessions method and it allows to improve the environmental efficiency of the SOFC use. The criterion of environmental efficiency is the amount of biogas used for the SOFC operation for the estimated period of time:

$$V_{BIO\Sigma} = \sum_{0}^{T}\left[P_{SOFC}(t) \times F_{SOFC}\right] \qquad (14)$$

The methodology for the SOFC capacity optimization consists of the following stages.

First, the initial data of the livestock enterprise and the power supply system are set. The main initial data are: the number of cattle (M_{CAT}), the tariff for purchased electricity (T_{NL}), the tariff for the sale of surplus generation of SOFCs (T_{SN}), the graphs of electrical load.

Next, the minimum reasonable (P_{MIN}) and maximum allowable (P_{MAX}) of the SOFC capacities are determined:

$$P_{MIN} = P_{L.MIN} \qquad (15)$$

$$P_{MAX} = \frac{V_{MAX}}{24 \times F_{SOFC}} \qquad (16)$$

where: $P_{L.MIN}$ – is the minimum electrical load of the enterprise.

To implement the bitwise search method, the following are set: the permissible error in determining the extremum point (ε), the value of the SOFC capacity for the zero point (P_0) and the initial step (Δ):

$$P_0 = P_{MIN} \qquad (17)$$

$$\Delta = \frac{P_{MAX} - P_{MIN}}{4} \qquad (18)$$

The optimal value of the SOFC capacity ($P_{NOM.C}$) is determined according to the $C_{D\Sigma}$ criterion using the bitwise search method. The SOFC parameters required for the calculation are requested from the SOFC database. The values of the total costs for the power supply of the enterprise ($C_{D\Sigma.C}$) and the volume of biogas used for the operation of SOFC ($V_{BIO\Sigma.C}$) are determined for the $P_{NOM.C}$

value. When $P_{NOM.C}$, $C_{D\Sigma.C}$ and $V_{BIO\Sigma.C}$ are determined, the transition to the successive concessions method is carried out.

The three coefficients are set at the beginning of the successive concession method:

- K_{CAP} – is the coefficient of the permissible increase in capital costs for the SOFC installation;
- K_V – is the coefficient of an appropriate increase in the volume of biogas for the SOFC operation;
- K_C – is the coefficient of the received increase in the discounted total costs of the enterprise's power supply.

Next, the permissible concession is calculated according to the economic criterion (ΔC) and the new SOFC capacity (P_Δ) is determined. P_Δ corresponds to the capital costs increased by the permissible concession:

$$\Delta C = C_{CAP.C} \times K_{CAP} \tag{19}$$

$$P_\Delta = \frac{C_{CAP.C} + \Delta C}{C_{UN.SOFC}} \tag{20}$$

where: $C_{CAP.C}$ – is the capital cost of the SOFC-based power plant, selected by the bitwise search method; $C_{UN.SOFC}$ – is the average unit cost of 1 kW of the SOFC capacity.

The SOFC capacity is being optimized according to the criterion of environmental efficiency. For the new SOFC's capacity (P_Δ), the calculation of the discounted total costs for the power supply of the enterprise ($C_{D\Sigma.V}$) and the volume of biogas for the SOFC operation ($V_{BIO\Sigma.V}$) is carried out. The feasibility of switching from $P_{NOM.C}$ (the optimal SOFC capacity in terms of economic efficiency only) to $P_{NOM.V}$ (the optimal SOFC capacity taking into account environmental efficiency) is determined on the basis of the expert assessment:

$$\frac{V_{BIO\Sigma.V} - V_{BIO\Sigma.C}}{V_{BIO\Sigma.C}} > K_V \tag{21}$$

$$\frac{C_{D\Sigma.V} - C_{D\Sigma.C}}{C_{D\Sigma.C}} < K_C \tag{22}$$

Thus, the developed methodology enables to determine the optimal SOFC capacity for the livestock enterprise's hybrid power supply system according to the criterion of economic and environmental efficiency.

Research on the efficiency of the SOFC on biogas in the livestock enterprise's hybrid power supply system

Using a computer program based on Microsoft Excel, which is based on the algorithm for the SOFC capacity optimization (Fig. 3) and the equations (1) – (10), research on the effectiveness of the use of SOFCs on biogas in a hybrid power supply system of a livestock enterprise was carried out

The study was conducted for the estimated period (*T*) of 7 years. The main initial data for the research are shown in Table 1.

The initial data on the electrical load were set on the basis of daily electrical load graphs of typical livestock enterprises for each month of the year. A year was divided in two parts depending on probable consumption, the period of low consumption (April - September) and the period of high consumption (October - March).

Table 1. The initial data for the research

Parameter	Designation	Measure unit	Value
Number of cattle	M_{CAT}	units	2000
Unit cost of 1 kW of SOFC capacity	$C_{UN.SOFC}$	EUR/kW	3000
Average specific biomethane consumption of SOFC	F_{SOFC}	m^3/kW·h	0.24
Electricity purchase tariff	T_{NL}	EUR/kW·h	0.11
Tariff for the sale of the surplus of SOFC generation	T_{SN}	EUR/kW·h	0.08
Discounted rate	r	%	15

The following assumptions were made for calculating the operate indicators of the hybrid power supply system:

- the possibility of additional use of thermal energy from the SOFC for the enterprise heat supply was not taken into account;
- the unit cost of 1 kW of the SOFC capacity and the unit biomethane consumption of the SOFC were taken to be the same for all the SOFC models.

The boundaries for the search of the optimal SOFC capacity are set. The P_{MIN} value is assumed to be 90 kW (the enterprise's minimum electrical load). The P_{MAX} value is determined by the Equation (2) taking into account the maximum possible daily biogas production (V_{MAX} = 3025 m^3) and is equal to 525 kW.

The SOFC capacity was optimized for T = 7 years based on the developed methodology (Fig. 3). The permissible error ε = 50 kW was set and the initial step Δ = 108.75 kW was determined to optimize the SOFC capacity according to the $C_{D\Sigma}$ criterion. The results of determining $P_{NOM.C}$ are given in Table. 2.

Table 2. The results of the SOFC capacity optimization according to the criterion of discounted total costs.

Search point	Δ, kW	$P_{NOM.C}$, kW	P_{DB}, kW	$C_{D\Sigma.C}$, mln. EUR
0	-	90	100	1.151
1	108.75	198.75	200	1.129
2	108.75	308.75	300	1.131
3	-27.19	272.81	275	1.128
4	-27.19	247.81	250	1.127
5	-27.19	222.81	225	1.128

The P_{DB} is the nominal power of the SOFC from the database.

The optimal SOFC capacity according to the criterion of discounted total costs for the enterprise's power supply is equal to 250 kW. With the SOFC of such capacity, the values of the efficiency criteria will be $C_{D\Sigma.C}$ = 1.127 million EUR, $V_{BIO\Sigma.C}$ = 525.6 thousand m^3 per year. The distribution of the livestock enterprise's electrical load at the SOFC capacity of 250 kW is shown in Fig. 4 and 5.

To optimize the SOFC capacity according to the $V_{BIO\Sigma}$ criterion, an increase in capital costs for SOFCs by 10% (K_{CAP} = 10%) was assumed. The new SOFC capacity P_Δ = 300 kW was determined using the Equations (19) and (20).

The efficiency criteria were calculated for P_Δ = 300 kW: $C_{D\Sigma.V}$ = 1.131 million EUR and $V_{BIO\Sigma.V}$ = 630.72 thousand m^3 per year.

The electricity distribution between the SOFC and the centralized electric network in the hybrid power supply system for 1 year with the SOFC capacity equal to 250 and 300 kW is shown in Fig. 6.

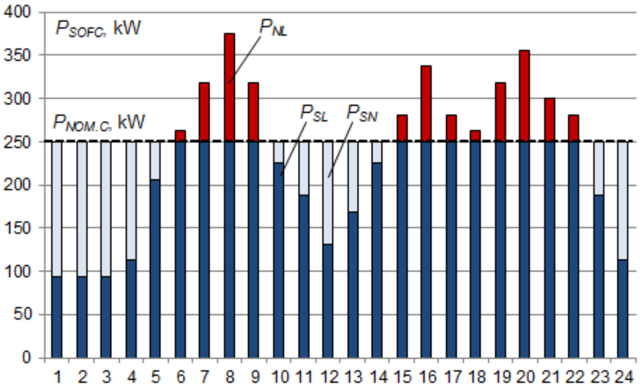

Fig.4. Electrical power distribution in the hybrid power supply system with P_{NOM} = 250 kW (April)

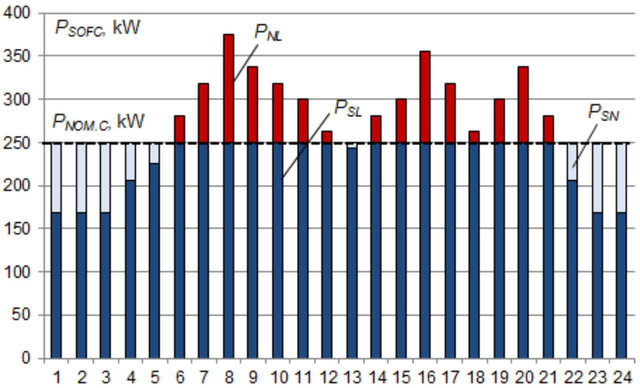

Fig.5. Electrical power distribution in the hybrid power supply system with P_{NOM} = 250 kW (October)

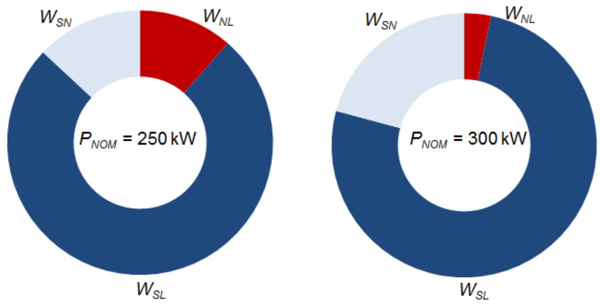

Fig.6. Electricity distribution between the SOFC and the centralized electrical network in the hybrid power supply system

Fig. 6 shows that with an increase in the SOFC's capacity, the consumption of electricity from the centralized electric network decreases. The ratio of costs for the estimated period with the SOFC capacity equal to 250 and 300 kW is shown in Fig. 7.

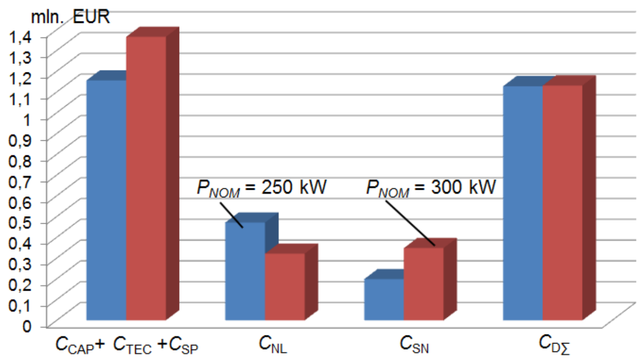

Fig.7. Cost ratio for the estimated period

It can be seen from the Fig. 7 that with an increase in the SOFC capacity from 250 to 300 kW, capital costs increase. However, the cost of purchasing electricity from the centralized electrical network decreases and the profit from the sale of the SOFC generation surplus increases. It leads to the same discounted total cost of electricity supply of the enterprise.

During the transition from $P_{NOM.C}$ = 250 kW to $P_{NOM.V}$ = 300 kW, the discounted total costs of the livestock enterprise's power supply (over 10 years) remained practically unchanged. The volume of biogas used for SOFC operation (hence, the mass of recycled agricultural waste) increased by 10 % (Fig. 8).

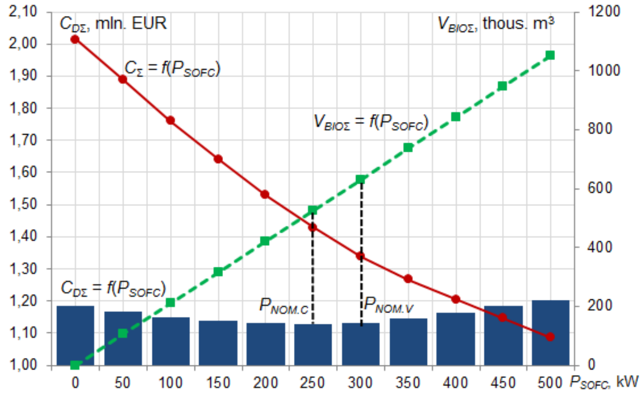

Fig.8. The search results for the optimal SOFC capacity

Fig. 8 shows that with an increase in the SOFC's capacity, the non-discounted total costs of the enterprise's power supply decrease. However, the discounted cost function graph $C_{D\Sigma} = f(P_{SOFC})$ is curved (convex downward) due to the fact that with an increase in the SOFC capacity the costs of power supply of the enterprise first begin to decrease because of the predominant supply of consumers from their own environmentally friendly source of electricity and the sale of the SOFC generation surplus to the centralized electrical network. However, having reached the minimum zone, the costs of the enterprise's power supply begin to increase again due to a significant increase in capital costs for the SOFC in the first year of the project.

Conclusion

The use of the SOFC on biogas is a promising approach to improving the quality of agricultural enterprise's power supply and solving the problem of agricultural waste utilization. The SOFCs are energy efficient and environmentally friendly sources, but they are characterized by low maneuverability and quite high unit cost of 1 kW of capacity.

A methodology of the SOFC capacity optimization has been developed for use in the livestock enterprise's power supply system. The methodology allows to determine the optimal SOFC's capacity according to the criteria of discounted total costs for the enterprise's power supply and the volume of biogas for the SOFC operation. The Optimization of the SOFC capacity is based on the modified successive concessions method, the bitwise search method and the developed SOFC database.

The optimization methodology has been tested on the example of a livestock enterprise. The study of the effectiveness of SOFC application in the enterprise's power supply system has been carried out for the estimated period of 7 years.

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REFERENCES

[1] N.I. Voropay, “Prospects and problems of electric power system trdnsformations”, *Electrichestvo*, 7 (2020), 12-21 (in Russian).

[2] S. Filippov, A. Golodnickij, and A. Kashin, “Toplivnye elementy i vodorodnaya energetika”, *Energeticheskaya politika*, 11 (2020), 29-39 (in Russian).

[3] Zhou Shengzhe, Cui Qiang, Zhang Maoyuan, Xia Guoting, and Wang Kai, “Study on the Management of Fuel Cell Vehicle Energy System Using Hybrid Fuzzy Logic Controller”, *Power Generation Technology*, 39 (2018), 554-560.

[4] E. Sosnina, A. Shalukho, and L. Veselov, “Application of SOFCs on biogas in power supply systems for agricultural enterprises“, *Smart electrical engineering*, 4 (2020), 27-41 (in Russian).

[5] L. Kit Gan, J. K.H. Shek, and M. A. Mueller, “Optimisation Sizing of Hybrid Wind-Diesel Systems using Linear Programming Technique”, Proceedings of the 7th IET International Conference on Power Electronics, Machines and Drives, 2014.

[6] S. Biesheuvel, and H. Nouri, “Coverage optimization of UK renewable energy sources: GA based approach”, Proceedings of the 52nd International Universities Power Engineering Conference, 2017.

[7] T. Zhou, and W. Sun, “Optimization of Wind-PV Hybrid Power System based on Interactive Multi-objective Optimization Algorithm”, Proceedings of the International Conference on Measurement, Information and Control, 2012.

[8] S. S. Kumar, C.M. Nirmal Mukundan, P. Jayaprakash, and M.V. Manoj Kumar, “Grid Tied Solid Oxide Fuel Cell Power Generation System for Peak Load Management”, Proceedings of the IEEE International Conference on Electrical, Computer and Communication Technologies, 2019.

[9] M. Münch, T. Seidel, and M. Pruggmayer, “Solid Oxide Fuel Cells as an Economic Approach for Continuous Power Supply in Off-Grid Applications”, Proceedings of the IEEE International Telecommunications Energy Conference, 2018.

[10] S. Baudoin, I. Vechiu, H. Camblong, J.-M. Vinassa, L. Barelli, and S. Kreckelbergh, “Analysis and validation of a biogas hybrid SOFC/GT emulator”, Proceedings of the IEEE International Workshop on Intelligent Energy Systems, 2014.

[11] K. K. Hossain, and T. Jamal, “Solar PV- Hydrogen Fuel Cell System for Electrification of a Remote Village in Bangladesh”, Proceedings of the International Conference on Advances in Electrical Engineering, 2015.

[12] A. Gougui, A. Djafour, D. M. Bilal, N. Khalfaoui, and R. Youssef, “Techno-economic Analysis and Feasibility Study of a Hybrid Photovoltaic/Fuel Cell Power System”, Proceedings of the International Conference on Sustainable Renewable Energy Systems and Applications, 2019.

[13] E. Sosnina, A. Shalukho, and L. Veselov, “Research on Application Efficiency of SOFC on Biogas for Power Supply of Agricultural Enterprises”, Przegląd Elektrotechniczny, 97 (2021), 64-68.

[14] A. Loskutov, E. Sosnina, A. Chivenkov, and E. Kryukov, “The Development of Hybrid Power Source Based on SOFC for Distant Electricity Consumers Power Supply”, Proceedings of the IEEE Innovative Smart Grid Technologies - Asia, 2015.

[15] B. Eder, and H. Schulz, “Biogas Praxis. Basics – Planning – Engineering – Examples – Economy – Environment”, *Okobuch Magnum*, 5th revised edition, 2012 [Online]. URL: http://www.fachbuch-erneuerbare-energien.de/schulz.htm.

[16] E. Sosnina, A. Shalukho, I. Lipuzhin, and L. Veselov, Solid Oxide Fuel Cell (SOFC) Database, Certificate of state registration No. 2020622076; application No. 2020621942 dated 21.10.2020. Registered on 28.10.2020. Copyright holder: NSTU n.a. R. E. Alekseev.