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Research on Application Efficiency of SOFC on Biogas for Power Supply of Agricultural Enterprises

Abstract. *The article is devoted to the problem of the integration of SOFC-based power plant into the power supply system of agricultural enterprises. The structural diagram of the power supply of a livestock enterprise with a combined power source (SOFK on biogas and a centralized electrical network) is presented. The method of the optimal nominal SOFC's capacity selection is described. The research on the application efficiency of a combined SOFC-based energy source in a power supply system has been carried out on the example of a livestock complex with 2,000 units of cattle. The dependence of total costs for the enterprise power supply on the nominal SOFC's capacity has been established.*

Streszczenie. *W artykule analizowano problem integracji źródła energii bazującego na ogniwach paliwowych bazującym na biogazie z siecią energetyczną wykorzystywaną w rolnictwie. System zbadano na przykładzie rzeczywistej farmy z 2000 sztuk bydła. (**Badania możliwości wykorzystania źródła energii bazującego na biogazie na przykładzie przedsiębiorstwa rolniczego**)*

Keywords: SOFC, biogas, agricultural enterprise, power supply system.
Słowa kluczowe: ogniwa paliwowe, biogaz, farma rolnicza.

Introduction

Agriculture is the most important sector of a country's economy. The efficiency of agricultural enterprises is largely determined by the reliability of power supply and environmental friendliness of production.

Poor quality of power supply and the need to dispose of industrial waste are serious challenges for agricultural enterprises [1]. The solution to these issues is the development of local energy sources operating on biogas from utilized production waste [2].

Biogas can be used as fuel for gas piston or gas turbine power plants as well as fuel cells. Solid oxide fuel cells (SOFC) have the greatest advantages when operating on biogas in comparison with other energy sources (high efficiency, zero polluting emissions into the atmosphere, the possibility of their thermal energy beneficial use, modularity and compact design) [3, 4].

The disadvantages of SOFC are the high cost of power plants and their low maneuverability. The latter makes it impossible to combine the daily generation and load schedules. When supplying energy to an agricultural enterprise, the problem of SOFC-based power plant's low maneuverability can be effectively solved by combining it with other energy sources (for example, with a centralized electrical network) [5]. At the same time, the larger nominal SOFC's capacity, the more electrical and thermal energy the enterprise can receive from its own environmentally friendly source. However, with an increase in the SOFC's capacity, the capital costs of the enterprise's power supply also increase. In addition to this, some part of the SOFC-generated energy may be unclaimed. All this will reduce the economic efficiency of the project. Therefore, the problem of selecting the optimal nominal SOFC's capacity as part of the power supply system of an agricultural enterprise is definitely urgent.

There is much scientific research devoted to optimizing the use of SOFC-based power plants. The developed methods are aimed at increasing energy efficiency and environmental friendliness as well as reducing the SOFC's cost [6, 7]. The proposed solutions make it possible to improve the technical characteristics of individual SOFC's elements and thereby increase the total efficiency of SOFC's power plants use. It should also be noted that some works are devoted to the research on the SOFC-turbo generator system [8, 9]. In this case, solutions to the optimization problem are aimed at increasing the power generation by the system and reducing fuel consumption. However, as far as we know, there is no literature to study the issue of selecting the optimal SOFC's capacity as a part of a combined energy complex with a centralized electric network.

The issue of selecting the optimal capacity of energy sources for use in combined energy complexes is considered in many works. The proposed methods can be divided into the two main groups:

1) determination of the optimal power of the energy source by mathematical optimization methods (for example, linear programming [10], various variations of the genetic algorithm [11], etc.)

2) determination of the optimal power of the energy source is simplified – by enumerating and comparing options [12].

Methods of mathematical optimization are used for combined power plants with variable operation mode. Simplified methods are effective with a few options available.

The proposed approach to the selection of the optimal SOFC's capacity uses a simplified method of enumerating options. The approach is the result of the research [13]. However, when determining the minimum of the objective function, an imitation of the energy complex's operating modes for the estimated period is used.

The goal of our work was to develop a method for selecting the optimal biogas-powered SOFC's capacity as a part of an energy complex and to study the effectiveness of SOFCs using by example of a livestock enterprise.

The paper hereafter is formed as below. Section 2 describes the energy supply scheme for a livestock enterprise. The method for selecting the optimum SOFC's capacity is described in Section 3. Section 4 presents the results of the research on application efficiency of a combined SOFC-based energy complex for power supply of a livestock complex with 2,000 units of cattle. Section 5 sums up the conclusions.

Energy supply scheme for a livestock enterprise with biogas-power SOFC

The object of the research is a remote livestock enterprise that is supplied with electric energy from a centralized electrical network. The fossil-fired boiler house supplies the enterprise with thermal energy. The article considers the efficiency of using a combined energy source with a SOFC power plant operating on biogas. Biogas is produced from cattle waste. The enterprise has a biogas plant and biogas accumulation and purification plants. The structural scheme for the livestock enterprise energy supply is shown in Fig. 1.

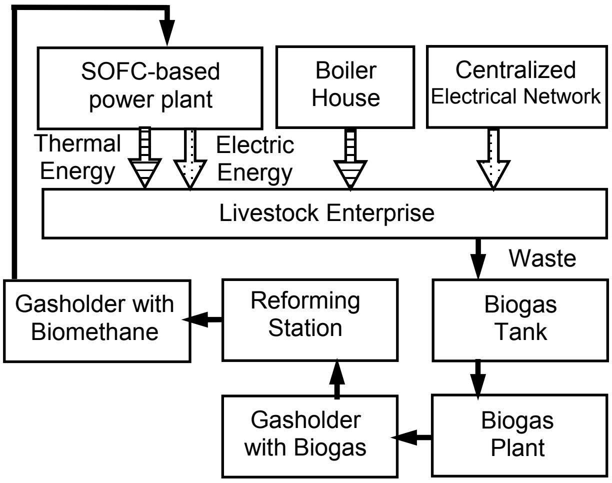

Fig.1. The structural scheme with the combined energy source for the livestock enterprise energy supply

The SOFC-based power plant is the main source of electric and thermal energy at the minimum load of the enterprise. During the period of maximum load, the enterprise is supplied with additional electricity from the centralized electrical network:

(1) $$P_j = P_{SOFCj} + P_{Nj}$$

where: P_j – the electric load of the enterprise at the j-th moment of time (kW), P_{SOFCj} – the electric power consumed from the SOFC (kW), P_{Nj} – the electric power consumed from the centralized electrical network (kW).

During the period of minimum load, surplus generation from the SOFC can be diverted to the centralized electrical network:

(2) $$P_j = P_{SOFCj} - P_{SNj}$$

where: P_{SNj} – the electric power generated by the SOFC and transmitted to the centralized electrical network.

The enterprise is mainly supplied with thermal energy from the SOFC. With a lack of SOFC-generated thermal energy, the enterprise is supplied additional heat from a nearby boiler house:

(3) $$Q_j = Q_{SOFCj} + Q_{BPj}$$

where: Q_j – the thermal load of the enterprise (Gcal), Q_{SOFCj} – the thermal power consumed from the SOFC, Q_{BPj} – the thermal power consumed from the boiler house.

The use of electric and thermal energy storage units in the explored power supply system is not considered.

Materials and methods

The optimization criterion is the total costs of the enterprise energy supply for the estimated period:

(4) $$C_{\Sigma} = \sum \left(C_{CAPi} + C_{TECi} + C_{STi} + C_{WNi} + C_{QBPi} - C_{WSNi} \right)$$

where: C_{CAP} – the capital costs of the SOFC-based power plant, C_{TEC} – the costs of the SOFC-based power plant's maintenance and repair, C_{ST} – the costs of service staff, C_{WN} – the costs of purchasing electricity from the centralized electrical network, C_{QBP} – the costs of the purchased thermal energy from the boiler house, C_{WSN} – the profit from the sale of surplus SOFC-generated electricity to the centralized electrical network.

The total energy costs of the enterprise can be divided into the two groups:

1) fixed costs (for example C_{CAP} and C_{ST});

2) variable costs depending on the modes of the energy complex (C_{WN}, C_{QBP}, C_{WSN}).

The optimization parameter is the nominal SOFC's capacity (P_{NOM}). The choice of P_{NOM} affects both groups of costs. With an increase in P_{NOM}, fixed costs increase, and variables can decrease. The optimization task is to find the P_{NOM}, at which $C_{\Sigma} \rightarrow \min$.

A method for selecting the optimal biogas-powered SOFC's capacity has been developed. The block diagram of the method's algorithm is demonstrated in Fig. 2.

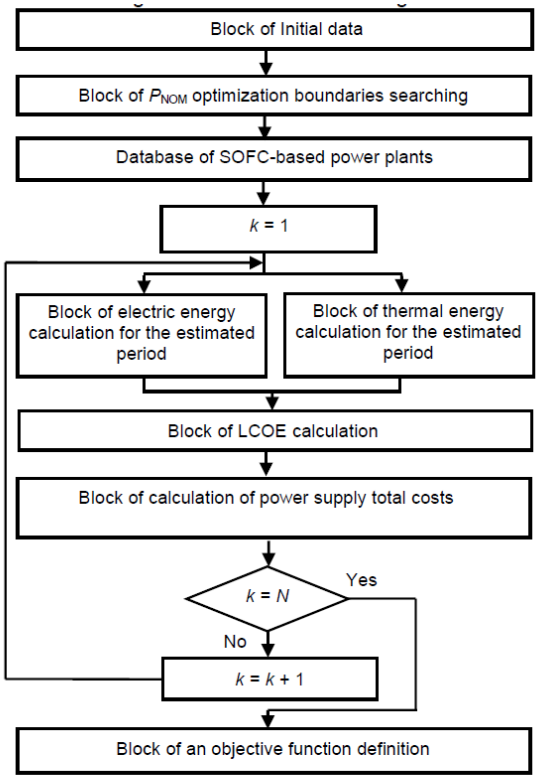

Fig.2. The block diagram of the algorithm for selecting the optimal biogas-powered SOFC's capacity

The choice of the optimal SOFC's capacity is based on determining the minimum of the objective function by simulating the operation of a combined energy source during the estimated period using various SOFC-based power plants (taken from the database) the capacities of which are within optimization boundaries.

In *the Block of initial data* the following is set: the number of years in the estimated period, the livestock enterprise parameters, information on energy carriers and tariffs.

The Block of P_{NOM} optimization boundaries searching is used to determine the minimum possible (P_{MIN}) and maximum allowable (P_{MAX}) of SOFC's capacity:

(5) $$P_{MIN} \leq P_{NOM} \leq P_{MAX}$$

P_{MIN} is taken equal to the minimum electric load of the enterprise at the normal operation mode. P_{MAX} is calculated taking into account the daily biogas production:

(6) $$P_{MAX} = V_M / \left(F_{SOFC} \cdot t_{SOFC} \right)$$

where: V_M – the daily volume of biogas production, which is determined according to the number of cattle (M_{CAT}) (m^3)

[14], F_{SOFC} – the specific biogas consumption for 1 kWh of electricity production (m^3/kWh), t_{SOFC} – the SOFC's daily operating time (h).

The Database of SOFC-based power plants contains information on technical characteristics, energy parameters and costs of SOFC-based power plants with different nominal capacities.

When the P_{NOM} optimization boundaries have been determined, *N* SOFC-based power plants are selected from the Database, the P_{NOM} values of which are within P_{MIN} to P_{MAX}. A cycle of *N* calculations of energy and economic indicators for the estimated period is beginning.

Using *the Blocks of electric and thermal energy calculation for the estimated period* for each *k*-th SOFC-based power plant out of *N* selected power plants, the components of electrical and thermal energy are determined for each *i*-th year of the estimated period:

- W^k_{SOFCi} – the electricity consumed by the enterprise from the SOFC-based power plant (kWh),
- W^k_{Ni} – the electricity consumed by the enterprise from the centralized electrical network (kWh),
- W^k_{SNi} – the SOFC generated electric power sold to the centralized electrical network (kWh),
- Q^k_{SOFCi} – the thermal energy consumed by the enterprise from the SOFC-based power plant (Gcal),
- Q^k_{BPi} – the thermal energy consumed by the enterprise from the boiler house (Gcal).

To calculate the components of electric and thermal energy, each *i*-th year of the estimated period is divided into *j*-th time intervals. The values of W^k_{SOFCi}, W^k_{Ni}, W^k_{SNi}, Q^k_{SOFCi} and Q^k_{BPi} are determined by distributing electric and thermal load of the enterprise between the combined energy complex's sources for each *j*-th time interval during the entire estimated period. The breaks for scheduled maintenance and repair of power plants are taken into account.

In *the Block of LCOE calculation* for each *k*-th SOFC-based power plant out of the *N* selected power plants, the LCOE values are calculated:

(7) $$LCOE = \sum \left[\frac{\left(C^k_{CAP} + C^k_{TEC} + C^k_{ST} - C^k_Q\right) \cdot (1+r)^{-t}}{W^k_{SOFC} + W^k_{SN}} \right]$$

where: C^k_Q – the savings from reducing the fuel consumption of the boiler house due to the beneficial use of SOFC generated thermal energy (EUR), *r* – the discount rate for the year *t*.

The C^k_Q value is taken into account at calculation of LCOE by analogy with a cogeneration plant. It's calculated by the equation:

(8) $$C^k_Q = \left(Q^k_{SOFC} \cdot T_{BP}\right) / \left(Q_{BP.MIN} \cdot \eta_{BP}\right)$$

where: T_{BP} – the average cost of fuel consumed by the boiler house (EUR/unit), $Q_{BP.MIN}$ – the lower calorific value of fuel consumed by the boiler house (kcal/unit), η_{BP} – the boiler house efficiency (relative unit).

The LCOE indicator corresponds to the long-term price per 1 kWh of SOFC generated electricity and is used in the analysis of the costs of the enterprise's energy supply.

In *the Block of calculation of power supply total costs* for each *k*-th SOFC-based power plant out of *N* selected power plants, the components of the total costs are calculated for each *i*-th year and the entire estimated period:

(9) $$C_{WNi} = T_N \cdot W_{Ni}$$

(10) $$C_{WSNi} = T_{SOFC} \cdot W_{SNi}$$

(11) $$C_{QBPi} = T_{BP} \cdot Q_{BPi} / \left(Q_{BP.MIN} \cdot \eta_{BP}\right)$$

where: T_N – the tariff for electricity consumed from the centralized electrical network (EUR/kWh), T_{SOFC} – the tariff for SOFC generated electricity sold into the centralized electrical network (EUR/kWh).

The capital costs relate to the first year of the calculation period and the savings due to the use of SOFC ensure the return of the capital investments in subsequent years. The capital costs relate to the first year of the calculation period, and the savings due to the use of LTTE ensure the return of capital investments in subsequent years. The capital costs relate to the first year of the calculation period, and the savings due to the use of LTTE ensure the return of capital investments in subsequent years. In order to bring multi-temporal cash flows in a comparable form to one point in time, it is proposed to calculate additionally the total costs using the discounting method:

(12) $$C_{D\Sigma} = \sum C_{Di} = \sum \left[C_i \cdot (1+r)^{-t} \right]$$

where: *r* – the discount rate, *t* – the number of years before the considered date.

The discounting method enables to estimate the multi-temporal cash flows by the time of the SOFC-based power plant integration into the energy complex.

In *the Block of an objective function definition*, the number of the results of C_Σ and $C_{D\Sigma}$ calculations are remain and the objective function $C_\Sigma = f(P_{NOM})$ and $C_{D\Sigma} = f(P_{NOM})$ are formed. By enumerating and comparing options for energy supply costs, the optimal value of P_{NOM} is determined.

The results of the research on application efficiency of a combined energy complex with SOFC on biogas

Using the developed method (Fig. 2), the research on application efficiency of a combined energy complex with SOFC on biogas for the power supply of a livestock enterprise has been carried out. The essence of the research consisted in the calculation and comparative analysis of undiscounted and discounted total costs for three options of the enterprise power supply:

- Option 1 – the enterprise is supplied with power from a centralized electrical network and a boiler house without SOFC;
- Option 2 – the enterprise is supplied with power from SOFC, centralized electrical network and a boiler house. Surplus of SOFC generated electrical energy during the period of minimum load can be transferred to the network;
- Option 3 - the enterprise is supplied with power from SOFC, centralized electrical network and a boiler house. The surplus of SOFC generated electrical energy is not transferred to the network (surplus of electricity is utilized to ballast load).

The initial data for the research are presented in Table 1.

Table 1. The initial data for the research

Parameters	Unit of measurement	Values
M_{CAT}	units	2,000
T_N	EUR/kWh	0.15
T_{SOFC}	EUR/kWh	0.1
T_{BP}	EUR/tn	75
$Q_{BP.MIN}$	kcal/tn	5,200
η_{BP}	%	75
R	%	15

The boiler house uses coal. The estimated period is taken equal to 10 years. Each year of the estimated period is divided into 8760 *j*-th time intervals.

The initial data on the electric and thermal load of a livestock enterprise have been preset by daily load schedules for summer and winter periods. The daily schedules of electric load are shown in Fig. 3.

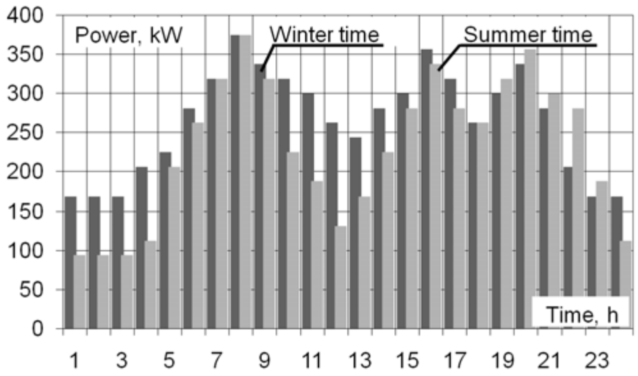

Fig.3. The daily schedules of electric load for summer and winter periods

In one year, the enterprise consumes 2,150 thousand kWh of electricity and 7088 Gcal of thermal energy.

The calculations to determine the P_{NOM} optimization boundaries have been carried out. At a livestock enterprise for 2,000 head of cattle, the daily output of manure is 90,600 kg, which allows to produce 3,024.08 m^3 of biogas per day. Taking this into account (according to equation (6)), the value of P_{MAX} is 500 kW. The P_{MIN} value is equal to the minimum electrical load in winter period and is 90 kW.

For comparative analysis, SOFC-based power plants with nominal capacities in the range from 90 to 500 kW have been selected from the database. The database contained 5 such power plants (N = 5): P_{NOM1} = 100 kW, P_{NOM2} = 200 kW, P_{NOM3} = 300 kW, P_{NOM4} = 400 kW, P_{NOM5} = 500 kW. The electrical efficiency of the all SOFC-based power plants is 53-65% [15].

For each SOFC-based power plant, the components of electric and thermal energy for one year were determined (Table 2).

Table 2. The components of electric and thermal energy for one year

P_{NOMi}, [kW]	W^k_{SOFCi}, [kWh·10^3]	W^k_{Ni}, [kWh·10^3]	W^k_{SNi}, [kWh·10^3]	Q^k_{SOFCi}, [Gcal]	Q^k_{BPi}, [Gcal]
100	872	1278	3.8	6447	641
200	1600	550	151	5864	1224
300	1867	283	322	5596	1492
400	2062	88	565	5329	1759
500	2150	0	2229	4260	2828

The consumption of electric and thermal energy is assumed as constant over the years of the estimated period.

Using the equations (7) and (8), LCOE was calculated for a ten-year life cycle of the system. The C^k_{CAP} values were determined based on the unit cost of 1 kW of SOFC capacity equal to EUR 3,300 and the cost of a biogas plant. C^k_{TEC} values were taken equal to 5% of C^k_{CAP}. The C^k_{ST} values are taken equal to EUR 15,000 per year. The Q_{SOFCi} values were determined taking into account the passport thermal characteristics of the SOFC (HR = 1.8 kcal/kWh).

Fig. 4 shows the results of LCOE calculations for Option 2 and Option 3.

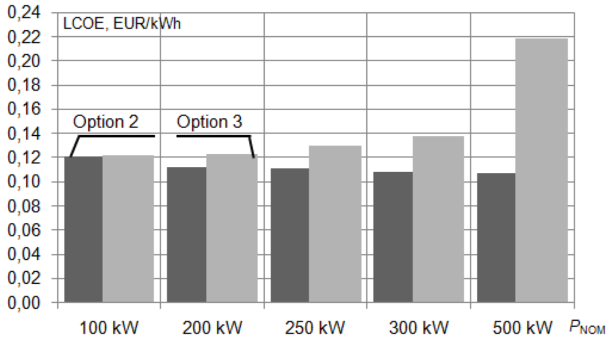

Fig.4. The results of LCOE calculations

For Option 3, the LCOE values increase with an increase in the nominal SOFC's capacity. This is due to the fact that the SOFC generated electric power is increased, but is not used in a useful way (it is utilized to ballast load).

Using the equations (4) and (12), the total costs of the livestock enterprise power supply for the estimated period were calculated. Table 3 shows an example of calculation for a combined energy source with a 100 kW SOFC-based power plant.

Table 3. The example of power supply costs calculation

The costs when using a 100 kW SOFC-based power plant [EUR·10^3]											
Year	1	2	3	4	5	6	7	8	9	10	Σ
C_{CAP}	464	0	0	0	0	0	0	0	0	0	464
C_{TEC}	0	24	24	25	25	26	26	26	27	27	468
C_{ST}	15	16	16	16	17	17	18	18	19	19	174
C_{WN}	323	199	203	207	210	214	218	222	226	230	2256
C_{QBP}	136	72	74	75	77	78	79	81	82	83	839
C_{WS}	0	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	3.8
C_{Σ}	938	311	317	324	330	336	342	348	355	361	3964
$C_{D\Sigma}$	816	236	209	185	164	145	128	13	101	89	2188

Fig. 5 and Fig. 6 show the results of total costs calculation for the three options of the enterprise's power supply.

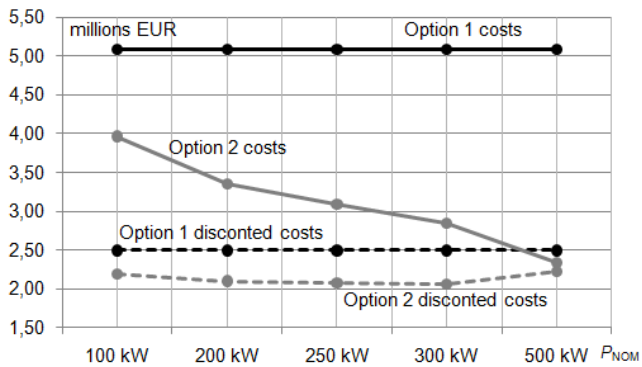

Fig.5. The total costs of the livestock enterprise power supply (Option 1 and Option 2)

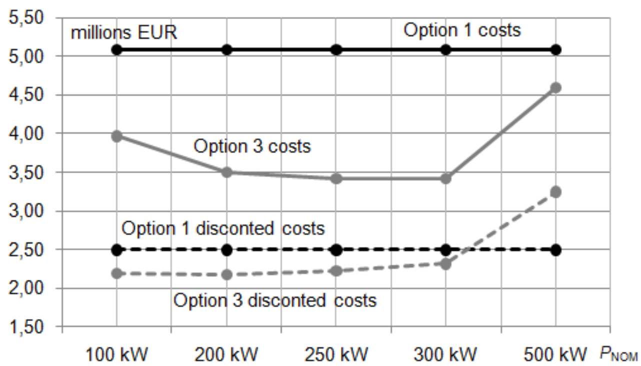

Fig.6. The total costs of the livestock enterprise power supply (Option 1 and Option 3)

Fig. 5 and Fig. 6 show that when using a combined energy source with SOFC on biogas (Options 2 and Option 3), the undiscounted and discounted total costs of the enterprise's power energy supply (for most SOFC-based power plants) will be less than the corresponding costs when the enterprise is supplied with power only from the centralized electrical network and the boiler house. That confirms the economic feasibility of using a combined energy complex with SOFC on biogas.

However, as a result of the research it was established that the graphs of dependences of undiscounted and discounted total costs of power supply on the nominal SOFC's capacity may differ. If we look at the undiscounted costs for Option 2, the optimal solution is the use of a SOFC-based power plant with P_{NOM} = 500 kW. But when using this power plant, the discounted costs of power supply will be the highest due to the too high capital costs in the first year of the project. Therefore taking into account the discount rate, it is more efficient to use a SOFC-based power plant with lower capacity (P_{NOM} = 200, 250 or 300 kW).

It should be taken into account that due to the significant variability of the initial information on the parameters of the livestock enterprise, energy carriers and tariffs, as well as the limited information on the SOFC-based power plants cost, the calculations are quite approximate. The results of the calculations allow to assess the qualitative dependence of undiscounted and discounted total costs of an enterprise's power supply on the nominal SOFC's capacity.

Conclusion

SOFCs are effective sources for electric and thermal energy generation using as a fuel biogas obtained from agricultural waste disposal.

A method to determine the optimal capacity of a SOFC-based power plant as part of a combined energy source for an agricultural enterprise's power supply has been developed. The optimization criterion is the total costs of the enterprise's power supply for the estimated period which is calculated using the discounting method.

On the example of a livestock complex for 2,000 units of cattle the research on application efficiency of a combined energy complex with SOFC on biogas was carried out using the developed method. For comparative analysis, SOFC-based power plants with nominal capacities in the range from 90 to 500 kW were selected from the developed database. The database contained 5 such power plants. The total costs of the enterprise's power supply were calculated.

It was established that the use of a combined energy source with SOFC on biogas for an agricultural enterprise generally is cost effective. It was determined that the dependences graphs of undiscounted and discounted total costs of power supply on the nominal SOFC's capacity may differ.

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