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Modelling the energy balances community under conditions increasing energy independence and reducing greenhouse gas emissions

Abstract. There is a need to develop effective technical and technological solutions to optimise the use of renewable energy in combined energy supply systems, which will solve the problems of uneven load and stochastic generation, ensuring energy independence of communities and minimising environmental impact. The aim of the work was to create a model of optimal loading of the installations of the technological structure of the combined energy supply of the community when covering the daily schedules of the electric and thermal load of the microenergy system. Its use made it possible to form the structure of annual monthly forecast balances of heat and electricity of an energy-independent community with minimisation of negative impact on the environment for further forecast analysis and determination of directions of innovative improvement of the community energy system in terms of climate change prevention and sustainable development of society. The results of model calculations of monthly annual balances of heat and electricity for the formed variants of the technological structure of the combined energy system of the Smila territorial community showed that an increase in the share of renewable energy capacities in its structure from 55% to 69% with a 30% limitation of electricity consumption (imports) from the external grid leads to a 3.5-fold reduction in greenhouse gas emissions (CO_{2eq}) from electricity production. The overall reduction in GHG emissions of the community's combined energy supply system amounted to 42%. The increase in the share of green generation in the technological structure of the community's combined energy supply caused a surplus of electricity in the local grid, the share of which in the total annual consumption

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of the community for the option with the largest volume of green generation was 2.5 The research results showed that ensuring the alignment of renewable energy generation with the variable load local grid required further consideration of the possibility using energy storage systems to transfer excess electricity or technologies for converting it into heat energy. This would allow for the replacement of equivalent amounts of heat generation from natural gas boilers, contributing to an increase in the community's energy independence and reducing greenhouse gas emissions

Keywords: mathematical programming model; daily load curve; technological structure; energy balance; combined energy supply system; energy independent community

INTRODUCTION

Widespread implementation objects of renewable energy soursys and the current state of development of the latest technical and technological solutions for the conversion of biofuels for combined production of electricity and heat created opportunities for managing the efficiency energy supply to territorial communities under the conditions of increasing their energy independence and environmental friendliness. The strategic goal of decarbonisation of Ukraine's energy sector by the middle of this century has been proclaimed at the state level (Order of the Cabinet of Ministers of Ukraine No. 373-p, 2023) requires a further increase in the share of energy from renewable energy sources (RES) in the balance of regional energy systems, which until now have traditionally relied on generation from fossil fuels. The National Action Plan on Renewable Energy until 2030 (Order of the Cabinet of Ministers of Ukraine, 2024) is a supplement to the National Energy and Climate Plan (NECP) (Order of the Cabinet of Ministers of Ukraine No. 587-p., 2024) and determines the trajectories of its development by sectors until 2030, taking into account the policies and measures identified by the NECP: share of RES in gross final energy consumption in Ukraine in 2030 will be 27%.There will be in in heat supply and cooling systems – 33%; in electricity production – 29%; in the transport sector – 17%.

Local micropower grids have opportunities for the integration RES, taking into account the peculiarities of their interaction in meeting the demand of end consumers and coordinating the using the external energy system. Support for the development of local energy in Ukraine is envisaged by the Strategy for the Development of Distributed Generation for the period until 2035 (Order of the Cabinet of Ministers of Ukraine No. 713-p, 2024). The Strategy defines highly maneuverable natural gas installations, as well as RES – wind and solar power plants and energy storage facilities – as expedient for the creation of distributed generation systems. Further substitution of natural gas as a fuel with renewable gases, in particular biomethane, at gas reciprocating and gas turbine plants, in cogeneration, will contribute to the overall decarbonisation of the energy system.

In the reasearch by G. Kostenko & A. Zaporozhets (2023) the role of micropower systems with RES in increasing the stability of the power system was analysed. It was determined that the concept of local networks with distributed generation, storage and management of energy can reduce dependence on the common power grid and centralised power supply, as well as its vulnerability, while increasing its overall and local resilience and significantly reduce recovery time.

In the paper by Y. Varetsky & Z. Hanzelka (2015) presented a model for evaluating different strategies for electricity dispatching in a hybrid system connected to the grid, which includes solar and wind installations, as well as a grid storage system, taking into account the load profile of the microgrid. To calculate the flow of electricity in the system, statistical indices of solar radiation and wind speed data were used. O. Hotra *et al.* (2023) proposed a mathematical model for studying the processes of frequency and power regulation in power systems with distributed generation, which integrates renewable energy sources (primarily wind and solar power plants – wind and solar power plants – wind farms and solar power plants) and energy storage systems according to the principles of their self-sufficiency, which means that all activities of such a combined energy system, including stabilisation of energy frequency and capacity, are carried out exclusively through the use of own energy of local origin.

The research by V. Babak & M. Kulyk (2023) was devoted the creating of a fundamentally new structure and foundations for the functioning of the electrothermal system that connects the unified energy system of Ukraine and the district heating system (DHS) through the electrification of DHS through using of energy from autonomous wind and solar power plants and the capacities of nuclear power plants, which ensures high manufacturability, efficiency, reliability and environmental friendliness of each of these components.

In the paper by V. Derii *et al.* (2023) the results of the assessment the impact of structural changes in the DHS on greenhouse gas emissions were presented. It was shown that the increase in the consumption of biomass and solar energy in the DHS with the simultaneous reduction of the consumption of fossil fuels – coal and natural gas – contributed a significant reduction in greenhouse gas emissions (GE).

The theoretical and applied foundations of structural implementations of combined energy systems (CES) for energy supply of territorial communities with heterogeneous sources, formulated in the work by V. Kaplun (2023). It was based on a resource-process analysis of the functioning of local networks by searching for the optimal using local biofuels and RES in the combined production of electricity and heat, taking into account their present value. The key feature of such CES were their ability to predictably change the structure of the energy balance by replacing the main component of energy consumption from external networks and, under certain conditions, switch to an isolated (island) mode of operation without reducing the quality of energy supply. Synchronisation with external grids provided operational flexibility when using distributed generation sources with stochastic parameters, primarily from solar power and wind plants, and allowed maneuvering distributed generation in a micropower system.

Compilation of monthly balances of production and consumption of electricity and heat usually consists in determining the monthly volumes of energy generation of CES technologies based on the coefficients of use of their rated capacity for the production of electric and thermal energy in the monthly cycle. However, the unevenness of the daily load schedules of the local energy system, their seasonal, monthly and daily differences, the stochasticity generation of solar power and wind plants and the discrepancy of their capacity profiles to the form the daily schedule of electric load without the ability to control the supply of their power to the grid requires an analytical and computational study of the corresponding energy balances in the daily context.

Optimal composition and utilisation of generating capacities of the local power grid of the community covering daily schedules of electrical loads (DSEL) determined using the model of mathematical programming with integer variables, which belongs to the class of mathematical models for solving the problem optimal dispatching of generating capacities the power system (Abdou & Tkiouat, 2018).

The reasearch was devoted a model of optimal loading of units the technological structure combined energy supply when covering the daily schedules of electrical and thermal load of the micropower system. The use of such a model made possiblity to form the structure of annual monthly forecast balances of heat and electricity a non-volatile community with minimisation of the negative impact on the environment for further forecast analysis and determination directions for innovative improvement of the community's energy system under the conditions of climate change prevention and sustainable development of society.

MATERIALS AND METHODS

The model optimal loading of agreggats the technological structure combined power supply micropower system was developed on the basis of the model optimisation of the loading the generating capacities of the power system. The optimisation criterion was the minimisation production costs in compliance with the requirements of balance sheet reliability, as in S. Shulzhenko *et al.* (2020), T. Nechaieva (2021). At the same time, coverage of daily schedules of electric and heat load was provided. The main factors taken into account in the simulation were:

- actual structure, physical, technical and technical and economic indicators of electric and heat energy generation installations local CES. Relevant forecast indicators of generating plants that can be implemented in the process of technological development and improvement of the power system. In particular, cogeneration plants and power generating plants based on piston engines, gas turbines and combined-cycle gas technologies using natural gas, biogas and synthetic gases;
- simultaneous observance of the hourly balance of production and consumption of electric and heat energy in the power system in accordance with the daily schedules of electric and heat loads local power grid throughout the calendar year;
- hourly profiles of electricity generation by wind and solar power plants throughout the calendar year.

The formation of the forecast annual monthly balance of heat and electricity of the energy-independant community consisted in optimising the simultaneous coverage of the daily schedules electric and heat load of consumers local community with the summation of the obtained daily indicators of production and consumption in monthly and annual terms.

The main limitations of the developed mathematical model were balances for each time period of the day between the volumes of consumption and production of electricity and heat by electricity, heat and cogeneration plant. They were considered in modelling using artificial variables of import and export from the external power grid to settle the imbalance of electricity and artificial variable closing technology of heat production to settle the imbalance of thermal energy.

The balance of electricity production and consumption of the local power grid of the community for each hour of the day was as follows:

$$P_t^{WPP} + P_t^{PV} + \sum_{k \in K^{TPP}} p_{kt}^{TPP} + z_t^I - z_t^E = D_t, \forall t \in T, \quad (1)$$

where T – set of modelling time periods. Since the daily hourly schedule of electrical loads is simulated (SEG), the set T consisted of 24 (1...24) items, everyone corresponds to a certain time of day; P_t^{WPP}, P_t^{PV} – capacity of electricity supply of wind farms and solar power plants to the local power grid of the community within an hour t, MWh; K^{TPP} – set of heat power plants local network the community considered in modelling (gas pistons, gas turbine plants with a quick start on natural gas, biogas cogeneration plants, cogeneration plants on natural gas, local mini-CHPs); p_{kt}^{TPP} – a variable from a set of real numbers, corresponding to the total power generated by installations from the set K^{TPP} during an hour t, MWh; z_t^I – variable of the amount of electricity imported from the external network during the hour t, MWh.; z_t^E – variable of the volume of exported excess electricity from the local network of the community to the external network within an hour t, MWh.; D_t – electricity consumption (power) by the local community within an hour t, MWh.

The hourly generation capacities of WPP and SPP were input data of the model and set in accordance with the profiles of their generation for a certain location of their location and installed electrical capacity. Heat power plants were defined by their unit capacities, the number available for operation, the range of power change relative to the previous period, the duration continuous operation and the number of possible start-ups during the day (Shulzhenko *et al.*, 2020).

The balance of production and consumption of heat energy of the CES of the community for each hour of the day was as follows:

$$\sum_{k\in K^{HP}} p_{kt}^{H\_HP} + \sum_{k\in K^{CHP}} p_{kt}^{H\_CHP} + z_t^{HI} - z_t^{HE} = D_t^H,\ \forall t\in T, \quad (2)$$

where K^{HP} – a variety of technologies for the production of heat energy the local grid heating network of the community (fossil fuel boilers, biofuel boilers, etc.)); $p_{kt}^{H\_HP}$ – a variable set of real numbers, which corresponds to the total power of heat generation by heat production units from a set K^{HP} of the loca heating network of the community (fossil fuel boilers, biofuel boilers); K^{CHP} – multiple combined heat and power plants and cogeneration plants (biogas cogeneration plants, natural gas-piston cogeneration plants), $K^{CHP}\subset K^{TPP}$, which are integrated into the local heating grid of the community; $p_{kt}^{H\_CHP}$ – a variable from a set of real numbers, corresponding to the total power heat energy generation by installations from a set K^{CHP}; z_t^{HI} – "artificial" variable for regulating the imbalance of heat production and consumption with determination of the volume of power deficit during the hour t, MWh; z_t^{HE} – "artificial" variable to settle the imbalance of production and consumption of heat energy with the determination volume of power surplus in the hour t, MWh; D_t^H – heat consumption power in the local community's CES within an hour t, MWh.

The power of heat supply cogeneration plants and combined production depends on the technological ratio between electric and heat power:

$$p_{kt}^{H\_HP} \leqslant p_{kt}^{TPP}\,\kappa_k^{E2H},\ \forall k\in K^{CHP}, \forall t\in T, \quad (3)$$

where κ_k^{E2H} – correlation between electrical and heat power of a combined power and heat unit k.

The energy independence of the community is ensured by a certain level of self-sufficiency in its own electricity generation with a reduction in electricity consumption (imports) from the general centralised electricity supply network, which is set in the model by the share of electricity consumption from the external network from the total electricity consumption local community k^1:

$$\sum_{t=1}^{T} z_t^I \leqslant k^I \sum_{t=1}^{T} D_t. \quad (4)$$

The conditions for the use of heat and power plants for DSEG coating are formulated using restrictions on the number of their start-ups, composition and permissible load modes, described in detail S.V. Shulzhenko *et al.* (2020). Conditions for the use of heat generation units to cover the daily heat load schedule (DSEG) is formulated using restrictions on the number of their start-ups, composition and permissible load modes, similar to the restrictions for heat and power plants to cover DSEG.

The criterion of the optimisation problem is to minimise the costs of supplying electric and heat energy during the day using the generating power involved in the coating DSEG та DSHG, the cost of electricity consumed from the external network and supplied to the external network, the cost of heat energy of the technology to settle the heat imbalancea:

$$\sum_{t=1}^{T}\Big(\sum_{k\in K^{TPP}} p_{kt}^{TPP} c_{kt}^{TPP} + z_t^I c_t^I + z_t^E c_t^E + \sum_{k\in K^{HP}} p_{kt}^{H\_HP} c_{kt}^{HP} + \sum_{k\in K^{CHP}} p_{kt}^{H\_CHP} c_{kt}^{HP} + z_t^{HI} c_t^{HI} + z_t^{HE} c_t^{HE}\Big) \to \min, \quad (5)$$

where c_{kt}^{TPP} – the cost of electricity supply by an installation of the type k during an hour t, USD/ MWh; c_t^I – the cost of electricity imported from the external network during an hour t, USD/ MWh; c_t^E – cost of electricity exported to the external grid within an hour t, USD/ MWh; c_{kt}^{HP} – cost of heat supply by heat generation and combined heat generation units during an hour t, USD/ MWh; c_t^{HI} – cost of "closing" heat production technology to settle the imbalance of heat energy in the event of a shortage of heat energy, USD/ MWh; c_t^{HE} – coefficient at an artificial variable of the export excess heat energy to settle the imbalance of heat energy in the event of a power surplus, which is much more important than the cost of other technologies, USD/ MWh.

The total monthly balance of electricity production and consumption of the CES of the local community consisted of the sum of the resulting indicators of daily optimisation calculations for the corresponding month of the year:

$$\sum_{d=1}^{N_m}\Big(E_d^{WPP} + E_d^{PV} + \sum_{k\in K^{TPP}} E_{kd}^{TPP} + E_d - I_d\Big) = D_m,\ m = 1 \div 12, \quad (6)$$

where N_m – number days of the month m, m = 1 ÷ 12; E_d^{WPP} – volume of released WPP electricity per day d, MWh; E_d^{PV} – volume of released SPP electricity per day d, MWh; E_{kd}^{TPP} – the volume of electricity supplied by heat power installation type k per day d, MWh; E_d – the volume of excess electricity supplied to the network per day d, MWh; I_d – the amount of electricity consumed from the grid per day d, MWh; D_m – electricity consumption in month m, MWh.

The annual balance of electricity production and consumption of the CES of the local community consisted of the sum of monthly balances:

$$\sum_{m=1}^{12}\sum_{d=1}^{N_m}\Big(E_d^{WPP} + E_d^{PV} + \sum_{k\in K^{TPP}} E_{kd}^{TPP} + E_d - I_d\Big) = \sum_{m=1}^{12} D_m, \quad (7)$$

The total monthly balance of heat energy production and consumption CES local community consisted of the sum resulting indicators of optimisation calculations each day corresponding month:

$$\sum_{m=1}^{12}\Big(\sum_{k\in K^{HP}} H_{kd}^{HP} + \sum_{k\in K^{CHP}} H_{kd}^{CHP} + H_d^I + H_d^E\Big) = DH_m,\ m = 1 \div 12, \quad (8)$$

where, H_{kd}^{HP}, H_{kd}^{CHP} – volumes of heat output by heat generation units and combined generation of electricity and heat type k per day d, MWh; H_d^I – the volume of heat energy deficit local heating system of the community per day *d*, MWh; H_d^E – the volume of excess heat energy in the local heating system of the community per day *d*, MWh; DH_m – consumption of heat energy in the local heating system of the community in the month m year, MWh.

The annual balance of heat production and consumption in the local heating system community consisted of the sum of monthly balances:

$$\sum_{m=1}^{12}\sum_{d=1}^{N_m}\left(\sum_{k\in K^{HP}} H_{kd}^{HP} + \sum_{k\in K^{CHP}} H_{kd}^{CHP} + H_d^I + H_d^E\right) = \sum_{m=1}^{12} D_m. \quad (9)$$

Data on energy consumption of the Smila Community Cherkasy region of Ukraine for 2021 were used modelling the optimal loading of the generating power of the micro-energy system with the formation monthly balances of production and consumption electric and heat energy (Smila city territorial community, n.d.), which covered both the population and legal entities. This year was the first after the lifting of quarantine restrictions caused by the pandemic COVID-19, and the last before the start of full-scale Russian aggression against Ukraine. Indicators of electricity and heat consumption for this period served as the basis for the formation forecasts the post-war energy recovery community.

Model calculations of the optimal utilisation of the power of the CES with the coating of DGEN and DGTN local network of the Smila Community with the formation of monthly balances electric and heat energy was carried out using a software and information complex for modelling multi-node integrated and autonomous electricity and heat supply systems, developed using a combination of standard software Microsoft Excel and plug-in SolverStudio.

RESULTS AND DISCUSSION

The projected transformation of the technological structure of the microgrid of the Smila Community is based on the use of SPP, WPP and combined energy production units on solid biofuels and biogas. The energy independence of the community is ensured by the restriction 30% the share of daily electricity consumption from the external network from the volume of daily consumption of the community. As a maneuverable technology to ensure the balance of production and consumption of electricity, cogeneration gas piston units (KGPU) on natural gas with a total installed electric power of 10 MW were adopted. Excess electricity production that may occur during periods of "failure" of the GEN and the presence of significant base generation can be exported to the external (centralised) power grid, sold to third parties or accumulated.

The introduction of cogeneration is possible both on the basis of gas turbines and gas piston agregats. Gas piston agregats have a higher electrical efficiency than open-cycle gas turbines. Such agregats work best at biogas plants and in municipal heat supply, where there is a possibility of introducing cogeneration and using energy for heating.

The advantages of equipping existing boiler houses centralised supply systems (CCS) in Ukrainian cities with cogeneration gas piston units are availability appropriating infrastructure at the industrial sites of existing boiler housesю These are connected power lines and existing transformer substations for supplying electricity to local distribution power grids, which does not require additional costs for their construction. Boiler CCS are consumers of electricity of the first and second categories, which makes it possible using two power lines (main and backup) at the same time to supply electric power to the distribution grid. Gas pipelines for the supply of natural gas have already been supplied to these boiler houses (Teslenko, 2024). KSPE have high energy efficiency due to the cogeneration of electrical and heat energy (short terms of delivery, installation and adjustment of equipment with the presence of highly professional personnel, easier permitting procedures and faster construction times). They are responsible the requirements for frequent rapid starts and stops, which are becoming more and more necessary as the share of wind and solar energy in the energy mix increases. The simplification of the procedure for connecting generating installations (gas turbine, gas piston, cogeneration, etc.) to electricity networks, introduced by the National Regulator in May 2024, will help reduce the time for connecting such installations to electrical networks with priority using the exister energy infrastructure.

There is a mini-thermal power plant (mini-CHP) on wood chips and agricultural waste on the territory of the Smila Community. CHP provides 20-31% Community's total electricity demand. The production of electric and heat energy is provided using two modernised biofuel boilers DKVR-10-39-44 (Ukraine). Part of the high-pressure steam from which is supplied to two turbine generators, with a capacity of 6 MW each. The rest in the form of heat energy and hot water is supplied through the district heating system to the municipal sector, social and industrial enterprises of the city of Smila. To produce heat during the peak periods of the heating season, the CHP uses a KVGM-20 (Ukraine) natural gas water heating boiler with a heat power of 20 Gcal/h (23.2 MW).

For calculations, the monthly supply of electricity and heat of the Smila CHPP in 2021 were used. In model calculations, it is assumed that the CHP operates in the basic mode during the day without changing the power.

Determination of generation profiles of wind and solar power plants located within the Smila Community was carried out using a system for modelling the generation RES System Advisor Model (SAM), developed by the National Renewable Energy Laboratory (NREL) (Nate *et al.,* 2018). The detailed model of the PV simulation system SAM (Gilman, 2015) calculates the electrical power of the grid-connected PV system according to the number and specification of the system's PV modules and inverters, taking into account the impact on the performance the modules, the temperature of the environment and the structural features of the station construction. The Wind Power model of the SAM simulation system is capable of simulating the generation of electrical energy from either a single wind turbine or a wind plant with multiple turbines (Freeman *et al.,* 2014).

To determine the generation power WPP and SPP meteorological data of the area of their location are necessary. For SPP, they can be downloaded from the national solar radiation database NREL (NSRDB) by coordinates of the location of the installations. For wind farms, SAM only supports meteorological data for the continental USA. From June 2024, it became possible to download data on wind speed and direction in Ukraine from the RE Data Explore information resourcer. This resource allows to obtain data on wind speed at different heights and directions both for a separate location and for a certain area, which are used as an information resource to determine the performance of wind plants in the Wind Power model of the SAM modelling system.

The received monthly volumes of electricity generation from WPP and SPP with a nominal power of 1 MW, which are installed within the Smila Community, are given in Figure 1.

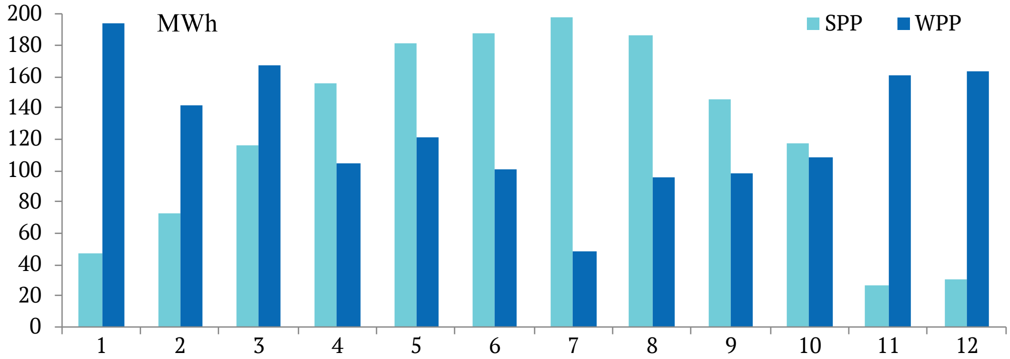

Figure 1. The monthly volumes of electricity generation from WPP and SPP with a nominal power of 1 MW within the Smila Community

Source: compiled by the authors

Model calculations of the optimal load power of the CES when covering the DGEN and DGTN of the local network Community were performed in forming variants of the technological structures of the power supply Smila Community (Table 1). During the simulation, it is assumed that the biogas gas compressor plant operates in the basic mode with a power change range of 10%. Natural gas KSPE is used as a highly maneuverable energy source with the possibility of frequent starts and stops. The heat load coverage takes into account the use of biomass CHP power, cogeneration plants, CHP hot water boiler and gas boiler houses CCS Community.

Table 1. Experimental data of the prototype sample of the SEMC

Technology	CSE structure options			
	1	2	3	4
CEC(PV)	1	2	3.5	4.5
BEC (WPP)	1.6	2.4	3.2	4.8
Biomass CHP plant	8.5	8.5	8.5	8.5
KSPE on biogas (BCGU)	1	2	3	4
KSPE on natural gas (NGCGU)	10	10	10	10

Source: compiled by the authors

The results forming monthly balances electricity for the corresponding variants of the technological structures CES Smila Community are shown in Figure 2.

As can be seen from the electricity balance coverage structures shown in Figure 2, the increase in the share of renewable generation in the structure CES leads increasing in excess electricity volumes for Community consumption. This is due to both the limited range of regulation of biomass and biogas installations, and the uncontrolled supply of energy from WPP and SPP to the grid, especially during night and day failures of DGEN. Figure 3 shows the structure of DGEN coverage for variant 4 of the technological structure CES for winter and summer days with the largest volumes of excess energy in these seasons.

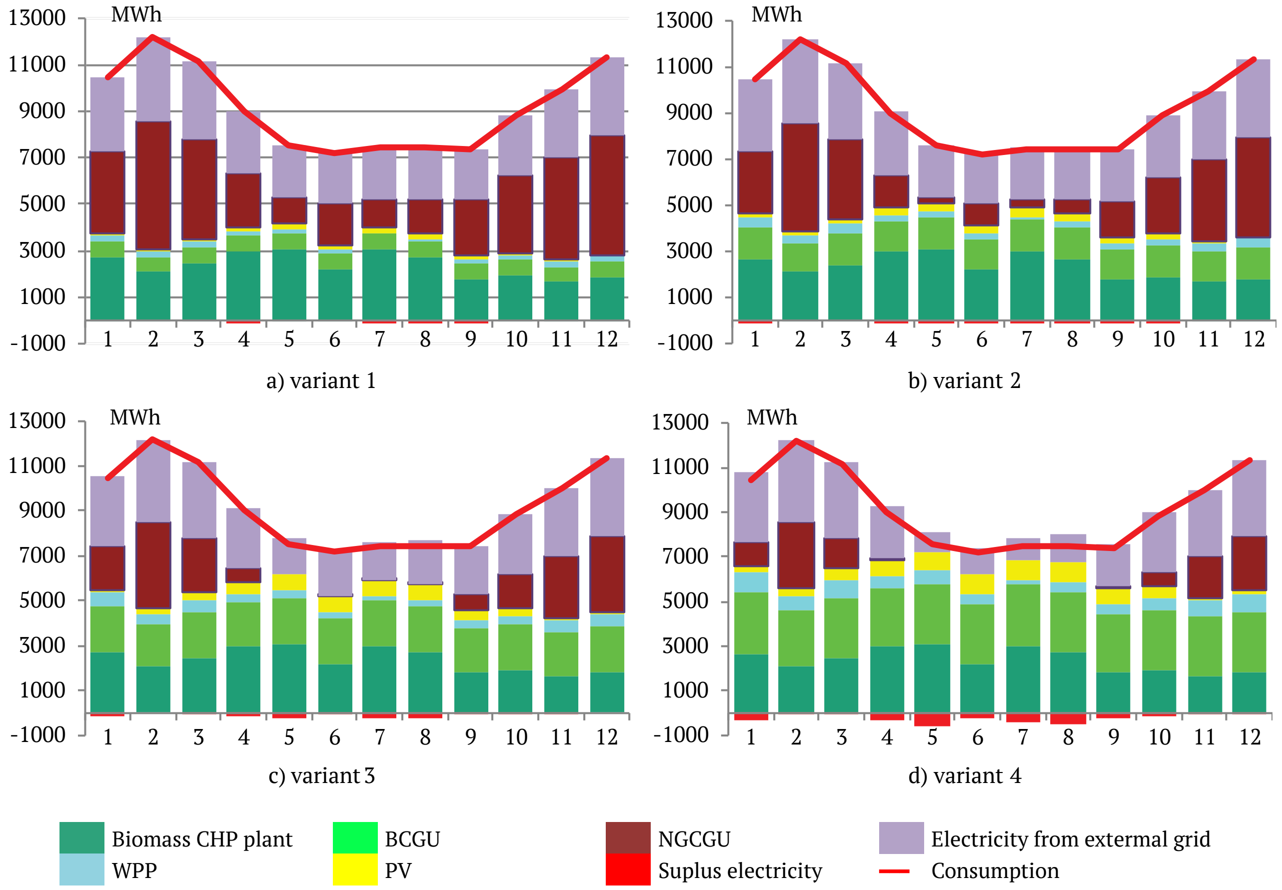

Figure 2. The monthly balances electricity for the corresponding variants of the technological structures CES Smila Community

Source: compiled by the authors

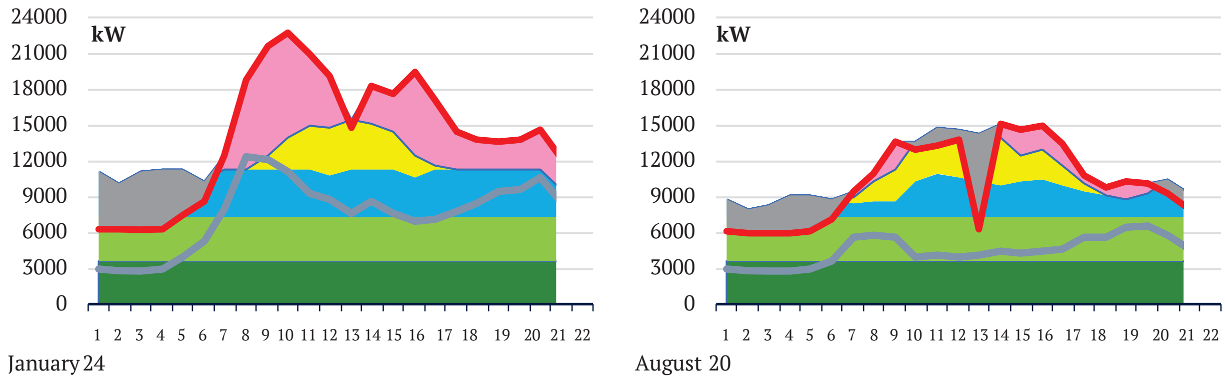

Figure 3. The load coverage schedules for variant 4 of the technological structure CES for summer and winter days with the largest amount of excess energy

Source: compiled by the authors

The analysis of outdoor temperature indicators showed that the minimum air temperatures in Smila Community were recorded on January 18, 2021 and reached -18.4°C (World weather, n.d.). For this day, the calculation method determined the hourly DHT, which was used in further studies as a base period for predicting and comparing the results obtained. The structure of coverage the schedules of electric and heat load of the day with the minimum air temperature according to the variants of the technological structure CES Smila Community is shown in Figure 4.

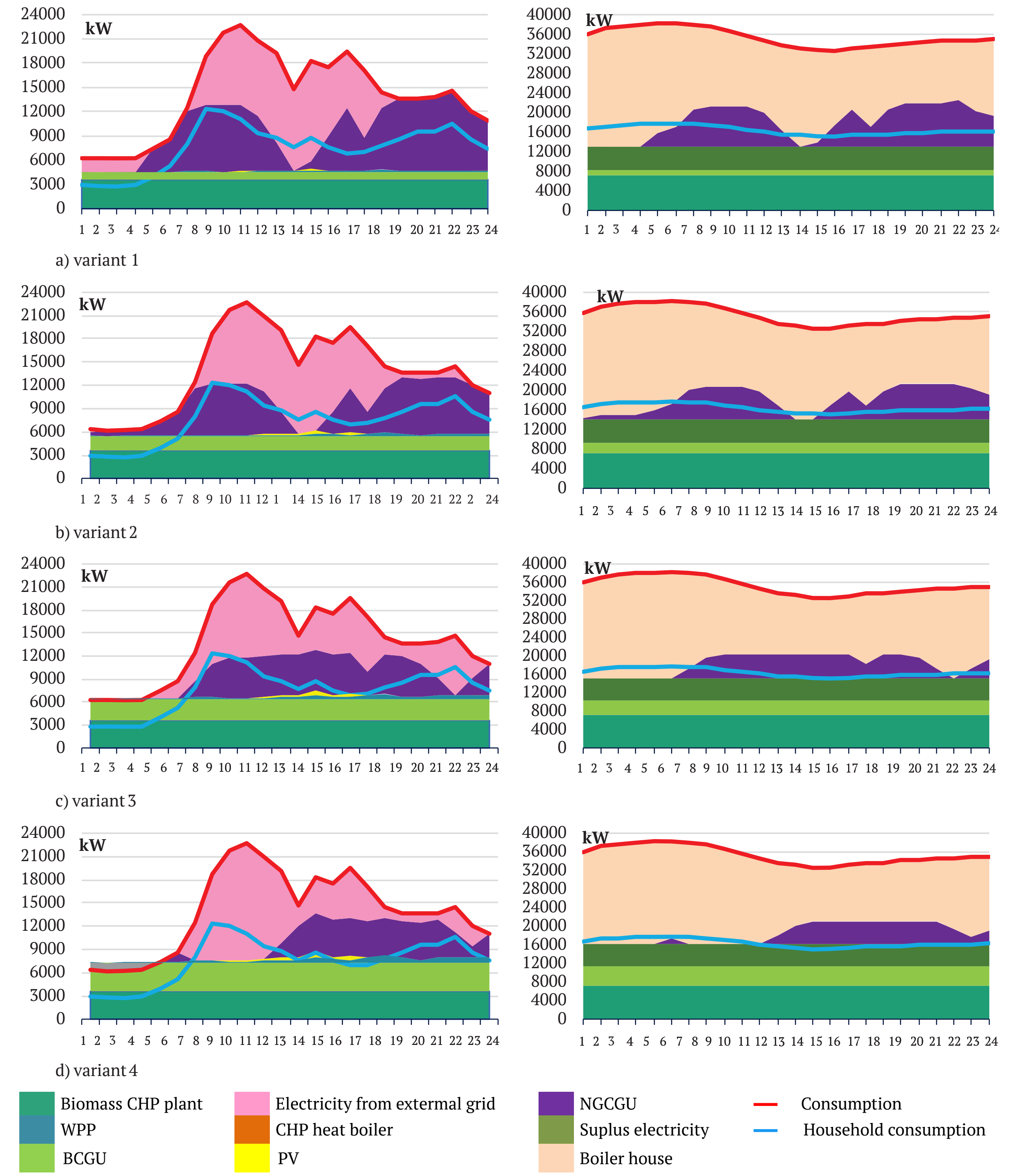

Figure 4. The structure of coverage the schedules of electric and heat load of the day with the minimum air temperature January 18

Source: compiled by the authors

The results of monthly heat energy balances for the formed variants of the technological structures of heat generation Smila Community are shown in Figure 5. The structures of the annual electricity and heat balances for the existing variants of the technological structures of the Smila community's generating capacities, as well as the cost of electricity and heat and CO_2 emissions are shown in Table 2.

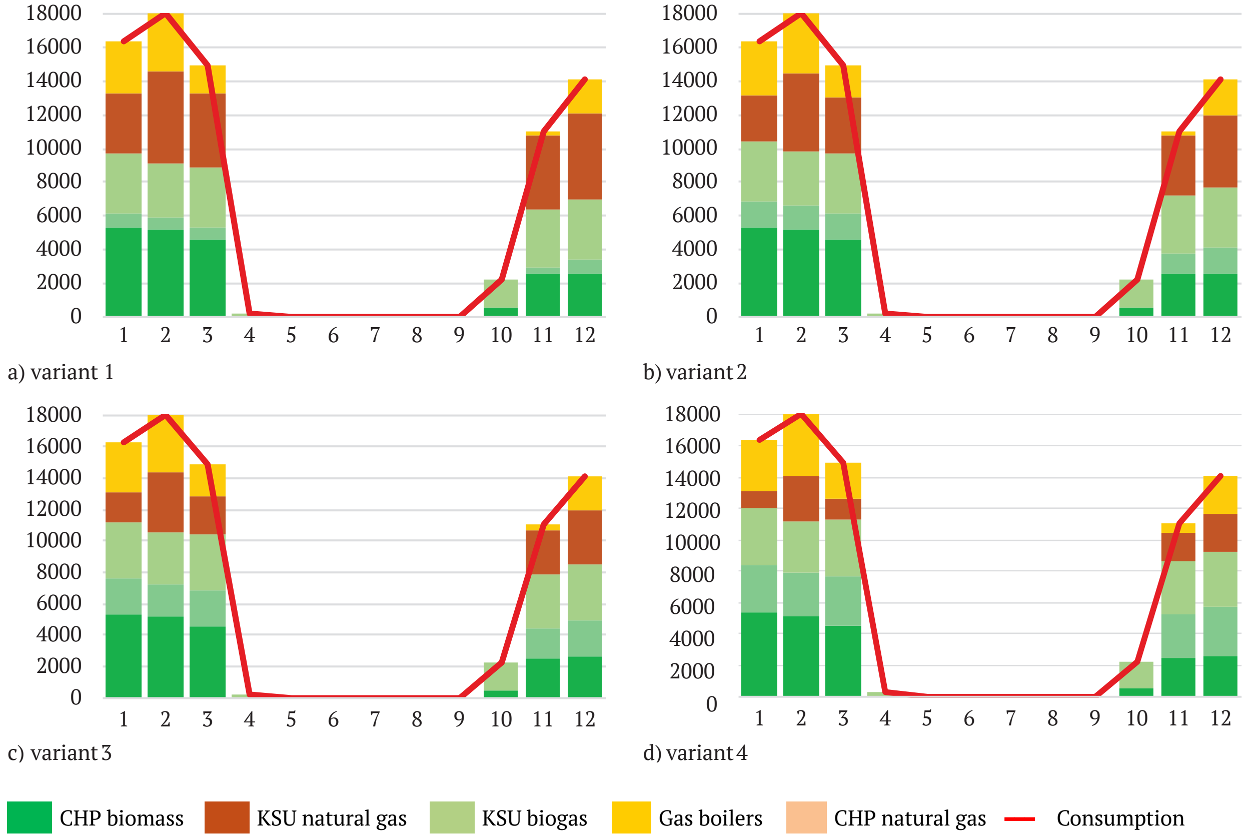

Figure 5. The monthly heat energy balances for variants of technological structures of heat generation power Smila Community

Source: compiled by the authors

Table 2. Structures of annual balances of electricity and heat energy Smila Community

Indicators	Variant of the technological structure			
	12	2	3	4
Electricity consumption, MWh	110052	110052	110052	110052
Electricity supply in total, MWh, including technology	77038	77299	79723	85032
CHP biomass	28373	28373	28373	28373
KSU biogas	8061	16120	24182	32242
WPP	2406	3609	4812	7218
SPP	1464	2927	5122	6586
KSU natural gas	36735	26270	17233	10613
Electricity consumption from the external network, MWh	33016	32989	31417	27780
Excess electrical energy, MWh	2	237	1087	2759
Cost of electricity, \$/MWh	76	79	82	85
CO_2eq emissions from natural gas consumption during electricity generation, t	8161	5836	3828	2358
Supply of heat energy in total, MWh, including technologies	76870	76870	76870	76870
CHP biomass	20692	20692	20692	20692
CHP boiler natural gas	19395	19395	19395	19395
KSU biogas	3425	7245	11002	14859
KSU natural gas	22954	18691	14362	9716
Gas boilers	10404	10849	11418	12206
Cost of heat energy, \$/MWh	51.4	51.4	51.5	51.5
CO_2eq emissions from natural gas consumption during heat production, t	11720	10359	10036	9179
Total CO_2eq emissions, t	19880	16195	13864	11537

Source: compiled by the authors

The results of model calculations showed that an increase in the share of renewable energy generating power in the technological structure CES Smila Community from 55% to 69% with a 30% restriction of electricity consumption from the external grid leads to a reduction in greenhouse gas (GHG) emissions (in $CO_{2eq)}$ during electricity production by 3.5 times. The overall reduction in gas emissions of the combined energy supply system is 42%. This is primarily due to a decrease in electricity and heat production by natural gas cogeneration plants. Biomass and biogas plants are considered carbon neutral and are not included in the calculation total greenhouse gas emissions. The growth of the share of RES generation in the technological structure CES caused a surplus in the local electricity grid, which share of the total annual community consumption for the option with the largest volume green generation implementation was 2.5%.

In the future, when forming the forecast annual balances of electric and heat energy, it is advisable to take into account the technological possibility of accumulating excess electricity in storage systems with the subsequent transfer to peak hours community electricity consumption or converting it using heat generators (electric boilers or electrically driven compression heat pumps) into thermal energy for use in local community heat supply networks.

The research by D. Akinyele *et al.* (2021) modelling of hybrid systems on renewable energy is devoted determining the optimal structure of an autonomous energy system responsibility the needs rural communities. A comprehensive analysis of existing modelling tools and approaches for sustainable planning, design and development of microgrids based on clean energy resources, as well as energy modelling software was carried out in in this work.

In the paper by A. Alzahrani *et al.* (2017) the microgrid is considered as a system of systems (SoS) with the possibility of using different energy sources. Microgrid electrical component models use complex system simulation techniques, such as agent-based and system dynamics-based methods, or a combination of different methods. Neural networks were used to simulate the power output of microgrid components to provide electrical load.

Optimisation of the mode of loading energy capacities is one of the most important tasks in managing the operation of power systems. Consideration of methods and models for solving the problem of optimal load of installations (eng. Unit Commitment – UC) is devoted to a significant number research publications. UC formulations have been a particularly active area of research because of their practical importance in the operation of the power grid. In the paper by B. Knueven *et al.* (2020) provided a comprehensive overview of mixed integer programming formulations for the UC problem. In the review by L. Montero *et al.* (2022), this task was considered taking into account such emerging trends as the high penetration of RES or the widespread use of non-traditional energy storage technologies. The evolution of the formulation of mixed integer linear programming with the improvement of commercial solvers with consideration of its predominant use for the problem of optimal loading plants was presented.

In the works by M.K. Deshmukh & S.S. Deshmukh (2008) presented the results of mathematical modelling of hybrid energy systems that use electricity generation from RES. A. Gupta *et al.* (2011) presented a mixed integer linear mathematical programming model for the optimal structure of an off-grid energy system to meet the electrification needs of remote rural areas, consisting of photovoltaic, fuelwood installation, biogas, small/micro hydropower, battery storage and fossil fuel generation. A model of an autonomous hybrid system on renewable energy, consisting of solar, wind, biomass, biogas plants, fuel cells with batteries, is proposed in the reasearch by V. Suresh *et al.* (2020). Optimisation calculations to minimise the cost of the system with the determination of its structure under the conditions of reducing the net present value, energy cost, CO_2 emissions responsible requiring demand were carried out using the Genetic Algorithm (GA) and HOMER Pro software. The model was used daily and annual load profiles. The calculation of the daily solar radiation, the average wind speed and the optimal size system of the reasearch hybrid system location was carried out using the HOMER Pro Software.

CONCLUSIONS

The integration of RES into local networks communities contributes to the growth of their sustainability, environmental friendliness and reduces dependence on external energy supply. The unevenness of the daily load schedules of the local energy system, their seasonal, monthly and daily differences, the stochasticity generation of SPP and WPP led to a detailed modelling of the coverage of the daily schedules electrical load the end consumers local electricity system and the heat load community district heating system using approaches modelling the optimal load generating power system.

The developed model of mathematical programming for the formation of the forecast annual monthly balance heat and electricity of the non-volatile community allows to determine in detail the optimal power utilisation combined power supply system local network community, taking into account the profiles of daily schedules electric and heat loading in compliance with the requirements of balance reliability, modes using power of electric and heat energy generation units, cost of their production electric and heat energy.

The formation of forecast annual monthly balances of electricity and heat using the developed model was carried out on the data on electricity and heat consumption Smila territorial Community formed variants of its technological structure, taking into account the operation existing biomass CHP. They provide for the introduction into the combined power supply network to consumers from 1.6 to 4.8 MW WPP and from 1 to 4.5 MW SPP, from 1 to 4 MW cogeneration gas piston plants on biogas formed during the conversion of local raw materials, as well as 10 MW of highly maneuverable cogeneration gas piston plants on natural gas, which are advisable to install on existing boiler houses of centralised power supply systems.

The results of model calculations monthly annual balances heat and electricity Smila territorial Community forming variants of its technological structure showed that an increase in the share of RES power in its structure from 55% to 69% with a 30% restriction of electricity consumption from the external power grid leads to a reduction in greenhouse gas emissions (in CO_2eq) during electricity production by 3.5 times. The overall reduction in gas emissions the combined energy supply system community is 42%. The surplus of electricity generated by the increase in RES power can be used by accumulating with subsequent transfer to the hours of shortage or conversion into heat energy to replace the corresponding production from natural gas boilers.

In the future, for a more objective reasearch hybrid energy systems electric and heat generation, the authors recommend investigating the impact on the optimisation the daily schedule electricity generation of the following technologies electric heat generators: electric boilers and compression heat pumps with an electric motor as potential consumers – electricity regulators.

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CONFLICT OF INTEREST

None.

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Моделювання енергетичних балансів громади за умов збільшення енергонезалежності та скорочення викидів парникових газів

Анотація. Існує необхідність розробки ефективних техніко-технологічних рішень для оптимізації використання відновлюваної енергії в комбінованих систем енергозабезпечення, що дозволить вирішити проблеми нерівномірності навантаження та стохастичності генерації, забезпечуючи енергетичну незалежність громад і мінімізуючи вплив на довкілля. Метою роботи було створити модель оптимального завантаження установок технологічної структури комбінованого енергозабезпечення громади при покритті добових графіків електричного та теплового навантаження мікроенергетичної системи. Її використання дозволило сформувати структуру річних щомісячних прогнозних балансів теплової та електричної енергії енергонезалежної громади із мінімізацією негативного впливу на довкілля для подальшого прогнозного аналізу та визначення напрямів інноваційного вдосконалення енергосистеми громади за умов запобігання змінам клімату та стійкого розвитку суспільства. Результати модельних розрахунків помісячних річних балансів теплової та електричної енергії для сформованих варіантів технологічної структури комбінованої енергетичної системи Смілянської територіальної громади засвідчили, що збільшення частки енергетичних потужностей відновлювальних джерел енергії у її структурі з 55 % до 69 % при 30 % обмеженні споживання електроенергії (імпорту) з зовнішньої електромережі приводить до скорочення викидів парникових газів ($CO_{2екв}$) при виробництві електроенергії у 3,5 рази. Загальне скорочення викидів ПГ системи комбінованого енергозабезпечення громади склало 42 %. Зростання частки зеленої генерації у технологічній структурі комбінованого енергозабезпечення громади обумовило надлишок в локальної мережі електроенергії, частка якої від загального річного споживання громади для варіанту з найбільшим обсягом впровадження зеленої генерації склало 2,5 %. Результати дослідження показали, що забезпечення відповідності генерації відновлюваних джерел енергії змінному навантаженню локальної мережі потребувало подальшого врахування можливості використання акумуляційних систем накопичення енергії для перенесення надлишків електроенергії або технологій її перетворення на теплову енергію. Це дозволило б заміщувати відповідні обсяги теплової генерації від котлів на природному газі, сприяючи підвищенню енергонезалежності громади та скороченню викидів парникових газів

Ключові слова: модель математичного програмування; добовий графік навантаження; технологічна структура; баланс енергії; комбінована система енергозабезпечення; енергонезалежна громада