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Structuring the energy balance of territorial communities with local infrastructure assets for combined energy production

Abstract. The structure analysis of the energy balance allows use optimal of available resources and infrastructure to maximize energy production, this is especially important for territorial communities with limited resources. The article was devoted to conduct a statistical analysis of combined energy production from wind-solar power plants and sources of thermal generation as part of a typical system of centralized electricity supply and heat for the territorial community of Smila, Cherkasy region, Ukraine. To promote the use of distributed resources, the concept of a microenergy system (MES) has been proposed and its basic structure with energy production, conversion and storage devices. Based on indeterminacy MES leaded a probability distribution model. The results showed that the MES could integrate different types of energy, such as wind, photovoltaic and gas. Multiple energy cycles were achieved through energy conversion and storage devices, and different energy needs were met. Seasonality imposed significant restrictions on the use of heat power plant on solid

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biofuel (HPP) and biofuel cogeneration gas-piston plant (BCP) in the summer, even without taking into account possible maneuvering modes. The level of losses increased from 19.51% till 40.83%, which leads to an increase in the cost of electricity generation. Average values of the specific cost of electricity on the monthly interval for the selected structure sources (SPP – 1.0 mW, WPP – 1.6 mW, HPP – 8.5 mW, BCP – 1.0 mW) grew in the summer from 23.63% till 53.37%. At the same time, $F_5^e(Y_L)$ reached the highest value in the non-heating season 0.689. The research can be used for practical purposes in the dispatching of generated electric and thermal energy

Keywords: energy supply of territorial communities; energy balance; micropower system; combined production of electricity and heat

INTRODUCTION

The concept of the energy green transition is related to the decarbonization of energy systems which have traditionally depended on fossil fuels. The formation of the energy policy of territorial communities on the basis of the concept of energy security and environmental protection is a modern global trend to ensure the conditions for sustainable development. At the level of territorial communities, this leads to increased interaction between the production processes of the two main types of energy: electricity and heat (European Directive 2018/2001/EU, 2018).

U.J.J. Hahnel *et al.* (2020) noted known experience in the production of green energy by local cooperatives at the regional level through the establishment of an independent supplier. The creation of a local supplier opens up opportunities to provide consumers with an alternative way of energy supply with further technological reorganization of infrastructure in accordance the development strategy of the territory. Decentralized management of energy resources helps to achieve three main goals: energy production at the local level, investment of community resources in regional sustainable development projects, strengthening the role of end consumers in the economic model of formation of energy independence of the territorial community.

Interest in increasing the energy independence of communities through the use of local alternative fuels and renewable sources draws attention to the creation and improvement of local micropower systems for combined energy production of electricity and heat. Local communities are transforming and striving to move away from the traditional role of passive consumers. E. Ghiani *et al.* (2019) demonstrated the current development of small-scale renewable energy makes it possible to form an environment of active users who are both consumers and producers of energy.

V. Kaplun & V. Osypenko (2020) related the research of the interaction combined energy supply systems at the regional level, taking into account functional interrelation in the production of electricity and heat to cover a demand in the long term. As components, it is proposed to consider the subsystems of electricity and heat production in order to manage energy efficiency. Preliminary results of using the method for estimating the technical and economic achievable levels of local energy supply based on micropower systems with polygeneration are presented.

A comprehensive novel approach is presented in this paper by N. Saeed *et al*. (2024) to revolutionized energy trading within microgrids through integration of blockchain technology and smart contracts. Energy token and demand response contracts in decentralized peer to peer energy trading enhance security, efficiency and transparency in microgrid operation. The proposed research on blockchain based microgrid system presents a promising future scope and few limitations. The paper by M.M. Stojiljkovic (2017) was aimed for solving the scientific problem of managing energy supply costs in the medium and long term by coordinating the processes formation of the energy balance on the basis of heterogeneous sources. Access to modern management technologies in the energy sector at the local level is a prerequisite for solving this complex problem. In order to provide territorial communities with scientific and methodological tools that would meet their priorities and be as close as possible to practical realities, it was substantiated the theoretical foundations of the formation of technological and organizational components of energy supply management at the local level.

According to B.P. Koirala e*t al.* (2016), the creation of decentralized energy supply systems for territorial communities is an important factor in the formation of their energy independence. The priority is the consolidation of combined energy production based on the introduction of heterogeneous sources at the system (centralized) level. From the point of view of technical and economic indicators functioning and using of local biofuels, there are technologies for combined production of heat and electricity at local heat power plants (mini-HPPs on solid biofuels, gas reciprocating stations on biogas, etc.).

The scientific solutions for combined heat and power generation with an assessment of their maneuvering capabilities for operation in the combined local energy production (CEP) system with projected energy supply costs for the end consumer are interested. In the existing district heating systems, there is significant potential for modernizing power generating and increasing their efficiency in general. It is mini-HPPs with high fuel efficiency and the ability to maneuver power in a wide range of loads that will be most in demand given changes in prices for heat and electricity with the support of the stochastic mode RES. In addition, the dispatching of combined energy production to cover the specified load schedules (especially for peak periods) also requires the research of different modes of co-production of heat and electricity, taking into account seasonal changes in load schedules.

The paper was devoted to the statistical analysis of combined energy production in the composition of wind-solar power plants and sources of thermal generation (power plants with gas turbines of combined cycle and cogeneration plants with internal combustion engines on biofuels) in a typical system of centralized electricity and heat supply of a separate territory

MATERIALS AND METHODS

A micropower system with combined energy production of electricity and heat in the form of a local energy node was considered (Fig. 1). The structure of combined heat and power system (CHPS) included local heterogeneous sources (Fig. 2) of the network level: solar power plant (SPP), wind power plant (WPP), heat power plant on solid biofuel (HPP), biofuel cogeneration gas-piston plant (BCP), heat grid (HG) and centralized power supply system (CPSS).

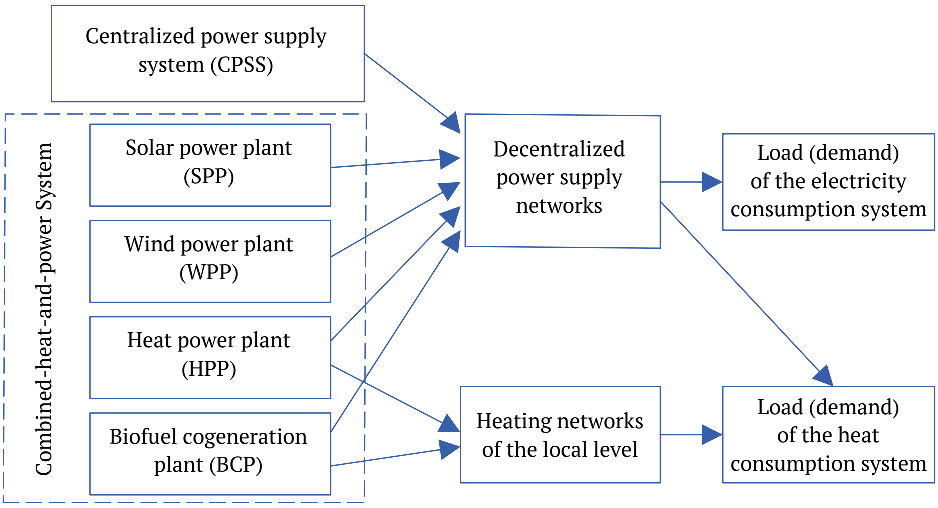

Figure 1. Structure of combined energy supply of the territorial community
Source: compiled by the authors

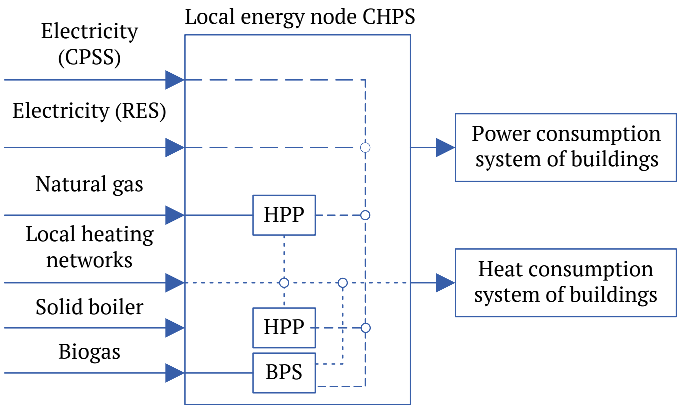

Figure 2. Structure of energy flows of a local CHPS node
Source: compiled by the authors

It was assumed that all energy sources were distributed. Energy streams are transmitted to various end users who were connected to the grid infrastructure. In this case, it considered a homogeneous distributed micropower system, in which each end user has the opportunity to receive energy from all selected sources of the MES in the research time interval $t_{i1} = t_{i2} = \cdots t_{im} = t_i$, everyone $i = \overline{1, n}$.

In the general case, the objective function for *the i-th* technological structure CHPS would look like:

$$min\, obj_i = \sum_{t=1}^{T} g_{SES} \cdot W^e_{SES} + g_{WES} \cdot W^e_{WES} + g^e_{CHPS} \cdot W^e_{CHPS} + g^e_{BCP} \cdot$$
$$\cdot W^e_{BCP} + g^e_{CPSS} \cdot W^e_{CPSS} + g^h_{HG} \cdot W^h_{HG} + g^h_{CHPS} \cdot W^h_{CHPS} + g^h_{BCP} \cdot W^h_{BCP}, \quad (1)$$

where $g^{e,h}_{*}$ *UAH/kWh* – unit costs of end users of energy types (*e*- electrical, *h* – heat); $W^{e,h}_{*} = P^{e,h} + E \cdot t$, *kWh* – the amount of energy (electrical and heat) that will be generated in the CHPS to cover the load schedule; $E \cdot t$ – energy of mutual conversion of primary fuels into final types of energy of the user. To calculate the unit costs of electricity and heat in CHPS, it used a simplified calculation according to the formulas (for the first month):

$$g^e_{CHPS} = \frac{A_i+B_i+C_i+D_i}{W^e_i} \cdot \eta^e(\%); \quad (2)$$

$$g^h_{CHPS} = \frac{A_i+B_i+C_i+D_i}{W^h_i} \cdot \eta^h(\%), \quad (3)$$

where A_i – specific capital expenditures attributable to the entire estimated period of operation); B_i – primary fuel consumption for the technological cycle per calendar month; C_i – annual overhead; D_i – unpredictable costs caused by the shutdown of energy production; $\eta_i(\%)$ – coefficient of the basic power of the CHPS unit for the production of electricity and heat in the monthly cycle. Similarly, calculation g^h_{CHPS} was for heat energy.

HPP i BCP – were the aggregate that simultaneously produce electricity and heat in the same production process, also known as cogeneration. The electricity generated was either used locally or fed into a centralized grid, while heat energy could only be used to be discharged into the district heating grid.

The variable range of heat load made it possible to reduce the installed power of the plant to produce the same amount of heat and electricity depending on demand. From the point of view of HPP and BCP technologies, the ratio of electricity to heat (control limits for maneuvering the power of systems) depended on the electrothermal characteristics of the systems.

In general, the balancing of a combined MES to cover the demand for electricity could be as:

$$W^e_{SES}(t) + W^e_{WES}(t) + W^e_{CHPS}(t) + W^e_{BCP}(t) + W^e_{CPSS}(t) = L^e(t) \pm L^e_f(t) + \Delta L^e_{const}(t), \quad (4)$$

where $L^e(t)$ – baseline electrical load (according to the seasonal daily power consumption profile); $\pm L^e_f(t)$ – deviation from the baseline load forecast (the forecast error can be determined by the addition of the study of extended statistical information); $\Delta L^e_{const}(t)$ – the part of the electrical load to cover the heat load (mutual conversion within a combined microgrid system). Similarly, to cover the demand for thermal energy, the determination of the balance from the selected sources would be as follows:

$$W^h_{HG}(t) + W^h_{CHPS}(t) + W^h_{BCP}(t) + W^h_{const}(t) = L^h(t) \pm L^h_f(t). \quad (5)$$

The research was conducted in 2023 on the example of a typical district heating system in the territorial community of Smila, Cherkasy region, Ukraine. The system of combined energy production included a heat power plant with gas turbines operating in a combined cycle, as well as one cogeneration station equipped with internal combustion engines. The study focused on analysing the integration and performance of these systems within the existing infrastructure. The annual electricity consumption is 59214 mWh, heat – 39436 mWh). At the first stage, it was necessary to conduct a retrospective analysis of the nature of energy consumption and justify such a technological structure of CHPS that would cover demand with the lowest cost of electricity production based on available local biofuels TC and RES.

Based on statistical observations and information in Table 1 on real energy production aggregate P6-35/5M (Germany), which operates as part of the regional MES, the initial data for the research were formed.

Table 1. 1. Initial data for modelling the structure of monthly energy balances CHPS

Month	Demand, mW·h	Type of energy: electricity (e); heat (h)	The amount of energy (of the i-th source and its specific cost in the time interval	The type of energy source: SPP	WPP	CHPS	BCP	CPSS	HG	Total cost, ($) and specific costs ($/mW·h) for covering demand
January	6726.02	e	W^e_i	116.04	538.56	2027.86	504.32	3539.24	0	430837.39
			g^e_i	262	85.3	15.26	146.8	70.5	0	64.06
	7898	h	W^h_i	0	0	7108	310.99	0	479.01	174541.49
			g^h_i	0	0	18.15	68.1	0	50.84	22.10
February	7802.05	e	W^e_i	260.1	442.82	1953	498.97	4647.16	0	544309.45
			g^e_i	262	85.3	19.21	146.8	70.5	0	69.76
	9082	h	W^h_i	0	0	3365.38	307.68	0	5408.94	380784.75
			g^h_i	0	0	25.21	68.1	0	50.84	41.93
March	4946.15	e	W^e_i	576.3	626.48	1401.08	478.11	1864.18	0	431848.48
			g^e_i	262	85.3	18.42	146.8	70.5	0	87.31
	6245	h	W^h_i	0	0	2670.91	294.77	0	3279.32	256371.67
			g^h_i	0	0	26.05	68.1	0	50.84	41.05
April	4964.78	e	W^e_i	681.56	644.05	1711.64	490.36	1437.17	0	467163.94
			g^e_i	262	85.3	35.26	146.8	70.5	0	94.10
	2674	h	W^h_i	0	0	1265.88	302.16	0	1105.96	161415.52
			g^h_i	0	0	66.84	68.1	0	50.84	60.36

Continued Table 1.

Month	Demand, mW·h	Type of energy: electricity (e); heat (h)	W_i^e	The type of energy source g_i^e	WPP	CHPS	BCP	CPSS	HG	Total cost, ($) and specific costs ($/mW·h) for covering demand
May	4469.65	e	W_i^e	1075.3	676.92	2063.27	501.52	152.64	0	450986.13
			g_i^e	262	85.3	13.15	146.8	70.5	0	100.90
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
June	4350.27	e	W_i^e	1124.52	418.75	1946.72	488.17	372.11	0	451932.,31
			g_i^e	262	85.3	12.17	146.8	70.5	0	103.89
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
July	4192.11	e	W_i^e	1168.22	432.79	674.95	469.14	1447.01	0	521332.78
			g_i^e	262	85.3	11.05	146.8	70.5	0	124.36
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
August	4234.14	e	W_i^e	924.1	365.94	1337.18	382.98	1223.94	0	429905.25
			g_i^e	262	85.3	10.52	146.8	70.5	0	101.53
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
September	4204.12	e	W_i^e	612.24	584.68	550.68	515.05	1941.47	0	428848.07
			g_i^e	262	85.3	11.05	146.8	70.5	0	102.01
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
October	4873.95	e	W_i^e	473.9	534.36	2289.64	490.13	1085.92	0	344742.29
			g_i^e	262	85.3	11.57	146.8	70.5	0	70,73
	0	h	W_i^h	0	0	0	0	0	0	0.00
			g_i^h	0	0	0	0	0	0	0.00
November	5440.12	e	W_i^e	138.24	232.56	2326.31	479.06	2263.95	0	317209.81
			g_i^e	262	85.3	13.42	146.8	70.5	0	58.31
	6670	h	W_i^h	0	0	5269.08	295.42	0	1105.5	196930.96
			g_i^h	0	0	22.89	68.1	0	50.84	29.52
December	7277.83	e	W_i^e	67.66	658.92	2463.68	505.19	3582.38	0	440194.54
			g_i^e	262	85.3	16.05	146.8	70.5	0	60.48
	10245	h	W_i^h	0	0	9546.95	311.54	0	386.46	256910.98
			g_i^h	0	0	22.63	68.1	0	50.84	25.08

Source: compiled by the authors based on Smila city territorial community (n.d.)

Additional characteristics of mini HPPs: Boiler units – KVGM-20, DKVR-10-39-44 (Ukraine); Turbines – P6-35/5M (Germany) No. 1, 2 with a capacity of 6 MW. To form the technological structure of CHPS, network level sources with installed powers were selected for analysis, namely: SPP – 1.0 mW, WPP – 1.6 mW, HPP – 8.5 mW, BCP – 1.0 mW.

The scientific idea of the study was the assertion of the possibility of determining the limit levels of the ratio of particles of electric and thermal energy during a given calculation period. This would make it possibility to determine the time periods of participation of homogeneous sources in the formation of optimal energy balances (daily, monthly, annual) of the combined energy supply system with the selected structure of heterogeneous sources and a deterministic load profile.

RESULTS

The using of several local sources that form the structure of CHPS and were integrated into existing centralized networks requires an analysis, namely:

1) determination of annual consumption (demand) and opportunities of the territorial community for the production of biofuels and the power generating capacities in accordance with the Green Deal;

2) research of the structure CHPS energy balance with selected sources to cover demand during the billing period. It was assumed that own energy production should only cover current energy needs. The limitation was that the possibility surplus energy produced in previous periods cannot cover the needs in future periods in which production is insufficient;

3) determination of short-, medium- and long-term energy profiles of CHPS for combined heat and power generation based on a predictive assessment of the cost indicators of energy supply to end users;

4) the formation of energy independence of territorial communities through the integration of several heterogeneous sources of distributed generation of small power requires the justification of certain rules and procedures. The major feature of the construction of such combined energy production systems is their ability to predictably change the structure of the energy balance by replacing the main component of energy consumption from external networks with their own generation. Under certain conditions, CHPS can switch in isolating (island) mode of operation without reducing the quality of power supply. At the same time, synchronization with external grids allows maneuvering distributed generation in the micropower system, taking into account the stochastic parameters of own generation, and having operational flexibility when using sources of local heat generation.

Wide opportunities for variability ratio of electricity and heat production expanded the cost ranges of energy supply for end consumers. The using of multi-unit mini-HPPs provided a fairly wide range of maneuvering load of station, which created the prerequisites for the search for economically justified operational indicators in seasons with medium or low demand for heat production.

Technological opportunities and constraints for the electrical and heat generation in the combined cycle generally is lied in the seasonal demand for final energy (electricity and heat) and access to local primary fuels.

The schematic flow diagram of the combined heat and power generation is shown in Figure 3.

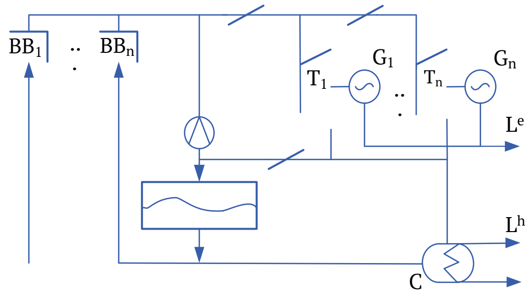

Figure 3. Technological scheme of combined energy production by Heat power plant

Note: BB – solid biofuel boiler, T – turbine, G – generator, C – condenser, L^e – electrical network, L^h – heating network)

Source: compiled by the authors

The graphs of monthly profiles of demand for electricity and heat (Fig. 4) and total costs for energy supply (Fig. 5) of the territorial community city Smila, Cherkasy region, were obtained.

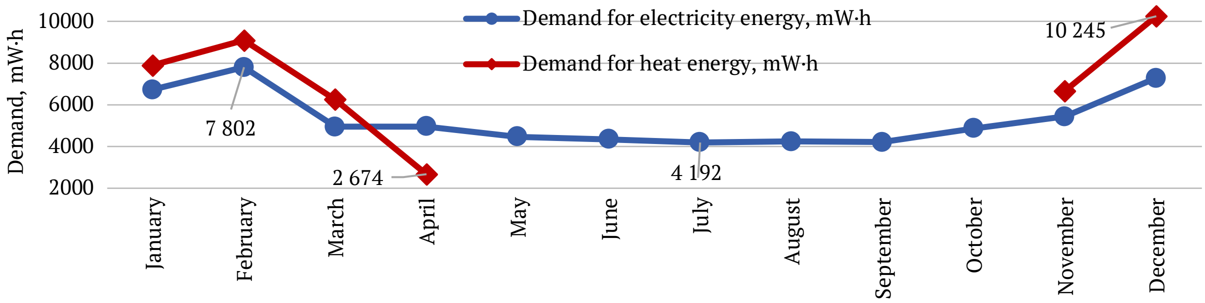

Figure 4. Monthly load profile (demand for electricity and heat energy)

Source: compiled by the authors

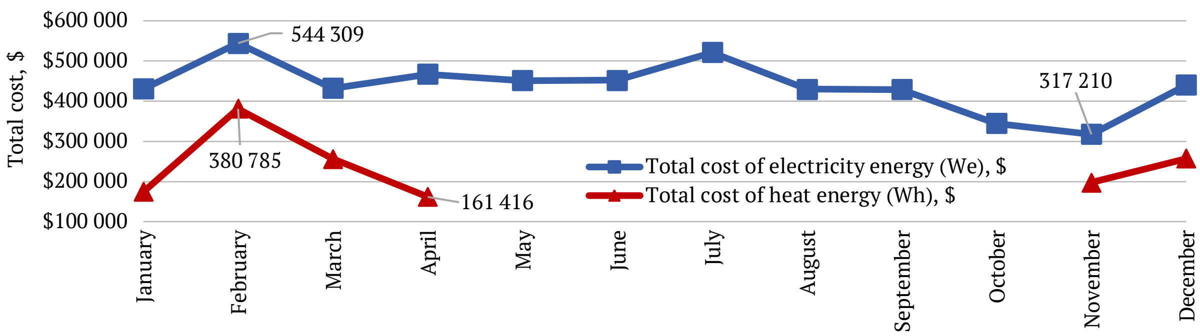

Figure 5. Total monthly energy costs of the territorial community to cover the demand for electricity and heat energy

Source: compiled by the authors

To test the efficiency of proposing structure combined energy supply micro-energy system the values the unit costs of electricity and heat averaging on the monthly interval (Fig. 6) were obtained. It was taken into account the peculiarities of technological cycles of conversion of primary fuels of heat generation sources and the possibility of balancing micro-energy systems from external grid.

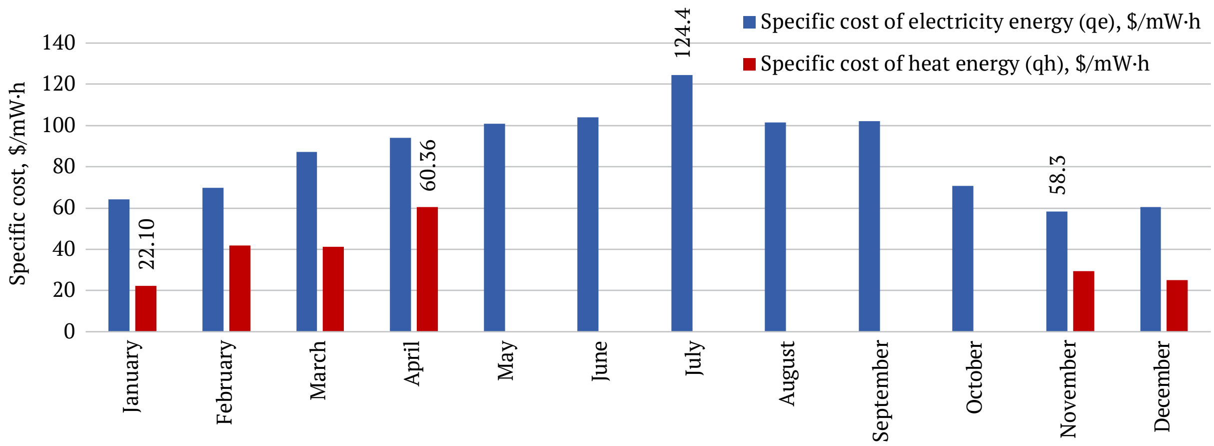

Figure 6. Average values of unit costs of electricity and heat for the structure of sources micro-energy systems with installed power

Note: SPP – 1.0 mW, WPP – 1.6 mW, HPP – 8.5 mW, BCP – 1.0 mW

Source: compiled by the authors

Combining production of heat and electricity with an assessment of their maneuvering capabilities for operation in the local energy production system make it possible to predict the cost indicators of energy supply for the end consumer, taking into account the efficiency of conversion of primary fuels in sources of heat generation. Figure 7 shows the interrelation between electricity and heat generation, energy losses in HPP and BCP in non-maneuvering mode of operation without taking into account seasonality, when heat recovery does not occur. This mode of operation of heat generation sources is not optimal. It is applied on the bject, where the statistical data are used in research.

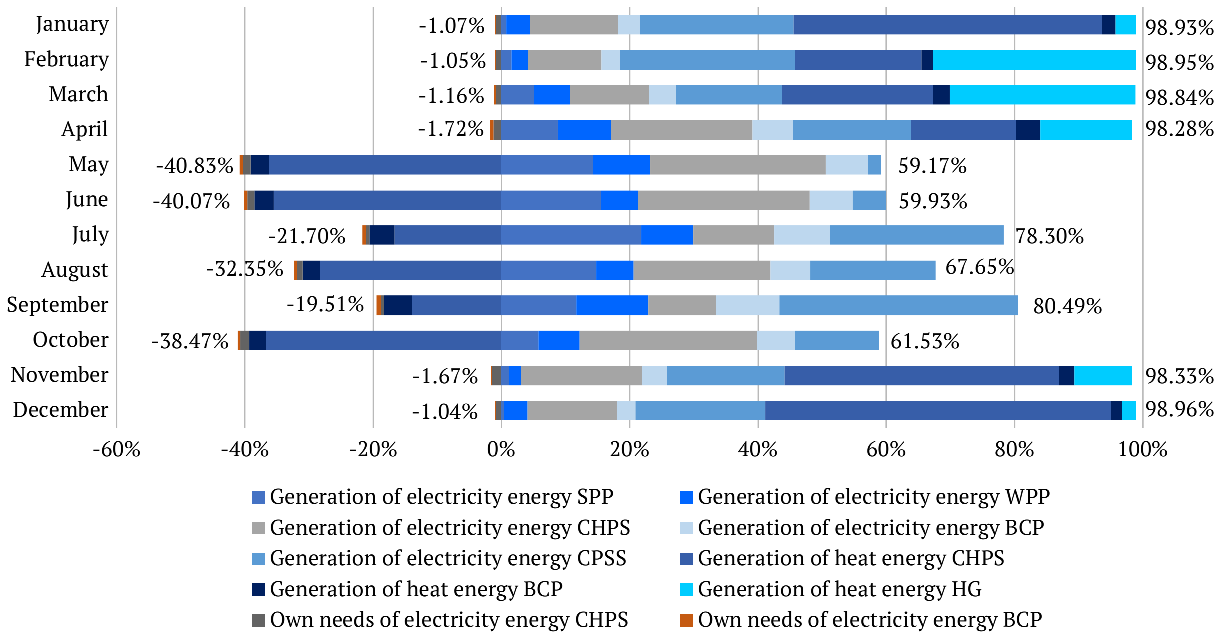

Figure 7. Interrelation between electricity and heat generation, energy losses in HPP and BCP in non-maneuvering mode of operation without taking into account seasonality, when useful heat recovery does not occur

Source: compiled by the authors

To algorithmize the operation of the micro-energy system, taking into account seasonal changes in local generation and demand, it is necessary to determine model series taking into account the provision of the basic part of demand during the calendar year and the response to demand taking into account seasonal changes. At the same time, the formation of MES energy balances with the selected structure of sources should be considered as management efficiency of the system as a whole. Combined energy sources with high fuel efficiency and the ability to maneuver power in a wide range of loads will be the most request a season with demand for heat energy. The demand for electricity (primarily in the summer) should be provide by the generation of wind and solar power plants. Dispatching of combined energy production to cover specified load schedules (especially for peak periods) also requires the research of different modes of co-production heat and electricity energy, taking into account seasonal changes in load schedules.

To analyse the efficiency of structuring a micro-energy system with the selected sources, it was used the approach proposed by V. Kaplun (2023). Let denote the vector of parameters of external factors in the formation of the energy balance $D(t)$ such as the cost of primary fuel, the efficiency of combined energy production technologies, and the interdependence between electricity and heat production in the cogeneration cycle. The structuring vector $R(t)$ includes the structural implementations of micro-energy systems with the stochastic nature of RES (renewable energy sources). The vector of control influences is denoted as $Y(t)$, and the criterion functionality as F_T.

The criterion (goal) functional is integral, since in multicomponent systems, optimal solutions, as a rule, are determined not by the instantaneous reaction of the system, but for a certain calculation period T:

$$F_T = \int_0^T F_i\big(D(t), R(t), Y(t)\big)dt, \quad i = \overline{1,n}. \qquad (6)$$

With this representation (6), the value of the F_T is a function of input parameters and control influences $Y(t)$. Parameters $D(t)$, $R(t)$, $Y(t)$ depend on the season and the selected structure of the sources and their being in the active state (state of generation), are variable and are given by an expression of the type:

$$D_{min} \leqslant D \leqslant D_{max}.$$

Changes in these parameters are also mutually dependent

$$\Delta_t(D(t), R(t), Y(t)) \geqslant 0.$$

To understand the features of the formation of functionality F_T is considering the diagram of electricity, heat generation and technological energy losses related to the sources of heat generation (Fig. 6). Results of functional calculations F_T as the coefficient of imbalance of the selected structure MES in the conditions of deterministic definition of the output data combining production of electricity and heat are given in Table 2.

Table 2. Results of functional calculations F_T

$Y(t)$ \ D_i	$F_1^{e,h}$	$F_2^{e,h}$	$F_3^{e,h}$	$F_4^{e,h}$	$F_5^{e,h}$	$F_6^{e,h}$	$F_7^{e,h}$	$F_8^{e,h}$	$F_9^{e,h}$	$F_{10}^{e,h}$	$F_{11}^{e,h}$	$F_{12}^{e,h}$
Y^e	0.533	0.608	0.401	0.312	0.038	0.098	0.409	0.328	0.497	0.233	0.421	0.494
Y^h	0.581	0.534	0.411	-	-	-	-	-	-	-	0.166	0.562
Y_L	0.011	0.012	0.011	0.016	0.689	0.668	0.277	0.478	0.242	0.625	0.017	0.011

Source: compiled by the authors

The functionality F_T is calculated Table 1 as an unbalance coefficient for the selected structure of electricity sources (Y^e) and ranges from 0.038 till 0.608, which indicates an insufficient share in the balance of MES solar generation in the summer calendar period, especially for July and August ($F_7^e = 0.409$ та $F_8 = 0.328$). It is foreseeable that the electricity balance will be sufficiently structured in the periods from May to September on the basis of the generation of wind-solar systems with minimal consumption from the centralized CPSS grid.

The heat supply system has a slightly different design of the energy balance of the territorial community. The lack of demand for district heating from April to October imposes restrictions on the use of heat generation with combined energy production, since most of the heat energy cannot be disposed of in the summer. The constancy of the heat consumption schedule requires the operation of heat generation sources at the rated power of HPP and BCP without the use of shunting modes in the periods from November to March. Balancing MES by heat (Y^h) should be carried out at the expense of the heat grid (HG) and local (objects) tools of heat supply. Only in November, the demand for heat energy is provided with sufficient efficiency $F_{11} = 0.409$.

Dispatching of combined energy production to cover specified load schedules (especially for peak periods) requires the research of different modes of co-production heat and electricity energies, taking into account seasonal changes in load schedules. Combined energy supply processes will encourage territorial communities to a new type of activity, which is due to own energy production based on the use of local fuels and renewable energy sources (RES). The outlined approaches can be a theoretical basis for the development scenarios for the formation energy independence of territorial communities.

The dispatching strategy based on the specific value indicators of energy generation opens the way for the maximization of operating income. The priority of balancing the micro-power system to cover the demand is given to WPPs and SPPs, which are highly profitable generating facilities. Optimal cost performance and energy efficiency performance of primary biofuels conversion are key criteria during periods when CHPS and BCP operate in the "heat load determined capacity" mode. It was shown that the results of functional calculations, from which it can be seen that combined energy supply (supply of electricity and heat) can be achieved due to energy complementarity, provided that reducing the cost of energy is the goal of optimization.

The results of the research can be used to develop dynamic energy management systems, which will allow formation tariff plans for end consumers of the territorial community, taking into account combined energy production based on local biofuels, the positive impact of MES of this class on the survivability energy islands in case of an unpredictable decrease in the power of centralized sources, system accidents, blackouts, etc.

M. Bagheri *et al.* (2019) noted the introduction of local energy supply systems for territorial communities is an important factor in gradually increasing their level of energy independence. The priority direction is the fusion of combined energy production through the use of decentralized sources at the system (centralized) and local (on the side of the end consumer) level.

A. Karimi *et al*. (2024) researched that from the point of view technical and economic indicators of the functioning and using local fuels, the technologies, which are combined production heat and electrical energy at regional heat power plants are attractive. New challenges, in territorial communities are mainly associated with the consequences of rising prices in electricity market, as well as the variability of generation resulting from an increasing deal of RES. In many existing district heating systems, there is significant potential for modernizing power generating and improving their efficiency in general. The study suggests a management strategy that involves using a new decentralized controller for the effective organization and coordination of ESSs and RESs to enhance the operation of isolated microgrids. According to M. Bagheri *et al.* (2019) for the combined production of thermal and electrical energy with an assessment of their maneuverability, working in a combined local energy system with predicted specific values of energy supply for the end consumer are solutions of interest. Exactly local heat power plants with high fuel efficiency are able to maneuver power in a wide range of loads. Therefore, they will be the most in demand given the increase in tariffs for heat and electricity with the support of the stochastic mode with RES. In addition, the dispatching of combined energy production to cover the specified load schedules (especially for peak periods) also requires the research of different modes of co-production of heat and electricity, taking into account seasonal changes in load schedules.

L. Mehigan *et al.* (2018) researched the prerequisites for the technical modernization of traditional energy industries, highlighting the challenges that drive the development of innovative energy Internet platforms. X. Zhao *et al.* (2018) explored how micro-energy systems serve as prototypes for object-oriented decentralized microgrids within the energy Internet framework. Their work suggests that these systems could promote the formation of multi-energy and polygenerational energy supply models for territories and communities, emphasizing the use of renewable energy sources and local fuels. In the notable publications by L. Ju *et al.* (2016), research on microgrids is devoted to the coordination of operational planning and the solution of optimization problems aimed at minimizing operating costs and reducing environmental impact. The principles of constructions a dispatching system and the strategy of energy management in the long term are presented in detail. In a paper by K. Fellah & R. Abbou (2024) a layer-like optimization model based on the modes of the regulated thermoelectric cogeneration unit's coefficient is presented. At the first level, the criterion of minimum energy costs was applied, and the second level of efficiency is according for the economic criterion. H.A. Gabbar *et al.* (2015) presented the results of optimizing the functioning of regional networks with minimal energy consumption and environmental impact. The works of G. Guandalini *et al.* (2017) and X. Zhang *et al.* (2018) were dedicated to the introduction of carbon credits as a market commodity using technical and economic indicators (minimum costs for electricity production) and carbon emissions trading on the performance of the system. Photovoltaic modules, energy storage devices and heat exchangers for local load were integrated into the microgrid system, which helped to reduce the cost of electricity generation. These articles did not address the uncertainties associated with the functioning of microgrids with polygeneration. This complicates the understanding formation of energy security levels for such objects. The uncertainty of micropower systems with polygeneration is mainly related to the operation of wind and solar power plants, the lack of use of controlled generating units, energy storage and flexible load for optimal matching of supply and demand. In the research by F.J. Heredia *et al.* (2010), the method of stochastic optimization of electricity generation by a wind-solar station by means of two-level dispatch optimization for virtual power plants is described. J. Li *et al.* (2024) proposed day-ahead scheduling model is a mixed-integer, nonlinear, large-scale, stochastic optimization problem with high dimensional random variables, which is difficult to be solved directly by traditional centralized method. The simulation results show that the proposed distributed optimization algorithm has high accuracy and good convergence, the virtual power plant can achieve day-ahead optimal scheduling and effectively promote renewable energy accommodation under the security and reliability of the grid. The problem of wind consumption based on fast maneuvering control with the help of gas generators has been solved by J. Mohammadi *et al.* (2007), H. Yang *et al.* (2014).

Methods based on stochastic programming optimization are the most common for processing indetermination. However, it is problematic to obtain a probabilistic analysis of the stochastic processes on which stochastic optimization depends. Therefore, optimization procedures are often characterized by boundary parameters of indetermination factors and the selection of a reliable optimum. As a rule, it's a conservative decision. Solving multi-purpose optimization models is also a key problem in microgrids functioning. In general, multi-purpose models are solved with the help of related algorithms, but the introduction of indetermination and several optimization criteria significantly complicates the models and introduces contradictions into the solutions. Solving algorithms mainly incorporate traditional approaches and heuristic intelligent algorithms, which were reviewed by Z.-F. Tan *et al.* (2014). In the first case, problems in defining parameters and transforming constraints are shown, which leads to low optimization effectiveness. In the second case, the best solutions are obtained, but the research and selection of the extremum is carried out without taking into account the principles of multi-purpose programming. Therefore, according to Z.-F. Tan *et al.* (2014), the algorithm stops at the local extremum, which limits the possibility of finding the optimum. As noted by Y.-W. Jiang *et al.* (2008), the solution of the problem dispatching energy flows in a multicomponent system by optimizing particles and algorithms of differential evolution. It shows the solution of the multi-purpose model as the main problem in structure optimal strategies for dispatching micropower systems.

A. Bloess *et al.* (2018) researched that the presence of commonality of modes of combined energy production of electricity and heat is characterized by the fact that the cost of accumulating heat energy is much lower compared to the cost of accumulating electrical energy, which makes the planning and operation of electricity and heat more and more attractive in practical implementation. Coordinated management of energy flows between electricity and heating networks can simultaneously contribute the decarbonization of the heating sector and provide the greater flexibility needed for renewables with indetermination generation. By D. Connolly *et al.* (2014) noted that energy system modelling tools are usually created for the electricity sector, and the potential benefits of local district heating systems are generally overlooked.

Obviously, in order to assess the potential of district heating networks, it is necessary to take into account the availability of local infrastructure and available fuel. As a rule, modelling tools are used that do not take into account the interaction between the processes of combined energy production of electricity and heat. At the same time, it is important to understand that in this case, there are naturally restrictions on the use of tools that would embody a holistic approach, considering both systems as an integrated whole.

CONCLUSIONS

The research focused on the statistical analysis of combined energy production in wind-solar power plants and thermal generation sources (gas turbine power plants in combined cycles and cogeneration plants with biofuel internal combustion engines) within a typical centralized electricity and heat supply system. The territorial community of Smila, Cherkasy region, Ukraine, served as the case study.

The results showed that combined energy production systems with high fuel efficiency and flexible load management are crucial for minimizing heat and electricity costs, especially when dealing with the stochastic nature of Renewable Energy Sources (RES) generation. These systems, including biofuel-based cogeneration plants (BCP) and heat power plants (HPP), face challenges such as increased energy losses during the summer season, where losses rose from 19.51% till 40.83%, leading to higher electricity generation costs. The average specific cost of electricity for the selected energy sources (SPP – 1.0 mW, WPP – 1.6 mW, HPP – 8.5 mW, BCP – 1.0 mW) increased in the summer from 23.63% till 53.37%. The imbalance coefficient reached its highest value of 0.689 during the non-heating season, indicating significant inefficiencies in the summer months.

From the perspective of electricity demand coverage, thermal generation and, to some extent, wind energy systems are foundational in the energy structure, while solar power contributes to covering morning load peaks during the spring and summer. BCPs act as operational power reserves, ensuring flexibility during both peak demand periods and load decreases.

The study also established that the efficiency of combined heat and electricity generation strongly correlates with the demand for thermal energy, suggesting further research into optimal dispatching strategies. These findings highlight that local energy systems, particularly micro-energy systems (MES), can be more self-sufficient and cost-effective with decentralized power generation.

Future research will explore the development of decentralized microgrids with polygeneration capabilities and short-term load forecasting, providing better energy balancing and reliability. This shift towards energy-independent islands and peer-to-peer energy trading within energy communities will create new opportunities for decentralization, enabling consumers to actively manage their energy use and enhance energy efficiency in local systems.

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CONFLICT OF INTEREST

None.

REFERENCES

[1] Bagheri, M., Delbari, S.H., Pakzadmanesh, M., & Kennedy, C.A. (2019). City-integrated renewable energy design for low-carbon and climate-resilient communities. *Applied Energy*, 239, 1212-1225. doi: 10.1016/j.apenergy.2019.02.031.

[2] Bloess, A., Schill, W.-P., & Zerrahn, A. (2018). Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials. *Applied Energy*, 212, 1611-1626. doi: 10.1016/j.apenergy.2017.12.073.

[3] Connolly, D., Lund, H., Mathiesen, B.V., Werner, S., Möller, B., Persson, U., Boermans, T., Trier, D., Østergaard, P.A., & Nielsen, S. (2014). Heat roadmap Europe: Combining district heating with heat savings to decarbonise the eu energy system. *Energy Policy*, 65, 475-489. doi: 10.1016/j.enpol.2013.10.035.

[4] European Directive 2018/2001/EU of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast). (2018, December). Retrieved from https://eur-lex.europa.eu/eli/dir/2018/2001/oj.

[5] Fellah, K., & Abbou, R. (2024). Modelling and formal verification approach for microgrid energy management systems under random load. *IFAC-PapersOnLine*, 58(1), 270-275. doi: 10.1016/j.ifacol.2024.07.046.

[6] Gabbar, H.A., Runge, J., Bondarenko, D., Bower, L., Pandya, D., Musharavati, F., & Pokharel, S. (2015). Performance evaluation of gas-power strategies for building energy conservation. *Energy Conversion and Management*, 93, 187-196. doi: 10.1016/j.enconman.2014.12.060.

[7] Ghiani, E., Giordano, A., Nieddu, A., Rosetti, L., & Pilo, F. (2019), Planning of a smart local energy community: The case of Berchidda Municipality (Italy), *Energies*, 12(24), article number 4629. doi: 10.3390/en12244629.

[8] Guandalini, G., Robinius, M., Grube, T., Campanari, S., & Stolten, D. (2017). Long-term power-to-gas potential from wind and solar power: A country analysis for Italy. *International Journal of Hydrogen Energy*, 42(19), 13389-13406. doi: 10.1016/j.ijhydene.2017.03.081.

[9] Hahnel, U.J.J., Herberz, M., Pena-Bello, A., Parra, D., & Brosch, T. (2020). Becoming prosumer: Revealing trading preferences and decision-making strategies in peer-to-peer energy communities. *Energy Policy*, 137, article number 111098. doi: 10.1016/j.enpol.2019.111098.

[10] Heredia, F.J., Rider, M.J., & Corchero, C. (2010). Optimal bidding strategies for thermal and generic programming units in the day-ahead electricity market. *IEEE Transactions on Power Systems*, 25(3), 1504-1518. doi: 10.1109/TPWRS.2009.2038269.

[11] Jiang, Y.-W., Chen, C., & Wen, B.-Y. (2008). Application of stochastic simulation's particle swarm algorithm in the compensation of reactive power for wind farms. *Proceedings of the Chinese Society of Electrical Engineering*, 28, 47-52.

[12] Ju, L., Li, H., Zhao, J., Chen, K., Tan, Q., & Tan, Z. (2016). Multi-objective stochastic scheduling optimization model for connecting a virtual power plant to wind-photovoltaic-electric vehicles considering uncertainties and demand response. *Energy Conversion and Management*, 128, 160-177. doi: 10.1016/j.enconman.2016.09.072.

[13] Kaplun, V. (2023). Principles of resource-process modeling of territorial communities combined energy supply in the climate change prevention context. *System Research in Energy*, 4(75), 54-64. doi: 10.15407/srenergy2023.04.055.

[14] Kaplun, V., & Osypenko, V. (2020). Energy efficiency analyses in polygeneration microgrids with renewable sources 2020. In *IEEE 7th international conference on energy smart systems (ESS)* (pp. 139-143). Kyiv: IEEE. doi: 10.1109/ESS50319.2020.9160346.

[15] Karimi, A., Nayeripour, M., & Abbasi, A.R. (2024). Coordination in islanded microgrids: Integration of distributed generation, energy storage system, and load shedding using a new decentralized control architecture. *Journal of Energy Storage*, 98(B), article number 113199. doi: 10.1016/j.est.2024.113199.

[16] Koirala, B.P., Koliou, E., Friege, J., Hakvoort, R.A., & Herder, P.M. (2016). Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems. *Renewable and Sustainable Energy Reviews,* 56, 722-744. doi: 10.1016/j.rser.2015.11.080.

[17] Li, J., Mo, H., Sun, Q., Wei, W., & Yin, K. (2024). Distributed optimal scheduling for virtual power plant with high penetration of renewable energy. *International Journal of Electrical Power & Energy Systems*, 160, article number 110103. doi: 10.1016/j.ijepes.2024.110103.

[18] Mehigan, L., Deane, J.P., Gallachóir, B.P.Ó., & Bertsch, V. (2018). A review of the role of distributed generation (DG) in future electricity systems. *Energy*, 163, 822-836. doi: 10.1016/j.energy.2018.08.022.

[19] Mohammadi, J., Rahimikian, A., & Ghazizadeh, M.S. (2007). Aggregated wind power and flexible load offering strategy. *IET Renewable Power Generation*, 5(6), 439-447. doi: 10.1049/iet-rpg.2011.0066.

[20] Saeed, N., Wen, F., & Afzal, M.Z. (2024). Decentralized peer-to-peer energy trading in microgrids: Leveraging blockchain technology and smart contracts. *Energy Reports*, 12, 1753-1764. doi: 10.1016/j.egyr.2024.07.053.

[21] Smila city territorial community. (n.d.). *Statistical data on energy consumption*. Retrieved from http://surl.li/pcelaf.

[22] Stojiljkovic, M.M. (2017). Bi-level multi-objective fuzzy design optimization of energy supply systems aided by problem-specific heuristics. *Energy*, 137, 1231-1251. doi: 10.1016/j.energy.2017.06.037.

[23] Tan, Z.-F., Ju, L.-W., Li, H.-H., Li, J.-Y., & Zhang, H.-J. (2014). A two-stage scheduling optimization model and solution algorithm for wind power and energy storage system considering uncertainty and demand response. *International Journal of Electrical Power & Energy Systems*, 63, 1057-1069. doi: 10.1016/j.ijepes.2014.06.061.

[24] Yang, H., Yi, D., Zhao, J., Luo, F., & Dong, Z. (2014). Distributed optimal dispatch of virtual power plant based on ELM transformation. *Journal of Industrial and Management Optimization*, 10(4), 1297-1318. doi: 10.3934/jimo.2014.10.1297.

[25] Zhang, X., Yang, J., Wang, W., Zhang, M., & Jing, T. (2018). Integrated optimal dispatch of a rural micro-energy-gridwith multi-energy stream based on model predictive control. *Energies*, 11, article number 3439. doi: 10.3390/en11123439.

[26] Zhao, X., Yang, L., Qu, X., & Yan, W. (2018). An improved energy flow calculation method for integrated electricity and natural gas system. *Transactions of China Electrotechnical Society*, 33, 467-477.

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Структурування енергетичного балансу територіальних громад з локальними інфраструктурними активами для комбінованого виробництва енергії

Анотація. Аналіз структури енергетичного балансу дозволяє оптимально використовувати наявні ресурси та інфраструктуру для максимізації виробництва енергії, що особливо важливо для територіальних громад з обмеженими ресурсами. Метою статті було проведення статистичного аналізу комбінованого виробництва енергії від вітро-сонячних електростанцій та джерел теплової генерації у складі типової системи централізованого постачання електричної та теплової енергії для територіальної громади міста Сміла, Черкаська область, Україна. Щоб сприяти використанню розподілених ресурсів, запропонована концепція мікроенергетичної системи (МЕС) та її основна структура з пристроями виробництва, перетворення та зберігання енергії. На основі невизначеностей МЕС вводиться модель розподілу ймовірностей. З цілями максимізації операційного доходу та мінімізації операційного ризику та викидів вуглекислого газу було створено багатоцільову скоординовану модель оптимізації диспетчеризації. Результати показують, що МЕС може інтегрувати різні типи енергії, такі як вітер, фотоелектрична енергія та газ. Кілька енергетичних циклів досягається за допомогою пристроїв для перетворення та зберігання енергії, і задовольняються різні потреби в енергії. Сезонність накладає суттєві обмеження на використання теплових електростанцій на твердому біопаливі (ГЕС) та біопаливних когенераційних газопоршневих установок (БГУ) в літній період, навіть без урахування можливих маневрових режимів. Рівень втрат зростає з 19,51% до 40,83%, що призводить до збільшення собівартості виробництва електроенергії. Середні значення питомої собівартості електроенергії на місячному інтервалі для обраної структури джерел (СЕС – 1,0 мВт, ВЕС – 1,6 мВт, ГЕС – 8,5 мВт, БГУ – 1,0 мВт) зростають влітку з 23,63 % до 53,37 %. При цьому $F_5^{\varepsilon}(Y_L)$ досягає найбільшого значення в неопалювальний сезон 0,689. Дослідження можуть бути використані у практичних цілях при диспетчеризації генерованої електричної та теплової енергії

Ключові слова: енергозабезпечення територіальних громад; енергетичний баланс; мікроенергосистема; комбіноване виробництво електроенергії і тепла