ISSN 2076-2429 (print)
ISSN 2223-3814 (online)
Proceedings of Odessa Polytechnic University, Issue 2(72), 2025

UDC 658.264

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HYBRID ENERGY SUPPLY SYSTEM FOR A MULTI-STOREY BUILDING WITH RENEWABLE ENERGY SOURCES

Г. Баласанян, В. Верстак, А. Остапенко., П. Колесниченко. **Гібридна система енергозабезпечення багатоповерхового будинку з відновлювальними джерелами енергії.** Запропоновано конфігурацію гібридної системи енергозабезпечення з відновлювальними джерелами енергії щодо автономного постачання електрики та тепла сучасного багатоповерхового будинку. Поєднання в гібридний системі різних за природою та енергетичним потенціалом джерел енергії сприяє взаємодоповненню їх переваг та, одночасно, взаємокомпенсації їх недоліків. За своєю потужністю гібридної системи енергозабезпечення найбільш придатні для автономного енергозабезпечення невеликих промислових об'єктів, фермерських господарств, житлових, рекреаційних, сільськогосподарських комплексів, тощо. Для кліматичних умов України найбільш розповсюдженими є гібридної системи енергозабезпечення, до яких інтегровано вітроустановки та сонячні фотоелектричні панелі. Конфігурація запропонованої гібридної системи енергозабезпечення складається з вітроустановки, сонячних фотоелектричних панелей, що генерують електрику, когенераційної установки за технологією газової мікротурбіни, що генерує для споживача як електрику так і тепло та електрокотла, як додаткового джерела тепла при пікових навантаженнях. Проведено узагальнення експериментальних даних, щодо швидкості вітру та сонячної інсоляції, що накопичено у базі даних метеостанції національного університету «Одеська політехніка». Опрацьовано методику щодо визначення оптимальних режимів навантаження та параметрів гібридної системи енергозабезпечення запропонованої конфігурації за критерієм мінімізації небалансу між генерацією та споживанням електрики в системі. Параметрами, що оптимізуються, є площа фотоелектричних панелей та площа лопатей вітроустановки, які сумісно генерують додаткову електрику, та разом з когенераційної установкої забезпечують повне покриття потреб споживачів. Отримано оптимальні режими електричного та теплового навантаження гібридної системи та її складових частин за місяцями року. Підтверджено, що сезонна нерівномірність вітрових та сонячних енергоресурсів може бути повністю компенсована шляхом інтеграції до гібридної системи різних за енергетичним потенціалом та природою джерел енергії, оптимізації їх генеруючої потужності та режимів навантаження.

Ключові слова: відновлювальні джерела енергії, гібридна система енергозабезпечення, когенераційна установка, вітроустановка, фотоелектричні сонячні панелі, режими навантаження оптимізація параметрів

H. Balasanian, V. Verstak, A. Ostapenko, P. Kolesnichenko. **Hybrid energy supply system for a multi-storey building with renewable energy sources.** A configuration of a hybrid energy supply system (HES) with renewable energy sources for the autonomous supply of electricity and heat to a modern multi-storey building is proposed. The combination of energy sources that are different in nature and energy potential in a hybrid system contributes to the mutual complementarity of their advantages and, at the same time, mutual compensation for their disadvantages. In terms of power, a hybrid energy supply system are most suitable for the autonomous energy supply of small industrial facilities, farms, residential, recreational and agricultural complexes, etc. For the climatic conditions of Ukraine, the most common are a hybrid energy supply system that integrate wind turbines and solar photovoltaic panels. The configuration of the proposed hybrid energy supply system consists of a wind turbine, solar photovoltaic panels that generate electricity, a cogeneration unit based on gas microturbine technology that generates both electricity and heat for the consumer, and an electric boiler as an additional source of heat during peak loads. A summary of experimental data on wind speed and solar insolation accumulated in the database of the meteorological station of the Odessa Polytechnic National University has been carried out. A methodology was developed to determine the optimal load modes and parameters of the proposed configuration based on the criterion of minimizing the imbalance between electricity generation and consumption in the system. The parameters to be optimized are the area of photovoltaic panels and the area of wind turbine blades, which jointly generate additional electricity and, together with the control unit, ensure full coverage of consumer needs. The optimal electrical and thermal load modes of the hybrid system and its components for each month of the year have been obtained. It has been confirmed that the seasonal unevenness of wind and solar energy resources can be fully compensated for by integrating energy sources with different energy potentials and natures into the hybrid system, optimizing their generating capacity and load modes.

Keywords: renewable energy sources, hybrid energy supply system, cogeneration plant, wind turbine, photovoltaic solar panels, load modes, parameter optimization

Introduction

The use of hybrid energy supply systems is becoming increasingly widespread in Ukraine and around the world [1]. This is due to the high energy efficiency of hybrid energy systems, which combine traditional energy technologies and renewable energy sources (RES) in a single system [2]. The combination of energy sources that differ in nature and energy potential in a single system contributes to the

DOI: 10.15276/opu.2.72.2025.05

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ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

mutual complementarity of their advantages and, at the same time, the mutual compensation of their disadvantages [3]. The widespread use of HES is also linked to the steady rise in prices for fossil fuels, heat and electricity, as well as increased environmental requirements for energy facilities and energy supply reliability. The energy capacity of HES is lower than that of traditional power generation systems. This is due to limitations in the energy potential of RES and their high specific cost, but systems with a capacity of several kW to several MW are quite widespread.

Analysis of literature data and problem statement

The use of HES is most effective in the autonomous supply of electricity and heat to consumers. In terms of their capacity, RES are most suitable for the autonomous energy supply of small industrial facilities, farms, residential, recreational and agricultural complexes, etc. [4]. For the climatic conditions of Ukraine, the most common are HES that integrate wind turbines (WT) and solar photovoltaic panels (SPP) [5, 6]. Depending on the operating mode, HES can be either completely autonomous or connected to electricity and gas networks. Autonomous operation also requires the system to have storage devices to compensate for the variability of wind and solar energy resources.

HES for electricity generation only have become more widespread, but for certain categories of consumers HES systems are used to meet their heating and hot water supply (HWS) needs. Such systems have a more complex configuration, as they additionally integrate heat generators – gas or electric boilers, heat pumps, etc. For such HES systems, electricity consumption will increase significantly during the heating season, leading to a corresponding increase in RES generation capacity and reducing the economic efficiency of the system. Recently, cogeneration plants based on gas turbines or internal combustion engines have been used for combined electricity and heat production in various industries. Integrating a cogeneration plant into a HES can significantly increase the efficiency of the system during the heating season, while in the summer months, efficient generation will be carried out mainly by RES [7].

A configuration of a HES system with a cogeneration unit – a gas microturbine, a heat recovery unit and a photovoltaic solar power plant – is proposed for consideration (Fig. 1). The proposed HES only needs to be connected to the gas network and is completely autonomous in terms of electricity generation. CU based on gas microturbines have found wide application for autonomous supply of electricity and heat to consumers [8] with high energy efficiency. The efficiency indicator of CU, the fuel utilisation factor (FUF), reaches up to 90%. During the non-heating period, consumer demand for heat is significantly reduced and, accordingly, the CU FUF can drop to 30%. The presence of a wind turbine and a solar photovoltaic system in the proposed HES configuration will largely compensate for the low efficiency of the CU during the non-heating period. The energy efficiency of the wind turbine is significantly higher in the winter months, while the solar photovoltaic system reaches its maximum in the summer months, so the proposed hybrid energy system is quite relevant for supplying consumers with significant heat consumption during the heating period with full electricity supply throughout the year.

For the proposed HES, the question of the optimal capacity of each energy source in the system becomes relevant [9, 10].

Purpose and objectives of the study

The purpose of the study is to investigate load modes and optimise the parameters of the HES for combined energy supply to consumers, taking into account the climatic conditions of the Odessa region.

To achieve the aim of the study, the following tasks must be solved:

– summarise experimental data on wind speed and solar insolation accumulated in the database of the meteorological station of the Odessa Polytechnic National University;

– develop a methodology for optimising the load modes and parameters of the proposed configuration of the solar energy system, taking into account the wind and solar radiation potential for the Odessa region;

– conduct research on the HES system to determine the optimal energy parameters of the system and load modes of the system components.

Research materials and methods

Fig. 1 shows the functional diagram of the proposed HES system. The object of energy supply is a modern 150-apartment multi-storey residential building.

The configuration of the proposed HES consists of a wind turbine, solar photovoltaic panels that generate electricity, a gas microturbine control unit that generates both electricity and heat for the consumer, and an electric boiler as an additional source of heat during peak loads. The electrical power

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)
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generated by the wind turbine and solar panels is usually supplied as direct current, which is quite convenient for charging batteries. The controller's function is to protect the battery from deep discharge and overcharging. Next, the inverter converts direct current into alternating current with a standard frequency of 50 Hz and a voltage of 220 or 380 V. Due to the utilized heat from the cogeneration unit, the main share of heat supply in the system is provided, additional peak heat loads are compensated by the electric boiler.

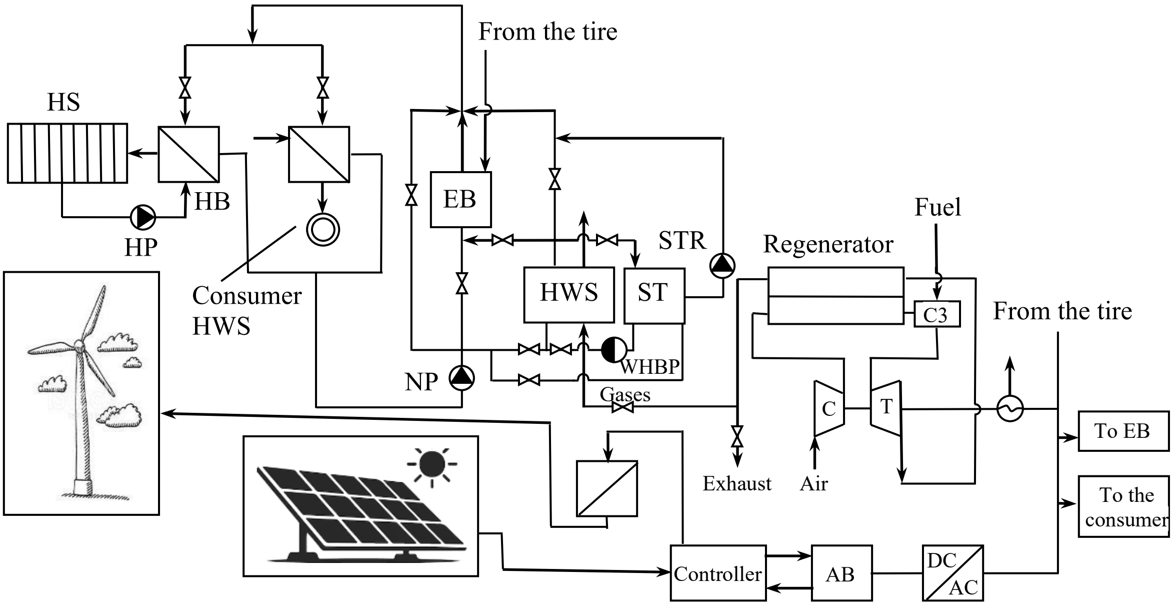

Fig. 1. Functional diagram of a HES system: T – gas turbine; C – compressor; ST – storage tank; EB – electric boiler; WHB – waste heat boiler; HS – heating system; HB – heating boiler; NP – network pump; HP – heating pump; STR – storage tank pump; WHBP – waste heat boiler pump

Methods for determining the capacity and performance of HES systems integrated with heat recovery boilers and solar panels are based on generalised climate data from long-term observations of wind speed and solar insolation for a given region. The parameters and structure of the SHE can be optimised in various ways: for example, according to technical indicators that characterise the reliability and efficiency of energy supply, or according to economic indicators such as the cost of energy products or capital investment in system components [11].

To optimise load modes and HES parameters, a target function (TF) is proposed that minimises the imbalance between electricity generation and consumption in the system: $F = E_{\text{gen}} - E_{\text{con}} \to 0.$ The parameters to be optimized are the area of photovoltaic panels F_{PV} and the area of wind turbine blades F_{WT}, which jointly generate additional electricity and, together with the CU, ensure full coverage of consumer needs.

In addition to the TF, the task of optimising load modes and HES parameters also includes a system of balance equations (BE) and corresponding constraints (CC) on the generation and consumption of electricity and heat in the system.

The balance between heat consumption and production is described by the equation:

$$Q^i_{\text{hs}} + Q^i_{\text{HWS}} = Q^i_{\text{CU}} + Q^i_{\text{EB}}, \tag{1}$$

where:

$Q^i_{\text{hs}}, Q^i_{\text{HWS}}$ are the average monthly values of the thermal power of the heating system and HWS, respectively;

$Q^i_{\text{CU}}, Q^i_{\text{EB}}$ are the average monthly values of the utilised thermal power of the heating system and hot water supply, respectively;

i is the ordinal number of the month of the year.

The balance of electricity consumption and production is described by the equation:

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$$E^i_{\text{con}} + E^i_{\text{EB}} = E^i_{\text{CU}} + E^i_{\text{PV}} + E^i_{\text{WT}}, \tag{2}$$

where:

E^i_{con}, E^i_{EB} – average monthly values of electricity consumer capacity and EC capacity, respectively;

E^i_{CU}, E^i_{PV}, E^i_{WT} – the average monthly values of the electrical power of the CU, SPP and WT, respectively.

Additional conditions may also be included in the system of equations, for example, the ratio between the nominal capacities of the wind turbine and photovoltaic panels $E^{\text{nom}}_{\text{PV}} / E^{\text{nom}}_{\text{WT}}$, which for this SPP is accepted as $E^{\text{nom}}_{\text{PV}} / E^{\text{nom}}_{\text{WT}} = 1$. The ratio between the nominal capacities of the heat source and photovoltaic panels can also be specified, for example, provided that the capital investments in the heat source ($K_{\text{heat source}}$) and photovoltaic panels (K_{PV}) are equal: $K_{\text{heat source}} / K_{\text{PV}} = 1$.

System of restrictions on electricity and heat generation in the HES:

$$Q^i_{\text{CU}} \le Q^{\text{nom}}_{\text{CU}} E^i_{\text{CU}} \le E^{\text{nom}}_{\text{CU}};\ E^i_{\text{PV}} \le E^{\text{nom}}_{\text{PV}};\ E^i_{\text{WT}} \le E^{\text{nom}}_{\text{WT}},$$

where: $Q^{\text{nom}}_{\text{CU}}$, $E^{\text{nom}}_{\text{CU}}$, $E^{\text{nom}}_{\text{PV}}$, $E^{\text{nom}}_{\text{WT}}$ are the nominal values of the thermal and electrical power of the CU, the electrical power of the SPP and the WT, respectively.

Finally, the task of optimising the load modes and parameters of the HES of the proposed configuration is as follows:

$$\begin{cases} F = E_{\text{gen}} - E_{\text{con}} \to \min \text{ (TF)}; \\ Q^i_{\text{hs}} + Q^i_{\text{HWS}} = Q^i_{\text{CU}} + Q^i_{\text{EB}} \text{(BE)}; \\ E^i_{\text{con}} + E^i_{\text{EB}} = E^i_{\text{CU}} + E^i_{\text{PV}} + E^i_{\text{WT}} \text{ (BE)}; \\ Q^i_{\text{CU}} \le Q^{\text{nom}}_{\text{CU}};\ E^i_{\text{CU}} \le E^{\text{nom}}_{\text{CU}};\ E^i_{\text{PV}} \le E^{\text{nom}}_{\text{PV}};\ E^i_{\text{WT}} \le E^{\text{nom}}_{\text{WT}} \text{ (CC)}; \\ E^{\text{nom}}_{\text{PV}} / E^{\text{nom}}_{\text{WT}} = 1 \text{ or } \dfrac{K_{\text{WT}}}{K_{\text{PV}}} = 1; \\ i = \overline{1.12}. \end{cases} \tag{3}$$

The “Find Solution” option in Excel spreadsheets was selected as the tool for solving the task of optimising the parameters of the HES. The result of solving the problem is the optimal values of the wind turbine blade area $F_{\text{ВУ}}$, the area of photovoltaic panels – F_{PV}, the average monthly values of utilised heat and electrical power of the CU – Q^i_{CU}, E^i_{CU}, the average monthly value of the electrical power of the EC, WT and SPP – E^i_{WT}, E^i_{EB}, E^i_{PV}, which satisfy the conditions of the problem.

Research results

The energy supply facility considered in this work is a modern 150-apartment multi-storey residential building with the following calculated technical characteristics:

– total heated area – 11.250 m²;
– number of residents – 370;
– specific heating characteristic – q_0 =1.4 W/(m²°C);
– hot water consumption – 100 litres per person per day;

The parameters for heat consumption for hot water supply and heating are determined according to the methodology [13].

Table 1 shows the total electricity and heat consumption at the facility during the calendar year.

The average monthly heat load of the facility for heating and hot water supply throughout the year is shown in Fig. 2. The facility's heat demand in winter and summer differs significantly and, accordingly, has a ratio of about 7:1, due to the fact that heat in summer is consumed only for hot water supply.

A cogeneration unit is installed at the facility – a Capstone-200 gas microturbine (manufactured in the USA) with the following nominal technical characteristics:

– turbine electrical power, kW – 200;
– utilised thermal power, kW – 393;
– natural gas consumption, nm³/hour – 65;
– turbine rotation speed, rpm – 65,000;
– exhaust gas temperature, °C – 280;

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)
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– turbine electrical efficiency, % – 33;
– fuel utilisation factor (FUF), % – 90.

Table 1

Generalised electricity and heat consumption volumes

Electricity consumption, kWh	97500	89700	89700	82500	65625	84375	93750	93750	65625	78000	97500	97500
Average monthly electricity load, kW	135	133	125	115	88	117	126	126	91	105	135	135
Average monthly heating load, kW	331	331	236	142	0	0	0	0	0	158	221	284
Heat consumption for hot water supply, kW	82	82	82	48	45	64	64	64	45	48	50	82
Total thermal load, kW	413	413	318	190	45	64	64	64	45	206	271	366

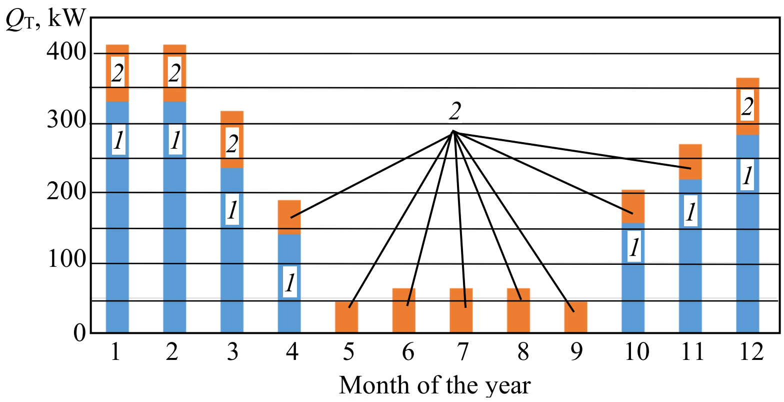

Fig. 2. Thermal load of the facility by month of the year: *1* – Heating; *2* – HWS

Analysis of the data in Table 2 shows that the electrical power of photovoltaic panels in the summer months is 6…8 times higher than in winter, which, accordingly, will contribute to their effective use with limited power of the CU in summer (Fig. 3). On the contrary, the electrical power of heat engines is 4…5 times higher in the autumn and winter months than in the summer, which contributes to natural gas savings for heat engines.

Table 2

Electricity generation by wind turbines and photovoltaic panels by month of the year

Month	1	2	3	4	5	6	7	8	9	10	11	12
Insolation, kWh/m²	28	47	115	161	177	211	200	184	130	70	32	27
Specific electricity generation of solar power plants, W/m²	7.6	14.2	31	45.4	46.7	57.5	52.5	48.2	36.7	19.4	8.5	7.4
Average monthly electrical capacity of solar power plants, kW	14	26	59	85	88	109	99	91	68	36	16	14
Average monthly wind speed, m/s	4.8	5	4.8	4.8	3.7	2.9	2.9	2.7	2.9	3.2	4.4	4.7
Average monthly electrical power of the WT, kW	15.6	17.7	15.6	15.6	7.2	3.4	3.4	2.8	3.4	4.6	12	14.7

The results of solving the problem of optimising load modes and HES parameters under the condition of equal nominal capacities of wind turbines and photovoltaic panels $E_{PV}^{nom} / E_{WT}^{nom} = 1$ are as follows:

– total SPP – 1638 m²;

– the area of the rotor blades is 995 m², which corresponds to a wind turbine diameter of 62 m.

Fig. 4 shows the optimal modes for utilised heat from the CU and heat from the EC by month of the year.

Analysis of Fig. 4 shows that during the heating season (October to April), heat utilised from the CU provides the majority of heat for the consumer. The EC is used to coordinate the thermal and electrical load schedules in the system and to cover peak loads, so the share of heat from the EC is significantly lower. The heat recovered from the CU is used only for HWS in the summer, so the CU operates periodically only to accumulate hot water, and the EC is switched on to coordinate the thermal and electrical loads of the system.

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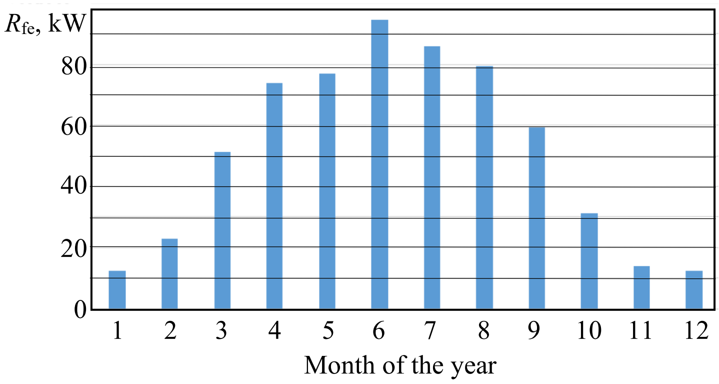

Fig. 3. Power of photovoltaic panels by month of the year

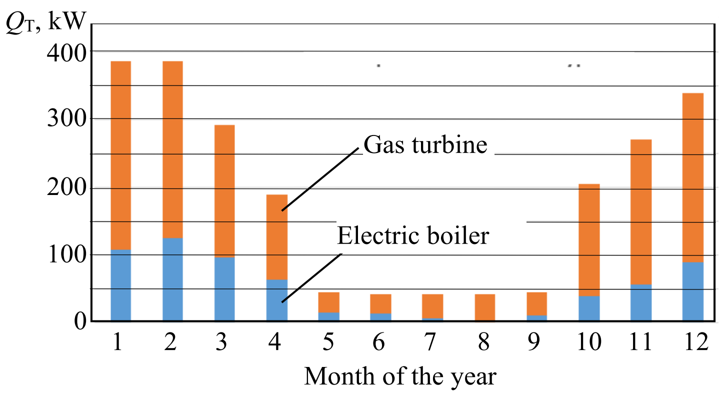

Fig. 4. Optimal modes of heat generation from the CU and EC by month of the year

Fig. 5 shows the optimal modes of electricity generation by the CU, WT and SPP by month of the year. Analysis of Fig. 5 shows that the main share of electricity during the heating period in the HES is provided by a gas microturbine. Although the share of electricity from the heat pump is smaller than that from the heat exchanger, it is several times greater than the share of electricity from the heat pump. Electricity supply to consumers in the summer months is mainly provided by the heat pump. The share of electricity from the microturbine is small and is due to the supply of utilised heat to the DHW. In the summer months, the WT generates several times less electricity than the SPP.

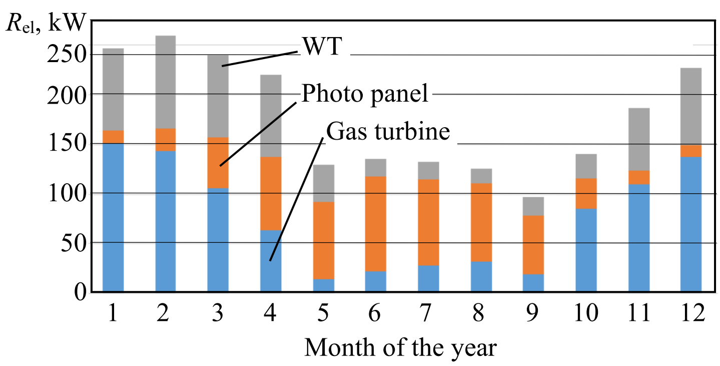

Fig. 5. Optimal electricity generation modes in the HES by month of the year, assuming equal nominal capacities of WT and photovoltaic panels

If the task of optimising the parameters and load modes of the HES is solved under the condition of equal capital investments in accordance with the WT(K_{WT}) and photovoltaic panels (K_{PV}):

$$K_{WT} / K_{PV} = 1,$$

then the optimisation results change significantly (Fig. 6). The share of electricity from CU and SPP increases significantly, while electricity from WT, on the contrary, does not have a significant impact on the energy balance of the SGE.

ISSN 2076-2429 (print)
ISSN 2223-3814 (online)
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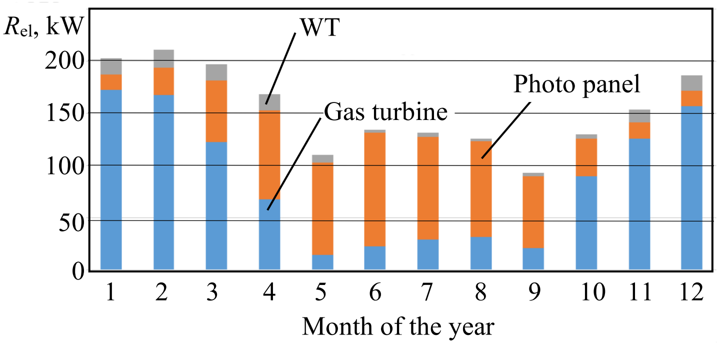

Fig. 6. Optimal electricity generation modes in the HES by month of the year, assuming equal capital investments in thermal power plants and photovoltaic panels

Conclusions

1. A HES system for autonomous electricity and heat supply of a modern multi-storey residential building has been proposed, taking into account the energy potential of wind and solar energy for the Odessa region.

2. A methodology has been developed for determining the optimal load modes and parameters of the proposed HES configuration based on the criterion of minimising the imbalance between electricity generation and consumption in the system.

3. The optimal modes of electrical and thermal load of the hybrid system and its components by month of the year have been obtained.

4. It has been confirmed that the seasonal unevenness of wind and solar energy resources can be fully compensated by integrating energy sources with different energy potentials and natures into the hybrid system, optimising their generating capacity and load modes.

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ISSN 2076-2429 (print)
ISSN 2223-3814 (online)

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Received September, 24, 2025

Accepted October 27, 2025