

RESEARCH ON ENSURING ANNUAL ENERGY CONSUMPTION OF A RESIDENTIAL BUILDING WITH A PHOTOELECTRIC PLANT

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Purpose. To assess the capability of rooftop photovoltaic power plant (PVPP) to supply the operation of engineering systems in multi-apartment residential buildings and to determine a set of engineering and technical measures that ensure the effective integration of rooftop photovoltaic power plants in order to achieve regulatory energy-efficiency indicators and minimize climate impact.

Methodology. Calculation and analytical methods were applied to determine the energy consumption of residential buildings, along with a methodology for calculating electrical loads of multi-apartment buildings to evaluate changes in electricity demand under different configurations of building climate systems. Scenario analysis and energy modeling were used to assess the interaction between heating technologies, operating conditions, and renewable energy generation.

Findings. Rooftop photovoltaic systems equipped with modern photovoltaic modules and inverter equipment and installed on typical five-storey multi-apartment residential buildings are capable of covering the annual electricity demand of building climate systems, which corresponds to the requirements for achieving operational climate neutrality. Comprehensive modeling was carried out to analyze the interaction between building climate system configurations, energy sources, heating system temperature regimes, and actual outdoor temperature conditions on the achievable level of energy efficiency in typical residential buildings. The modeling of rooftop photovoltaic system operation and the comparison of expected electricity generation with the electricity demand of thermally modernized buildings equipped with heat-pump-based climate systems demonstrated the feasibility of balancing annual energy consumption with on-site renewable generation. It was found that comprehensive thermal modernization of typical five-storey buildings combined with the transition to electric heating using heat pumps as the primary heat source enables the electricity demand of building climate systems to be supplied by rooftop photovoltaic systems.

Originality. The study substantiates a set of energy-efficient measures, including the integration of rooftop photovoltaic systems, that allow achieving operational climate neutrality indicators for typical five-storey multi-apartment residential buildings. It is shown that the transition to heat-pump-based electric heating can reduce electricity consumption by 1,8-2,0 times under actual average outdoor temperature conditions compared with conventional electric heating systems. Furthermore, the implementation of low-temperature heating regimes reduces electricity consumption by 2,8-3,2 times compared with direct electric heating and enables achieving operational climate neutrality for building climate systems.

Practical value. The results can be applied in the development of renovation projects for existing multi-apartment residential buildings, in new residential construction, and in the design of electric heating systems that utilize electricity generated by rooftop photovoltaic systems. The proposed solutions contribute to the objectives of the Energy Strategy of Ukraine until 2035, strengthen national energy security, and support the implementation of international commitments on reducing primary energy consumption and greenhouse gas emissions.

Keywords: energy efficiency; photovoltaic system; electricity consumption; climate neutrality; building climate systems; heat pump.

I. INTRODUCTION

Ukraine participates in international initiatives aimed at climate change adaptation, reduction of greenhouse gas emissions, and the transition to a low-carbon economy. In this context, increasing the energy efficiency of buildings and gradually introducing renewable energy sources (RES) to meet consumer

energy demand are becoming particularly important [1].

The main challenges faced by residential building owners when implementing renewable energy sources, particularly rooftop photovoltaic systems as the most widespread renewable energy technology, include:

- the legal status of the roof;
- the technical condition of the roofing structures;

- the load-bearing capacity of building structures;
- the complexity of connection to internal electrical networks;
- limited electricity generation capacity.

Internal building electrical networks are often outdated and were not designed to receive and distribute energy from distributed generation facilities. Modernization of power supply systems and replacement of electrical networks require significant additional financial resources. In addition, the mismatch between peak electricity consumption and generation periods prevents buildings from achieving energy autonomy. These challenges often create barriers to the integration of solar power plants into building energy systems.

The residential sector is one of the largest consumers of energy resources. Climate control systems, including heating and cooling, account for the largest share of energy consumption in the annual energy balance of buildings. In order to fulfill national and international commitments, regulatory requirements are being introduced to improve the efficiency of energy use and reduce greenhouse gas emissions.

One of the technical solutions increasingly used in new residential construction projects is the implementation of electric heating systems. This approach allows achieving the minimum energy performance requirements of buildings in accordance with the Law of Ukraine "On Energy Efficiency of Buildings" by minimizing losses in district heating networks and due to the relatively simple control and higher efficiency of electric heating systems compared to centralized and autonomous heating systems based on fossil fuels. However, such a solution cannot always be implemented in existing buildings due to the limited capacity of electrical networks to accommodate additional loads associated with the transition to electric heating.

A promising solution is the integration of heat pumps into building climate control systems. The use of such systems allows heat energy to be obtained with relatively low electricity consumption [2].

One of the approaches to improving the energy efficiency of building heating systems is the use of low-temperature heating supply schedules. These schedules reduce electrical loads, improve the efficiency of heat utilization, and increase the performance of heat pumps. Studies show that the combination of modern heating systems with energy-efficient technologies significantly reduces building energy consumption and improves their overall energy performance [3].

Renewable energy sources are also increasingly used in building energy supply systems to improve energy efficiency. Their implementation reduces dependence on conventional energy resources and contributes to decreasing environmental impacts. Recent studies emphasize the importance of integrated application of various energy-saving technologies to improve the overall efficiency of building energy systems [4].

Thus, a relevant scientific task is the comprehensive

assessment of energy consumption in residential buildings when implementing rooftop photovoltaic systems and transitioning from conventional to combined climate control systems using heat pumps.

II. ANALYSIS OF LAST RESEARCHES

The residential sector is one of the largest consumers of energy and a significant source of greenhouse gas emissions. According to international reviews, buildings account for up to 40% of global final energy consumption. Climate control systems and domestic hot water supply represent a major share of this energy consumption. To ensure the operation of these systems, buildings largely rely on fossil energy resources [5].

In recent years, there has been growing interest in methods and technologies capable of significantly reducing both primary energy consumption and greenhouse gas emissions from residential buildings. One promising solution is the integration of rooftop photovoltaic systems with heat pumps (HP), which together ensure high efficiency in energy resource utilization [6].

The use of hybrid energy supply systems combining heat pumps and photovoltaic systems potentially allows simultaneous coverage of building thermal and electrical energy demand, opening the way to achieving near-zero energy building (NZEB) performance levels [6]. In [7], it is shown that the combination of heat pumps and photovoltaic panels significantly reduces energy consumption and operational costs while contributing to substantial reductions in greenhouse gas emissions.

Practical monitoring studies confirm that in multi-apartment buildings with high energy performance levels, the use of heat pumps combined with photovoltaic systems or solar thermal collectors can provide an annual energy balance, especially when applying comprehensive measures to reduce heat losses in the building envelope [8].

Increasing the share of heat pumps and renewable energy sources in building energy supply is considered one of the key directions of decarbonization in the residential sector in Ukraine and Europe. For example, market analysis data indicate a significant increase in heat pump sales in EU countries, reflecting stronger renewable energy support policies and a shift away from gas- and solid-fuel-based heating systems [9].

Despite numerous advantages, the integration of photovoltaic systems and heat pumps in residential buildings faces several technical and economic challenges. These include increased peak electrical loads during the transition to electric heating, the need for optimal placement of photovoltaic panels, ensuring reliable operation during cold periods, and determining effective strategies for electrical and thermal energy balancing [10].

This article presents a comprehensive analysis of energy consumption in a residential building equipped

with a rooftop photovoltaic system when transforming the heating system and introducing a heat pump as the main energy source for building climate systems. The calculations were carried out according to current methodologies for determining building energy consumption and designing electrical equipment for civil facilities (DSTU 9190:2022, DBN V.2.5-23) in order to determine the baseline annual load, analyze renewable energy integration scenarios, and assess the potential for achieving climate neutrality.

III. FORMULATION OF THE WORK PURPOSE

To assess the capability of rooftop photovoltaic power plant to supply the operation of engineering systems in multi-apartment residential buildings and to determine a set of engineering and technical measures that ensure the effective integration of rooftop photovoltaic power plants in order to achieve regulatory energy-efficiency indicators and minimize climate impact.

IV. EXPOUNDING THE MAIN MATERIAL AND RESULTS ANALYSIS

Electrical loads of a building are calculated based on the requirements of DBN V.2.5-23. The analysis of this regulatory document shows that electrical loads are determined for buildings without considering the energy efficiency class indicators and expected energy consumption modes.

According to the specified methodology, the calculated load of a group of dwellings with the same specific electrical load, referred to the supply line, building input, or 0,4 kV transformer substation busbars, P_{dwN} is determined by the following formula [11]:

$$P_{dwN} = P_{dwS} \cdot N,$$

where P_{dwS} – specific calculated electrical load of one dwelling (apartment), selected according to Table 3.1 [11] depending on the adopted electrification level and the number of apartments connected to the given network section, kW/dwelling;

N – number of dwellings (apartments) connected to the input line or transformer substation.

Appendix D, Table D.2 [11] provides an example of calculating loads for type-1 dwellings using full electric heating for apartments with an average area of 70 m² and an electric stove of 8,5 kW (see Table 1).

Table 1. Example of determining calculated loads of type-1 dwellings using full electric heating (average apartment area 70 m² with an 8,5 kW electric stove)

Groups of electricity consumers in a dwelling	Specific calculated load, kW/dwelling (number of dwellings)		
	12	24	100
Type-1 dwelling	3,76	2,72	1,73
Direct electric heating	7,37	7,37	7,37
Total with electric heating	11,13	10,09	9,1

Modern approaches to comprehensive energy modernization of buildings and bringing them into compliance with the minimum requirements established by the Law of Ukraine “On Energy Efficiency of Buildings” significantly affect the energy consumption of engineering systems, particularly heating and cooling systems. Therefore, it becomes necessary to assess the specific load of direct electric heating and heating systems using heat pumps for different classes and types of residential buildings. This makes it possible to take into account the actual condition of residential buildings, the installed engineering equipment, and to refine specific energy consumption indicators for selecting the main electrical equipment of building power networks.

An improved algorithm for determining electrical loads is proposed, which takes into account energy efficiency indicators (Fig. 1) determined using the methodology approved by DSTU 9190. These indicators are converted into electricity consumption of the heating system.

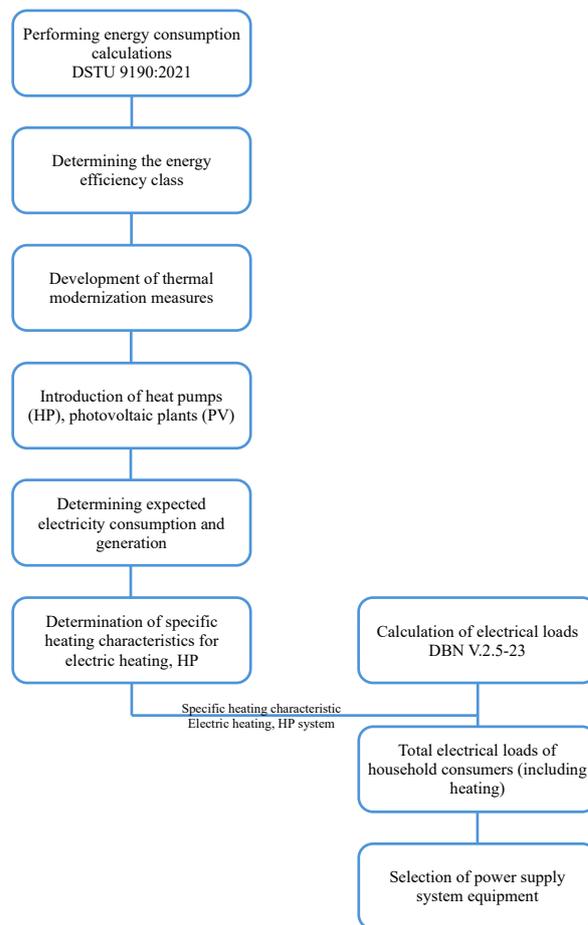


Figure 1. Algorithm for determining building electrical loads

To compare the generation and consumption modes of electrical and thermal energy in a typical building equipped with a rooftop photovoltaic system, the main

energy consumption indicators were modeled according to existing methodologies.

The determination of the annual and monthly energy demand and consumption of the heating system was carried out according to the methodology approved by DSTU 9190:2022 [12]. The methodology defines the annual energy balance of the building, which includes:

- transmission heat losses through building envelopes;
- ventilation losses;
- internal heat gains;
- solar heat gains.

The energy demand of the heating system is determined by the formula [12]:

$$Q_{H,nd} = Q_{H,nd,cont} = Q_{H,ht} - \eta_{H,gn} Q_{H,gn} - Q_{ve,pre-heat}$$

where $Q_{H,nd,cont}$ – energy demand for continuous building heating, $W \cdot h$, must be ≥ 0 ;

$Q_{H,ht}$ – total heat transfer in heating mode, $W \cdot h$, defined in accordance with 7.2.3.1 [12];

$\eta_{H,gn}$ – dimensionless gain utilization factor, defined in accordance with 12.2 [12];

$Q_{H,gn}$ – total heat gains during heating operation, $W \cdot h$, defined in accordance with 7.2.3.2 [12];

$Q_{ve,pre-heat}$ – energy demand for central preheating of ventilation air, $W \cdot h$ defined in accordance with 9.4 [12].

To model energy consumption modes of building climatization systems (heating and air conditioning), a typical four-entrance five-storey multi-apartment residential building located in the city of Dnipro was used. The number of apartments per floor is four in the corner entrances and three in the intermediate entrances, which corresponds to typical layouts. According to DBN V.2.6-31:2021 [13], the building is located in the first temperature zone. The building walls are made of 400 mm expanded clay concrete blocks, which do not meet the minimum energy efficiency requirements in terms of thermal properties. Transparent structures include windows, glazing of balconies and loggias mainly made of double-chamber glazing units in 5-7 chamber aluminum profiles; some double wooden windows remain. Such a condition of transparent structures is typical for most residential buildings in Ukraine. Facade glazing coefficient 0,22 which is typical for this type of building. The roof structure is a combined flat roof consisting of reinforced concrete panels, a slope-forming layer, and roofing felt. The floor above the unheated basement is the floor of the first level and consists of a 220 mm reinforced concrete slab covered with a cement-sand screed and decorative finishing. Both the roof slab and the slab above the basement require thermal insulation according to current energy efficiency standards. The external entrance doors are insulated metal

doors with vestibules and do not require modernization. The total heated area of the building is 3974,9 m².

The building climatization systems include a centralized heating system with an elevator unit at the input and a dependent connection scheme, as well as individual household air conditioners with split systems that provide cooling for separate rooms and apartments. The heating system uses hot water as the heat carrier with a temperature schedule of 80/60 °C, which is typical for most Ukrainian cities.

The heating system operation was modeled under the following conditions:

- absence of circulation pumps, the circulation of the coolant in the heating system is carried out due to the pressure difference in the supply and return pipelines.;
- one-pipe dead-end vertical heating system with bottom distribution;
- steel pipelines;
- steel and cast-iron radiators placed along external walls;
- partial absence or damage of pipeline insulation in unheated spaces;
- manual riser and radiator valves as regulating fittings, partially absent.

These conditions are typical for most multi-apartment buildings, allowing the obtained simulation results to be considered representative for this building class.

For typical five-storey apartment buildings constructed between 1950 and 1980, the energy consumption of climatization systems before comprehensive thermal modernization exceeds 160 kW·h/m² per year, corresponding to energy class G and not meeting minimum requirements.

Thus, the energy consumption of the climatization system for the current state of the building is about 635 MW·h, while the rooftop photovoltaic system can generate only about 190 MW·h.

For the existing energy supply system, two types of heat sources are considered – direct electric heating using heating elements and heat pumps.

The main difference between centralized heating and heat pump systems lies in the efficiency indicators of the heat generation and accumulation subsystems. As a result, the model with heat pumps yields heating energy consumption expressed in kW·h of electricity. Since it is this parameter that determines the consumption of either thermal or electrical energy, depending on the selected source of thermal energy.

If the centralized heating system is replaced by direct electric heating using heating elements, not only the generation efficiency indicators change but also the linear heat transfer coefficients and pipeline lengths. With direct heating, distribution losses are almost zero (see Table 2).

Table 2. Generation subsystem indicators for calculating energy losses in the heating system.

Indicator	Indicator value for:		
	Centralized heating	Direct electric heating	Heat pump installation
Generation subsystem			
Efficiency indicator of heat production/generation and storage subsystems	0,93	0,99	2,6-3
Heat losses in pipelines located in unheated spaces			
Linear heat transfer coefficient of the connecting pipeline	0,2	0	0,2
Length of the connecting pipeline	209	0	209
Equivalent length of shut-off and control valves	24	0	24
Heat losses in pipelines located in heated spaces			
Linear heat transfer coefficient of the vertical pipeline	0,3	0	0,3
Length of the vertical pipeline	349	0	349
Linear heat transfer coefficient of the horizontal pipeline	0,4	0	0,4
Length of the horizontal pipeline	176	0	176
Overall efficiency level of the heat emission subsystem in the room	0,82	0,91	0,82

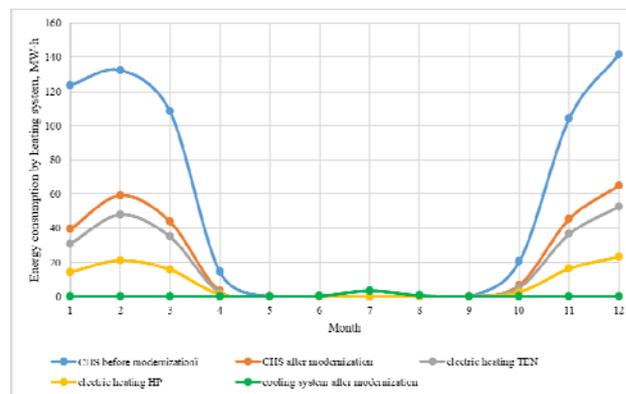
Modeling of the considered energy sources allowed determining the specific energy consumption of the heating system. The results for the current building state are presented in Table 3.

Since Ukraine has committed to reducing greenhouse gas emissions, including in the energy and building sectors, thermal modernization of buildings and achieving minimum energy efficiency requirements is mandatory. Order of the Ministry for Communities and Territories Development of Ukraine №260 (27.10.2020) establishes specific minimum energy efficiency indicators and energy class requirements (class C for new or reconstructed buildings). Therefore, the heating system energy consumption was also determined after building modernization. The thermal resistance of building envelopes was brought to minimum requirements for the first temperature zone, and the energy consumption parameters were recalculated for the modernized building.

All values and modeling results are presented in Table 3 and Figure 2. Cooling energy consumption changes insignificantly because it is usually provided by household air conditioners and accounts for no more than 5% of the total climatization energy consumption.

Table 3. Specific energy consumption of the heating system

	With centralized heating	With direct electric heating (heating elements)	With heat pump installation
Heating system energy consumption before modernization, kW·h/m ² ·year	162,32	134,49	58,06
Cooling system energy consumption before modernization, kW·h/m ² ·year	2,67	2,67	2,67
Energy consumption after modernization, kW·h/m ² ·year	66,11	53,05	23,65
Cooling system energy consumption after modernization, kW·h/m ² ·year	1,06	1,06	1,06

**Figure 2.** Heating system energy consumption before and after modernization

Analyzing the obtained graphs in Fig. 2 and the values in Table 3, we can say that the energy consumption of the heating system after modernization decreases by 2,5 times, and when installing an electric heating system with a HP – by 6,9 times. In this case, the rooftop photovoltaic system becomes capable of covering the electricity consumption of heating and cooling systems throughout the year.

Further analysis shows that switching to direct

electric heating does not significantly reduce energy consumption. In the conditions of prolonged war and destruction of energy infrastructure, such a transition may be forced but would require significant modernization of low-voltage distribution networks. In the case of a forced transition to electric heating for entire residential districts, such modernization would inevitably extend to urban distribution networks of medium voltage levels (6-10-35 kV). In addition, centralized heating systems can use various types of primary energy sources, including natural gas, coal, firewood, pellets, and fuel briquettes. In contrast, the transition to electric heating requires mandatory electricity generation, which to some extent narrows the choice of energy sources and simultaneously requires enhanced measures to ensure reliable backup power supply for consumers.

An alternative method that allows reducing electricity consumption in heating systems is the use of heat pumps. When switching to heat pump heating systems, the internal building heating networks require modernization. Advances in compressor technologies, heat exchangers, and refrigerants make it possible to achieve acceptable seasonal efficiency indicators for air-to-air and air-to-water heat pumps under climatic conditions typical for Ukraine. In this case, the expected energy consumption of heating systems decreases by 2,8-3,2 times compared to centralized and direct electric heating. Additional rooftop photovoltaic systems with or without storage systems and hybrid inverters can further improve the energy independence of buildings. This makes it possible to partially protect the building from prolonged power outages and also compensate for part of the electrical energy that will be consumed by the heat pump during the heating season.

To assess expected energy efficiency indicators of buildings with heat pump heating systems, the annual operation modes of the rooftop photovoltaic system were modeled.

First, the electricity generation of the photovoltaic power plant (PV system) is preliminarily estimated and analyzed. Figure 3 shows the monthly annual generation of a 175 kW rooftop photovoltaic system installed on the roof of the five-storey building. The installed capacity was determined considering the available roof area and the need to maintain technical service passages. For multi-storey residential buildings, typically 75–80% of the roof area can be used for PV installation.

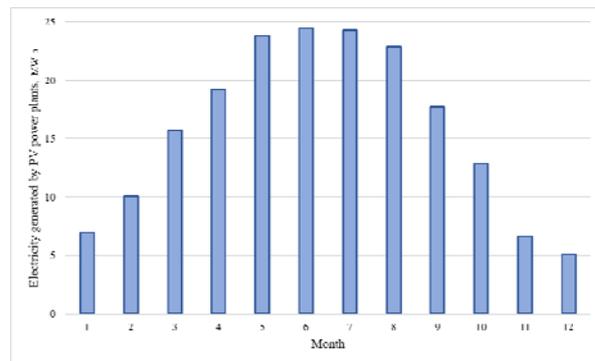


Figure 3. Annual generation of the rooftop photovoltaic system

The photovoltaic power plant is installed on the roof of a five-storey residential building. As shown in Fig. 3, the annual generation of the PV system amounts to almost 190 MW·h. Obviously, the energy generated by the station is insufficient to cover all the building's needs either annually or on a monthly basis. Therefore, individual engineering systems of the building that could potentially be supplied by this station are considered separately. To evaluate and determine the capability of the PV system to supply electricity to one of the building's engineering systems, the consumption of the most energy-intensive system – the climatization system – is analyzed.

Table 4 presents the main characteristics of solar panels that can be used for the installation of a rooftop photovoltaic power plant for the selected building.

Table 4. Solar panel characteristics

Panel power, W	Panel efficiency, %	Geometric dimensions, m	Panel area, m ²	Specific panel power, W/m ²
600	23,2	2,278x1,134	2,58	232,56
620	23	2,382x1,134	2,7	229,63
615	22,8	2,382x1,134	2,7	227,78
610	22,6	2,382x1,134	2,7	225,93
580	22,5	2,278x1,134	2,58	224,81
605	22,4	2,382x1,134	2,7	224,07
575	21,3	2,384x1,134	2,7	212,96

From Table 4 it can be seen that the higher the panel efficiency, the higher the specific power of the panel. Therefore, when modeling the rooftop PV system, the specific power of the first panel will be used, which equals 0,233 kW/m².

To model the operation of the solar power plant, the

effective roof area available for PV installation is first determined:

$$A_{ef.PV} = 0,75 \cdot A_{roof} = 0,75 \cdot 916,7 = 687,53 \text{ m}^2,$$

where 0,75 – area utilization factor, which accounts for the tilt angle of the panels, row spacing, technical maintenance passages, and setbacks from the parapet;

A_{roof} – roof area, determined according to the design documentation of the selected building, m².

The installed capacity of the photovoltaic power plant is determined as follows:

$$P_{PV} = A_{ef.PV} \cdot p_{PVM} = 687,53 \cdot 0,233 = 159,89 \text{ kW},$$

where $A_{ef.PV}$ – effective roof area, m²;

p_{PVM} – specific power of a photovoltaic module, kW/m².

The estimated annual generation of the PV system is calculated as follows:

$$\begin{aligned} E_{year} &= P_{PV} \cdot H_{ef} = 159,89 \cdot 1100 = \\ &= 175878,5 \text{ kW} \cdot \text{h per year}, \end{aligned}$$

where P_{PV} – PV system capacity, kW;

H_{ef} – effective solar hours for the central region of Ukraine, hours per year [14].

If the annual PV generation compensates the annual electricity consumption of the heat pump, the heating system can be considered operationally carbon neutral.

Thus, the amount of electrical energy required to ensure the operation of the heating system during the year is determined:

$$\begin{aligned} E_{ee} &= q_{H,nd} \cdot A_H = 25,65 \cdot 3974,9 = \\ &= 101956,19 \text{ kW} \cdot \text{h per year}, \end{aligned}$$

where $q_{H,nd}$ – annual specific energy demand of the heating system, kW·h/m²;

A_H – heated floor area of the building, m².

Figure 4 presents the results comparing PV generation with energy consumption of climatization systems under different building thermal characteristics.

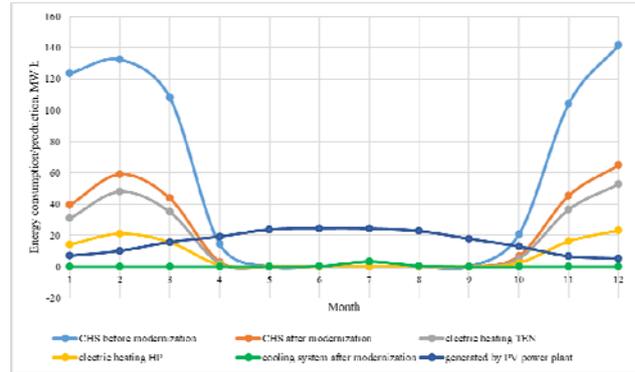


Figure 4. Capability of rooftop PV system to cover climatization loads

The modeling results show that the rooftop PV system can ensure independent operation of the climatization system on an annual basis provided that the building undergoes thermal modernization and heat pump systems are implemented (Fig. 5).

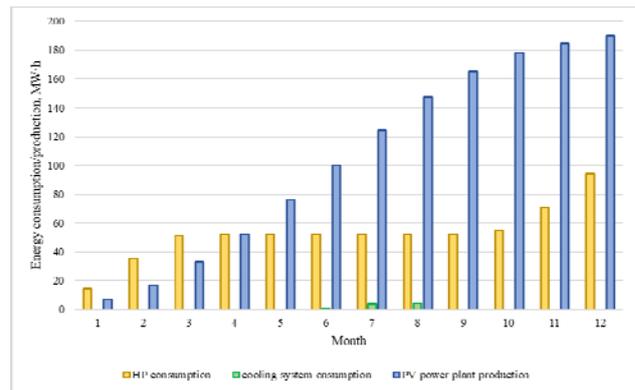


Figure 5. Cumulative annual balance of PV generation and climatization system consumption

Thus, comprehensive thermal modernization of buildings combined with heat pump integration and rooftop photovoltaic systems makes it possible to achieve operational climate neutrality for typical five-storey residential buildings in the climatic conditions of Ukraine. The proposed modeling algorithm allows evaluating the energy performance of other types of residential buildings, including new constructions and buildings located in different climatic regions.

Conflict of interest. The authors declare that they have no conflicts of interest.

V. CONCLUSION

The study analyzed and established that a rooftop photovoltaic system can cover the operation of the building climatization system provided that comprehensive thermal modernization of multi-apartment residential buildings and their climatization systems is

carried out, the heat source and heating system temperature regimes are changed, and the actual ambient temperature conditions are taken into account.

It was determined that for typical five-storey residential buildings in the climatic conditions of Ukraine, installing rooftop photovoltaic systems and switching to low-temperature heating regimes using heat pumps allows achieving operational climate neutrality of climatization systems.

The transition to low-temperature heating schedules increases the seasonal coefficient of performance from 1,8-2,0 to 2,8-3,2, considering averaged outdoor temperatures over the last five years during the heating season. This reduces electrical loads associated with the transition to heat pump systems and improves the reliability of energy supply, which is especially important under conditions of ongoing attacks on Ukraine's energy infrastructure.

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ДОСЛІДЖЕННЯ РІЧНОГО ЕНЕРГОСПОЖИВАННЯ ЖИТЛОВОЇ БУДІВЛІ З ФОТОЕЛЕКТРИЧНОЮ СТАНЦІЄЮ

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Мета роботи. Оцінити спроможність дахової фотоелектричної станції (ФЕС) забезпечити роботу інженерних мереж багатоквартирних житлових будинків, визначити комплекс заходів, які забезпечать ефективну інтеграцію дахових фотоелектростанцій з позицій досягнення нормативних показників енергетичної ефективності та мінімізації кліматичного впливу.

Методи дослідження. Використано розрахунково-аналітичні методи визначення енергоспоживання житлових будівель, а також методику розрахунку електричних навантажень багатоквартирних будинків для оцінки змін електроспоживання при різних варіантах обладнання систем кліматизації, застосовано метод сценарного аналізу та енергетичного моделювання.

Отримані результати. Дахові фотоелектричні станції, оснащені сучасними фотоелектричними модулями та інверторним обладнанням, розміщені на багатоквартирних п'ятиповерхових будівлях типового планування, здатні упродовж року покрити енергоспоживання систем кліматизації, що відповідає вимогам досягнення операційної кліматичної нейтральності. У роботі виконане комплексне моделювання взаємного впливу типів систем кліматизації будівель, вибору джерела енергії, температурних режимів системи опалення, фактичних температур оточуючого середовища на досяжний рівень енергетичної ефективності типових будівель житлового фонду. Моделювання режимів роботи дахової сонячної електростанції та порівняння очікуваного обсягу генерації електричної енергії з електроспоживанням типових будинків після комплексної термомодернізації і запровадження систем кліматизації з тепловими насосами дозволило встановити досягнення показників. Встановлено, що комплексна термомодернізація типових п'ятиповерхових будівель з переходом на електроопалення з використанням теплових насосів в якості основного джерела теплової енергії, дозволяють забезпечувати електроспоживання систем кліматизації будинків даховими фотоелектричними станціями.

Наукова новизна. У роботі обґрунтовано комплекс енергоефективних заходів, які включають встановлення дахових фотоелектричних станцій та дозволяють досягти показників операційної кліматичної нейтральності для типових п'ятиповерхових багатоквартирних житлових будинків. Встановлено, що перехід на електроопалення з використанням теплових насосів в якості основного джерела енергії, дозволяє в умовах фактичних осереднених температур зовнішнього повітря знизити споживання електричної енергії в 1,8-2,0 рази при існуючих температурних режимах системи опалення. Перехід на низькотемпературні графіки роботи систем опалення житлових будинків дозволяє знизити електроспоживання у 2,8-3,2 рази порівняно з прямим електроопаленням і забезпечити вихід на показники операційної кліматичної нейтральності систем кліматизації будинків.

Практична цінність. Результати можуть бути використані при розробці проєктів повної або часткової модернізації багатоквартирних житлових будівель, новому будівництві та при проєктуванні систем електроопалення будівель у тому числі з використанням електричної енергії, отриманої від дахових ФЕС. Отримані рішення відповідають ключовим задачам Енергетичної стратегії України до 2035 року, сприяють зміцненню енергетичної безпеки України, виконанню міжнародних зобов'язань в частині скорочення споживання первинних енергетичних ресурсів, зниження викидів парникових газів.

Ключові слова: енергетична ефективність, фотоелектрична станція, режими електроспоживання, кліматична нейтральність, системи кліматизації, тепловий насос.