Development and Simulation of Operating Modes of a Hybrid PV-T System for Integrated Energy Supply of Urban Residential Buildings

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Abstract. The aim of this work is to assess the technical and economic efficiency of using hybrid photovoltaic-thermal (PV-T) panels in the energy supply system of an urban residential complex in the Republic of Moldova, to improve energy efficiency and relieve centralized energy supply networks. This aim is achieved by developing a mathematical model of PV-T system integration into urban infrastructure in Simulink MATLAB, selecting and justifying the main equipment (PV-T panels, inverters, heat pumps, energy storage), simulating characteristic operating modes, and a comparative techno-economic analysis of the existing and proposed supply strategies. The proposed hybrid system uses solar energy to simultaneously generate electricity, provide domestic hot water and support space heating in a multi-apartment complex. The most important result is the substantiation of the technical feasibility and economic viability of integrating PV-T panels into urban buildings, reducing grid energy use during peak load with an acceptable payback period. The significance of the results lies in a comprehensive method for assessing the efficiency of hybrid solar systems under regional conditions. The study showed that PV-T panels not only increase solar energy conversion efficiency through effective cooling of the photovoltaic cells, but also relieve transformer capacity and reduce losses in distribution networks. The results can support regional programmes for renewable energy in the housing and utilities sector of the Republic of Moldova, the design of autonomous and hybrid energy supply systems for social facilities, and further research on optimizing distributed generation within an urban Smart Grid.

Keywords**:** renewable energy sources, solar energy, photovoltaic-thermal (PV-T) modules, hybrid energy supply systems.

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Elaborarea și modelarea regimurilor de funcționare ale unui sistem hibrid PV-T pentru alimentarea integrată cu energie a clădirilor rezidențiale urbane

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Rezumat. Scopul lucrării este evaluarea eficienței tehnice și economice a utilizării panourilor hibride fotovoltaice-termice (PV-T) în sistemul de alimentare cu energie al unui complex rezidențial urban din Republica Moldova, pentru creșterea eficienței energetice și descărcarea rețelelor centralizate. Scopul este atins prin elaborarea în Simulink MATLAB a unui model matematic de integrare a sistemului PV-T în infrastructura urbană, selectarea și argumentarea echipamentului principal (panouri PV-T, invertoare, pompe de căldură, sisteme de stocare a energiei), modelarea regimurilor caracteristice de funcționare și analiza tehnico-economică comparativă a strategiei existente și a celei propuse. Sistemul hibrid propus utilizează energia solară pentru a produce simultan energie electrică și apă caldă menajeră și pentru a susține încălzirea unui complex de blocuri locative. Cel mai important rezultat este argumentarea fezabilității tehnice și a oportunității economice a integrării panourilor PV-T în clădirile urbane, reducând consumul din rețea la vârf de sarcină, cu o perioadă de recuperare acceptabilă. Semnificația rezultatelor constă într-o metodologie complexă de evaluare a eficienței sistemelor solare hibride în condițiile regiunii. Studiul a arătat că panourile PV-T nu doar cresc randamentul conversiei energiei solare prin răcirea eficientă a celulelor fotovoltaice, ci și descarcă transformatoarele și reduc pierderile în rețelele de distribuție. Rezultatele pot susține programe regionale de energie regenerabilă în sectorul locativ-comunal al Republicii Moldova, proiectarea sistemelor autonome și hibride de alimentare cu energie a obiectivelor sociale și cercetări ulterioare privind optimizarea generării distribuite în cadrul unei rețele Smart Grid urbane.

Cuvinte-cheie**:** surse regenerabile de energie, energie solară, module fotovoltaice-termice (PV-T), sisteme hibride de alimentare cu energie.

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Разработка и моделирование режимов гибридной PV-T системы для комплексного энергоснабжения городской жилой застройки

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***Аннотация*.** Целью работы является оценка технической и экономической эффективности применения гибридных фотоэлектрических тепловых (PV-T) панелей в системе энергоснабжения одного из городских жилых комплексов, эксплуатируемых в Республике Молдова для повышения энергоэффективности и снижения нагрузки на централизованные сети энергоснабжения. Поставленная цель достигается посредством решения следующих задач: создания математической модели интеграции PV-T системы в городскую инфраструктуру на базе Simulink MATLAB, выбора и обоснования состава основного оборудования (PV-T панелей, инверторов, тепловых насосов, накопителей энергии), моделирования характерных режимов работы системы, проведения сравнительного технико-экономического анализа существующей и предлагаемой стратегий энергоснабжения. В ходе выполнения работы была предложена и исследована гибридная система энергоснабжения для многоквартирного жилого комплекса с использованием солнечной энергии для одновременного получения электроэнергии, обеспечения горячего водоснабжения и поддержки системы отопления. Наиболее важным результатом является обоснование технической возможности и экономической целесообразности интеграции PV-T панелей в городскую застройку, что позволяет снизить потребление энергии из внешних сетей в периоды пиковой нагрузки и достичь приемлемого срока окупаемости предлагаемого технического решения. Значимость полученных результатов состоит в создании комплексной методики оценки эффективности гибридных солнечных систем для условий региона. Исследование показало, что использование PV-T панелей не только повышает КПД использования солнечной энергии за счет эффективного охлаждения фотоэлементов, но и способствует разгрузке трансформаторных мощностей и снижению потерь в распределительных электрических сетях. Результаты исследования также могут быть использованы для разработки региональных программ по внедрению возобновляемых источников энергии в жилищно-коммунальном хозяйстве Республики Молдова, проектирования автономных и гибридных систем энергоснабжения социальных объектов, а также в качестве базы для дальнейших научных исследований по оптимизации режимов работы распределенных источников генерации в составе городской Smart Grid.

***Ключевые слова*:** возобновляемые источники энергии, солнечная энергетика, фотоэлектрические тепловые модули (PV-T), гибридные системы энергоснабжения.

INTRODUCTION

The global energy sector is undergoing a fundamental transformation driven by the shift to clean and renewable energy sources (RES). This process, known as the “energy transition” or “green transition”, is dictated not only by environmental commitments under the adopted climate agreements, but also by the desire of states to ensure energy security and independence from fossil fuel imports [1,2]. For regions lacking their own hydrocarbon resources, the development of local solar-based microgeneration is becoming a strategic priority that helps stabilize the energy balance and reduce the load on centralized power systems [3,4,31].

One of the most innovative and rapidly developing areas of solar energy is the technology of hybrid photovoltaic-thermal (PV-T) panels (photovoltaic thermal hybrid solar collector). Historically, photovoltaic (PV) generation and solar thermal collectors (T) developed in parallel, but using them separately on the limited area of urban rooftops is often inefficient. In addition, a fundamental problem of standard PV modules remains the drop in their electrical efficiency when heated: as the temperature of silicon cells rises above 25°C, electricity output decreases proportionally [5,6,32]. PV-T technology resolves this dilemma by integrating a heat exchange circuit directly into the panel design. Active cooling of the photovoltaic cells by a heat transfer fluid not only stabilizes their electrical efficiency, but also yields useful thermal energy for domestic hot water (DHW) and space heating [7,8,33].

In recent years, significant progress has been made in optimizing the architecture of PV-T systems. The focus is shifting towards new types of heat transfer fluids, including nanofluids, and the use of phase change materials (PCM) to increase system thermal inertia and smooth out daily temperature fluctuations [12,13,14]. Integrated solutions of this kind can achieve an overall solar energy utilization factor of up to 80%, making them a key element in implementing the concepts of Net Zero Energy Buildings and Smart Cities [9,10,15,16].

However, large-scale integration of such distributed sources into the existing urban distribution network (DN) infrastructure requires solving a number of engineering problems. Traditional urban power grids were designed, and are operated, according to a radial scheme [17,34]. The emergence of active consumers capable of generating energy requires revising the approaches both to managing the operating modes of transformer substations and to power quality parameters at load nodes [18,19,20]. The need to prevent overvoltages during peak insolation hours and to ensure reliable power supply when there is no solar activity leads researchers to use advanced numerical simulation and intelligent load forecasting methods [21,22,23,35].

The scientific novelty of this work lies in the development and verification of a comprehensive mathematical model coupling hybrid PV-T systems with real nodes of municipal 0.4 kV distribution networks. Unlike existing theoretical studies, the proposed approach is based on the dynamic interaction between the thermal characteristics of the panels and the electrical parameters of the inverter equipment under the specific climatic profile of the region. An energy flow control algorithm is proposed that optimizes system operation not only by the criterion of maximum generation, but also by the criterion of minimum thermal ageing of DN power equipment, through partial unloading of transformers during daytime consumption peaks. The developed model makes it possible to estimate with high accuracy the synergistic effect of the combined generation of two types of energy for multi-apartment housing [24,25,26].

The techno-economic significance of the study is confirmed by life cycle assessment (LCA) of modern PV-T installations, which shows a substantial advantage of the technology in reducing the carbon footprint compared with conventional separate energy supply schemes [27,28]. Assessment of the investment attractiveness of PV-T projects in the housing and utilities sector shows that payback periods of 7–8 years are achievable, which opens wide prospects for scaling up the technology as part of urban infrastructure modernization [29,30].

PROBLEM STATEMENT AND SIMULATION CONDITIONS

The object of the study is a hybrid energy supply system based on PV-T technology, integrated into the heating network and the 0.4 kV electrical distribution network of a typical residential complex supplied from a 10/0.4 kV transformer substation. The residential complex consists of four 9-storey, one 5-storey and one 3-storey residential buildings (Fig. 1).

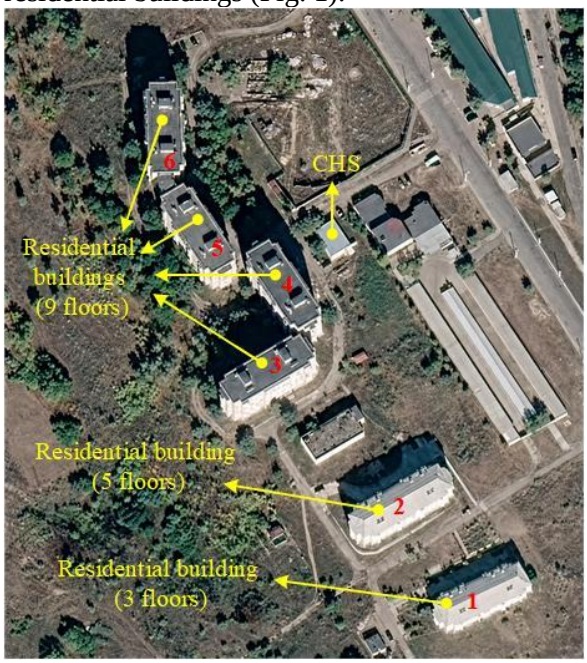


Fig. 1. Typical residential complex.

The subject of the study is the process of generation, conversion and distribution of the electrical and thermal energy produced by PV-T panels, as well as the modes of joint operation of this system with the centralized power and heat supply networks.

To solve the research tasks, a structural simulation model was built in Simulink MATLAB; its simplified block diagram is shown in Fig. 2.

The integrated model was built under the following conditions and assumptions:

- the residential complex is supplied from a 10/0.4 kV substation with an installed capacity of 1×400 kVA;
- the average transformer load is about 43% of its rated capacity;
- heat is supplied from the centralized heating network;
- installed electrical capacity of the system: ≈ 205 kW;
- installed thermal capacity: ≈ 126 kW;
- minimum ambient temperature: –20°C;
- maximum permissible panel temperature: up to 80°C in summer;
- solar radiation was assumed to be variable (up to 400 W/m² in the calculations for characteristic modes);
- the efficiency of the thermal part is taken in the range of 20–50% (35% in the calculations);

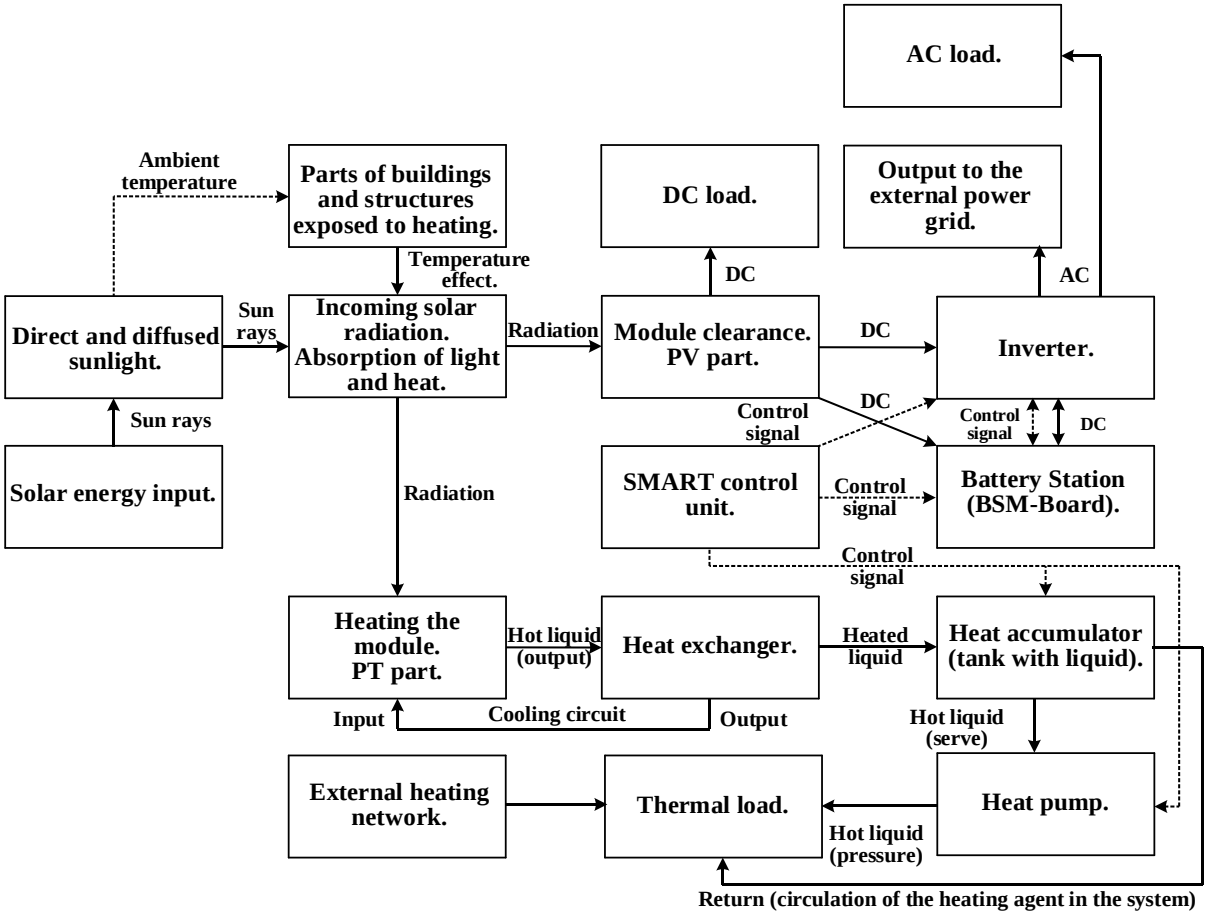


Fig. 2. Block diagram of the structural simulation model of a hybrid power supply system.

- the thermal system operates together with the centralized network;
- the simulation took into account equipment parameters, real load profiles (Fig. 3) and network constraints for the various operating modes of the system.

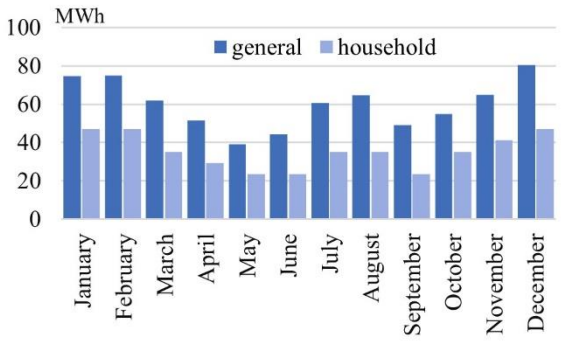


Fig. 3. Annual load profile.

The model also took into account:

- the position of the Sun (azimuth and elevation angle);
- the climatic and atmospheric conditions of the region;
- the daily non-uniformity of solar radiation;
- the openness of the site, i.e. the absence of shading from buildings, terrain and vegetation;
- the tilt of the solar panels relative to the mounting surface and to the ground.

The research model consists of two interconnected blocks, based on a mathematical description of the physical processes of trigeneration and ensuring parallel operation with the existing urban energy supply networks:

1. Electrical block

Since ambient temperature affects the operation of photovoltaic panels, the influence of the regional ambient temperature was taken into account when determining the open-circuit DC voltage levels at the output of the PV-T panels:

$$V_{\max.realV} = V_{OCV}(1+(t_{\min}-25)T_{coef}), \quad (1)$$

where

$V_{\max.realV}, V$ – maximum voltage of the solar panel system;

V_{OCV}, V – open-circuit voltage according to the datasheet;

$t_{\min}, °C$ ℃℃ – minimum temperature for the current operating mode (–20°C was adopted, the minimum temperature observed in the region);

$T_{coef}, 1/℃$ – temperature coefficient of the open-circuit voltage, ranging from –0.0028 $1/℃$ to –0.0036 $1/℃$; for monocrystalline PV-T panels, –0.0032 $1/℃$ was adopted.

Based on the above, the simulation model used PV-T panels with the technical characteristics given in Table 1.

Table 1. Technical characteristics of the PV-T panel.

Parameter	Value
Generated electrical power, *W*	590
Generated thermal power, *W*	517
Nominal voltage at maximum load, *V*	31.6
Rated current at maximum load, *A*	17.4
Nominal voltage without connected load, *V*	37.9
Short-circuit current, *A*	18.52
Dimensions: W×L×H, *mm*	1134×2279×35

For each building (Fig. 1), the maximum possible electrical and thermal generation capacities were determined, taking into account the area, shape and orientation of the roofs (Table 2).

Table 2. Generated power for each building.

Building number	Number of panels	Electric power, *kW*	Thermal power, *kW*
1	62	36.58	32.05
2	62	36.58	32.05
3	80	47.2	41.36
4	48	28.32	24.82
5	48	28.32	24.82
6	48	28.32	24.82

To ensure the energy autonomy of the residential complex during the hours when the PV-T panels do not generate electricity (from 20:00 to 05:00), the model includes a hybrid inverter and a battery storage station. The open-circuit voltage was calculated from the inverter parameters, in the maximum voltage mode, subject to the condition:

$$V_{\max.realV} < V_{Inv.\max}, \qquad (2)$$

where

$V_{Inv.\max}, V$ – maximum permissible inverter voltage, in the range of $600 \div 1500 V$ ($1100 V$ adopted in the model).

The required capacity of the battery station was determined as:

$$C = \frac{P_d \cdot n_d}{V_{sys} \cdot EOD \cdot \eta}, \qquad (3)$$

where:

C, Ah – required storage capacity;

P_d, Wh – daily electricity consumption;

n_d – number of days of autonomous operation of the PV-T system;

V_{sys}, V – system voltage in the DC network;

$EOD, \%$ – depth of discharge (End of Discharge), defining the permissible discharge level of the battery without damage to its structure (80% adopted for Li-ion batteries);

η – system efficiency with respect to the hybrid inverter.

When choosing the battery cell configuration, it was taken into account that series connection increases the string voltage, while parallel connection increases the total capacity. Thus, increasing the number of cells in one group increases the DC power available to the inverter:

$$N_{ser} = \frac{V_{sys}}{V_{Ci}}, \quad N_{par} = \frac{C}{C_i}, \qquad (4)$$

where:

N_{ser} – number of batteries connected in series;

N_{par} – number of batteries connected in parallel;

V_{Ci}, V – rated voltage of one battery;

C_i, Ah – capacity of one battery.

The batteries were checked for compliance of the permissible group voltage and power with the inverter parameters.

Power of the battery group:

$$P_C = (N_{ser} V_{Ci}) \cdot (N_{par} C_i) \cdot \eta_{Inv}, \qquad (5)$$

where:

P_C, W – power of the battery station (considered as the maximum throughput of the battery group);

η_{Inv} – efficiency of the hybrid inverter.

Check of power and voltage against the inverter parameters:

$$\begin{cases} P_C < P_{Inv} \\ V_C < V_{Inv} \end{cases}, \quad (6)$$

where:

P_{Inv}, W – maximum inverter power for the input network;

V_C, V – voltage of the battery group;

V_{Inv}, V – rated inverter voltage.

If a scheme with two or more inverters is used, the powers of all inverters connected to the battery station must be summed. The model uses a three-phase hybrid inverter with the characteristics given in Table 3.

Table 3. Technical characteristics of the inverter.

Parameter	Value
Maximum input power, *W*	96000
Nominal output power, *W*	60000
Nominal output power, *VA*	66000
Type of protection	IP66
Ambient temperature, °*C*	-30÷60
Output voltage,	380
Maximum allowable DC voltage, *V*	1100
Maximum number of MPPT-controllers	4
Maximum current of each MPPT controller, *A*	4×40
Maximum short-circuit current of each MPPT controller, *A*	4×60
MPPT operating range, *V*	180-1000
Starting voltage, *V*	200.0
Maximum input current, *A*	136.4
Maximum output current, *A*	100
Efficiency of one channel, *%*	98.4
Power factor, $\cos\varphi$	0.8

The characteristics of the lithium-ion battery group used in the simulation model, determined according to the load level and the inverter parameters, are given in Table 4.

Table 4. Battery specifications.

Parameter	Value
Capacity, *Ah*	124.8
Number of parallel connections	28
Number of serial connections	26
Maximum voltage, *V*	117.6
Minimum voltage, *V*	75.6
Nominal voltage, *V*	96

2. Thermal engineering block

To determine thermal energy generation, a refined analysis of solar radiation was carried out for the 46–47° N parallels, which corresponds to the location of the PV-T system in the central part of the Republic of Moldova. For this region, the solar radiation flux density is usually taken as 1000 W/m^2, which is in fact overestimated and may lead to an incorrect determination of the PV-T technical characteristics.

The simulation used refined values of solar radiation flux density on winter and summer days for horizontal and vertical surfaces at the 46–47° N parallels [37]. The corresponding dependencies are shown in Fig. 4a, b.

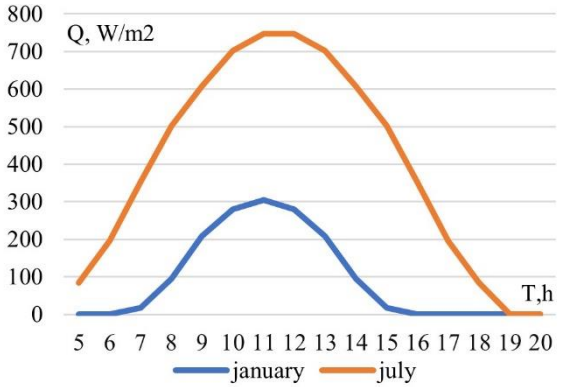


Fig. 4a. Total radiant flux density on horizontal surfaces.

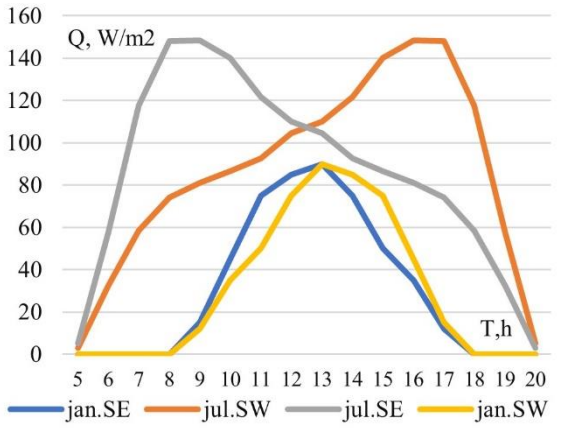


Fig. 4b. Total radiant flux density on vertical surfaces.

The model uses an algorithm for calculating solar radiation for the south-east, south and south-west orientations of the PV-T panels:

$$Q_\Sigma = Q_{SE} \times K_{SE} + Q_{SS} \times K_{SS} + Q_{SW} \times K_{SW}, \quad (7)$$

where:

$Q_\Sigma, W/m^2$ – total solar radiation heat flux at the current moment, calculated separately for each hour;

$Q_{SE}, Q_{SS}, Q_{SW}, W/m^2$ – maximum solar radiation heat flux for the south-east, south and south-west orientations, respectively;

K_{SE}, K_{SS}, K_{SW} – heat flux density coefficients for open terrain.

Physically, the coefficient accounts for the combined influence of the factors that reduce or change the incoming solar energy compared with its theoretical maximum.

The operating hours of the PV-T system were considered from 05:00 to 20:00, taking into account diffuse radiation from the south-east and south-west directions. Based on the analysis of solar radiation for the 46–47° N parallels, the heat flux density coefficients and their values for each operating hour were determined and used in the simulation (Table 5).

Table 5. Heat flux density coefficients.

hour	Jan.	Jul.	Jan. SE	Jan. SW	Jul. SE	Jul. SW
5		0.11	0.00	0.00	0.03	0.02
6		0.26	0.00	0.00	0.39	0.22
7		0.47	0.00	0.00	0.79	0.39
8	0.06	0,67	0.17	0.13	1.00	0.50
9	0.31	0.81	0.50	0.39	1.00	0.55
10	0.68	0.94	0.83	0.56	0.94	0.58
11	0.92	1.00	0.94	0.83	0.82	0.62
12	1.00	1.00	1.00	1.00	0.74	0.70
13	0.92	0.94	0.83	0.94	0.70	0.74
14	0.68	0.81	0.56	0.83	0.62	0.82
15	0.31	0.67	0.39	0.50	0.58	0.94
16	0.06	0.47	0.13	0.17	0.55	1.00
17		0.26	0.00	0.00	0.50	1.00
18		0.11	0.00	0.00	0.39	0.79
19		0.00	0.00	0.00	0,22	0.39
20		0.00	0.00	0.00	0.0	0.0

To use the heat produced by the PV-T panels more effectively, the model provides for fan coils that transfer heat or cooling to the premises through a built-in heat exchanger and fan.

In the research model, the fan coil parameters were selected taking into account the thermal characteristics of the liquid circuit of the PV-T system, its operating mode, and the regulatory requirements for heating and indoor climate. Both the heat transfer fluid parameters (temperature, flow rate) and the characteristics of the room where the equipment is installed were considered.

The proposed method for calculating the heat supply scheme takes into account both the heated area and the volume of the premises of the residential complex:

$$Q_{\text{Pr}} = V \times \Delta T \times k, \quad (8)$$

where

Q_{Pr}, W – heat load of all premises of the residential building;

V, m^3 – room volume;

$\Delta T, °C$ – difference between the required and actual temperature. According to the standards, the required temperature in residential premises was taken as $20\,°C$, and the actual temperature in an unheated room as $5\,°C$);

k – heat loss coefficient.

The thermal power of each PV-T panel circuit was determined as:

$$Q_{PV-T} = Q_{PV-Ti} \times N, \quad (9)$$

where

Q_{PV-T}, W – total thermal power of the PV-T panel circuit;

Q_{PV-Ti} – heat produced by one PV-T panel, W;

N – total number of panels.

Formula for converting thermal energy into electrical power:

$$P_{FAN} = \frac{Q_{FAN}}{\eta \cdot \Delta T \cdot c_p \cdot \rho}, \quad (10)$$

where

P_{FAN}, W – electrical power of the fan coil;

Q_{FAN}, W – thermal energy required from the fan coil;

η – fan coil efficiency;

ΔT – difference between the required and actual temperature;

c_p – heat capacity of air;

ρ – air density.

The fan coils were selected subject to the conditions:

$$\begin{cases} Q_{FAN} > Q_{Pr} \\ Q_{FAN} > Q_{PV-T} \end{cases}, \quad (11)$$

The model uses duct fan coils with the characteristics given in Table 6.

Table 6. Technical characteristics of the fan coil.

Parameter	Value
Nominal voltage, *V*	210…240
Fan coil type	Duct
Cooling, *kW*	21.9
Heating, *kW*	33
Water consumption, *l/min*	57.05
Electric power consumption, *W*	950

The number and capacity of the fan coils provided in the model for each building of the residential complex are given in Table 7.

Table 7. Number and capacity of fan coils.

Building number	Q_{Pr}, kW	Number of fan coils	Q_{FAN}, kW	P_{FAN}, kW
1	58.8	2	66	1.9
2	98	3	99	2.85
3	176.3	6	198	5.7
4	176.3	6	198	5.7
5	176.3	6	198	5.7
6	176.3	6	198	5.7

The parameters of the heat pump and the heat accumulator were determined by the design heat load of the building for space heating, hot water supply and, if necessary, ventilation. Based on this load and the analysis of its distribution among the buildings of the complex, the minimum heat pump capacity was determined:

$$Q_{HP} = m \cdot c \cdot \Delta T, \qquad (12)$$

where

Q_{HP}, kW – minimum power drawn from the heat pump;

m, kg – mass of water; here kilograms are equal to litres (the desired tank volume);

$c, kJ/(kg \times °C)$ – specific heat capacity;

$\Delta T, °C$ – desired water temperature rise (it is assumed that the cold water temperature in this water supply network does not exceed $25\,°C$ and a rise of $40\ °C$ is expected; the actual hot water temperature will thus be $65\,°C$, which fully complies with current standards, excluding losses).

Calculation of the electrical power of the required heat pump, taking into account the coefficient of performance (COP), here assumed equal to 4:

$$P_{HP} = \frac{Q_{HP}}{COP} \qquad (13)$$

Based on the above, a heat pump was selected for the thermal engineering block model (its technical characteristics are given in Table 8); under normal climatic conditions it can cover up to 70–90% of peak heat demand.

The heat accumulator (storage tank) was considered as a backup or auxiliary heat source ensuring reliable space heating and hot water supply in the residential complex . Its capacity was determined as the difference between the design peak load and the heat pump capacity.

Table 8. Heat pump specifications.

Parameter	Value
Nominal heating capacity, *kW*	23
Maximum water temperature, *℃*	60
Hot water supply, *t/h*	0.48
Average heating power consumption, *kW*	4.68
Operating temperature range, *℃*	-20÷45
Water flow, m^3/h	3.72

The number and capacity of heat pumps for the residential complex are given in Table 9.

Table 9. Number and capacity of heat pumps.

Building number	Q_{HP}, kW	P_{HP}, kW	Number of heat pumps
1	46.44	11.61	2
2	92.89	23.22	4
3	139.33	34.83	6
4	139.33	34,83	6
5	139.33	34.83	6
6	139.33	34.83	6

In some cases, the tank can be combined or operate automatically together with the heat pump, switching on when thermal capacity is insufficient.

The proposed model uses a heat accumulator with the characteristics given in Table 10.

Table 10. Technical characteristics of the heat accumulator.

Parameter	Value
Volume, *l*	1000
Maximum working pressure, *bar*	3
Installation of electric heaters	up to 4 pcs.

The number and volume of heat accumulators are given in Table 11.

Table 11. Number and volume of heat accumulators.

Building number	$V_{\min}, l$	Number of heat accumulators
1	881.63	1
2	1469.39	2
3	2644.90	3
4	2644.90	3
5	2644.90	3
6	2644.90	3

The useful (minimum) volume of the tank was calculated from the required thermal power and the water flow rate in the system, using an empirical formula proposed by the authors.

$$V_{\min} = \frac{\sum v_i \cdot 1000}{m \cdot c \cdot \Delta T}. \quad (14)$$

The minimum useful volume of the heat accumulator is the ratio of the sum of the hot water flow rates of each heat pump to the product of the water mass, its specific heat capacity and the temperature difference in the hot water supply system.

TECHNICAL AND ECONOMIC EFFICIENCY

A series of computational experiments was carried out on the developed model, and the results confirmed the technical efficiency of the proposed solution. The technical efficiency of the proposed hybrid PV-T system is due to the synergistic effect of simultaneously generating two types of energy and to the adaptation of the equipment to the climatic conditions of the 46th parallel. Unlike conventional photovoltaic plants, where a significant part of the solar radiation is spent on parasitic heating of the panels, this system actively removes low-grade heat. This keeps the operating temperature of the photovoltaic cells in the optimal range, preventing their thermal degradation and ensuring consistently high electrical efficiency. Integrating heat pumps and buffer storage tanks, whose volume is optimized using the developed method, turns the excess heat of the panels into a useful resource for DHW and space heating, raising the overall solar energy utilization factor to 80%.

The technical effect in 0.4 kV distribution networks consists in improved power quality parameters and higher operational reliability of network equipment. Simulation of operating modes in the residential sector showed that automatic control of the inverter equipment and the use of battery storage make it possible to reduce the load and losses in 10/0.4 kV power transformers in winter by up to 20–30% (Fig. 5). At the same time, in summer, at peak solar activity, transformer losses increase somewhat, which can be explained by PV-T generation exceeding the consumption of the residential complex. This problem can be solved by installing electricity storage.

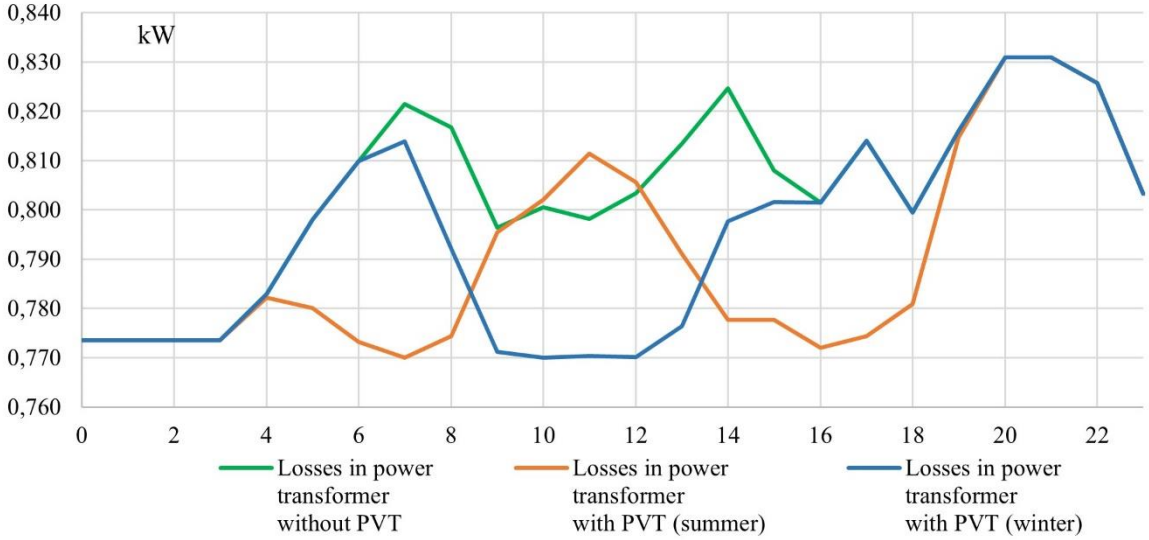


Fig. 5. Daily graph of losses in a power transformer.

Implementing such projects not only minimizes the risk of overvoltages at load nodes, but also considerably slows equipment wear, enabling more flexible control of the operating modes of the urban power system.

The simulation results for the heating and hot water supply systems, which take into account real daily load profiles, are shown in Fig. 6 and Fig. 7 for winter and summer, respectively.

In summer, the solar system shows high energy efficiency, providing an integral coverage of daily DHW demand of 60.13%.

This confirms the feasibility of using PV-T for hot water supply of residential buildings in the climatic zone studied. At midday (10:00 to 14:00) there is a steady surplus of thermal energy (coverage ratio up to 165%).

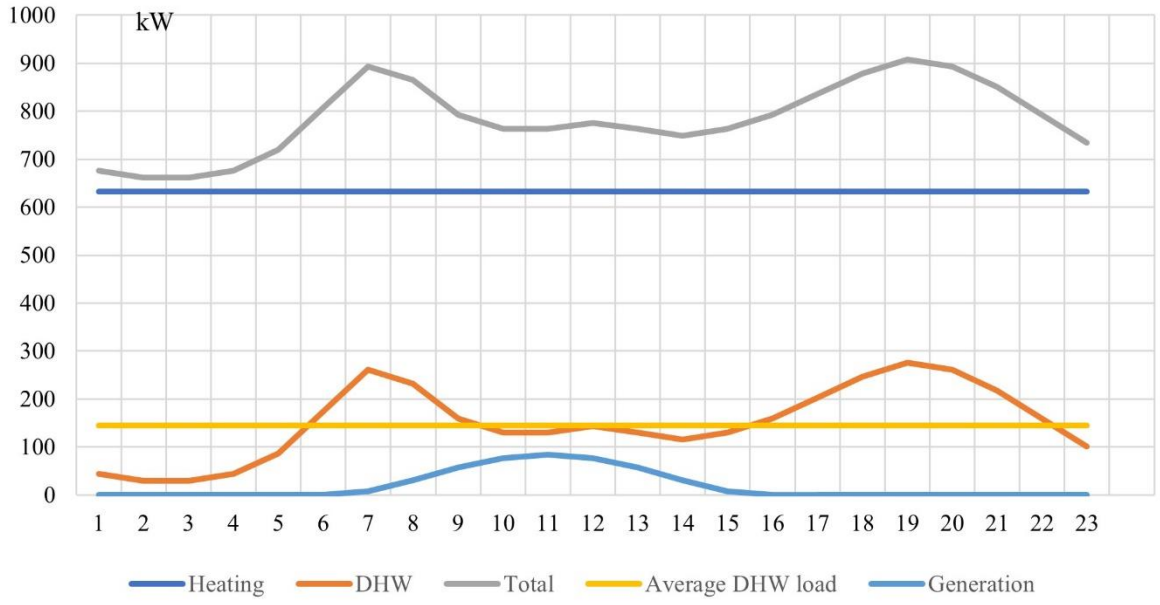


Fig. 6. Thermal load profile for the winter time.

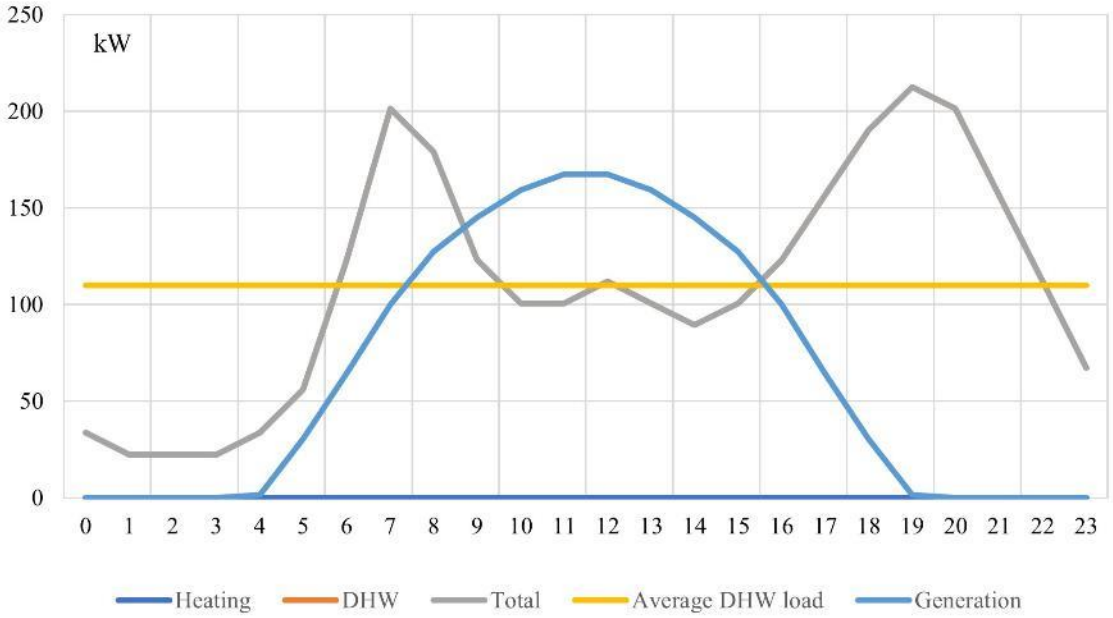


Fig. 7. Thermal load profile for the summer time.

The analysis shows that even with high daily coverage (60%), direct use of solar energy is also inefficient because the generation peak (midday) does not coincide with the consumption peak (evening). For full year-round operation of the complex, storage tanks are required that can absorb the surplus 340.8 kWh of daytime heat in summer and shift it to the evening peak of hot water use, which would raise the share of autonomous DHW coverage in summer to almost 100%.

The economic efficiency of the study is confirmed by shorter payback periods for capital investment and lower specific costs of energy supply for housing. According to the techno-economic analysis, for a design service life of 25 years the payback period (PBP) is 7.67 years (Fig. 8), which is an acceptable indicator for renewable energy projects.

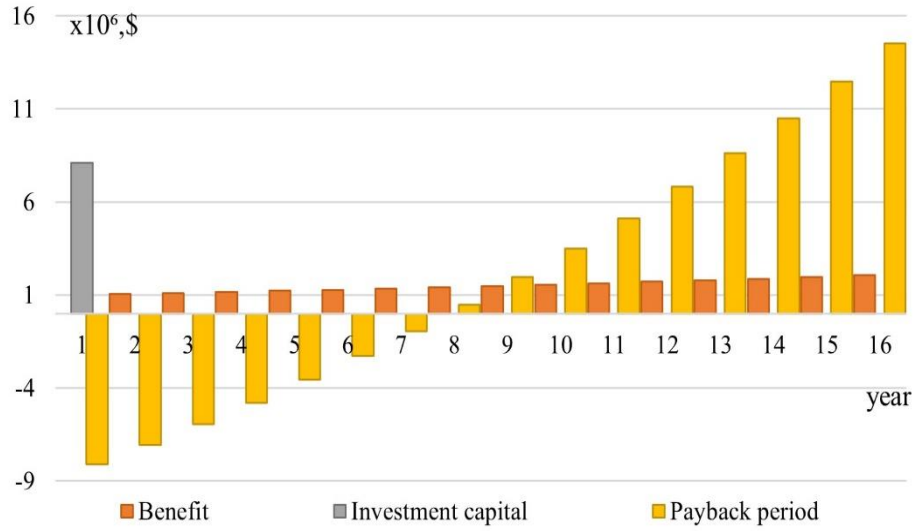


Fig. 8. Cash flow dynamics of a hybrid PV-T system project.

Despite the high initial costs, by the 16th year the project shows a significant profit, almost twice the initial investment. The economic benefit comes from replacing part of the electricity and heat purchased from centralized networks, and from lower operating costs for the building services. Thus, the deployment of hybrid PV-T installations is a well-founded solution that can accelerate the energy transition and increase the commercial attractiveness of housing and utility facilities.

CONCLUSIONS

Based on the study on the development and simulation of a hybrid PV-T system for urban housing, the following conclusions are drawn:

1. Mathematical simulation confirmed that integrating a heat exchange circuit into photovoltaic panels not only enables trigeneration of energy, but also stabilizes the operation of the semiconductor elements. Active cooling prevents thermal degradation of the panels, which increases electrical efficiency and brings the overall solar energy utilization factor up to 80% during peak periods.
2. Using refined insolation data for the 46–47° N parallels instead of averaged tabulated values improved the accuracy of generation forecasting. The calculated heat flux densities (up to 747 W/m² for south orientation) show that in a temperate climate PV-T systems can cover up to 30–40% of the annual DHW and electricity demand of a residential building.
3. The developed method for calculating electrical parameters, taking into account their temperature dependence, provided a sound basis for selecting the inverter equipment. It was found that using such systems in 0.4 kV distribution networks unloads power transformers by 20–30% during daytime hours, which slows insulation ageing and improves power quality for consumers.
4. The empirical relationship proposed for calculating the heat accumulator volume from the heat pump capacity and water consumption profiles made it possible to minimize capital costs by avoiding oversizing of auxiliary equipment.
5. The economic analysis showed that, at current tariffs and a design life cycle of 25 years, the payback period of the system is 7.67 years. This confirms the investment attractiveness of hybrid solar technologies in the housing and utilities sector as an effective tool for the energy transition and the modernization of urban infrastructure.
6. The shift to local microgeneration will significantly reduce the carbon footprint and is consistent with global energy transition trends, supporting the sustainable development of urban infrastructure.

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