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Integration of a solar power plant and a heat pump into a hot water supply system based on a digital twin

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Abstract. In the context of growing threats to Ukraine’s energy security and the need to increase the autonomy of the residential sector, the study of the effective combination of heat pumps and solar generation is highly relevant. The aim of the study was to justify the feasibility of integrating an air-to-water heat pump into the hot water supply system of an multi-apartment building equipped with a solar power plant, using a digital twin to improve energy efficiency and autonomy. The following methods were used in the study: analysis of the actual energy consumption database, energy modelling in the PV*SOL programme, instrumental monitoring of temperatures, water and electricity consumption, as well as comparison of system configuration options taking into account seasonal characteristics. A comparison of heat pump operating modes was carried out: full heating (up to 55°C) and bivalent (up to 35°C with reheating). Seasonal efficiency, coverage of needs from the solar power plant and system balancing options were calculated. As a result, it was found that the actual hot water consumption is 21.5 times lower than the standard, and more than 60% of the thermal energy is spent on circulation. Excess generation by the solar array (over 16,000 kWh/year) can be effectively used to heat water through a heat pump. In the heating mode up to 35°C, electricity consumption is reduced by 50.9% compared to the full water heating mode (up to 55°C). The study also proposed a digital twin of a hybrid solar power plant-heat pump system that adapts to changes in load and operating conditions. For the first time, a quantitative assessment of the efficiency of the bivalent mode in real-life conditions has been carried out, taking into account actual consumption. The results can be used for adaptive design of hot water supply systems in residential buildings. The proposed approach allows reducing costs, increasing autonomy, reducing the load on the network, and adapting systems to crisis conditions and changes in consumer behaviour

Keywords: autonomous heat supply; multi-apartment building; renewable energy sources; energy modelling; energy efficiency

Introduction

In the context of the full-scale military aggression against Ukraine, accompanied by regular attacks on critical energy infrastructure, the issue of ensuring the energy independence of the housing stock has acquired not only technical, but also social and national security significance. This challenge is particularly acute in multi-apartment buildings, where stable electricity supply and hot water provision are prerequisites for maintaining the basic living conditions of the population during prolonged or sudden crises.

The problem of improving the energy efficiency of multi-apartment buildings through the use of renewable energy sources is actively studied in the global scientific

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literature (Martorana *et al*., 2021). Special attention is given to the synergistic combination of photovoltaic systems (PV) and heat pumps (HP) for domestic hot water (DHW) supply, which reduces dependence on centralised energy sources and increases the resilience of the residential sector to energy challenges. The work of M. Alhuyi Nazari *et al*. (2023) highlighted the significant potential of hybrid systems that combine PV and HP to reduce fossil fuel consumption and greenhouse gas emissions. The issue of solar energy storage in the context of DHW demand was explored by A. Gagliano *et al*. (2025), who analysed the role of buffer tanks in smoothing out seasonal imbalances between generation and consumption. Research by R. Dumoulin *et al.* (2021) also confirmed the promise of seasonal storage as a strategy for enhancing the autonomy of heat generation systems, demonstrating the effectiveness of combining a heat pump with a building-integrated photovoltaic/thermal system (BIPV/T), capable of adapting to changes in electricity demand profiles and interacting with the grid for real-time energy balancing.

Within the study by C. Zhang *et al*. (2021), the efficiency of air-to-water heat pump systems integrated with PV was experimentally verified. It was shown that with appropriate configuration, the seasonal coefficient of performance (COP) can reach 4.2 even in winter, significantly improving the efficiency of renewable energy use during the heating season. Practical approaches to the design of rooftop PV systems were analysed in the report by A. Borodinecs *et al*. (2024b), which proposed a methodology for assessing the feasibility of installing solar systems considering architectural and insolation constraints, as well as financial payback criteria. In another study by A. Borodinecs *et al*. (2024a), the use of real electricity consumption data in multi-storey residential buildings was examined for optimising the calculated capacity of PV systems. The authors noted that accurate knowledge of daily consumption profiles helps to avoid excessive daytime generation and improve the balance between consumption and generation. In particular, it was proposed to take into account changes in residents' living patterns caused by social circumstances.

Special attention in the literature has also been devoted to dynamic modelling of PV-HP hybrid systems, accounting for climate parameter variations throughout the year. In the context of hybrid system development, a promising approach is the integration of photovoltaic-thermal (PVT) collectors with heat pumps, which, according to A. Miglioli *et al*. (2021), makes it possible to cover all thermal needs of a building with a high share of renewable energy, increasing the efficiency of both solar generation and heat pump equipment. In the studies by R.E. Alden *et al*. (2023) and B. Xiang *et al*. (2021), the authors emphasised the use of decision-making algorithms (such as ELECTRE) for selecting the optimal system configuration, considering climate conditions, consumer behaviour models and the local energy context. Such an interdisciplinary approach enables the consideration of not only technical but also social parameters of hybrid system operation. In the work by I. Sokolovska *et al*. (2024) it was investigated key barriers to the implementation of heat pump technologies in district heating. They also systematised European experience in technical, economic and regulatory support for the transition to low-carbon heat sources. The analysis of proposed measures – ranging from preferential tariffs to professional staff training – may be applied to shape an effective strategy for deploying heat pumps in Ukrainian multi-apartment buildings.

Thus, there was a need to study the techno-economic parameters and energy operating modes of heat pumps in combination with solar power plants to provide hot water supply under real multi-apartment building conditions. In particular, the relevant issue was the proper selection of heat pump parameters, taking into account seasonal load variations, actual consumption profiles, the type of selected water reheating scheme, and the characteristics of local generation. The aim of this study was to determine the optimal conditions for the application of a heat pump in the hot water supply system of a multi-apartment building, considering solar generation parameters, seasonal load fluctuations and real consumption profiles.

Materials and Methods

A comprehensive scientific approach was applied in this study, incorporating instrumental measurements, energy modelling, regulatory framework analysis, and digital system modelling using the PV*SOL premium (n.d.). This approach made it possible to assess the efficiency of heat pump integration under real operating conditions of a multi-apartment building. A range of scientific methods were employed, including: the analytical method – for the analysis of regulatory documentation, literature sources, and studies in the field of renewable energy; the empirical method – for collecting data on actual hot water consumption, supply and return temperatures, circulation volumes, etc.; the comparative method – for comparing normative and actual consumption indicators, as well as the efficiency of different heat pump operating modes. Mathematical modelling was also applied – to calculate thermal loads under various operating modes of the heat pump – alongside computer-based modelling carried out in PV*SOL to assess the annual PV generation, determine electricity surpluses, and evaluate their utilisation efficiency. In a previous study, M.V. Politykin & O.I. Yatsenko (2025) presented the results of PV*SOL-based modelling of a PV system for a multi-apartment building and identified seasonal surpluses of unused electricity, which could be effectively integrated into heat pump operation.

The object of the study was a typical multi-apartment building located in Kyiv, operating under conditions of district heating. The building belongs to the category of high-rise residential development and has characteristic parameters typical of the housing stock of the late 20th – early 21st century. The main technical and operational characteristics of the building are presented in Table 1.

Parameter	Value
Purpose	multi-apartment building
Number of floors	16 (+ technical floor and basement)
Number of apartments	75
Total number of residents	210
Temporarily not living there due to the war	63
Total area (m²)	9,664
Living area of the building (m²)	3,800.3
Total height of the building (m)	53

Table 1. *Parameters of a multi-apartment building*

Source: *technical passport and energy performance certificate of the building, provided by the condominium association "Poryadok Sheptytskoho, 12"*

The heating and hot water supply system of the building is centralised. Heat supply is provided through an individual heat substation (IHS) located in the basement. This configuration enables basic modernisation without the need for complete dismantling of the systems, which is an important advantage during reconstruction. A rooftop PV system with a total installed capacity of 30.6 kW has been installed. The system consists of photovoltaic panels mounted on lightweight metal structures, ensuring an optimal tilt angle: 20°-30° towards the north and up to 10° in the east-west plane. The complex is complemented by hybrid inverters, a monitoring system (Leanheat® Monitor, Danfoss), protective equipment, and electricity storage based on battery units. Additionally, data were obtained from an Apator PoWoGaz JS-130-16 cold water flow meter, installed in the building's heat substation, which measures water consumption for the DHW module. Figure 1 presented the exterior view of the residential building and the layout of a typical floor.

Figure 1. *General view of the building and floor plan of a typical floor*

Source: *technical passport and energy performance certificate of the building, provided by the condominium association "Poryadok Sheptytskoho, 12"*

At the beginning of the study, initial data on the apartment building was collected: structural characteristics, number of residents, configuration of existing engineering systems, and parameters of the installed solar power plant. Next, instrumental measurements were taken of actual hot water consumption, supply and return temperatures, circulation losses, and electricity consumption by common building systems. Based on this data, thermal loads for the hot water supply system were modelled and energy modelling of the solar power plant was performed in the PV*SOL software environment to determine annual generation volumes and seasonal surpluses. After that, the operation of the heat pump was modelled using the passport characteristics of the MGSDC-080IIC air-water unit (manufactured in China) with a thermal capacity of 25 kW. The inlet water temperature was assumed to be 5°C during the heating period and 10°C during the non-heating period. Two modes were considered: heating to 35°C (with reheating in the heat exchanger to the standard value) and heating to 55°C without an external source. To compensate for hourly imbalances, two 1 m³ hot water storage tanks were installed. The average COP values of the heat pump depending on the month are summarised in Table 2. Electricity consumption, system balancing options, and a comparison of the standard and actual scenarios were calculated. To determine the energy balance of electricity generation and consumption in the building, measurements of electricity consumption for common building needs (cold water supply pumps, heating circulation, DHW circulation, lighting, elevators – total nominal load 11.92 kW) were taken, as well as measurements of actual electricity generation from the PV station and modelling of the heat pump under real consumption conditions. The final stage was the implementation of the concept of a digital twin of the building's energy system, which allows for hourly load changes, climatic parameters, behavioural aspects of consumption to be taken into account and the system's operating modes to be adapted in real time.

Table 2. *Heat pump parameters depending on the average air temperature and hot water temperature at the heat pump outlet*

Month	Average air temperature 2024, °C	COP (heating to 35°C)	COP (heating to 55°C)
January	-2.6	2.8	2.5
February	2.9	3.5	3.0
March	4.8	3.7	3.2
April	12.8	4.9	4.0
May	16.3	5.4	4.4
June	21.5	5.9	4.7
July	24.3	5.9	4.7
August	23.1	5.9	4.7
September	20.6	5.9	4.7
October	10.9	4.6	3.8
November	2.7	3.5	3.0
December	0.0	3.1	2.7

Source: *compiled based on data from the technical passport of the heat pump and Climatic data for the city of Kyiv (n.d.)*

The assessment of DHW needs was carried out in accordance with design standards. According to DBN V.2.5-64:2012 (2013), daily water consumption in multi-apartment residential buildings with centralised hot water supply for one resident in climate zone I is 250 litres/day, of which 100 litres/day is for hot water supply. Thus: average daily consumption of hot water per resident – 100 litres/day; total daily consumption of hot water for the building – 21,000 litres/day or 21.0 m³/day; the annual volume of hot water consumed is 7,665 m³/year; the approximate annual heat consumption for heating water from 10°C to 55°C:

$$Q = 7{,}665{,}000 \cdot 4.19 \cdot 45 = 1{,}445{,}516 \text{ kJ} = 401.5 \text{ MWh/year}.$$

To cover hot water supply loads, options for installing an air-to-water heat pump with a thermal capacity of 30-50 kW were considered. The approximate average annual COP value is assumed to be 3.0. Based on the preliminary calculation of the annual heat energy demand: $Q = 401.5$ MWh, the annual electricity consumption of the heat pump is determined as:

$$E_{HP} = Q / COP = 401.5 \text{ MWh/year} / 3.0 \approx 133.8 \text{ MWh/year}.$$

The solar power plant installed on the roof of the building generates approximately 42 MWh of electricity per year. Therefore, it is theoretically possible to cover HP's energy consumption using the PV:

$$42 / 133.8 \approx 31.4\%.$$

However, it is important to consider the seasonal discrepancy between the PV generation schedule and the actual demand for heat energy for DHW. Without energy storage, the direct use of PV electricity for DHW needs does not exceed 10-15%.

Results and Discussion

In many large cities of Ukraine (Kyiv, Khmelnytskyi, Cherkasy, Lviv, Dnipro, Rivne, Poltava, Sumy, Ternopil), as of 2025, centralised hot water supply systems are still in place, but their efficiency is becoming increasingly difficult to maintain. This is due to the prolonged absence of centralised heat supply in the off-season, as well as the growing number of consumers who are abandoning centralised services in favour of individual hot water preparation using electric boilers. This transition has systemic consequences – an increase in the load on internal electrical networks, which are often not designed for peak loads, especially in the morning and evening hours of consumption (Alden *et al.*, 2023). In addition, this situation is accompanied by an increase in the budgetary burden, in particular due to the need for subsidised regulation of gas prices for the needs of the population. In these conditions, the formation of local autonomous energy supply systems is becoming increasingly relevant – solutions that can provide the residential sector with stable energy even under restrictions imposed by centralised systems. One of the empirical indicators of increased interest in decentralised energy solutions is the rapid growth in the number of purchases of solar power plants in the budget sector. According to the Prozorro system, during 2024 and early 2025, 1,113 lots were recorded relating to the design, supply or installation of PV in state, municipal and educational institutions. The total expected cost of these purchases exceeded UAH 1.1 billion, of which 403 lots were related to design work (architectural and engineering design, development of design and estimate documentation, preparation of energy solutions), which indicates structural planning for modernisation (Prozorro BI module, 2025). Figure 2 illustrated the growth dynamics of the total number of procurements in the field of PV installation in the budget sector, as well as the share of design works, which makes it possible to conclude that there is a systematic increase in the potential of decentralised generation.

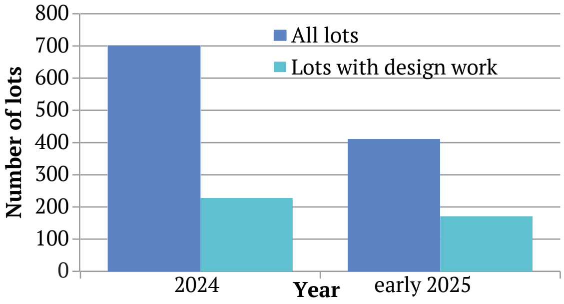


***Figure 2.** Dynamics of procurement by PV in the budgetary sector of Ukraine*
***Source:** developed by the authors based on data from the Prozorro BI module (2025)*

Another important factor stimulating the development of local energy systems is the state program for supporting residential energy efficiency – "GreenDIM". As of early 2025, within this program 188 applications have been submitted, of which 82 projects have already been implemented with full or partial grant disbursement. The total floor area of multi-apartment buildings covered by the projects exceeds 2.78 million m^2, while the number of households amounts to 31,940 (Energy Efficiency Fund of Ukraine, 2025).

The obtained results are based on the analysis of the technical characteristics of a typical multi-apartment residential building in Kyiv, equipped with a centralised heating system and a PV plant. The object of study has an architectural and operational profile typical of the modern housing stock, which allows the findings to be extrapolated to a broader residential sector. The PV plant is designed to supply electricity for common building needs: pumping equipment, lighting of common areas, and elevators. However, results of modelling conducted in PV*SOL in the previous study by M.V. Politykin & O.I. Yatsenko (2025), along with the analysis of actual 2024-2025 production and consumption data from the PV system, demonstrated the presence of a significant daytime generation surplus. In summer, up to 70% of the generated electricity remains unused, while in winter this figure is about 32%. On an annual basis, the unused surplus electricity within the building amounts to 16,529.7 kWh. Thus, it must always be taken into account that the operation of PV plants in the residential sector is characterised by strong seasonal variability, as also emphasised by A. Borodinecs *et al*. (2024a). This creates opportunities for surplus utilisation – either through the "Active Electricity Consumer" mechanism, which allows excess power to be fed into the grid, or by connecting additional loads, as highlighted by the Association of Solar Energy of Ukraine (2024). The most promising direction is the supply of an electric heat pump from the PV system, which can be integrated into the domestic hot water (DHW) system, thereby increasing both the efficiency and autonomy of the building. This approach allows for the effective use of summer surpluses and reduces electricity consumption from external grids (Gagliano *et al*., 2025). Similar conclusions were reached by F. Wang *et al*. (2024), who noted that coupling heat pumps with solar generation ensures high seasonal efficiency even in climates with moderate temperatures. In line with the present study, K. Tomczuk & P. Obstawski (2024) also identified the problem of low PV self-consumption (16.9-19.0%) due to the mismatch between generation and demand. In the current research, several technical and functional measures for system balancing were proposed: installation of DHW storage tanks with a two-day capacity (≈ 42 m^3); installation of electrical storage batteries systems (100 kWh); and optimisation of the heat pump's operational algorithms to maximise daytime operation. Comprehensive implementation of these measures allows the share of PV utilisation to be increased to 50-60%, while reducing dependence on external energy supply.

Instrumental measurements of the building's DHW system confirmed a significant deviation of actual consumption from the design values specified by DBN V.2.5-64:2012 (2013). Actual daily DHW consumption by residents amounted to approximately 1,250 L/day, corresponding to 456.2 m^3/year, which is almost 21.5 times lower than the normative daily consumption. At the same time, daily circulation water volume in the DHW system reached 108,000 L/day, or 39,420 m^3/year, which far exceeds the useful consumption by residents. This indicates low energy efficiency of the circulation loop. Particularly illustrative were the temperature profiles presented in Figure 3, showing the dynamics of supply (T3) and return (T4) water temperatures throughout the day. The average temperature difference between supply and return lines was only 0.79°C, which is an extremely low indicator. This may be attributable to oversized circulation pumps and insufficient hydraulic balancing of the system, resulting in excessive heat losses.

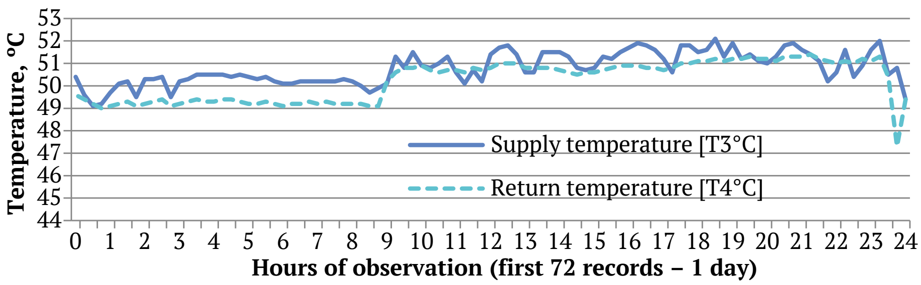


***Figure 3.** Graph showing temperature and hot water circulation over a 24-hour period*
***Source:** developed by the authors based on data from the Leanheat® Monitor (Danfoss) monitoring system*

Calculation of thermal loads on the DHW system based on measurement results allowed determining the following indicators: thermal demand for hot water heating (10 → 55°C) – 23.9 MWh/year; heat demand for maintaining circulation – 36.2 MWh/year; total heat demand of the DHW system – 60.1 MWh/year. It has been demonstrated that more than half of all heat energy consumed is used not to heat water for residents, but to maintain circulation. Additional information on the profile of actual daily consumption is shown in Figure 4, which depicts the average daily dynamics of DHW consumption in the summer period. The highest consumption occurs in the morning and evening hours, which corresponds to the typical behavioural pattern of residents.

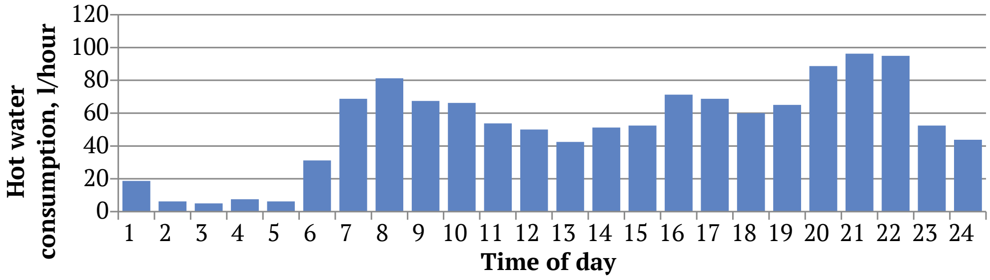


***Figure 4.** Daily hot water consumption graph (residents, without circulation)*
***Source:** developed by the authors based on data from the Apator PoWoGaz JS-130-16 cold water flow meter*

At the same time, Figure 5 illustrated a comparison of the calculated (design), actual, and adjusted heat consumption, the latter corrected according to the current number of residents. Taking into account that, as a result of the war, 63 people are temporarily absent, the actual number of residents has decreased to 147. This necessitated a revision of the energy calculations: DHW consumption – 5,365.5 m³/year; annual heat demand – 361.0 MWh; electricity consumption of the heat pump (COP = 3.0) – 120.3 MWh; share of demand covered by the PV system – increased to 35% (compared with 31.4% when the DHW demand was assessed according to design standards).

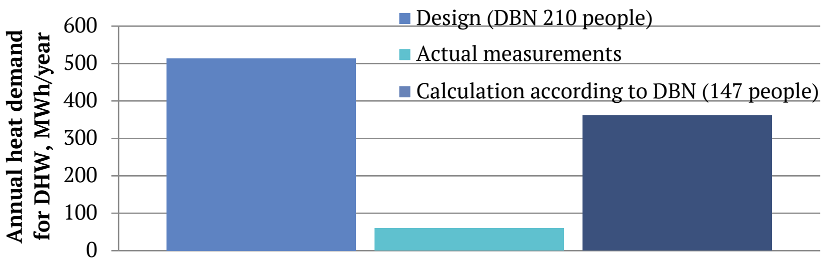


***Figure 5.** Comparison of calculated and actual heat energy requirements for domestic hot water supply in a building*
***Source:** compiled by the authors based on own calculations*

Based on these data, a comparative analysis of the balancing parameters of the hot water supply system was carried out for two scenarios – the standard scenario and the actual one. Table 3 showed the calculation results for the heat pump capacity, the volume of accumulator tanks, and the capacity of electricity accumulators for both options. In addition, the table shows the accepted parameters that were used in this study.

***Table 3.** Comparative parameters of the DHW balancing system*

Indicator	Unit of measurement	Estimate (standard consumption)	Estimate (actual consumption)	Accepted in the pilot project
Heat pump capacity	kW	45.8 kW	10.9 kW	25
Volume of the accumulator tank (2 days)	m³	42 m³	2.50	2
Capacity of the electricity accumulator (2 days)	kWh	100 kWh	43.6	75

***Source:** compiled by the authors based on own calculations*

The results obtained confirmed the feasibility of a flexible approach to the design of the domestic hot water (DHW) system based on actual monitoring data. With the help of an adaptive configuration of the elements of a hybrid energy complex, it is possible to significantly reduce the initial costs of equipment and increase the level of autonomy through the optimal use of existing PV generation. In addition, this approach ensures the stability of the temperature regime of consumption and allows for a quick response to changes in weather conditions or user behaviour, which is especially important for improving energy efficiency in decentralised heat supply conditions.

According to the modelling results obtained in PV*SOL premium (n.d.) and presented in the earlier study by M.V. Politykin & O.I. Yatsenko (2025), on a typical summer day around 70% of the electricity generated by the solar array remains unused, while in winter this figure is about 32%. In annual terms, 16,529.7 kWh of electricity produced by the PV system was not consumed within the building. This creates additional opportunities for its effective utilisation, in particular by directing part of the surplus generation to power the heat pump for DHW heating. The COP values obtained, as summarised in Table 2, served as the basis for calculating the building's energy balance. This enabled the determination of electricity consumption volumes and coverage for DHW demand through the integration of the existing solar generation. Based on this modelling, the energy balance presented in Table 4 was developed.

Table 4. *Electricity consumption and generation indicators for a residential building with a PV and heat pump*

Month	Total electricity consumption without HP (kWh)	Total electricity generation by PV (kWh)	Electricity consumption by HP (water heating to +35°C) (kWh)	Electricity consumption by HP (water heating to +55°C) (kWh)	Unused generation (kWh)
January	4,577.9	825.5	161.2	242.3	220.8
February	3,880.4	1,320	145.4	218.5	507.9
March	3,979.2	2,318.2	162.4	243.9	1,048.1
April	1,635.8	2,829.5	135.7	205.2	2,079.2
May	1,690.3	3,421.8	123.2	186.4	2,512.4
June	1,431.3	3,285.8	109.6	165.8	2,471.2
July	2,183.3	3,316.3	111.1	167.9	2,160.5
August	1,619.9	3,146.2	116.2	175.6	2,328.7
September	1,601.7	2,462	121.5	183.7	1,690.4
October	2,570.7	1,821.3	133.8	202.4	1,050.3
November	4,293.9	796.3	146.8	222	257.7
December	5,035.7	525.2	157.4	237.9	116.1
Per year	34,500.1	26,068.1	1,624.3	2,451.6	16,443.3

Note: *total electricity consumption without HP – measurement data; all other data – simulation data*
Source: *compiled by the authors of the study*

As a result of the analysis of Table 4, the annual electricity consumption of the heat pump decreased by 50.9%: from 2,451.6 kWh when heating fully to 55°C, to 1,624.3 kWh in the scenario of partial heating to 35°C. This approach allows for a more rational utilisation of solar generation under its constrained profile. However, the electricity savings were accompanied by an increased demand for thermal energy from external sources to reheat the water from 35°C to the normative level, which complicates a straightforward assessment of the scheme's overall effectiveness. The application of a bivalent heating scheme, whereby the heat pump performs the primary heating only up to 35°C and the final reheating to the normative 55°C is provided by an external thermal energy source (e.g. a district heating network), enables an average increase of 20% in the seasonal coefficient of performance (COP) of the heat pump over the year compared with the full heating mode to 55°C (Fig. 6). This effect is due to the reduced temperature lift at which the heat pump operates, which significantly improves its energy efficiency.

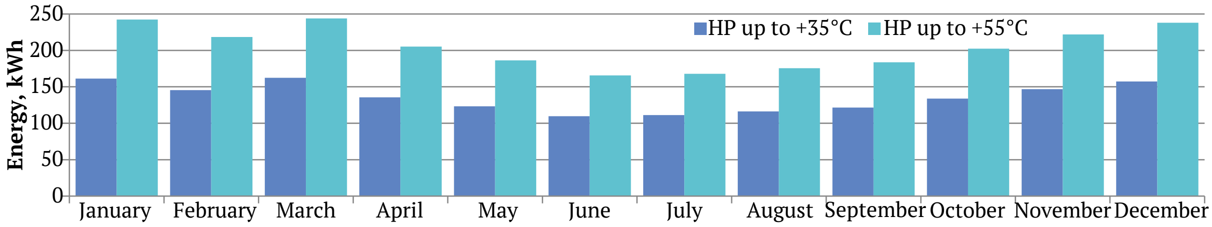
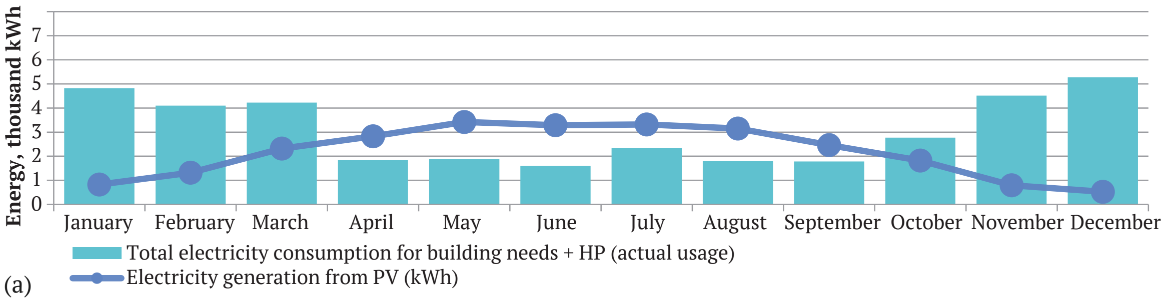


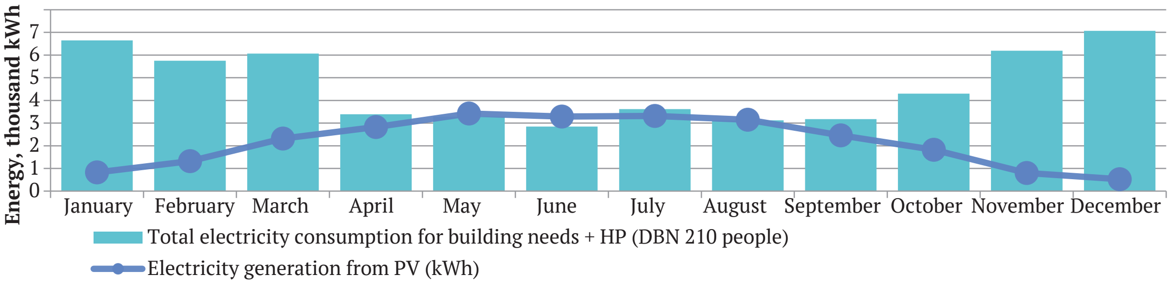
Figure 6. *Monthly energy consumption per heat pump at water heating temperatures of 35°C and 55°C*
Source: *compiled by the authors of the study*

Under standard regulatory conditions, the choice between monovalent and bivalent schemes is typically made on the basis of a techno-economic assessment. However, under the current conditions of martial law in Ukraine, the state's policy of subsidised heat tariffs for households, and the sharp rise in electricity costs driven by increased imports, capacity shortages and the expenses associated with restoring the energy infrastructure, conducting a full techno-economic comparison becomes considerably more challenging. In this context, integrated digital models are increasingly being applied to decision-making, as they enable real-time adjustment of input parameters (tariffs, consumption schedules, source capacities) and allow scenario forecasting that accounts for external factors. This approach was implemented in the present study.

Figure 7 presented a month-by-month comparison of electricity generation from the solar power plant and the total electricity consumption of the residential building, taking into account the operation of the heat pump in reheating mode up to 55°C. As shown in Figure 7a, between April and September a surplus of solar generation was observed: the monthly electricity output exceeded the system's requirements both for common-use building needs and for domestic hot water supply. This creates opportunities for the autonomous operation of the building's energy system during the warmer months, covering hot water demand entirely with solar energy without reliance on the district heating network. By contrast, in the autumn-winter period (October-March), the balance shifted: electricity consumption exceeded PV output, necessitating additional supply sources.



Graph (a)



Graph (b)

***Figure 7.** Comparison of electricity generation and consumption by a residential building, taking into account the installation of a heat pump*

***Note:** a – 25 kW and actual hot water consumption; b – 50 kW and estimated hot water consumption according to DBN V.2.5-64:2012 (2013)*

***Source:** compiled by the authors of the study*

A comparison of actual hot water consumption by residents (Fig. 7a) with the calculated standard consumption according to DBN V.2.5-64:2012 (2013) for 210 people (Fig. 7b) showed fundamental differences in the ratio of PV generation and total electricity consumption. The building's real energy consumption, when adjusted for the observed DHW profile and actual occupancy, is significantly lower than the regulatory estimate. This enables a more effective integration of the PV system into the energy supply, achieving a higher share of autonomous coverage, reducing the need for storage, and lowering peak loads. Given the large number of variables and their interaction over time, the optimal approach is to use a digital twin of the building's energy system. Such a digital twin allows not only to simulate the operation of the heat pump, taking into account climatic and behavioural data, but also to perform adaptive optimisation of operating modes in real time.

A schematic diagram of the energy complex with a solar power plant and a heat pump in a bivalent scheme is shown in Figure 8. It includes interaction between power sources (PV, Energy storage, power grid), thermal energy storage devices, heat exchangers and a heat pump that can operate in both mono- and bivalent modes. It also provides for the possibility of automated control of pumps, switches, heat exchangers and energy management modules.

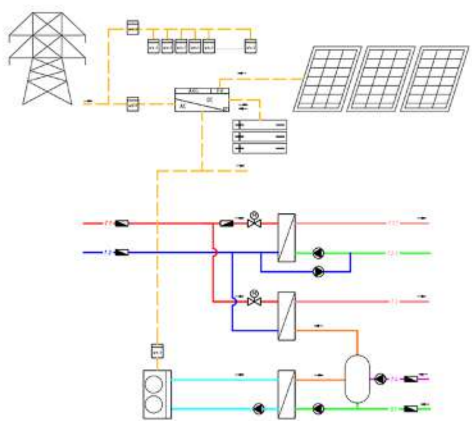


***Figure 8.** Schematic diagram of an energy complex with a solar power plant and a heat pump*

***Source:** compiled by the authors of the study*

For the verification of the digital twin, detailed monitoring of the system parameters is planned. A complete list of key parameters is presented in Table 5, which specifies both physical quantities (energy consumption, temperatures, water volumes) and the frequency of their collection. Particular attention is given to temperature control (T1-T4), PV generation, own consumption, the operation of the heat pump (EHP), as well as individual apartment-level electricity consumption by residents (Eap1…75), which is a key factor for the development of accurate models.

Table 5. *Monitoring parameters for digital twin verification*

Parameter	Designation	Unit	Monitoring period
Total heat energy consumption of the building	Qtotal	Gcal	2 min
Heat energy consumption for heating	Qheat	Gcal	2 min
Heat energy consumption for DHW with circulation	Qdhw	Gcal	2 min (Qgen-Qheat)
Outdoor air temperature	Tout	°C	2 min
Supply temperature from heat network	T1	°C	2 min
Return temperature to heat network	T2	°C	2 min
Supply temperature to DHW	T3	°C	2 min
Return temperature from DHW circulation	T4	°C	2 min
Cold water consumption for DHW	Vmin	m^3/year	2 min
Circulation water consumption	Vcirc	L/hour	2 min
PV generation	Gpv	kWh	1 min
Own PV consumption	Gconsu	kWh	1 min
Heat pump electricity consumption	EHP	kWh	1 min
Apartment-level electricity consumption	Eap1..75	kWh	1 month
Indoor air temperature	Tap1..75	°C	1 hour (sampled flats)

Source: *compiled by the authors of the study*

According to M. Bezrodnyi *et al*. (2017), the combined use of atmospheric air heat and solar energy in heat pump systems can significantly increase the efficiency of heat pumps during the cold season. This was confirmed by the results of the author's research. However, unlike the work of M. Bezrodnyi *et al*., which focused on increasing the air temperature in front of the evaporator using solar collectors, the current study demonstrated the possibility of effectively using excess solar generation to power the heat pump, which is particularly relevant in conditions of energy resource shortages. Unlike the studies by A. Borodinecs *et al*. (2024a), which analysed the potential of rooftop PV for communities under standard operating conditions, this study found significant deviations in actual hot water consumption from standard values (21.5 times lower), which highlighted the need for an adaptive approach to the design of hybrid systems. Although A. Borodinecs *et al*. emphasised the importance of analysing real electricity consumption data to optimise the capacity of PV (covering up to 77% of needs), the authors' results expanded this approach, demonstrating the key role of circulation losses (over 60%), the efficiency of the bivalent mode of the heat pump (50.9% reduction in electricity consumption), and the advantages of digital twins over static models (as in PolySun by A. Borodinecs *et al*.).

Research by F. Wang *et al*. (2024) on hybrid systems demonstrated an increase in COP to 3.92 (+18.7% compared to traditional systems) and a reduction in energy costs. These results are consistent with the findings of the current study on the effectiveness of integrating PV and heat pumps, especially in conditions of unstable solar radiation. In addition, M. Zohri *et al*. (2024) summarised the efficiency of hybrid systems based on collectors, PV and PVT, emphasising the importance of multi-source power supply and mathematical modelling for predicting their performance. However, unlike the proposed approach with parameter optimisation (PVT area, tank volume, etc.), the authors' solution with a digital twin allows the system to be dynamically adapted to real conditions without being rigidly tied to fixed geometric parameters.

The results of the study by Y. Lin *et al*. (2022) showed that research on SAHP (solar-assisted heat pump) systems is intensifying in China, with an emphasis on the efficiency of key components (evaporators, heat exchangers, compressors), but there is a lack of attention to intelligent control algorithms and economic feasibility, taking into account regional climatic characteristics. This study partially addressed these challenges, as the digital twin model took into account both climatic and behavioural consumption factors, as well as scenarios for bivalent heat pump control to improve energy efficiency. These conclusions were consistent with the author's approach to adaptive design and the use of a digital twin, which allows real operating conditions to be taken into account.

J. Uche *et al*. (2024) emphasised the high efficiency of RES-based polygeneration systems designed for multi-apartment buildings. The authors proposed strategies for an optimal energy mix, taking into account local needs and the architecture of the residential sector. The current study confirmed the relevance of such approaches in the context of Ukrainian realities, in particular the need to adapt the hot water supply system to the actual load, seasonal fluctuations and consumption patterns. In this context, it is worth mentioning the model of intelligent decision support for the modernisation of the housing stock proposed by S. Maliar (2024), which provides a comprehensive assessment of economic, technical and operational factors when selecting an effective configuration of energy solutions.

In addition, a study by R. Galvin (2022) highlighted the problem of households in Germany being unwilling to install PV systems that significantly exceed their own consumption due to a lack of economic motivation. The author suggested considering PV systems in combination with heat pumps as a single integrated complex, which allows increasing the share of self-consumption and reducing the payback period. R. Galvin also emphasised the importance of optimal PV system power calculation, taking into account behavioural factors, load profile and energy storage system potential. These conclusions are consistent with the approach implemented in this work, which emphasised the need for accurate modelling and personalised selection of equipment configuration.

Thus, the results obtained indicate the technical and economic feasibility of installing a heat pump in the hot water supply system of an apartment building with a solar power plant. Analysis of system operation scenarios at different times of the year demonstrated significant potential for increasing the autonomy of the building and reducing the load on centralised networks. An important part of the study was the creation of a digital twin of the energy system, which made it possible to take into account variable climatic, behavioural and technical factors when modelling the operation of the equipment. This approach ensures high accuracy of analysis and creates a basis for the development of adaptive control strategies.

Conclusions

This study carried out a comprehensive energy modelling of the domestic hot water (DHW) system for a typical multi-apartment building, taking into account the existing PV installation and the integration of an air-to-water heat pump. A distinctive feature of the approach was the use of both real monitoring data (temperature profiles, hot water consumption volumes, circulation losses) and simulation results obtained with the PV*SOL software environment, considering the climatic conditions of Kyiv. Actual hot water consumption by residents turned out to be significantly lower than the normative design values. This deviation is explained not only by the reduction in the number of residents due to the war, but also by changes in household habits (the replacement of baths with showers, the use of washing machines and dishwashers with autonomous heating, etc.). Such changes necessitate a revision of approaches to the design and justification of loads in DHW systems. The circulation component of the DHW system remained the main source of heat losses, even under conditions of a very small temperature difference between supply and return (0.79°C). This indicated the excessive capacity of circulation pumps and highlights the need to revise control algorithms and hydraulic balancing during the reconstruction of utility networks. The use of the heat pump in bivalent mode, with preliminary water heating to 35°C, makes it possible to increase the average monthly COP to 4.8 during the summer period and reduce annual electricity consumption by more than 50% compared with the scenario of full electric heating to 55°C. At the same time, part of the total thermal load is transferred to the district heating network, which is particularly relevant in the context of high electricity tariffs.

Solar electricity generation exceeds the building's demand for 6-7 months of the year, as confirmed both by PV*SOL modelling results and by analysis of actual measurements. The total unused potential of PV generation per year amounts to more than 16,000 kWh, which creates preconditions for the effective use of excess energy in the heating system through the heat pump and storage. The mathematical model developed on the basis of real data enabled the implementation of the digital twin concept of the building's energy system. Such a twin allows: modelling equipment operating modes depending on weather conditions and load profiles; optimising the choice of heat pump capacity, buffer tank volume and electricity storage; forecasting scenarios of autonomous building operation under conditions of critical shortages of centralised resources. Future research prospects include dynamic modelling of the system with hourly variability, optimisation of control algorithms, integration of real monitoring data, and evaluation of the economic feasibility of implementing hybrid system elements under conditions of unstable tariff policies.

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Conflict of Interest

None.

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Інтеграція сонячної електростанції та теплового насоса в систему гарячого водопостачання на основі цифрового двійника

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Анотація. В умовах зростання загроз енергетичній безпеці України та необхідності підвищення автономності житлового сектору, дослідження ефективного поєднання теплових насосів та сонячної генерації є вкрай актуальним. Метою дослідження було обґрунтування доцільності інтеграції теплового насоса типу «повітря-вода» у систему гарячого водопостачання багатоквартирного будинку, оснащеного сонячною електростанцією, з використанням цифрового двійника задля підвищення енергоефективності та автономності. У дослідженні застосовано наступні методи: аналіз фактичної бази енергоспоживання, енергетичне моделювання в програмі PV*SOL, інструментальний моніторинг температур, витрат води й електроенергії, а також порівняння варіантів конфігурації систем з урахуванням сезонних особливостей. Проведено порівняння режимів роботи теплового насоса: повного нагріву (до 55 °C) і бівалентного (до 35 °C з догрівом). Розраховано сезонну ефективність, покриття потреб від сонячної електростанції та варіанти балансування системи. В результаті встановлено, що фактичне споживання гарячої води у 21,5 раза нижче нормативного, а понад 60 % теплової енергії витрачається на циркуляцію. Надлишкова генерація сонячним масивом (понад 16 000 кВт·год/рік) може бути ефективно використана для нагріву води через тепловий насос. У режимі нагріву до 35 °C електроспоживання знижується на 50,9 % порівняно з режимом повного нагріву води (до 55 °C). Також, в роботі запропоновано цифровий двійник гібридної системи сонячна електростанція-тепловий насос, що адаптується до змін навантаження та умов роботи. Вперше проведено кількісну оцінку ефективності бівалентного режиму в умовах реального будинку з урахуванням фактичного споживання. Результати можуть бути використані для адаптивного проєктування систем гарячого водопостачання у житлових будинках. Запропонований підхід дозволяє знизити витрати, підвищити автономність, зменшити навантаження на мережу й адаптувати системи до кризових умов і змін у поведінці споживачів

Ключові слова: автономне теплозабезпечення; багатоквартирний будинок; відновлювальні джерела енергії; енергетичне моделювання; енергоефективність