UDC 620.91:621.31
DOI: 10.15587/1729-4061.2025.342027

IMPROVING THE MODEL OF A SYSTEM THAT MAINTAINS A MICROCLIMATE REGIME IN A SINGLE-FAMILY HOUSE BY USING A REVERSIBLE HEAT PUMP

Oleksandr Shavolkin
Doctor of Technical Sciences, Professor*
Iryna Shvedchykova
Corresponding author
Doctor of Technical Sciences, Professor*
E-mail: shvedchykova.io@knutd.edu.ua
Oleksandr Demianchuk
PhD Student*
Oleg Shcherbakov
PhD Student*
*Department of Computer Engineering and Electromechanics
Kyiv National University of Technologies and Design
Mala Shyianovska str., 2, Kyiv, Ukraine, 01011

This study mathematically models energy processes within the microclimate control system in a single-family house equipped with a reversible heat pump.

This paper reports an improved model of the microclimate system considering the dynamics to construct plots of electricity consumption under various operating conditions. Data from the calculated thermal parameters of the building were applied. A model of the reversible heat pump has been proposed, based on manufacturer specifications, allowing for the assessment of electricity consumption across the full range of power and temperature variations.

The microclimate system model of the building with a heat pump has been improved by accounting for the building's thermal inertia. This makes it possible to evaluate temperature regimes and energy consumption under dynamic modes, bringing the simulated electricity usage closer to real-world values.

Hourly profiles of solar radiation and outdoor temperature for the building's location, along with expected schedules of internal heat gains, were used. Energy consumption and instantaneous power values, including peak loads, were assessed. It is shown that, for a building in Kyiv with a floor area of 120 m², ***under a heating mode, minimum electricity consumption occurs at a minimum heat carrier temperature of 35°C at a COP of 3.44.***

The selected heat pump may operate under a monovalent mode down to –13°C. The potential for reducing energy consumption by adjusting the temperature regime is limited because of a significant increase in power demand from the heat pump under a dynamic mode.

Under a cooling mode, hourly air temperature profiles from historical data were used, along with representative values, to evaluate the range of energy consumption variation. An example involving changes in window area demonstrates the model's applicability for adjusting building parameters to reduce energy consumption

Keywords: heat pump, energy saving, building's thermal state, thermal inertia, energy storage device

Received 31.07.2025
Received in revised form 03.10.2025
Accepted 13.10.2025
Published 30.10.2025

How to Cite: *Shavolkin, O., Shvedchykova, I., Demianchuk, O., Shcherbakov, O. (2025). Improving the model of a system that maintains a microclimate regime in a single-family house by using a reversible heat pump. Eastern-European Journal of Enterprise Technologies, 5 (8 (137)), 38–47. https://doi.org/10.15587/1729-4061.2025.342027*

1. Introduction

On average, the largest share (65%) of energy consumption in residential buildings accounts for internal heating, and another 15% is used for domestic water heating [1]. Therefore, the current trend in global practice is the use of heat pumps (HPs) to reduce electricity consumption (EC) and environmental impact. Over the past few years, HP technology has been very successful in the EU market by increasing energy efficiency, reducing greenhouse gas emissions, and promoting renewable energy sources (RESs). HPs are considered to be devices that can significantly reduce energy consumption in buildings, both for heating and cooling. HPs also play a key role in balancing the heat load [2].

In the energy supply system at single-family houses, the use of HPs in combination with RES has become widespread. The general approach to the use of RES to meet one's own needs is also changing. Resolving this issue is related to the joint use of RES with HPs to reduce consumption to enable a microclimate inside the house. The cost of electricity to maintain the microclimate in the house, even when using a HP, is quite significant both in winter and summer. Thus, the task of correctly selecting the parameters for RES and HP, taking into account the energy processes in a single-family house, including EC costs, and management capabilities to reduce costs, is relevant.

2. Literature review and problem statement

Different types of heat pumps are used for single-family houses. In [3], economic and environmental results from using a geothermal heat pump, combined with photovoltaic panels, are reported. The heat load on the building, associated with heat losses through external partitions and gravitational ventilation, was calculated in accordance with the PN-EN 12831 standard. However, only the overall performance of the heat pump when used for heating was assessed.

In [4], the application and comparison of air and ground source heat pumps with calculation of the coefficient of efficiency *COP* are considered. It is noted that a ground source heat pump (GSHP) would not always be more efficient than an air source heat pump (ASHP). However, only use for heating was considered.

In [5], six different heating system configurations were studied for five locations of a single-family house in Canada. In addition to gas heating, electric heating options using heat pumps and electric baseboards were assessed. In particular, the options for heat pumps operating on air and ground, as well as with a mini-split system without air ducts, are considered. It is shown that the type of heating system affects the optimal design of the house. This emphasizes the importance of taking into account the thermal parameters of the house when designing the system; however, only general characteristics of different models are provided without their description with an estimate of electricity consumption per year or month.

Calculation of energy consumption of a house according to the DSTU 9190:2022 standard "Energy efficiency of buildings. Method for calculating energy consumption during heating, cooling, ventilation, lighting, and hot water supply" makes it possible to obtain values per month for the heating season and for cooling, based on average indicators. When choosing HP parameters, calculation by average values is not sufficient, current maximum values are required. In addition, when converting thermal power P_h to consumed electric power P, average values of HP efficiency coefficients $COP = P_h / P$ (heating) and *EER* (for cooling) are used. However, analysis of HP characteristics of the AERO ILM type [6] reveals that at the same temperature the power can change by a factor of 3 or more, and *COP* (*EER*) by a factor of 1.5 or more. This introduces a significant error into the results.

One of the options for improving the efficiency of systems with HPs is the use of storage tanks – thermal energy storages (TES). The advantage of systems using HP together with a thermal energy storage is noted in work [7]. This concerns the increase in productivity and efficiency of the installation compared to the option without an accumulator. The Type 88 building model in TRNSYS was used, which makes it possible to model a simplified single-zone building taking into account internal heat. The model does not take into account heat input from the sun.

TES is also an element of the hot water supply (HWS) system. At the same time, in the processes of energy redistribution in the system, TES plays the same role as the battery, and the energy intensity of TES can be significantly higher. In particular, this concerns the possibility of consuming excess photovoltaic energy (PV). In work [8], the possibility of increasing PV consumption is shown using the example of a school. The use of TES led to an average annual increase of 26% of own electricity consumption generated by a photovoltaic system (PVS). But the considered use of TES was effective only when the generation of PV is high.

In work [9], a PV option for a residential household in Poland without a battery but using TES with a capacity of 300 liters is considered. According to annual operation data, depending on the load schedule, the level of PV consumption per year in the absence of TES is from 27% to 38%. The use of ASHP leads to an increase in monthly self-consumption values from 7% to 18%, and annual values – up to 13%. TES provides maintenance of the tank temperature up to 55°C and is used during the day. The increase in consumption is associated with the use of TES but there is no justification for the choice of the tank volume.

At the same time, systems with TES have significant heat losses, which leads to an increase in EC. The requirements for thermal insulation of accumulator tanks in the EU are quite strict. Heat losses are also regulated by the national standard DSTU EN 12897:2022. "Water supply. Technical conditions for non-vented (closed) storage water heaters with indirect heating (EN 12897:2016+A1:2020, IDT)".

Energy losses are determined by the temperature regime in TES. This also applies to HP, the consumption and power of which significantly depend on the temperature of heat carrier *w*. For example, for TES with a volume of 500 liters with thermal insulation class C at a water temperature of 40°C, the losses are 10–11%. To reduce losses, the storage temperature should be reduced, but this simultaneously reduces the useful energy intensity. The dependence of the power and consumption of HT on the temperature of heat carrier *w* can be illustrated by the passport data of a reversible air-source heat pump of the NIBE F2120-8 (PL) type [10]: when *w* decreases from 50°C to 35°C, *COP* increases from 2.8 to 4.5. Therefore, the question arises of jointly optimizing the temperature in TES and the operating modes of HP.

The water temperature comfortable for consumption in the HWS system is 37–38°C. In the heating season, the temperature of the heat carrier and, accordingly, the water in TES ranges from 35°C to 60°C. At 35°C, additional heating is required – an auxiliary boiler. In addition, direct water withdrawal from TES leads to fluctuations – a decrease in temperature. That is, additional refinement of the structure of HWS system is required.

The issue of analyzing and studying energy consumption in heating systems is associated with mathematical modeling in a number of works. In [11], mathematical models for a boiler and a heat pump are given. To a greater extent, these models are intended for optimizing hot water preparation modes. Losses in the boiler are given on average in kWh/day without taking into account temperature. A similar model for an electric boiler is considered in [12] for the analysis of energy processes in a system with a photovoltaic power plant. Heat losses in the boiler are not taken into account. Energy costs for cooling a house are indirectly given in a range of values, without reference to specific conditions.

The model of an air-conditioned room using MATLAB is built in [13]. A similar version of a simplified thermal model of a house with heating included is considered in [14]. Only the transmission heat input to the house, caused by the temperature difference outside and inside the house, is taken into account. Heat input from solar radiation and internal sources is not taken into account. The temperature in the house is calculated taking into account only the mass and heat capacity of the air in the room. At the same time, the thermal inertia of the house itself is not taken into account, which significantly distorts the picture of temperature changes over time and, accordingly, energy consumption in dynamics. This leads to a calculation error. A similar version is implemented in the MATLAB/Simulink reference project [15], the purpose of which is only to illustrate the principles of heat exchange and does not contain components of electricity consumption.

An interesting mathematical MATLAB model of a house heat supply system with a reversible HP is given in [16]. The HP model is detailed and intended for studying the internal processes of the pump itself without reference to the energy balance of the house.

Obtaining a reliable pattern of thermal processes in buildings is important for the implementation of energy-efficient projects and the modernization of existing ones. Work [17] reflects the progress of thermal models used to estimate internal temperatures in residential premises, in particular the construction of "white" and "gray" box models. In this case, "gray" box models combine experimental data with analytical methods to provide accurate and predictable results.

An interesting approach to modeling, which takes into account the distribution of carbon dioxide (CO_2) at office premises through human respiration, is described in [18]. A heating system using ventilation with regulated demand is considered. However, heat input from solar radiation is not taken into account.

In [19] it is noted that the analysis of solar radiation falling on the building envelope is important. When determining the model parameters, the design and properties of the materials of the external walls of the building are taken into account. It is argued that simplification is possible using heat network models that use thermal resistance of materials and capacity. But even with the simplifications considered, the application of the model is difficult.

At the same time, accurate accounting of all heat inputs and heat losses without taking into account thermal inertia makes it possible under static modes (while maintaining the temperature in the house) to obtain sufficient data for the selection of HP. When calculating energy consumption under dynamic modes when regulating the temperature and under a cooling mode, it is necessary to take into account inertia with the determination of the time interval when cooling is carried out. A realistic approach to the analysis of thermal processes is provided by DSTU 9190:2022 with the introduction of a time constant that characterizes the thermal inertia of the conditioned zone. The approach taking into account the design of the external walls of the building is the same as in [19], with the difference that the standard normalizes the value of the internal heat capacity for 5 classes of building design. DSTU provides a normalized indicator without determining its application for the mathematical model.

At the level of technical implementation, much attention is paid to thermodynamic improvements. For example, in [20], a scheme with steam injection is proposed, which increases the efficiency of ASHP at low temperatures – a critical advantage in cold climates. However, the solution concerns the hardware improvement of HP during heating.

Thermal models of the building become an element of the control system and can complement the management of the energy consumption of the house according to the forecast. In [21], an energy management method is proposed for a smart house, which includes an implicit model of thermal dynamics. The basis is adversarial feedback learning with reinforcement (AIRL). However, the model is not available in explicit form, which complicates its use in design.

In [22] a method of Model Predictive Control (MPC) is reported to determine the required power consumption to optimize thermal comfort in residential buildings with PV and HP. Only heating is considered.

Our review of the literature [3–22] demonstrates that most available publications study the technical and economic indicators and environmental impact of electric power systems with HPs for single-family houses. The use of HP in conjunction with RES and heat accumulators to increase the efficiency of the systems is considered. When choosing parameters, the calculation is carried out using average values, and the heat consumption by the house during the modeling of thermal processes is taken into account in a simplified or indirect way, in particular, this concerns the thermal inertia of the building. The issue of modeling the energy consumption of a family house with a reversible HP with the determination of the current schedule of EC consumption in time according to climatic conditions has not been studied in detail. In this case, the calculations of the thermal parameters of the house must take into account all components of heat losses and heat inflows outside and inside the house according to changes in climatic conditions over time. It is also necessary to take into account the characteristics of a specific HP when calculating electricity consumption and the thermal inertia of the building to clarify the calculation under dynamic modes.

All this allows us to assert that the issue of improving the general model of the energy supply system for family homes with RES and HPs requires additional research and generalization.

3. The aim and objectives of the study

The purpose of our study is to improve the thermal model of the microclimate system in a single-family house with a reversible HP providing an increase in the degree of reliability of electricity consumption schedules over time. This will make it possible to use the model when designing structures and energy management systems for single-family houses with RES and HP to reduce energy costs.

To achieve this aim, the following objectives were accomplished:

– to calculate the thermal parameters of the house in accordance with modern energy saving requirements, taking into account all components of heat losses and heat gains outside and inside the house, including the provision of hot water;

– to build an HP model according to the manufacturer's characteristics under heating and cooling modes to estimate current electricity consumption across the entire range of its thermal power;

– to construct a thermal model of a house with a heat pump, taking into account the thermal inertia of the building with an assessment of the temperature regime and electricity consumption under the daily mode under different weather conditions;

– to perform modeling with an assessment of the temperature regime and energy consumption in the heating season and summer for static and dynamic modes.

4. The study materials and methods

The object of our study is energy processes for maintaining the microclimate and providing a hot water supply in a single-family house using a reversible heat pump. The subject of the study is the daily schedule of electricity consumption by the microclimate maintenance system in the house.

The main hypothesis of the study assumes that taking into account the thermal inertia of the house could make it possible to improve the adequacy in calculating energy costs taking into account the dynamics. In particular, this can be done for the cooling mode when the HP is turned on only at certain time intervals in accordance with temperature fluctuations in the room and outside.

When assuming a close value of the average temperature in the rooms, heat transfer through internal partitions was not taken into account. It was believed that this does not affect the overall energy balance.

A modern adjustable inverter HP is considered, assuming that at a constant temperature regime, the efficiency coefficient *COP* (*EER*) changes proportionally to its thermal power.

Warm water consumption is simplified with a distribution into three volumes: morning, afternoon, and evening.

The work considers an average single-story residential building with an area of 120 m^2 (dimensions 8 m × 15 m, floor height 2.8 m), located in the Kyiv oblast, II climatic zone (DSTU-N B V.1.1-27:2010. "Protection against dangerous geological processes, harmful operational influences, and fire. Building climatology"). The building is oriented with a long facade to the south and is operated under the mode of permanent residence of a family of four. The enclosing structures of the house under consideration are selected in such a way that the given heat transfer coefficients *U* meet or exceed the minimum regulatory values.

The calculation of the thermal parameters of the house is performed in accordance with the current energy saving standards of the EU and Ukraine. At the same time, heat inflows and losses were taken into account, including internal ones. Internal heat inflows of the house are set according to the expected values in time. Heat losses in the hot heating system are taken into account in accordance with the ES standard for thermal insulation. Mathematical modeling was also used to analyze and calculate temperature regimes in the hot water supply system. A structure with a storage tank at a water temperature equal to the HP heat carrier temperature of 35°C and a small electric boiler for further heating to ensure a comfortable water temperature is justified for the heating period. This will help reduce electricity costs for heating.

The HP model with calculation of the consumed electrical power based on the required value of thermal power is built in accordance with the manufacturer's specifications.

To take into account the thermal inertia of the house, the value of the internal heat capacity of the building is used, which is determined by the class according to the design of the external fence of the house in accordance with the standard. The calculation of temperature regimes is based on the use of the first law of thermodynamics. The general model of thermal processes in the room is built in a daily cycle, taking into account the current values of the power of heat losses and heat gains depending on external conditions.

The dependences of temperature outside the house and the intensity of solar radiation are given by hourly plots representative of the location of the house. These plots are standardized. To assess the limit cooling modes, temperature plots according to archive data were used.

The use of an inverter HP with an appropriate regulator is considered, and when maintaining a constant temperature in the room, the thermal power of the HP is equal to the value of the power of heat losses. At the same time, under a heating mode, the temperature in the room is maintained at a given value. Switching to the bivalent heating mode using an additional electric heater (EH) is carried out when the temperature decreases relative to the set one, and the EH is turned off when the temperature increases. Under a cooling mode, the HP is turned on when the set temperature in the house is exceeded and turned off when the temperature drops.

Our simulation considered static modes when maintaining the set temperature in the house and dynamic modes when changing and regulating the temperature. When regulating the temperature according to the task, the dynamic components of HP power were taken into account when limiting the maximum power.

5. Results of research on improving the model of the microclimate system of a single-family house

5. 1. Thermal parameters of the house in accordance with modern energy saving requirements

We propose a model that makes it possible to refine structural parameters to achieve target electricity consumption indicators and coordinate the choice of the power of a reversible HP. The structure of the microclimate system of a house with a reversible HP is typical when using a warm floor for heating and fan convectors for cooling. The heating and cooling circuits are separated. The heating circuit uses a tank – TES with water heating in the HWS system using HP.

The selection of TES capacity V_V is carried out taking into account the consumption of hot water. For a family of 4 people, a tank with a volume of $V_V = 160$ liters is sufficient. In the European Union, the use of thermal insulation of not lower than class C is allowed (DSTU 9191:2022. "Thermal insulation of buildings. Method for selecting thermal insulation material for building insulation"). This limits the heat loss power P_L to $12 + 5.93V^{0.4} \leq P_L < 16.66 + 8.33V^{0.4}$, for class *B* $8.5 + 4.25V^{0.4} \leq P_L < 12 + 5.93V^{0.4}$. Heat transfer coefficient of the tank to the outside

$$H_L = P_L / \Delta\tau = P_L / \left(\tau^*_{vin} - \tau^*_{vout}\right), \quad (1)$$

where $\tau^*_{vin} = 65°C$ – water temperature in the tank (given); $\tau^*_{vout} = 20°C$ – outside temperature (given).

For class *C* $P_L = 70$ W, then $H_L = 70/45 = 1.55$ W/°C and energy losses per day at a water temperature in the tank of 35°C and the temperature in the house $\tau_{in} = \tau^*_{out} = 20°C$ will be $W_{hL35} = 560$ Wh.

The option with the use of warm water directly from the tank is considered. The main water consumption is assumed to be in the form of three portions in the morning, afternoon, and evening. To analyze the temperature regime of TES, a model based on [13] was used. Water temperature in TES

$$\tau_{vin} = \tau_{vin0} + \frac{1}{m \cdot c} \int \left(\begin{array}{l} P_{he} - H_L\left(\tau_{vin} - \tau_{in}\right) - \\ - \frac{c}{60} \cdot v_B\left(\tau_{vin} - \tau_c\right) \end{array} \right) \mathrm{d}t, \quad (2)$$

where τ_{vin0} is the initial water temperature; *m* is the mass of water, corresponding to the volume of TES in liters $m = V$; P_{he} is the thermal power transmitted by the heater; H_L is the heat transfer coefficient through the walls of TES; τ_{in} is the temperature in the house, τ_c is the temperature of cold water entering the tank, v_B is the mass consumption of water from the tank, l/min, *c* is the heat capacity of water, J/kg °C.

In the case of using a mixer to obtain the desired (comfortable) water temperature for consumption τ_{vout} the value of v_B

$$v_B = \frac{v_{out}}{1 + \dfrac{\tau_{vin} - \tau_{vout}}{\tau_{vout} - \tau_{vc}}}, \quad (3)$$

where v_{out} is the mass consumption of water at the outlet of the mixer with temperature τ_{vout}, τ_{vc} is the temperature of water from the water supply.

The set value of the water temperature in the tank is equal to the temperature of the heat carrier *w*. At a temperature close to the comfortable one (37–38°C), mixing with cold water is not required and v_B is equal to the volume of consumption. The calculated plot of changes τ_{vin} and the volume of consumed water V_B at τ_{vin0} = 35°C is shown in Fig. 1, *a*, for 24 hours. In this case, heating with a power of P_{he} = 1 kW operates at time intervals corresponding to water consumption, and after its completion until τ_{vin} = 35°C is reached. At consumption intervals, the temperature decrease is up to 30°C at τ_c = 15°C (28°C at τ_c = 10°C), which is not permissible. When the tank volume is increased (500 l), the degree of temperature decrease is less. Increasing the temperature of the HP heat carrier to *w* = 40–45°C makes it possible to maintain the minimum water temperature to a comfortable value but will lead to a significant increase in the total amount of energy consumed for heating by 25% and above (as specified in chapter 5. 4).

A possible option is to use an additional electric boiler of a smaller volume, into which heated HP water is supplied from the tank (35°C). The plots of changes τ_{vin} and the volume of consumed water V_B at τ_{vin0} = 43°C are shown in Fig. 1, *b*. The minimum temperature in this case while maintaining consumption is τ_{vin} = 41.5°C, which is higher than the comfortable one. The calculation was performed for a boiler with a capacity of 80 l at H_L = 1.22 W/°C. In this case, the energy consumed by the boiler per day W_B = 1.706 kWh. The total EC consumption for a representative day in January increases by 6.3% (as stated in chapter 5.4).

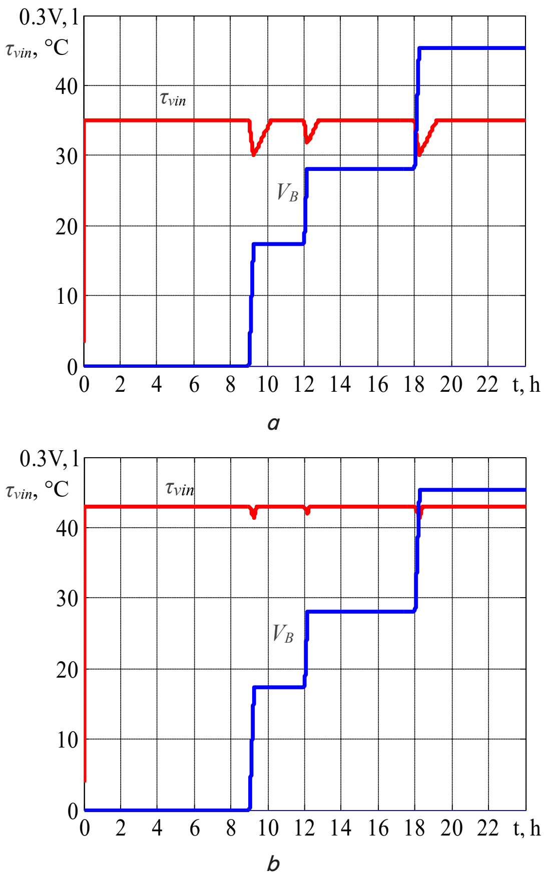


Fig. 1. Plots of temperature and volume of water consumed: *a* — for the tank; *b* — for the additional boiler

In the summer, the boiler may not be used, and the water is heated to τ_{in0} = 45°C by HP.

In winter, losses are additional heating costs and, at the same time, heat input to the house. Therefore, they can be ignored. In the summer, heat losses relate to internal heat input to the house. But they are taken into account when determining the costs of heating water in the tank. On days when HP is used for cooling, switching to tank heating is carried out in time intervals when there is no cooling. In the case of using a photovoltaic system, it is desirable to use heating during hours when excess PV is possible. In this case, it is useful to have information about the expected cooling power schedule and the moment of switching the HP mode.

The calculation of the thermal parameters of the house is carried out in accordance with modern energy saving requirements, taking into account all components of heat loss and heat input outside and inside the house. Since the energy consumption plot is determined over time, the values of all relevant capacities are used.

Total power of heat losses and gains P_h (P_C – under a cooling mode)

$$P_h = P_{tr} + P_{ve}, + P_{gn}, \tag{4}$$

where P_{tr} and P_{ve} are the heat transfer capacities by transmission and ventilation, respectively, $P_{gn} = (P_{int} + P_{sol})$ is the total heat input capacity, P_{int} is the internal heat input capacity, P_{sol} is the solar heat input capacity.

Heat transfer capacity through the building area by transmission

$$P_{tr} = H_{tr}\cdot(\tau_{in} - \tau_{out}),$$

where τ_{in} and τ_{out} are the temperatures inside and outside the room. H_{tr} is the total heat transfer coefficient of the fences by transmission.

When determining the heat transfer capacity (H_g) to the ground, the soil temperature is taken into account.

Heat transfer coefficient by transmission

$$H_{tr} = \sum_i b_{tr,i} A_i U_i,$$

where A_i is the area of the *i*-th structure m^2; U_i is its reduced heat transfer coefficient W/(m^2·K); $b_{tr,i}$ is the correction factor. Structural solutions are selected from typical serial materials according to DSTU 9190:2022.

The value of P_{ve}

$$P_{ve} = H_{ve}\cdot(\tau_{in} - \tau_{out}),$$

where H_{ve} is the generalized coefficient of heat transfer by ventilation, which depends on the exchange rate *n*, density, and heat capacity of air. For the studied building, natural air exchange *n* = 0.6 year^{-1} is assumed.

Internal heat gains include metabolic heat of people, lighting, electrical equipment and for the daily cycle are given by actual (expected) values in time.

Solar heat gains are determined based on the equivalent insolation areas $A_{sol.k}$ of the corresponding translucent and opaque elements of the building and on corrections for sun shading by external obstacles. The hourly solar radiation schedule $I_{sol.k}$ for the receptive area of the *k*-th surface for horizontal and vertical surfaces of different orientations is determined according to DSTU-N B V.1.1-27:2010.

5. 2. Heat pump model according to manufacturer's specifications under heating and cooling modes

The use of the AERO ILM 2-7 air-to-water heat pump with an inverter compressor is considered. The manufacturer's specifications [8] for the maximum, rated, and minimum modes are chosen as the basis for the model. Under a heating mode, the thermal power $P_{h\mathrm{MAX}}$, P_{hR}, $P_{h\mathrm{MIN}}$, the power consumption $P_{1\mathrm{MAX}}$, P_{1R}, $P_{1\mathrm{MIN}}$ and COP_{MAX}, COP_R, COP_{MIN} depend on the heat carrier temperature w = 35, 45, 55, 65°C and the temperature outside the house τ_{out}. The dependences P_h, P_1, COP for w = 35°C under a heating mode are given in Table 1.

Table 1

Dependences P_h, P_1, COP for w = 35°C under a heating mode for HP

τ_{out},°C		20	15	12	10	7	2	–7	–10	–15	–18
MAX	P_h, kW	10.65	10.52	10.38	9.9	8.91	6.56	6.19	5.61	4.78	4.3
	P_1, kW	2.24	2.22	2.22	2.21	2.19	2.05	2.01	1.92	1.84	1.89
	COP	4.75	4.74	4.68	4.48	4.07	3.2	3.08	2.92	2.6	2.28
RATED	P_h, kW	5.26	5.22	2.12	4.91	4.51	3.87	2.84	2.6	2.19	1.94
	P_1, kW	0.88	0.89	0.89	0.89	0.89	0.89	0.87	0.86	0.83	0.84
	COP	5.98	5.87	5.75	5.52	5.06	4.32	3.28	3.02	2.64	2.31
MIN	P_h, kW	2.58	2.57	2.55	2.5	2.35	2.05	1.33	–	–	–
	P_1, kW	0.41	0.41	0.42	0.43	0.44	0.46	0.45	–	–	–
	COP	6.29	6.27	6.07	5.81	5.34	4.46	2.96	–	–	–

Table 2 gives P_c, P_1, EER for w = 12°C under a cooling mode.

It is assumed that the COP values for intermediate values P_h for inverter HP vary linearly. Then, for $P_{h\mathrm{MAX}} > P_h > P_{hR}$, the COP values

$$COP = COP_R + \frac{\left(COP_{\mathrm{MAX}} - COP_R\right)\left(P_h - P_{hR}\right)}{P_{h\mathrm{MAX}} - P_{hR}}, \tag{5}$$

for $P_{hR} > P_h > P_{h\mathrm{MIN}}$ the COP value is determined similarly

$$COP = COP_{\mathrm{MIN}} + \frac{\left(COP_R - COP_{\mathrm{MIN}}\right)\left(P_h - P_{h\mathrm{MIN}}\right)}{P_{hR} - P_{h\mathrm{MIN}}}. \tag{6}$$

Table 2

Dependences P_c, P_1, EER for w = 12°C under a cooling mode for HP

τ_{out},°C		40	35	30	25	20
MAX	P_c, kW	6.45	6.89	7.44	8.0	8.6
	P_1, kW	3.16	2.87	2.64	2.41	2.28
	EER	2.04	2.4	2.82	3.32	3.77
RATED	P_c, kW	3.95	4.31	4.63	4.97	5.1
	P_1, kW	1.25	1.13	1.0	0.89	0.83
	EER	3.16	3.81	4.63	5.58	6.14
MIN	P_c, kW	2.0	2.15	2.2	2.2	2.24
	P_1, kW	0.58	0.51	0.45	0.41	0.38
	EER	3.43	4.19	4.89	5.37	5.89

The consumed electric power $P_1 = P_h/COP$.

Under a cooling mode – cooling power $P_{c\mathrm{MAX}}$, P_{cR}, $P_{c\mathrm{MIN}}$, consumed power $P_{1\mathrm{MAX}}$, P_{1R}, $P_{1\mathrm{MIN}}$ and EER_{MAX}, EER_R, EER_{MIN} depending on the heat carrier temperature w=18, 12, 7°C and the temperature outside the house τ_{out}. For intermediate values of P_c, the calculation is similar to heating.

5. 3. Thermal model of a house with a heat pump taking into account the thermal inertia of the house

Indoor air temperature τ_{in} taking into account the thermal inertia

$$\tau_{in} = \tau_{in0} + \frac{1}{a}\int\left(P_h - kP_{HP}\right)\mathrm{d}t, \tag{7}$$

where τ_{in0} is the initial temperature, $a = (C{\cdot}S + c_a m_a)$; C is the internal heat capacity of the building per unit area (W·h/m^2·°C); S is the area; c_a is the specific heat capacity of air 1.005 kJ/kg°C (kW·s/kg·C); m_a is the mass of air; P_{HP} is the thermal power of HP, k is the control function of HP.

Air mass at temperature τ_{in}

$$m = \frac{pV}{R\left(\tau_{in} + 273\right)},$$

where p = 0.101325 PA is atmospheric pressure; V is the volume of air in the room; R = 287 is the gas constant of air.

The value of C according to DSTU 9191:2022, depending on the class of the building (light, medium) is 35 – 50 (Wh/m^2°C). For comparison, in the case of the building under consideration, the value

$$c_a \cdot m_a = 418{,}000 \text{ W·s/°C},$$

and

$$C \cdot S = (30\text{–}50)120 \cdot 3{,}600 \text{ W·s/°C}.$$

At the design stage, in the absence of an exact value of C, the possible range of deviation of the value should be taken into account.

Regarding the temperature in the house τ_{in}, static modes can be distinguished when maintaining a given temperature value and dynamic modes when changing a given temperature value. In this case

$$P_{HP} = P_h + a\frac{d\tau_{in}}{dt}. \tag{8}$$

The use of an inverter HP with a regulator was considered in statics when maintaining a constant temperature in the room $P_h = P_{HP}$. In dynamics, when the set temperature value changes, a dynamic component of the HP power appears. The rate of temperature change is limited by the maximum HP power and the set rate of temperature change.

The general structure of the model (Fig. 2) contains:

– MT module for setting the hourly temperature schedule (τ_{out});

– MIR module for heat input from solar radiation PIR = Psol and internal sources Pin. The Pin value also includes heat losses in the tank;

– MTR module for calculating the power of transmission losses/heat input;

– MC module for cooling/heating control. It provides for limiting the HP power at the maximum value;

– MNR module for calculating the power consumed by HP from the network.

The P_{IR} value is calculated according to the components of solar radiation on the horizontal I_{sol} and vertical surface according to the cardinal points I_{solN}, I_{solS}, I_{solE}, I_{solW}. The corresponding hourly schedules are set.

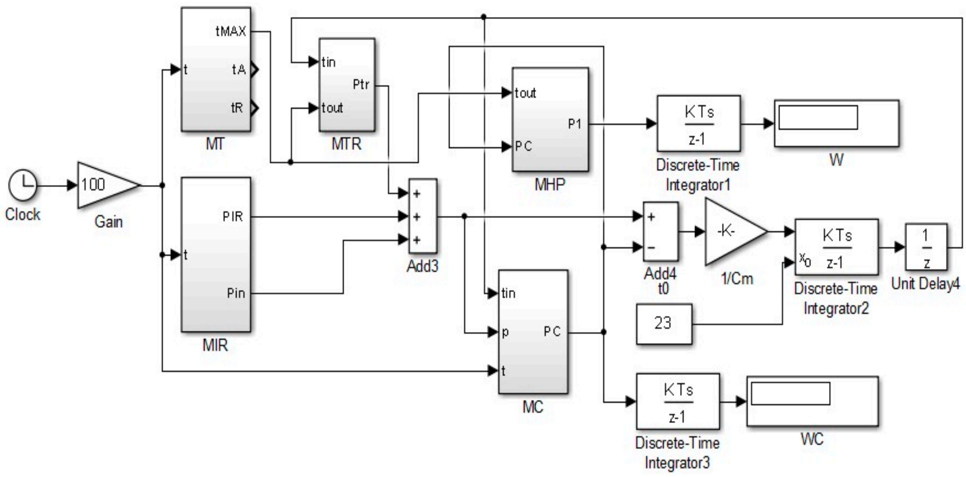


Fig. 2. Model structure for calculating the thermal regime of a house

5. 4. Simulation results with an assessment of the temperature regime and energy consumption

Monovalent heating mode using HP in statics while maintaining a given temperature value. The daily EC consumption W for heating was estimated at the average temperature for Kyiv in January $\tau_{out} = -4.7$°C and the temperature $\tau_{out}(t)$ for a representative day according to DSTU 9190:2022. The maximum value $\tau_{out}(t) = -7.4$°C. The simulation results at a temperature in the house $\tau_{in} = 20$°C and a heat carrier temperature $w = 35, 45, 55$°C are given in Table 3 (W_h – HP energy for heating, W_{35}, W_{45}, W_{55} consumed EC at w=35, 45, 55°C). The energy illumination of surfaces by diffuse radiation at 10-point cloudiness (January) is adopted according to DSTU 9190:2022. The maximum value $P_h = 4.5$ kW, the maximum thermal power of the used HP at $\tau_{out}(t) = -7$°C is 6.19 kW. Under equal conditions, EC consumption is minimal at $w = 35$°C with a total value of $COP = 3.441$. Thus, the value of $W_{45}/W_{35} = 1.256$. This confirms the feasibility of low-temperature heating when using a "warm" floor.

Table 3

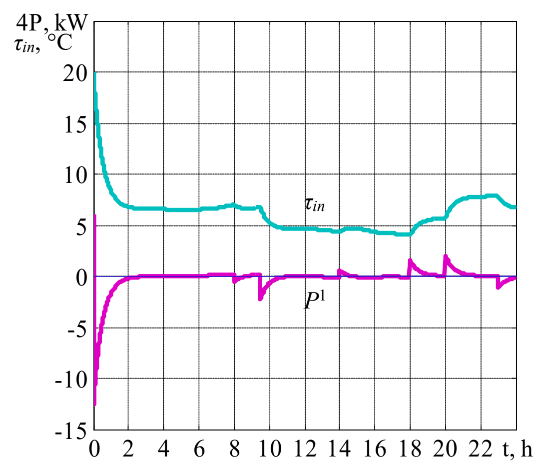
Energy consumption for heating

τ_{out}, °C	W_h, kW·h	W_{35}, kW·h	W_{45}, kW·h	W_{55}, kW·h
–4.7	92.52	26.9	33.77	42.01
$\tau_{out}(t)$	92.51	26.88	33.8	42.01

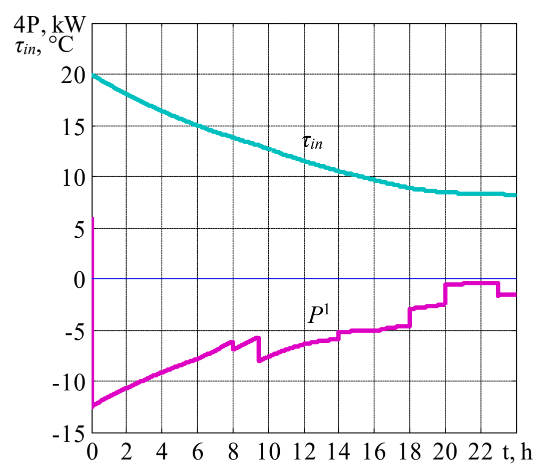
At $\tau_{out}(t) = -4.7$°C and a decrease of $\tau_{in} = 18$°C, the value of W_h = 81.34 kWh W_{35} = 23.25 kWh. At $\tau_{out}(t) = -4.7$°C and a decrease of τ_{in} = 16°C, the value of W_h = 70.2 kWh W_{35} = 20.01 kWh. Thus, it is possible to reduce energy consumption by lowering the temperature in the house for a period when the residents are away for several days.

Monovalent mode using HP under these conditions is possible at a constant temperature up to $\tau_{out} = -13$°C. When maintaining $\tau_{in} = 20$°C, W_h = 116.1 kWh, W_{35} = 42.47 kWh. When decreasing τ_{in} = 18°C, the value of W_h = 106.1 kWh and W_{35} = 38.67 kWh.

Dynamic mode when changing the set temperature value (Fig. 3). The thermal inertia of the building was estimated based on the change in temperature τ_{in} when the HP was turned off for a day and the outside temperature was 0°C. In the case of setting thermal inertia taking into account only the air mass, the temperature in the building decreases from 20°C to 6.7°C, and already at 3:00 τ_{in} = 6.5°C (Fig. 3, *a*), which is unrealistic. Further, the temperature is maintained due to internal heat inflows. When taking into account the internal heat capacity of the building C = 25, the temperature in the building decreases from 20°C to 8.2°C (Fig. 3, *b*), and at C = 50 the decrease from 20°C to 11.5°C, which is fully consistent with practice. Fig. 3 shows a plot of the heat loss power P^1 taking into account internal heat inflows.



a



b

Fig. 3. Plots of temperature changes τ_{in} when the heat pump is turned off: *a* — without taking into account the heat capacity of the building; *b* — taking into account the internal heat capacity of the building

From the perspective of assessing the possibility of reducing heating costs, a daily work cycle with a decrease in temperature at night to 18°C at 20°C during the day and $\tau_{out} = -4.7$°C (Fig. 4) was considered. In this case, the value of W_{35} = 25.93 kWh. That is, compared to the case of a decrease from 20°C to 18°C (a decrease in energy consumption of 3.63 kWh – 14%), the decrease in consumption in this case is less – by 4%. In particular, this is due to the fact that heating from 18°C to 20°C is carried out at the maximum power of the heating element and a decrease in *COP*.

Bivalent mode with the addition of energy from the heating element. At a constant temperature $\tau_{out} = -18$°C and maintaining $\tau_{in} = 0$°C, the value of $W_h = 103.2$ kWh, $W_{35} = 45.26$ kWh, the energy consumed by the heating element $W_{35} = 28.02$ kWh. When $\tau_{in} = 18$°C is reduced, the energy consumed by the heating element $W_{35} = 16.92$ kWh is reduced.

Cooling mode. The daily consumption of EC W for cooling a house in Kyiv was estimated for a clear day (solar radiation $I_S(t)$) and a day with average radiation ($0.75I_S(t)$). The set value $\tau_{in} = 24$°C. Thus, at $\tau_{in} \geq 24$°C, the heating element power compensates for the heat input into the house and $\tau_{in} = 24$°C. When the temperature decreases, the heating element is turned off.

The plots $\tau_{out}(t)$ for July days were used: with the maximum temperature in July (above 34°C) $\tau_{out}(t)_M$ according to archival data [23]; for a representative day $\tau_{out}(t)_R$ at an average value of 18.3°C according to DSTU 9190:2022 for a day with a maximum temperature above $\tau_{in} = 24$°C [23] $\tau_{out}(t)_A$.

The simulation results at a temperature of $\tau_{in} = 24$°C and w = 12°C are given in Table 4 (W_C – HP energy for cooling, W – EC consumption, P_{CM} – maximum HP power value). The energy illuminance of surfaces for a clear day and with average cloudiness (July) was adopted according to DSTU 9190:2022. The heat capacity values of the building were considered as C = 35 (walls made of monolithic slag concrete, blocks of aerated concrete with reinforced concrete or wooden floors), C = 50 (brick walls with reinforced concrete or wooden floors). The soil temperature was taken as 15°C in accordance with the minimum value $\tau_{out}(t)_R$.

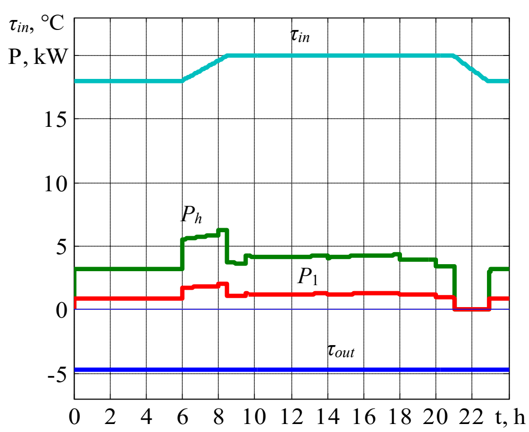


Fig. 4. Plots for daily mode with temperature changes

At average solar radiation and $\tau_{out}(t)$, cooling is not required. The maximum EC consumption for cooling occurs on a clear day at maximum temperature and decreases with increasing C. The plots of HP power P_c, consumption from the network P, temperatures outside τ_{out} and inside the house τ_{in} are shown in Fig. 5 at C = 35, for a clear day and $\tau_{out}(t)_A$. This is important when planning HP modes for water heating and cooling.

Table 4

Cooling energy consumption

Mode	C = 35, W·h/m²·°C						C = 50, W·h/m²·°C					
	I_S, τ_{outM}	I_S, τ_{outR}	I_S, τ_{outA}	$0.75I_S$, τ_{outM}	$0.75I_S$, τ_{outR}	$0.75I_S$, τ_{outA}	I_S, τ_{outM}	I_S, τ_{outR}	I_S, τ_{outA}	$0.75I_S$, τ_{outM}	$0.75I_S$, τ_{outR}	$0.75I_S$, τ_{outA}
W_C, kW·h	31.05	5.433	9.225	23.82	0	3.156	28.97	3.166	7.116	21.73	0	1.042
W, kW·h	7.157	1.007	1.717	5.420	0	0.589	6.706	0.588	1.32	4.963	0	0.192
P_{CM}, kW	3.9	1.94	2.13	3.25	0	1.5	3.9	1.7	2.1	3.25	0	1.12

The option of changing the building parameters is considered. In the initial version, the total area of windows is quite large – 20 m². If the area is halved, it is possible to significantly reduce the energy for cooling, for a clear July day at maximum temperature $W_C = 20.64$ kWh (instead of 31.05 kWh) at $W = 4.080$ kWh (instead of 7.157 kWh) and $P_{hM} = 2.97$ kWh (instead of 3.9 kWh). The energy for heating is reduced to a lesser extent – for a representative January day W_h = 86.7 kWh (instead of 92.51 kWh) at $W = 25.01$ kWh (instead of 26.88 kWh) and $P_{hM} = 4.3$ kWh (instead of 4.5 kWh).

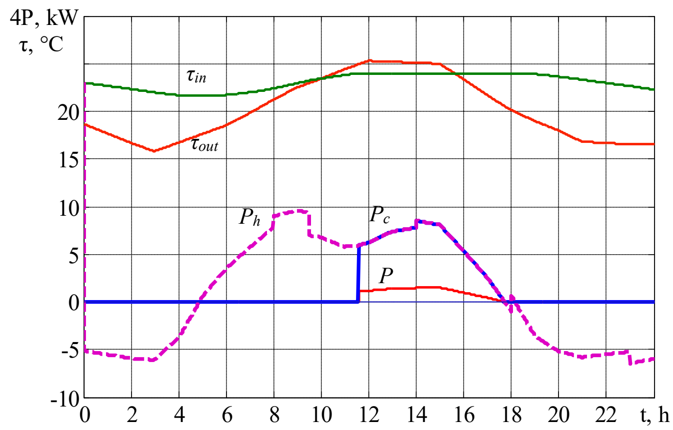


Fig. 5. Plots P_c, P, τ_{out}, τ_{in}

6. Results of research on improving the model of the microclimate system for a single-family home: discussion

The possibility of increasing the degree of approximation to real values for the plots of changes in heating/cooling power, consumed electrical power and temperature regime of a single-family house when using a reversible HP is achieved:

– by taking into account the thermal inertia of the building in the model according to (7), (8), which is given by the specific value of the heat capacity per m² of the conditioned area. Since the calculation of the exact value of the heat capacity is complex, standard values are used. A variant of the construction of a light-class building is considered when the energy for cooling is maximum. The difference in the plots of changes in τ_{in} over time with and without taking into account the heat capacity of the building is demonstrated in Fig. 3. The influence of thermal inertia on the plot of τ_{in} is also shown in Fig. 5. The significant influence of the value of the heat capacity on the energy consumed for cooling is given in Table 4;

– by taking into account all heat losses and heat gains according to expression (4), including transmission through fences and to the ground, heat from solar radiation through opaque and transparent structural elements, from internal heat sources, including heat losses in the HWS tank. In this case, the values of all calculated parameters are normalized in accordance with the current standard;

– by using hourly plots of temperature outside the house and solar radiation for the location of the facility in the calculation. Along with representative plots, plots based on archival data are used. The expected plot of internal heat gains was also taken into account. This makes it possible to us to estimate instantaneous power values (Fig. 4, 5), including maximum values;

– by using the mathematical model of HP (expressions (5), (6)), made in accordance with its technical characteristics, which makes it possible to determine the value of the consumed electric power (*COP* and *EER*) in accordance with the thermal power, air temperature, and heat carrier. In this case, it is possible to set the heat carrier temperature w. The influence of w on the consumed power is reflected in Table 3. This also applies to the value of the total *COP* value for HP, which at w = 35°C is 3.44. It is also important to take into account the limitation of HP power, which corresponds to the values of τ_{out} and w, which is reflected in Fig. 4. To a certain extent, this work builds on [14, 15], in which thermal models of the house are considered. In those studies, the calculation of the temperature inside the house is carried out taking into account heat losses. In this case, the heating (cooling) of the air mass in the volume of the house is actually considered. In the case of heating while maintaining a constant temperature inside the house (static mode), when the thermal power of HP compensates for heat losses, the calculation results are correct. Without taking into account the heat capacity of the building at a small time constant of the air mass, the temperature plot practically repeats the temperature plot from the outside with a small delay [14] and is not correct. Accordingly, the values of energy and power of HP under dynamic modes will be incorrect.

A feature of this solution is the orientation towards specifying indicators under dynamic modes, obtaining plots of current values in the daily cycle, which makes it possible to check the correctness of the choice of HP parameters by power. This makes it possible to assess the control capabilities for reducing energy consumption and planning HP operating modes for heating and cooling in the summer. It is also possible to adjust the building parameters in order to reduce electricity consumption. The distribution of HP consumption and electricity consumption over time is useful when calculating a power supply system using renewable energy.

The limitations on taking into account the thermal inertia of the building are associated with a significant discreteness in the values of the internal heat capacity of the building C, which is provided by the standard for five classes of construction (C = 25, 35, 50, 80, 110 W·h/m^2·°C). The deviation of the actual value of C from the standard causes an error in determining the EC costs under a cooling mode. This necessitates the consideration of a more severe mode with an underestimation of the value of C.

A general drawback of our work is the difficulty in accurately determining the thermal parameters of the building structures, which necessitates the use of a certain margin when making decisions.

Further studies involve the refinement of the proposed model for the possibility of using it together with the model of energy processes in the power supply system of a residential building with a photovoltaic power plant to improve the management of the system's energy consumption. This concerns the possibility of adjusting the parameters during operation.

7. Conclusions

1. When calculating thermal parameters, all components of heat losses and heat gains outside and inside the house are taken into account. The considered methodology involves calculating the current values of the power of heat losses and heat gains according to the building structure, temperatures outside, inside, and soil, as well as solar radiation according to the orientation of the enclosing structures. To reduce the total EC costs during heating, it is proposed to use an additional electric boiler in the hot water supply system to increase the water temperature to a comfortable level without increasing the temperature of the HP heat carrier. The calculation was performed for a specific one-story house.

2. Using the inverter HP model according to the manufacturer's characteristics under heating and cooling modes makes it possible to approximate the obtained EC consumption values to real values according to the heat carrier temperature and the HP power limitation. When maintaining τ_{in} at a given level, the value is $P_h = P_{HP}$, in case of changing τ_{in}, the dynamic component is taken into account. During cooling, the HP switch-on is determined by the value of τ_{in}.

3. The thermal model of the house, along with the calculation of thermal capacities, takes into account thermal inertia, which is determined by the internal heat capacity of the building. The EC consumption schedule in time is determined by the HP model. Hourly plots of solar radiation and τ_{out} for the location are used. This makes it possible to estimate the energy costs for maintaining the microclimate in the house and the current power values, including maximum values, to ensure the correct selection of HP and its control.

4. The simulation under a heating mode was performed according to the representative plot τ_{outR} and solar radiation at 10-point cloudiness in January for the city of Kyiv. The minimum EC consumption occurs at a minimum heat carrier temperature of 35°C. The need to take into account the internal heat capacity of the building to obtain reliable indicators under dynamic modes is confirmed. The possibility of using the selected HP at τ_{out} = – 13°C under a monovalent mode without an additional heat source is shown. Under a cooling mode at τ_{outR} the value of $W_C \leq$ 5.433 kW·h (EC consumption $W \leq$ 1 .005 kW·h). With a temperature plot with a maximum of 34°C the value is W_C = 31.05 kW·h (EC consumption W = 7.157 kW·h at the maximum value of the HP power P_{CM} = 3.9 kW·h) is shown. The possibilities of using the model at the design

stage to adjust the building parameters in order to reduce energy consumption are shown. Thus, in the considered application, reducing the window area makes it possible to reduce the cooling energy by 1.5 times while reducing the EC consumption by 1.75 times. For heating, the energy reduction is 6.7%, and the EC consumption is 7.5%.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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