The object of this study is the process of calculating the distribution of heat generation and energy consumption by heat sources. The task addressed was estimating the seasonal heat generation by a combined heat source with an air heat pump. A methodology for quantifying the seasonal heat generation and energy consumption by sources as part of a combined heat source with an air heat pump has been devised. This methodology makes it possible to take into account different bivalent operation schemes, variable mode of the heating system, and different electricity tariffs. The ability to take these factors into account increases the accuracy of the results but also increases the complexity of the calculation process. In order to automate the calculation using the devised methodology, an algorithm was built, and an example of its implementation was demonstrated. The results show that the distribution of seasonal heat generation largely depends on the values of the bivalent point temperature and the heat pump shutdown temperature. In addition, they demonstrate the dependence of the calculated amount of heat consumed during the heating period and the distribution of its generation between sources on the number of the last heating periods taken into account. With a decrease in the number of past heating periods taken into account, the amount of heat consumed per season gradually decreases and the share covered by the heat pump increases. This indicates a gradual decrease in the duration of low temperatures in winter and proves the importance of relevance of the climatic data used for analysis.

The methodology devised in this study makes it possible to determine the appropriate ratio of thermal power of heat sources in a combination and increases the accuracy of calculating the payback period of equipment

Keywords: air source heat pump, hourly temperature data, bivalent point

UDC 519.6:378

DOI: 10.15587/1729-4061.2025.323755

DEVISING A METHODOLOGY FOR ASSESSING SEASONAL THERMAL ENERGY GENERATION BY A COMBINED HEAT SOURCE

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Received 17.12.2024
Received in revised form 27.01.2025
Accepted 21.02.2025
Published 28.02.2025

How to Cite: *Pohosov, O., Pasichnyk, P., Kulinko, Y., Koziachyna, B., Melnychenko, O., Osypov, V. (2025). Devising a methodology for assessing seasonal thermal energy generation by a combined heat source. Eastern-European Journal of Enterprise Technologies, 1 (8 (133)), 56–67. https://doi.org/10.15587/1729-4061.2025.323755*

1. Introduction

The current stage of world development is accompanied by the aggravation of existing and the emergence of new energy and environmental problems. The main prerequisite for such a development is the rapid increase in the total level of energy consumption every year [1]. Therefore, the key conditions for the successful existence and development of humanity in the future are the optimization of energy consumption, energy conservation, increasing the share of renewable energy sources, and rational use of energy resources [2]. As a result of existing prerequisites, the utilization of renewable energy sources is becoming increasingly relevant [3]. One of the most effective technical solutions in this regard is the use of low-potential environmental heat using heat pumps to meet the needs of heating, hot water supply, and cooling systems [4]. Those systems account for a significant share of global energy consumption [5].

The constant growth of demand for heat sources with heat pumps necessitates devising effective circuit solutions, procedures, and algorithms for their operation. This task also requires a thorough economic analysis, which includes an approximate calculation of the payback period and proving the economic feasibility of implementation. This is especially true for heat pumps that use sources as a low-potential heat source, the thermal energy potential of which significantly depends on changes in seasonal and climatic factors, such as outdoor air. The outdoor air temperature during the heating period can fluctuate within significant ranges, which has a decisive impact on the thermal power and the value of the heat conversion coefficient of an air heat pump [6]. Given this, it is usually not advisable to install an air heat pump to cover heat loads during the heating period under a monovalent mode. Therefore, in most cases, combined heat sources are designed, in which the operation of an air heat pump is combined with a traditional heat source [7]. However, existing methodologies for estimating the distribution of participation in seasonal heat generation by a combined heat source are based on simplified temperature data and are imperfect. This is due to the fact that they do not allow for estimating the calculation results for different time periods, do not take into account the variable operating mode of the heating system, and different electricity tariffs. Thus, the task to devise a calculation methodology and develop an algorithm for its automation based on an array of hourly data remains relevant.

2. Literature review and problem statement

The most common objects of research are the parameters and types of the working fluid, the design features of the compressor and heat exchangers, the options for low-potential heat sources, as well as environmental aspects. In particular, in [5], the operation of two air heat pumps was simulated in the IMST-ART software environment with different working fluids for two variants of heating systems and for two variants of climate zones. In [1], the environmental impact of heat pumps on the environment is considered, taking into account the entire life cycle. Data on the average duration of standing outside air temperatures were taken into account for calculations in [1, 5]. Therefore, the results of the average seasonal COP of the air heat pump in these studies were determined without taking into account the use of the variable operating mode of the heating system and the existing climate changes. Therefore, it can be stated that there is a certain error in the obtained indicators of average seasonal energy consumption and, accordingly, in the indicators of environmental impact. In [8], modeling was performed using the SUEWS and EnergyPlus programs. This was done to assess the impact of the heat pump on the increase in outdoor overheating in summer and subcooling in winter for two idealized low-rise residential areas in the UK. In [6], a mathematical model was used to estimate the seasonal conversion coefficient of air-to-water heat pumps with different compressor options for several climate zones in Italy. The study emphasizes the importance of choosing the right heat pump power depending on the energy balance of the building and the climatic conditions in which it will be installed. In the cited works [6, 8], simplified temperature data were used for calculations. Therefore, it can be argued that the results of calculating the average seasonal COP have some error. In addition, these studies did not consider the possibility of using different bivalent schemes, which has a direct impact on the calculated capacity of the equipment. In [9], numerical studies of an air-to-air heat pump were conducted. The aim was to assess the impact of faults such as fouling of heat exchangers and refrigerant leakage on its efficiency for three climatic conditions [9]. In [10], the change in heat demand in UK households after switching from gas boilers to heat pumps was analyzed. However, in [9, 10], simplified climate data were used; therefore, it can be argued that the accuracy of the results could be improved by using detailed hourly data. In [7], the change in the seasonal heat conversion coefficient of two air-to-water heat pumps with a backup electric boiler for four climatic zones of Greece was investigated. However, the change in the seasonal conversion coefficient due to the change in the time period of the climate data taken for the analysis was not taken into account. In [8], the impact of climate data detailing on the accuracy of developing data on the average duration of outdoor air temperatures and on the accuracy of calculating the seasonal heat conversion coefficient was analyzed. In all the aforementioned works [1, 5–10], the calculation of the share of seasonal generation of an air-source heat pump was carried out using data on the average duration of certain intervals of outdoor air temperatures during the heating period. Therefore, it can be argued that there is a certain error in the calculations, which is associated with the inability to take into account a number of important factors that have a direct impact on the accuracy of accounting for energy consumption of systems.

In [11–15], a more detailed calculation is reported, which is performed on the basis of hourly temperature data. The purpose of work [11] was to study the influence of temperature and relative humidity of the outdoor air on the efficiency of an air-source heat pump, taking into account the defrosting process of the evaporator. Paper [12] shows that the use of hourly calculation of the heat conversion coefficient of heat pumps in energy system models helps more accurately estimate electricity consumption, especially in cold climates. However, the methodologies presented in works [11, 12] are not flexible enough and do not make it possible to take into account the possibility of operation of a combined heat source in different bivalent modes. Studies [13, 14] investigate the influence of different climatic conditions on electricity consumption of an air-source heat pump and its defrosting cycles. Although these studies are based on hourly climatic data, they did not report a detailed methodology for their use because devising the methodology was not the goal. Only [15] reports the methodology for calculating the distribution of seasonal heat generation. But the main goal of the study was to assess the impact of the spread of heat pumps on the increase in the total load on the power system. Therefore, the methodology from study [15] does not allow for the calculation for different bivalent schemes and does not provide for the possibility of taking into account the variable operating mode of the heating system.

Thus, our review of the literature [1, 5–15] revealed that the task to improve the accuracy of calculating the distribution of heat generation and energy consumption by combined heat sources remains unresolved.

3. The aim and objectives of the study

The purpose of our study is to devise a methodology for calculating the distribution of seasonal heat generation by a combined heat source and the distribution of seasonal energy consumption based on an array of hourly temperature data. This will make it possible to improve the accuracy of selecting heat-generating equipment for combined heat sources, as well as improve the accuracy in determining the payback period.

To achieve the goal of the study, the following tasks were set:

– to propose a mathematical apparatus for the methodology for calculating the distribution of seasonal heat generation and energy consumption by a combined heat source based on hourly temperature data;

– to build a calculation algorithm for automating the methodology being devised;

– to verify the performance of the algorithm and the capabilities of the methodology being devised.

4. The study materials and methods

The object of our study is the process of calculating the distribution of thermal energy generation and energy resource consumption by sources as part of a combined heat source.

The research is based on the use of statistical analysis and synthesis methods, as well as the principles of decision-making theory. The basic assumption of the study is that increasing the detail of the calculation by replacing data on the duration of certain temperature intervals with hourly temperature data would increase its accuracy. In turn, automation of the methodology using the algorithm being developed could increase the speed and flexibility of the calculation.

When implementing the algorithm, the Microsoft Excel software (USA) was used. This software package was adopted due to the convenience of analyzing large data sets. The source data was an array of hourly outdoor air temperatures for the climatic conditions of the city of Kyiv over the last 50 heating periods, which were provided by the Meteoblue company (Switzerland) [16], which specializes in climate modeling. These data represent stored forecasts, which are refined by measurement data from a weather station using the ERA5T model (Meteoblue, Switzerland). To obtain a model of the coefficient of variation of thermal power k and a model of COP of an air-source heat pump, a statistical analysis of the characteristics of 9 air-source heat pumps in the power range of 11–100 kW (under A2/W35 conditions), obtained from technical documentation [17], was carried out. In all heat pumps accepted for analysis, the working fluid is freon R410A.

5. Results of devising a methodology for assessing seasonal heat generation by a combined heat source

5. 1. Devising a methodology for assessing seasonal heat generation and energy resource consumption by a combined heat source

Depending on the operating mode of the combined heat source, which is assumed during development, the traditional heat source can be auxiliary or alternative. The auxiliary heat source covers the residual heat load during peak periods, and the alternative takes on the entire heat load after reaching a certain outdoor air temperature. The task of determining this temperature is key in determining the ratio of the capacities of the heat pump and the traditional heat source in a combination [6]. When solving this problem, it is necessary to take into account the factor of primary energy use and the economic feasibility of the heat pump. It is determined in relation to the auxiliary heat source and directly depends on the ratio of energy carrier tariffs.

When designing combined heat sources with air heat pumps, a useful tool is a heat consumption plot for the heating period. This plot is built on the basis of data on the average duration of certain intervals of outdoor air temperatures during the heating period [18]. The curve of the heating system heat load change and the curve of the heat pump power change are plotted on it. At the intersection of these curves is the bivalence point, its location directly depends on the value of the adopted calculated power of the air heat pump. The area under the heat load curve is numerically equal to the amount of heat energy that will be consumed on average for the needs of the heating system during the heating period [19]. In turn, the area under the heat pump power curve is numerically equal to the amount of heat energy that will be transformed by it on average during the heating period. These indicators can be calculated by integrating the curves.

However, this method does not allow us to take into account the change in heat load due to the use of a variable operating mode of the heating system, which is an excellent tool for energy saving during periods of absence of people. Also, this method does not make it possible to divide the amount of electricity that will be consumed by the heat pump into day and night periods. Usually, the cost of electricity consumed by the heat pump at night is lower than that consumed during the day, and the outdoor air temperature at night is lower, the heat load is higher. Thus, it can be argued that this introduces some error into the calculation of the average cost of heat generated by the combined source. In addition, data on the duration of certain intervals of outdoor air temperatures during the heating period are determined by analyzing temperature data on a significant period of time – often about 50 years. Therefore, these data are rarely updated in regulatory documents. And this can be considered another disadvantage of this method. After all, it does not make it possible to evaluate the results of the calculation for a different time period, that is, to take into account climate changes.

In order to avoid the described shortcomings, it is necessary to increase the detail of the calculation by replacing data on the duration of certain temperature intervals with hourly temperature data of heating periods.

Calculation of the average seasonal distribution of energy generation and consumption by a combined heat source based on an array of hourly temperature data begins with determining the heat load of a specific hour of the heating period.

– for the main operating mode of the heating system:

$$Q_{HS}^{i} = Q_{HS}^{I} \cdot \frac{t_{int}^{I} - t_{ext}^{i}}{t_{int}^{I} - t_{ext}^{D}}; \qquad (1)$$

– for the standby mode of operation of the heating system:

$$Q_{HS}^{i} = Q_{HS}^{II} \cdot \frac{t_{int}^{II} - t_{ext}^{i}}{t_{int}^{II} - t_{ext}^{D}}, \qquad (2)$$

where Q_{HS}^{i} is the heat load of the heating system at a specific hour of the heating period, kW; Q_{HS}^{I}, Q_{HS}^{II} – calculated heat load of the heating system of the main and standby modes, respectively (input data components), kW; t_{int}^{I}, t_{int}^{II} – calculated indoor air temperature of the main and standby modes, respectively (input data components), °C; t_{ext}^{i} – outdoor air temperature at a specific hour (taken from the climate data array), °C; t_{ext}^{D} – calculated outdoor air temperature for heating (input data component), °C.

In this case, the outdoor air temperature at a specific hour of the day is tied to a specific day of the week and month in which it was recorded.

The next step is to calculate the temperature of the bivalence point of the main and standby modes. To determine the bivalence point, it is necessary to solve a system of equations, taking into account that the heat capacity of the heat pump at the temperature of the bivalence point is equal to the heat load of the heating system at this temperature:

– the temperature of the bivalence point of the main mode of the heating system:

$$\begin{cases} Q_{HS}^{t_{biv}^{I}} = Q_{HS}^{I} \cdot \dfrac{t_{int}^{I} - t_{biv}^{I}}{t_{int}^{I} - t_{ext}^{D}}, \\ Q_{HP}^{t_{biv}^{I}} = Q_{HP}^{+2} \cdot k_i; \end{cases} \qquad (3)$$

– temperature of the bivalence point of the standby mode of the heating system:

$$\begin{cases} Q_{HS}^{t_{biv}^{II}} = Q_{HS}^{II} \cdot \dfrac{t_{int}^{II} - t_{biv}^{II}}{t_{int}^{II} - t_{ext}^{D}}, \\ Q_{HP}^{t_{biv}^{II}} = Q_{HP}^{+2} \cdot k_i, \end{cases} \quad (4)$$

where $Q_{HS}^{t_{biv}^{I}}$, $Q_{HS}^{t_{biv}^{II}}$ – heat load of the heating system at the temperature of the bivalence point of the main and standby modes, respectively, kW; t_{biv}^{I}, t_{biv}^{II} – temperature of the bivalence point of the main and standby modes, respectively, °C; $Q_{HP}^{t_{biv}^{I}}$, $Q_{HP}^{t_{biv}^{II}}$ – thermal capacity of the air heat pump at the temperature of the bivalence point of the main and standby modes, respectively, kW; Q_{HP}^{+2} – thermal capacity of the air heat pump under A2/W35 conditions (input data component), °C; k_i – coefficient of change of the thermal capacity of the air heat pump.

The coefficient of change of the thermal capacity of the heat pump is a function of the outdoor air temperature at this hour:

$$k_i = f\left(t_{ext}^{i}\right). \quad (5)$$

This dependence can be obtained by analyzing the characteristics of air-source heat pumps from the manufacturers' technical documentation. After calculating the bivalence points, a logical check is performed to see whether the outdoor air temperature at a given hour is higher than the bivalence point temperature t_{biv} and whether the outdoor air temperature at a given hour is higher than the heat pump shutdown temperature t_{off}. The heat pump shutdown temperature is a component of the input data. Checking for these logical conditions makes it possible to determine which of the heat sources is operating at a given hour or, possibly, the heat pump and the auxiliary source are operating together. The heat pump shutdown temperature was introduced to implement the calculation of all possible bivalent operating modes. In particular, here are the conditions for each of the bivalent operating modes:

– bivalent parallel operating mode of the combined heat source:

$$t_{off} \le t_{ext}^{D}, \quad (6)$$

under this mode, the heat pump operates throughout the heating period, but after reaching the bivalence point temperature, an auxiliary heat source is connected to help it and covers the residual heat load;

– bivalent sequential operation mode of the combined heat source:

$$t_{off} = t_{biv} \wedge t_{off} > t_{ext}^{D}, \quad (7)$$

Under this mode, the heat pump stops working after reaching the bivalence point temperature and the heat load is completely taken over by the auxiliary heat source;

– bivalent combined operating mode:

$$t_{biv} > t_{off} > t_{ext}^{D}, \quad (8)$$

under this mode, the heat pump continues to operate after reaching the bivalence point temperature, but until a certain temperature is reached. Then the heat load is completely transferred to the auxiliary heat source. Such an algorithm can be effective when the heat pump operation remains economically profitable after reaching the bivalence point.

After performing this check, three main calculation scenarios are possible for the *i*-th hour of the heating period:

a) at this hour, the heat load is completely covered by the air heat pump;

b) at this hour, the heat load is completely covered by the auxiliary heat source;

c) at this hour, the heat load is covered by the air heat pump and the auxiliary source together;

Scenario a. If in this hour the heat load of the heating system is completely covered by the heat pump, then the calculation of the amount of heat energy that will be transformed by it during this hour is performed according to the formula:

– if the daily electricity tariff is in effect at this hour:

$$E_{HP}^{d} = Q_{HS}^{i} \cdot \tau; \quad (9)$$

– if the night electricity tariff is in effect at this hour:

$$E_{HP}^{n} = Q_{HS}^{i} \cdot \tau, \quad (10)$$

where E_{HP}^{d}, E_{HP}^{n} is the amount of thermal energy that will be transformed by the heat pump at a specific hour in the daytime and nighttime periods, respectively, kWh; τ – duration of the heat load, h. Since the calculation is based on hourly temperature data, the duration of the heat load is 1 hour.

The division of the amount of thermal energy transformed by the heat pump is possible due to the use of the hourly array of outdoor air temperatures in the calculations.

The next step is to calculate the heat conversion coefficient of the heat pump at a given hour. The value of the heat conversion coefficient of the air heat pump depends on the temperature difference between the outdoor air and the heat carrier in the supply pipeline of the heating system at a specific hour:

$$COP_i = f\left(t_{in}^{i} - t_{ext}^{i}\right). \quad (11)$$

This dependence can also be obtained by analyzing the technical documentation of heat pump manufacturers. To calculate the heat conversion coefficient, it is necessary to have the value of the outdoor air temperature at a specific hour and the temperature of the heat carrier in the supply pipeline of the heating system at this hour. The temperature of the heat carrier at a given hour can be calculated from the formula:

$$t_{in}^{i} = \frac{t_{ext}^{i} - t_{ext}^{D}}{t_{int} - t_{ext}^{D}} \cdot \left(t_{int} - t_{in}^{D}\right) + t_{in}^{D}, \quad (12)$$

where t_{in}^{i} is the temperature of the heat carrier in the supply pipeline of the heating system at a specific hour of the heating period, °C; t_{int} – temperature of the indoor air at this hour, °C; t_{in}^{D} – calculated temperature of the heat carrier in the supply pipeline at the calculated outdoor air temperature for heating (input data component), °C.

After determining the conversion coefficient, the amount of electrical energy that will be consumed by the heat pump during a given hour is calculated for the day and night periods separately:

– if a daily electricity tariff is in effect at a given hour:

$$W_{HP}^{d} = \frac{E_{HP}^{i}}{COP_i}; \quad (13)$$

– if the night electricity tariff is in effect at this hour:

$$W_{HP}^{n} = \frac{E_{HP}^{i}}{COP_i}, \quad (14)$$

where W_{HP}^{d}, W_{HP}^{n} is the amount of electrical energy that will be consumed by the heat pump during a given hour during the day and night periods, respectively, kWh.

Scenario b. If at a given hour the heat load of the heating system is fully covered by the auxiliary heat source, then the amount of heat energy that will be produced by it during a given hour is calculated as:

$$E_{AS}^{i} = Q_{HS}^{i} \cdot \tau, \quad (15)$$

where E_{AS}^{i} is the amount of thermal energy that will be produced by the additional heat source during a given hour, kWh.

And then, depending on what is the auxiliary heat source, the amount of electrical energy or the amount of fuel that will be consumed during a given hour is calculated:

– if the auxiliary heat source is an electric boiler, then the amount of electrical energy that will be consumed during a given hour is calculated as:

$$W_{AS}^{i} = E_{AS}^{i}; \quad (16)$$

– if the auxiliary source of heat is a gaseous or solid fuel boiler, then the amount of fuel that will be consumed during this hour is calculated as:

$$B_{AS}^{i} = \frac{E_{AS}^{i}}{LCV \cdot \frac{\eta}{100}}, \quad (17)$$

where W_{AS}^{i} is the amount of electrical energy that will be consumed by the electric boiler during a given hour, kWh; B_{AS}^{i} – volume or mass of fuel that will be consumed by the gas or solid fuel boiler during a given hour, m^3 or kg; LCV – lower calorific value of the fuel, kWh/m^3 or kWh/kg; η – efficiency of the heat generator, %.

In the case when the auxiliary heat source is an electric boiler, the amount of electrical energy that will be consumed by it is calculated for the day and night periods separately. This separation is performed in order to be able to calculate the cost of electricity for these periods at different tariffs.

Scenario c. If at a given hour the heat load is covered jointly by an air heat pump and an auxiliary heat source, then the share covered by the heat pump is calculated as:

$$Q_{HP}^{i} = Q_{HP}^{+2} \cdot k_i. \quad (18)$$

Then the proportion of the heat load covered at a given hour by an auxiliary heat source is:

$$Q_{AS}^{i} = Q_{HS}^{i} - Q_{HP}^{i}. \quad (19)$$

The next step is to calculate the amount of thermal energy that will be transformed by the heat pump according to formulas (9), (10), and the amount of electricity that will be consumed by it during a given hour according to formulas (13), (14). Also, the amount of thermal energy that will be produced by the auxiliary source according to formula (15) and the amount of energy carriers that will be consumed by it during a given hour according to formulas (16), (17) are calculated.

The determination of the operating heat source and the calculation of the amount of energy carriers consumed by it are carried out for each hour of the heating period. After that, the indicators of the amount of thermal energy produced and the amount of energy carriers consumed are summed up for each heating period using an example of the following formula:

$$W_{HP}^{hsd} = \sum_{i=1}^{n} W_{HP}^{d}, \quad (20)$$

where W_{HP}^{hsd} – amount of electrical energy consumed by the heat pump during the day during one heating period, kWh; n – the number of hours of operation of the heating system in the heating period.

And depending on the number of heating periods taken into analysis, the obtained indicators are averaged using the following formula:

$$W_{HP}^{totd} = \frac{\sum_{i=1}^{n} W_{HP}^{hsd}}{n}, \quad (21)$$

where W_{HP}^{totd} – average amount of electrical energy consumed by the heat pump during the day over n heating periods, kWh; n – the number of heating periods taken into account for the analysis.

By using hourly outdoor temperatures and calculating the heat conversion coefficient for each hour of operation of the heat pump and each heating period, it becomes possible to estimate its weighted seasonal heat conversion coefficient:

$$SCOP_{net}^{hs} = \frac{\sum_{i=1}^{n} COP_i \cdot E_{HP}^{i}}{\sum_{i}^{n} E_{HP}^{i}}, \quad (22)$$

where $SCOP_{net}^{hs}$ is the average weighted heat conversion coefficient of the heat pump for one heating period; COP_i – the heat conversion coefficient of the heat pump for the i-th hour of the heating period; E_{HP}^{i} – amount of thermal energy transformed by the heat pump during the i-th hour of the heating period, kWh.

5. 2. Development of an algorithm for automating the calculation

Owing to the use of detailed hourly data as the basis for the calculation, the accuracy of the results improves but the volume and complexity of the calculation also increases. And therefore, there is a need for its automation, that is, the need to build a flexible program. To automate any calculation in any software environment, it is impossible to do without an algorithm.

Based on the proposed mathematical model of the methodology for assessing seasonal thermal energy generation by a combined heat source, it is possible to build an appropriate calculation algorithm (Fig. 1). The developed algorithm is based on the use of data on hourly outdoor air temperatures and makes it possible to take into account various bivalent schemes.

Parallelograms on the flowchart indicate input data modules; rectangles indicate calculation processes; and diamonds indicate logical operations. For easier perception, input data modules on the flowchart are located directly next to their application processes. The blue dashed line divides the algorithm into two parts. The first part represents the algorithm for calculating one hour of the heating period, and the second part contains modules in which the corresponding indicators for all hours of operation of the heating system for one heating period are added. The first module of input data is the heating system operation schedule, which should contain information about the calculated indoor air temperature for each hour of the day and day of the week. Detailed information about the indoor air temperature is required to calculate the heat loads of the main and standby modes separately.

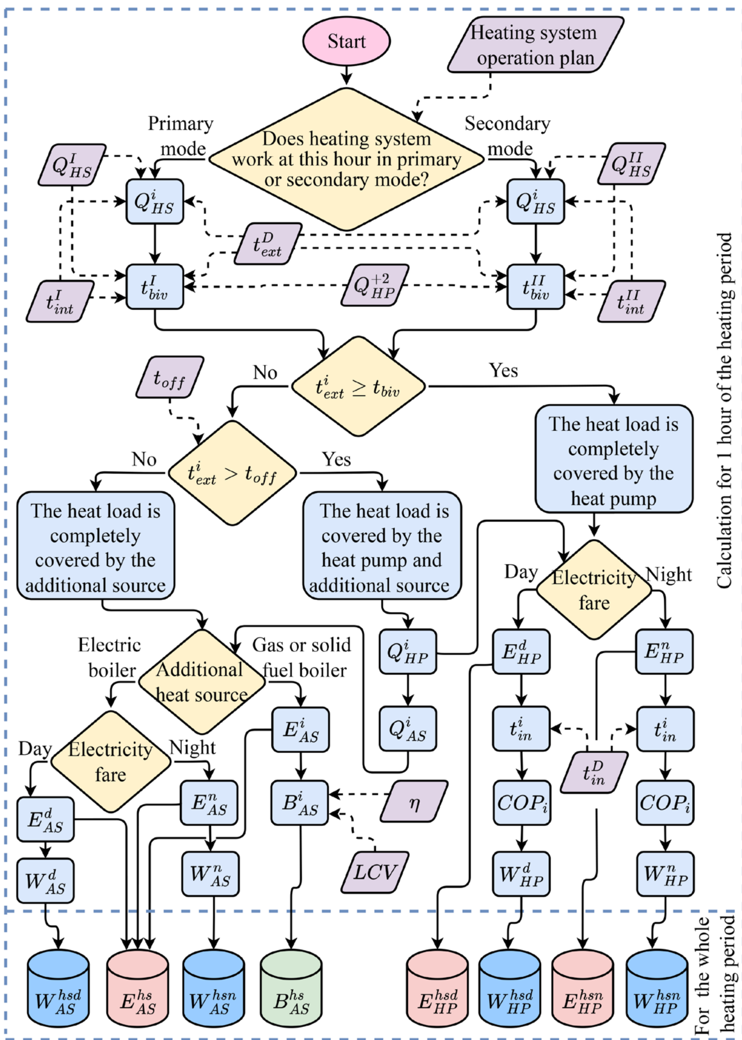

Fig. 1. Calculation algorithm using hourly data

5. 3. Example of the application of the algorithm and the possibilities of the methodology being devised

The results of statistical analysis and the obtained dependences of characteristics of air heat pumps that were accepted for calculation are shown in Fig. 2, 3.

To verify the resulting models, an assessment of the calculation error was carried out. The average error in the calculation of the thermal power varies within 3–4.5 %, and the maximum reaches 14 %. The average error in the calculation of the conversion coefficient varies within 3–6.6 %, and the maximum reaches 13 %. It should be noted that the largest error occurs at very low or high outdoor temperatures. With the most common operating algorithms, upon reaching these temperatures, the heat pump does not work or works for a short time. Therefore, it can be stated that the accuracy of our model is acceptable for practical calculations.

As the calculated heat load of the heating system when checking the algorithm, the value of 25 kW (at t^D_{ext} = –22 °C) for the main mode and 22.7 kW for the standby mode was taken. The thermal power of the air heat pump was taken to be 17.6 kW (under A2/W35 conditions). With such values of the calculated heat load and acceptable heat pump power, the temperature of the bivalence point is t^I_{biv} = –5.18 °C for the main mode, and t^{II}_{biv} = –7.84 °C for the standby mode. An electric boiler was taken as an auxiliary heat source. The calculation was carried out for three variants of bivalent modes:

a) bivalent sequential mode – the heat pump operates until the outdoor air temperature drops below the bivalence point temperature;

b) bivalent combined mode – the heat pump operates until the shutdown temperature t_{off}=–10 °C is reached. But after the outdoor air temperature drops below the bivalence point temperature, an auxiliary heat source is connected to help it;

c) bivalent parallel mode – the heat pump operates throughout the heating period, but after the outdoor air temperature drops below the bivalence point temperature, an auxiliary heat source is connected to help it.

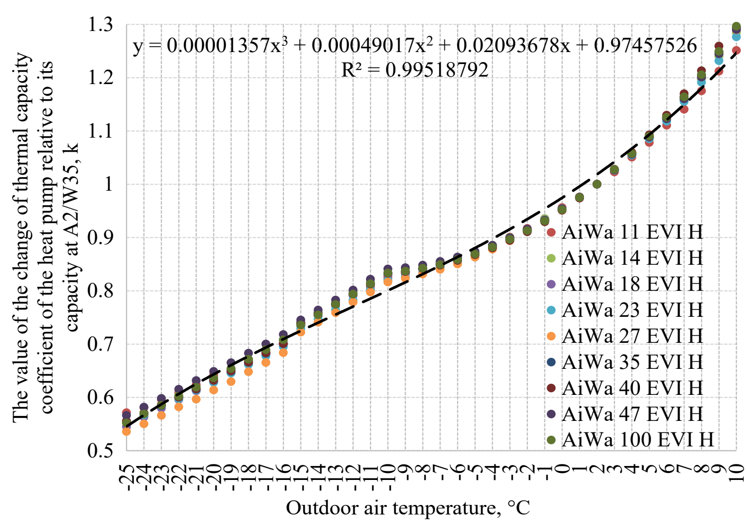

Fig. 2. Model of the coefficient of change in the thermal power of an air source heat pump

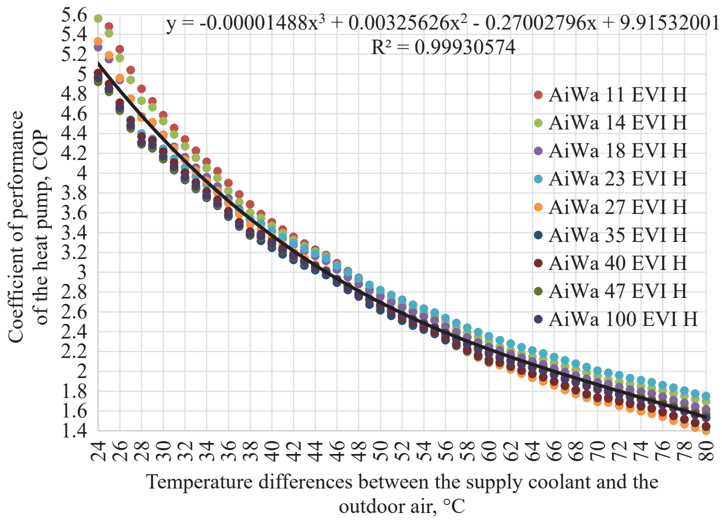

Fig. 3. Model of the heat conversion coefficient of an air source heat pump

The calculation results are represented as histograms in Fig. 4–6. The histogram in Fig. 4 shows the energy consumption of the heating system and the distribution of heat energy generation by heat sources in a combination depending on the number of recent heating periods taken into account for the analysis. The seasonal distribution of generation between heat sources is indicated in fractions of a unit.

The histograms in Fig. 5, 6 show the total electricity consumption and its distribution between the heat sources in a combination depending on the number of recent heating periods taken into analysis for two variants of the heating system temperature regime: 45/35 °C and 65/45 °C. These temperature regimes were adopted to compare the efficiency of the combined heat source when operating with a low-temperature and conventional heating system.

The results of calculating the weighted seasonal heat conversion coefficient of the heat pump for each of the last fifty heating periods for three variants of bivalent operating modes and two variants of temperature regimes of the heating system are shown in Fig. 7, 8.

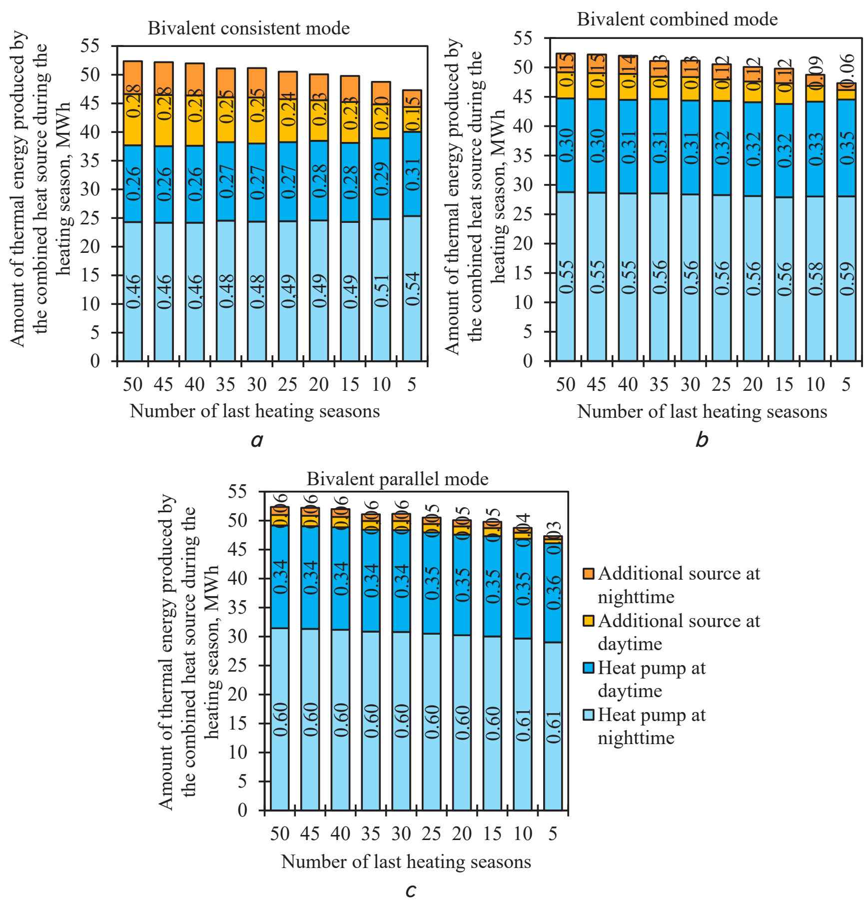

Fig. 4. Energy consumption of the heating system and distribution of thermal energy generation depending on the number of years taken into analysis: *a* — bivalent sequential; *b* — bivalent combined; *c* — bivalent parallel

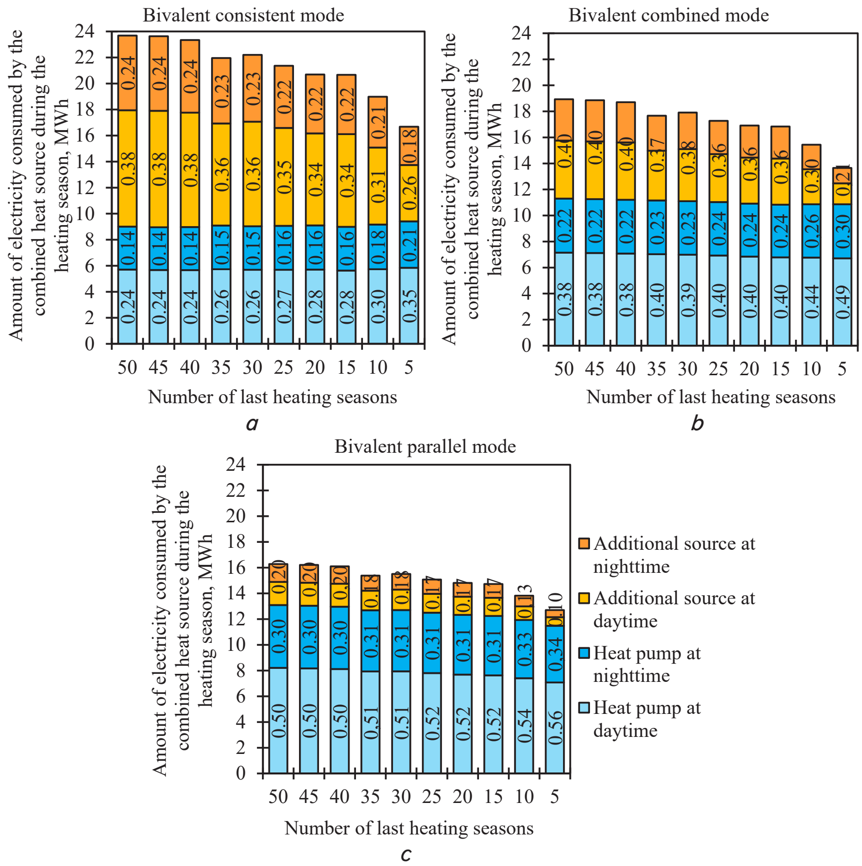

Fig. 5. Distribution of electricity consumption by sources in a combination at a heating system temperature regime of 45/35 °C depending on the number of years taken into analysis: *a* – bivalent sequential; *b* – bivalent combined; *c* – bivalent parallel

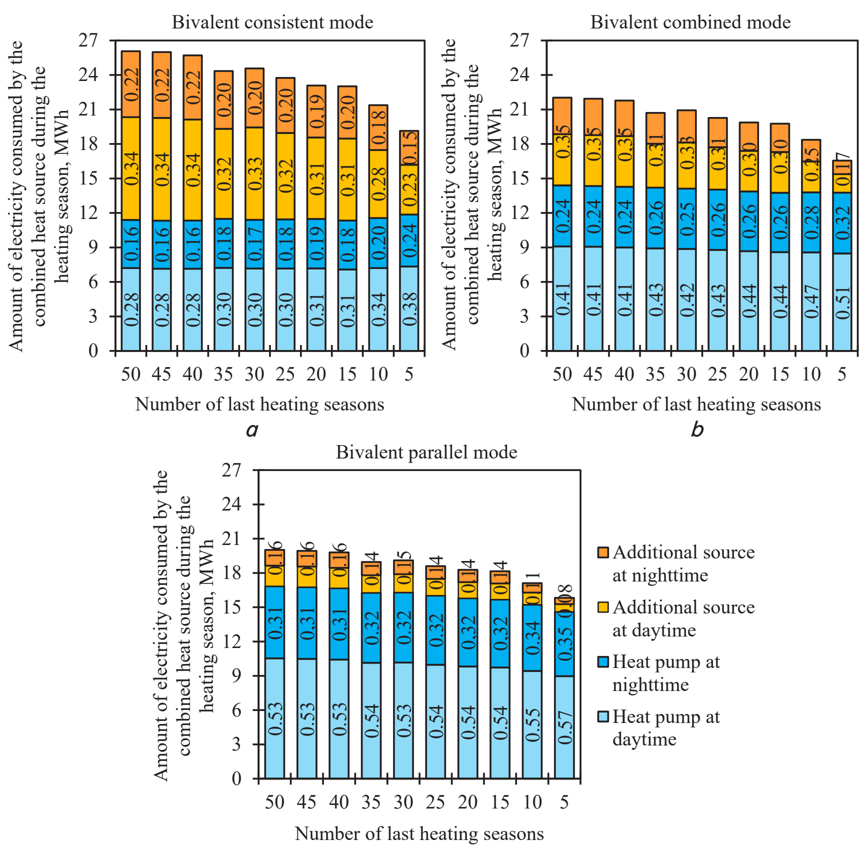

Fig. 6. Distribution of electricity consumption by sources in a combination at a heating system temperature regime of 65/45 °C depending on the number of years taken into analysis: *a* – bivalent sequential; *b* – bivalent combined; *c* – bivalent parallel

For a simpler analysis of the results of calculating weighted seasonal conversion factors, box diagrams were constructed in Fig. 9–11. The box plots show the mean values and range of the weighted average seasonal conversion coefficient depending on the number of recent heating periods taken into account for the analysis.

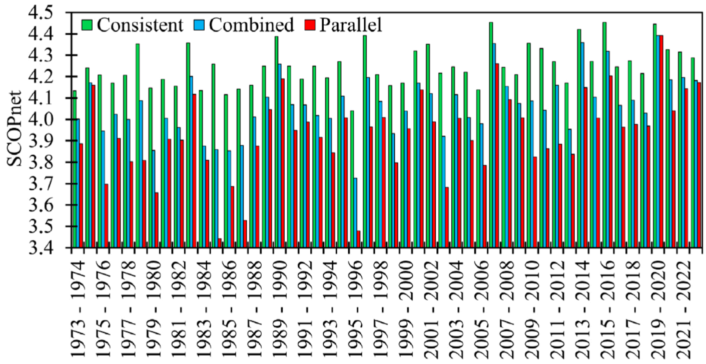

Fig. 7. Values of the weighted seasonal heat conversion coefficients of the heat pump over the last 50 heating periods when operating under a temperature regime of 45/35 °C

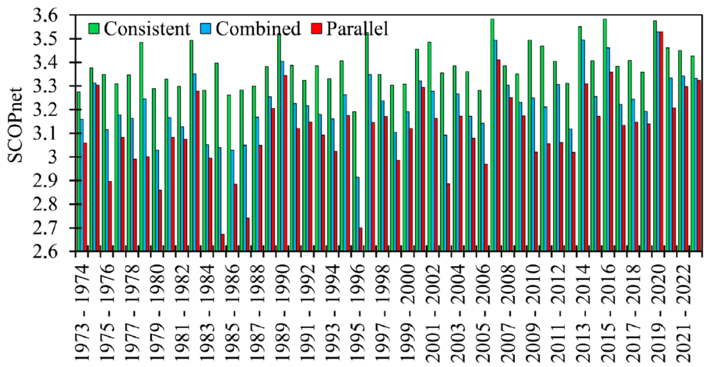

Fig. 8. Values of the weighted seasonal heat conversion coefficients of the heat pump over the last 50 heating periods when operating under a temperature regime of 65/45 °C

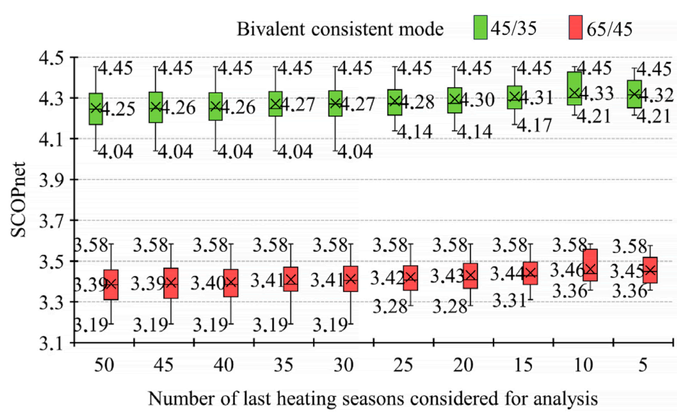

Fig. 9. Range of values of the seasonal heat conversion coefficient of a heat pump in bivalent sequential operation

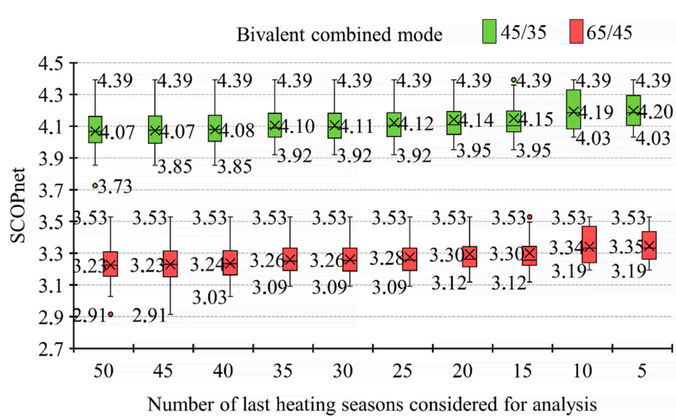

Fig. 10. Range of values of the seasonal heat conversion coefficient of a heat pump in bivalent combined operation

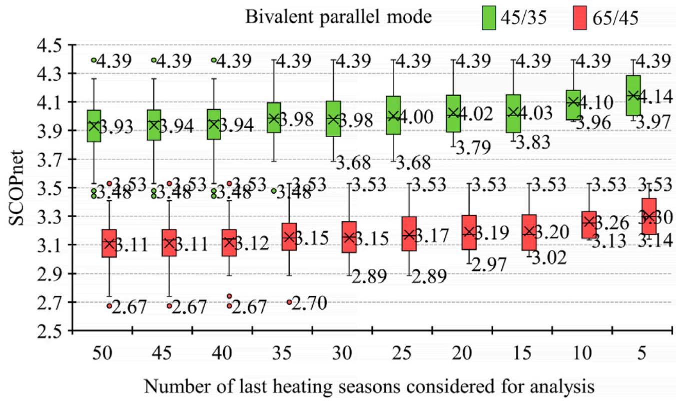

Fig. 11. Range of values of the seasonal heat conversion coefficient of a heat pump in bivalent parallel operation

6. Discussion of results based on testing the devised methodology and the developed algorithm

The devised methodology for estimating seasonal heat generation by a combined heat source (1) to (21) is based on an array of hourly climate data. Unlike the methodologies considered in other studies [13–15, 18, 19], this methodology makes it possible to take into account a number of important factors. They include variable heating system mode, various bivalent schemes, different energy tariffs. The developed algorithm for estimating seasonal heat generation (Fig. 1) is an effective tool for implementing the proposed methodology in practice. Our algorithm makes it possible to build a program that could simplify and speed up the calculation process. The efficiency of our methodology (1) to (21) was confirmed on the basis of numerical calculations using statistical data from [16].

The results of applying the devised methodology using a specific example are shown in the diagrams of Fig. 4–11. The histograms in Fig. 4 show that the total heat energy consumption by the heating system decreases with a decrease in the number of heating periods taken into analysis. At the same time, the share covered by the heat pump increases. This occurs due to a decrease in the recurrence of low outdoor air temperatures in heating periods and indicates gradual climate changes. Comparing the histograms of different bivalent modes with each other, a significant difference in the distribution of heat generation is visible, which is a consequence of the different duration of operation of heat sources.

The histograms in Fig. 5, 6 demonstrate that the total seasonal electricity consumption by a combined heat source decreases with a decrease in the number of years taken into analysis, which is a consequence of a decrease in the need for heat. At the same time, the share consumed by the auxiliary source decreases, and the share consumed by the heat pump increases, which is explained by the increase in the share of heat generation by the heat pump, and therefore, by the increase in the duration of its operation. About 40 % of the electricity during the heating period is consumed by the combined heat source at night. This factor is of particular importance, given that the night-time electricity tariff is usually much lower than the daytime tariff.

Comparing the total electricity consumption of the combined heat source when operating at different temperature regimes of the heating system, it is clear that it is much lower for the low-temperature system.

From the diagrams in Fig. 9–11 it is clear that the range of data is smaller if we analyze a smaller number of recent heating periods, and the average value of the seasonal conversion coefficient is higher. This once again proves the presence of climate change and the gradual softening of winter periods in recent decades. Among the adopted bivalent modes, the most favorable for the efficiency of the heat pump is the bivalent sequential one, because in it the heat pump is supposed to operate only until the temperature of the bivalence point is reached. Therefore, it is expected that all other modes will have a smaller value of the seasonal conversion coefficient. The difference between the average values of the seasonal conversion coefficient when the heat pump operates under the temperature regime 45/35 and 65/45 is significant. But, despite this, the SCOP values for the temperature regime 65/45 °C are quite high, taking into account the influence of existing climate changes.

From a practical point of view, the use of our methodology makes it possible to more accurately select equipment for combined heat sources and more accurately estimate its payback period. As a result of comparing the devised methodology with the methodology based on data on the average duration of temperature standing, it was found that with the same initial data, the deviation of the results of average seasonal energy consumption does not exceed 2 %.

The main disadvantage of using our methodology is the technique for calculating the heat load of the heating system for each hour. This calculation assumes a directly proportional dependence of heat load on the outside air temperature, i.e., a change in the outside air temperature in the next hour leads to an instantaneous change in the heat load. But in reality, there is a certain time delay in this process, the value of which depends on the thermal inertia of the enclosing structures. In addition, the methodology does not take into account the dependence of heat load on such climatic parameters as wind speed and solar radiation intensity. In order to take these factors into account, it is necessary to model the process of attenuation of the temperature wave in the thickness of the enclosing structures for each subsequent hour of the heating period. In this case, the mathematical model must take into account the intensification of the heat transfer process from the surface of the enclosing structures to the outside air due to the influence of the wind, as well as the process of the receipt of thermal energy by solar radiation. Therefore, the module of initial data must be supplemented with a geometric model of the building taking into account the orientation of the enclosing structures along the cardinal points. In addition, a set of hourly data on wind speed, direction, and solar radiation intensity is required.

Addressing the described limitations and shortcomings is a promising task for further research.

7. Conclusions

1. The proposed mathematical apparatus makes it possible to correct the shortcomings of existing approach to calculating the distribution of heat generation and energy consumption by a combined source. This is achieved due to the ability to take into account the variable operating mode of the heating system, different tariffs for energy carriers, and different bivalent modes of the combined heat source. For this purpose, it is proposed to determine the heat load, heat pump efficiency, and the degree of participation of sources in generation for each hour of the heating period. To implement such an approach, the array of simplified temperature data was replaced by an array of detailed hourly data, and the type of bivalent mode is usually set by the temperature values of the bivalence point and the heat pump shutdown. Another significant advantage of using an array of hourly temperature data is the ability to calculate the weighted average seasonal conversion coefficient of the heat pump. By addressing the described shortcomings, the accuracy of results improves, but the complexity of the calculation also increases.

2. The developed algorithm makes it possible to automate the calculation process. Its features include the ability to flexibly change the location of the bivalence point, the number of heating periods accepted for analysis, the parameters of the temperature regime, and operating modes of the heating system. All this together facilitates analysis of possible technical solutions and helps choose the most appropriate one.

3. The possibilities of using the proposed methodology were verified by numerical simulation. The deviation of the calculation of the average seasonal energy consumption compared to the less detailed, but commonly used methodology based on data on the average duration of outdoor air temperatures under the same conditions does not exceed 2 %. Therefore, the devised methodology can be considered reliable. In addition, the dependence of indicators of the average seasonal energy consumption of the heating system, the distribution of heat generation, and the heat conversion coefficient on change in the time period of the climatic data taken for analysis has been demonstrated. This proves the importance of using current climatic data and demonstrates the advantages of using detailed hourly data.

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.

References

1. Khan, S. A., O'Hegarty, R., Finn, D., Kinnane, O. (2024). Environmental footprint analysis of domestic air source heat pumps. Resources, Conservation & Recycling Advances, 22, 200217. https://doi.org/10.1016/j.rcradv.2024.200217
2. Skochko, V., Solonnikov, V., Pohosov, O., Haba, K., Kulinko, Ye., Koziachyna, B. (2024). Minimization of Heat Losses in District Heating Networks by Optimizing their Configuration. Problems of the Regional Energetics, 3 (63), 182–195. https://doi.org/10.52254/1857-0070.2024.3-63.15
3. Pasichnyk, P., Pryimak, O., Pohosov, O., Kulinko, Y., Koziachyna, B. (2024). Experimental Study of the Aerodynamic Characteristics of a Solar Air Collector with an Absorber Made of Carbon Textile. Proceedings of EcoComfort 2024, 426–435. https://doi.org/10.1007/978-3-031-67576-8_38
4. Srithapon, C., Månsson, D. (2023). Predictive control and coordination for energy community flexibility with electric vehicles, heat pumps and thermal energy storage. Applied Energy, 347, 121500. https://doi.org/10.1016/j.apenergy.2023.121500
5. Botticella, F., Viscito, L. (2015). Seasonal Performance Analysis of a Residential Heat Pump Using Different Fluids with Low Environmental Impact. Energy Procedia, 82, 878–885. https://doi.org/10.1016/j.egypro.2015.11.832
6. Naldi, C., Dongellini, M., Morini, G. L. (2015). Climate Influence on Seasonal Performances of Air-to-water Heat Pumps for Heating. Energy Procedia, 81, 100–107. https://doi.org/10.1016/j.egypro.2015.12.064
7. Mouzeviris, G. A., Papakostas, K. T. (2020). Air-to-water heat pumps: the impact of climate, compressor technology, water output temperature and sizing on the seasonal coefficient of performance for heating. IOP Conference Series: Materials Science and Engineering, 997 (1), 012150. https://doi.org/10.1088/1757-899x/997/1/012150
8. Xie, X., Luo, Z., Grimmond, S., Liu, Y., Ugalde-Loo, C. E., Bailey, M. T., Wang, X. (2024). Could residential air-source heat pumps exacerbate outdoor summer overheating and winter overcooling in UK 2050s climate scenarios? Sustainable Cities and Society, 115, 105811. https://doi.org/10.1016/j.scs.2024.105811
9. Mauro, A. W., Pelella, F., Viscito, L. (2023). Performance degradation of air source heat pumps under faulty conditions. Case Studies in Thermal Engineering, 45, 103010. https://doi.org/10.1016/j.csite.2023.103010

10. Terry, N., Galvin, R. (2023). How do heat demand and energy consumption change when households transition from gas boilers to heat pumps in the UK. Energy and Buildings, 292, 113183. https://doi.org/10.1016/j.enbuild.2023.113183
11. Vocale, P., Morini, G. L., Spiga, M. (2014). Influence of Outdoor Air Conditions on the Air Source Heat Pumps Performance. Energy Procedia, 45, 653–662. https://doi.org/10.1016/j.egypro.2014.01.070
12. Bogdanov, D., Satymov, R., Breyer, C. (2024). Impact of temperature dependent coefficient of performance of heat pumps on heating systems in national and regional energy systems modelling. Applied Energy, 371, 123647. https://doi.org/10.1016/j.apenergy.2024.123647
13. Milev, G., Al-Habaibeh, A., Fanshawe, S., Siena, F. L. (2023). Investigating the effect of the defrost cycles of air-source heat pumps on their electricity demand in residential buildings. Energy and Buildings, 300, 113656. https://doi.org/10.1016/j.enbuild.2023.113656
14. Gollamudi, S., Fauchoux, M., Krishnan, E., Ramin, H., Joseph, A., Simonson, C. (2024). Methodology to evaluate design modifications intended to eliminate frosting and high discharge temperatures in air-source heat pumps (ASHPs) in cold climates. Energy and Buildings, 312, 114209. https://doi.org/10.1016/j.enbuild.2024.114209
15. Ayad, A., Wong, S., Delisle, V. (2025). Modeling of heat pumps load profiles for power systems integration. Electric Power Systems Research, 238, 111059. https://doi.org/10.1016/j.epsr.2024.111059
16. Historical Weather Data. Meteoblue. Available at: https://www.meteoblue.com/en/weather/archive/export
17. AiWa H EVI Urban Outdoor. WAMAK. Available at: https://www.wamak.eu/en/commercial/heat-pumps/air-water/aiwa-h-evi-urban-outdoor
18. Chakyrova, D., Rusev, D., Doseva, N. (2019). Estimation of Seasonal Efficiency of Air-to-Water Heat Pump Used in Heating Mode for Different Climatic Zones in Bulgaria. Journal of Engineering Science and Technology Review, 149–153. Available at: https://www.researchgate.net/publication/352062767_Estimation_of_Seasonal_Efficiency_of_Air-to-ater_Heat_Pump_Used_in_Heating_Mode_for_Different_Climatic_Zones_in_Bulgaria
19. Glamazdin, P., Koziachyna, B. (2024). Accounting for climate changes when constructing the Rossander graph. Ventilation, Illumination and Heat Gas Supply, 49, 38–55. https://doi.org/10.32347/2409-2606.2024.49.38-55