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EFFICIENCY OF THE RENEWABLE ENERGY SOURCES APPLICATION FOR AN AUTONOMOUS HEAT SUPPLY SYSTEM

Abstract. *Description of the developed software and information complex for modeling autonomous heat supply systems provided, which allows optimizing the selection of units and their operation modes and ensuring the production and redistribution of thermal energy in accordance with the schedule of consumers. Optimized modes simulation operation of the autonomous heat supply system for a cottage village based on local energy resources with minimal use of external energy sources performed. The use of software and information complex made it possible to calculate the parameters that provide optimal coverage of the heat load schedule of a cottage settlement based on local energy resources. For the calculation, the predicted values of the installed thermal power of the units and the heat load graph which was obtained by adapting the real annual graph of the external temperature of Stockholm to the geographical location of the Kyiv region were used. The developed new software and information complex provide an opportunity for hourly modeling, research into the optimal modes of operation of heat units, and evaluation of the effectiveness of the use of renewable energy sources in autonomous heat supply systems. In the developed software and information complex, the model of optimization of operating modes is applied, which belongs to the class of problems of optimal loading of generating capacities of power systems with the criterion of minimizing costs for production, accumulation, and consumption of thermal energy. An example of simulation results using a heat load schedule for a selected typical day is presented. The obtained results indicate a decrease in the specific cost of hourly heat supply with an increase in the part of thermal energy supplied at the expense of renewable energy sources. This is due to a decrease in the share of gas, and in general, any other generation based on fossil fuel technologies, in the total volume of heat supply. Thus, the effectiveness of the use of renewable energy sources based on local energy resources as part of the heat supply system of the cottage village was confirmed.*

Keywords: autonomous heat supply, the efficiency of renewable energy sources based on local energy resources.

1. Introduction

Determining the structure of the heat supply system [1] according to possible loads is the first step in the process of determining possible combinations of consumers and producers in managing the energy balance. At the same time, there is a need to determine effective methods of heat energy exchange between consumption nodes and the heat supply system during the day, weeks, months, and finally, the whole year, accounting for limitations of the following parameters: the network operating range, heat loads, technologies, use of typical installations for different types of consumers, use of energy storage.

The articles [2, 3, 4, 5] provide an overview of recent research and developments in the use of renewable energy sources for building applications, with a focus on energy efficiency. The authors explore different renewable energy sources, including solar, wind, and geothermal, and discuss their potential for use in building applications. They also examine various approaches to energy efficiency, such as the use of energy-efficient materials and building design strategies.

On the other hand, this article focuses specifically on the application of renewable energy sources for heat supply systems. The author presents a mathematical model that analyzes the efficiency of different renewable energy sources for an autonomous heat supply system. The article provides a detailed analysis of the performance of different energy sources, including solar, wind, and geothermal, and discusses the potential advantages and disadvantages of each source in the context of a heat supply system.

In summary, while all mentioned articles focus on renewable energy sources, the articles [2, 3, 4, 5] provide a broad overview of renewable energy applications in building design and energy efficiency, while this article specifically examines the efficiency of renewable energy sources in the context of an autonomous heat supply system.

Traditionally, district heating and cooling networks distribute energy from a centralized generating plant to a number of remote consumers. The disadvantages of this approach are significant heat losses poorly studied potential of integration of various available energy sources, and high installation costs.

The FLEXYNETS team [6] proposes to use a new generation of intelligent district heating and cooling networks that reduce energy transport losses by operating at "neutral" (15–20°C) temperature levels. Reversible heat pumps are used for heat exchange with the network on the consumer side, providing the necessary heating and cooling of buildings. Thus, the same network can provide modern heating and cooling. Such networks make it possible to utilize the spent heat of the network, even at low temperatures, in contrast to traditional networks of centralized heat supply, which can collect thermal energy only at temperatures above 100°.

In connection with the difficult situation in Ukraine, the task of assessing the potential and efficiency of using renewable energy sources (RES) in designing an autonomous local heat supply system for a cottage village based on local energy resources and with minimal use of external energy sources [7] is an urgent task. It is also necessary to analyze the reduction of the negative impact on the environment due to the use of renewable energy sources.

The work goals. The research purpose:

- effectiveness assessment of RES use in autonomous heat supply systems with minimal use of external energy sources;
- assessment of the decrease in the specific cost of hourly heat supply with an increase in the part of thermal energy supplied at the expense of RES, and accordingly, a decrease in the part of gas, and in general, any other generation based on fossil fuel technologies, in the total volume of heat supply.

2. Materials and methods

The author developed a new software and information complex [8] for modeling the operating modes of an autonomous heat supply system on the Solver Studio [9] platform. It enables hourly simulation and research of optimal modes of operation of heat units of autonomous heat supply systems.

Next initial data for calculations chosen:

1. Forecast annual values matrix (Fig. 1): outdoor temperature, heating needs, cooling needs, heat load. The elements of the matrix were obtained by adapting the real annual schedule of the external temperature of Stockholm [10] to the geographical location of the Kyiv region. Hourly analysis data and formulas given in [6] and [11] were used during adaptation.

2. The forecast annual values vectors of solar and wind-heat supply capacity are obtained by adapting the actual values given in [11].

3. Matrices of the values (presented in Table 1) of the required volumes of heat supply and the cost of the technologies used in the modeling (gas boiler, geothermal well, reversible heat pump, thermal energy storage, solar collector, wind station) obtained from the Excel version of the FLEXYNETS-tool_ver-1-0+GNU.xlsm [12]. It is designed to carry out preliminary feasibility studies for the implementation of the FLEXYNETS concept under various scenarios.

Table 1. Matrices of the required volumes of heat supply and the cost of the technologies used in the modeling

Technologies	Power, MW	LCOE, €/MWh
Solar collector	6,71	1
Wind station	3,60	1

Continuation of Table 1.

Technologies	Power, MW	LCOE, €/MWh
Heat pump	7,32	27
Geothermal well	1,06	5
Gas boiler	30,00	37
Thermal energy storage discharge	7,96	3.25
Thermal energy storage charge	9,95	3.25

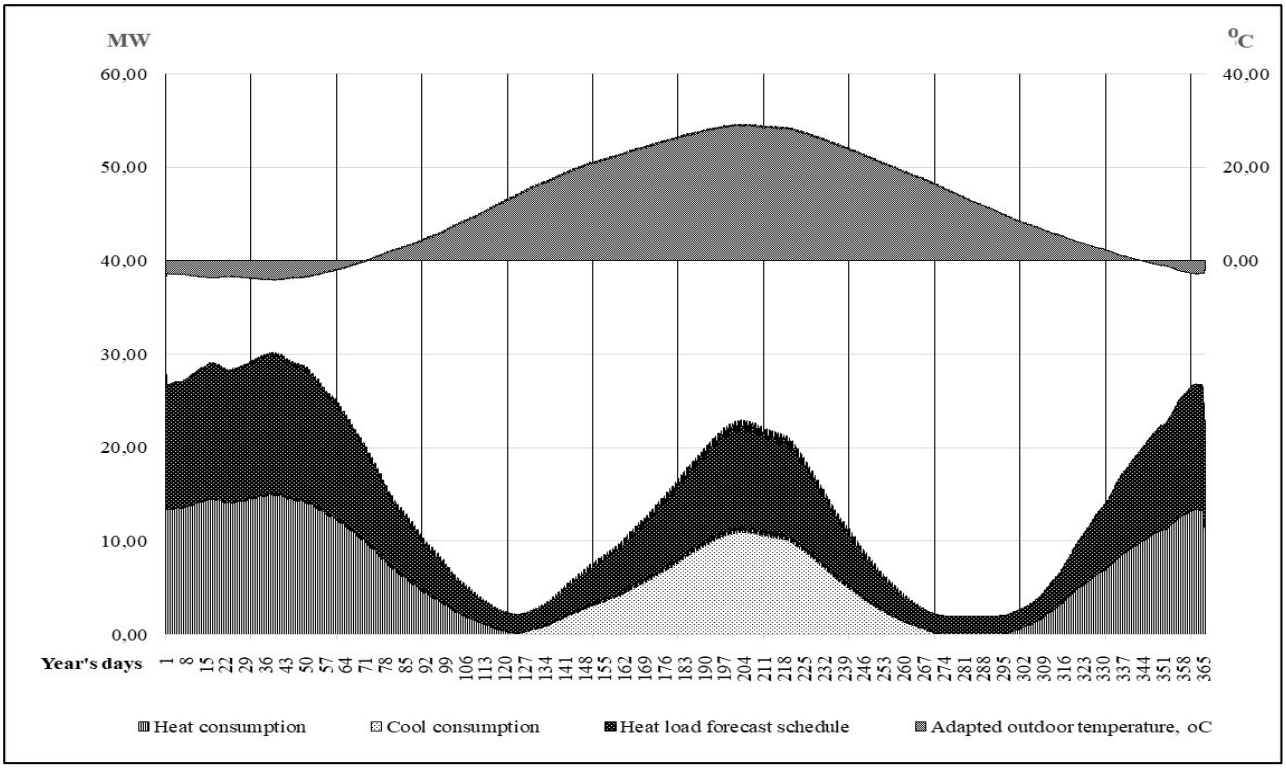

Fig. 1. Forecast schedules of external temperature, heating needs, cooling needs and heat load

Using the above as initial data, in the developed software and information complex, a model of the operating modes optimization of heat generating capacities is applied. It belongs to the class of optimization tasks – Optimal Unit Commitment of Power System (the task of optimal loading of generating capacities of power systems) with the criterion of minimizing costs for generation, storage, and consumption of both heat and electricity. In general, the mathematical model consists of an optimality criterion and constraints. The criterion of optimality (1) is the minimum costs for the production, storage, consumption of thermal energy while observing the exact coverage of the thermal load schedule (2). Technological restrictions on the modes of use for heat-generating units, thermal energy storage units (PTES) and heat network elements are strictly enforced.

$$\sum_{t}^{T}\left\{\sum_{g}^{G}\left(P_{tg}^{Gen}c_{tg}^{Gen}+S_{tg}^{Start}c_{tg}^{Start}\right)+\sum_{ptes}^{PTES}\left(P_{tptes}^{Gen}c_{tptes}^{Gen}+P_{tptes}^{Charge}c_{tptes}^{Charge}+S_{tptes}^{Start}c_{tptes}^{Start}\right)\right\}\to min, \tag{1}$$

$$\left\{\sum_{g}^{G}\left(P_{tg}^{Gen}\right)+\sum_{ptes}^{PTES}\left(P_{tptes}^{Gen}-P_{tptes}^{Charge}\right)-\sum P_{t}^{Loss}\right\}=DLP(s,t);\forall t\in T; \tag{2}$$

where: T – time in hours; G, $PTES$ – set of generating and accumulating capacities; P – power of: *Gen* –generation, *Charge* – accumulation, *Loss* – loss, MW; S – the number of heat unit starts; c – cost; $/MWh; $DLP(s,t)$ – thermal load, MW.

The model account specific features of the operation of the heat-generating and storage capacities of the autonomous heat supply system: the installed capacities of the power system components, and the limiting possibilities of changing the power of the heat energy storage and generation units. Thus, it has the advantage of adequate modeling of the modes of use of the units.

The model was implemented in the algebraic modeling language MathProg in the COIN-OR PuLP simulation environment [9].

The use of the model made it possible to investigate the possibilities of optimized dispatching of heat-generating capacities. As well as the generating and reserve capacities of large-capacity heat storage systems as part of the operation of an autonomous heat supply system, the limits of permissible values of the parameters of generating and storage capacities, at which stable and balanced operation of the heat supply system is possible. Also, evaluate the efficiency of the use of RES in autonomous heat supply systems with minimal use of external energy sources.

A new software and information complex [8], developed by the author, was used to determine the optimal modes of use of generating and storage capacities when covering heat load schedules. The complex provides an opportunity for hourly simulation and research of heat unit optimal modes at autonomous heat supply systems and evaluating the efficiency of using renewable energy sources in them.

3. Results and discussion

Ukraine has significant reserves of undeveloped local energy resources in the form of renewable energy sources, natural gas from substandard deposits, hydropower of small rivers, etc. [7]. Projects based on the integrated use of renewable energy sources – geothermal, solar, and wind – make it possible to create autonomous heat supply systems with minimal use of external energy sources.

A software and information complex for modeling the functioning of autonomous heat supply systems were developed. It allows for ensuring the optimal selection of aggregates and their operation modes, which will ensure the production and redistribution of energy in accordance with the schedule of consumers. Also, evaluate the effectiveness of the use of renewable energy sources in autonomous heat supply systems with minimal use of external energy sources.

With software and information complex, the simulation of optimized modes of operation of the heat supply system for a cottage village based on local energy resources with minimal use of external energy sources was carried out. Parameters, that provide optimized coverage of the heat load schedule of a cottage village calculated. Used predicted values of the installed thermal power of power units and the matrix of predicted annual values: external temperature, heat supply needs, cold supply needs, a heat load, obtained by adaptation of the real annual schedule of the external temperature of Stockholm [10] to the geographical position of the Kyiv region. Numerical estimates of the comparative effectiveness of the use of renewable energy sources in the autonomous heat supply system were obtained.

The values of the most important parameters that are used in calculations in the process of mathematical modeling are presented below.

Geographical location – Kyiv region of Ukraine. District type – land area/new district. The area of the cottage village is 3.1 km^2 with a low density of residential buildings of 2.6 km^2 and public space of 0.5 km^2. The annual heat demand – is 39.9 GWh. The volumes of the total heat load for the selected days ranged from 7.900 to 35.773 MWh.

Base and backup load heaters: natural gas boiler with an installed capacity of 30 MW. Geothermal well with a capacity of 1.06 MW. Reversible heat pumps with a thermal capacity of 7.32 MW. A wind farm with an electricity to heat converter of 3.6 MW. Solar collector with a capacity of 6.71 MW. Thermal energy storage has a capacity of 50 MWh and a capacity of 7.96 MW.

Heat energy exchange with the grid: annual heat withdrawal (net) – 39.9 GWh, condensation heat introduced into the grid – 14.6 GWh/year, annual heat losses from the grid – 3.62 GWh/year, available waste heat – 40.0 GWh, waste heat fed into the network – 22.7 GWh, annual heat production – 12.8 GWh/year.

Total heat load volumes for the selected days ranged from 79 to 358 MWh. The cost of heat supply, if only a gas boiler is used, is about 37 Euro/MWh. The cost of heat supply, if a gas boiler and renewable energy sources are used, varies from 19 to 28 Euros/MWh.

An example of simulation results using the heat load schedule for the day of January 10, 2018 presented in Table 2 and Fig. 2.

Table 2. Hourly heat load and heat capacity (MW) of heating units on January 10, 2018

Hours	Load	Gas boiler	Geotherm al well	Heat pump	Thermal energy storage, discharge	Thermal energy storage, charge	Solar collector	Wind station	% VDE	% Gas boiler	Cost, EU/MWh
1	14.20	5.00	1.06	7.32	0	0	0.00	0.82	65	35	27.40
2	14.27	5.18	1.06	7.32	0	0	0.00	0.71	64	36	27.69
3	14.33	5.35	1.06	7.32	0	0	0.00	0.60	63	37	28.06
4	14.39	5.47	1.06	7.32	0	0	0.00	0.54	62	38	28.22
5	14.44	5.84	1.06	7.32	0	0	0.00	0.23	60	40	29.01
6	14.49	5.81	1.06	7.32	0	0	0.00	0.30	60	40	28.84
7	14.52	5.91	1.06	7.32	0	0	0.00	0.23	59	41	29.06
8	14.52	6.02	1.06	7.32	0	0	0.00	0.12	59	41	29.34
9	14.42	5.76	1.06	7.32	0	0	0.08	0.21	60	40	28.84
10	14.25	5.59	1.06	7.32	0	0	0.22	0.06	61	39	28.78
11	14.01	4.99	1.06	7.32	0	0	0.54	0.10	64	36	27.70
12	13.75	4.13	1.06	7.32	0	0	1.18	0.06	70	30	25.97
13	13.51	3.55	1.06	7.32	0	0	1.53	0.06	74	26	24.87
14	13.32	3.67	1.06	7.32	0	0	1.24	0.03	72	28	25.52
15	13.18	3.95	1.06	7.32	0	0	0.81	0.06	70	30	26.55
16	13.09	4.06	1.06	7.32	0	0	0.58	0.08	69	31	27.05
17	13.05	4.54	1.06	7.32	0	0	0.05	0.09	65	35	28.43
18	13.10	4.61	1.06	7.32	0	0	0.00	0.11	65	35	28.55
19	13.24	4.74	1.06	7.32	0	0	0.00	0.12	64	36	28.63
20	13.44	4.96	1.06	7.32	0	0	0.00	0.11	63	37	28.71
21	13.68	5.22	1.06	7.32	0	0	0.00	0.09	62	38	28.95
22	13.90	5.36	1.06	7.32	0	0	0.00	0.16	61	39	28.86
23	14.05	5.47	1.06	7.32	0	0	0.00	0.21	61	39	28.89
24	14.17	5.58	1.06	7.32	0	0	0.00	0.22	61	39	28.93

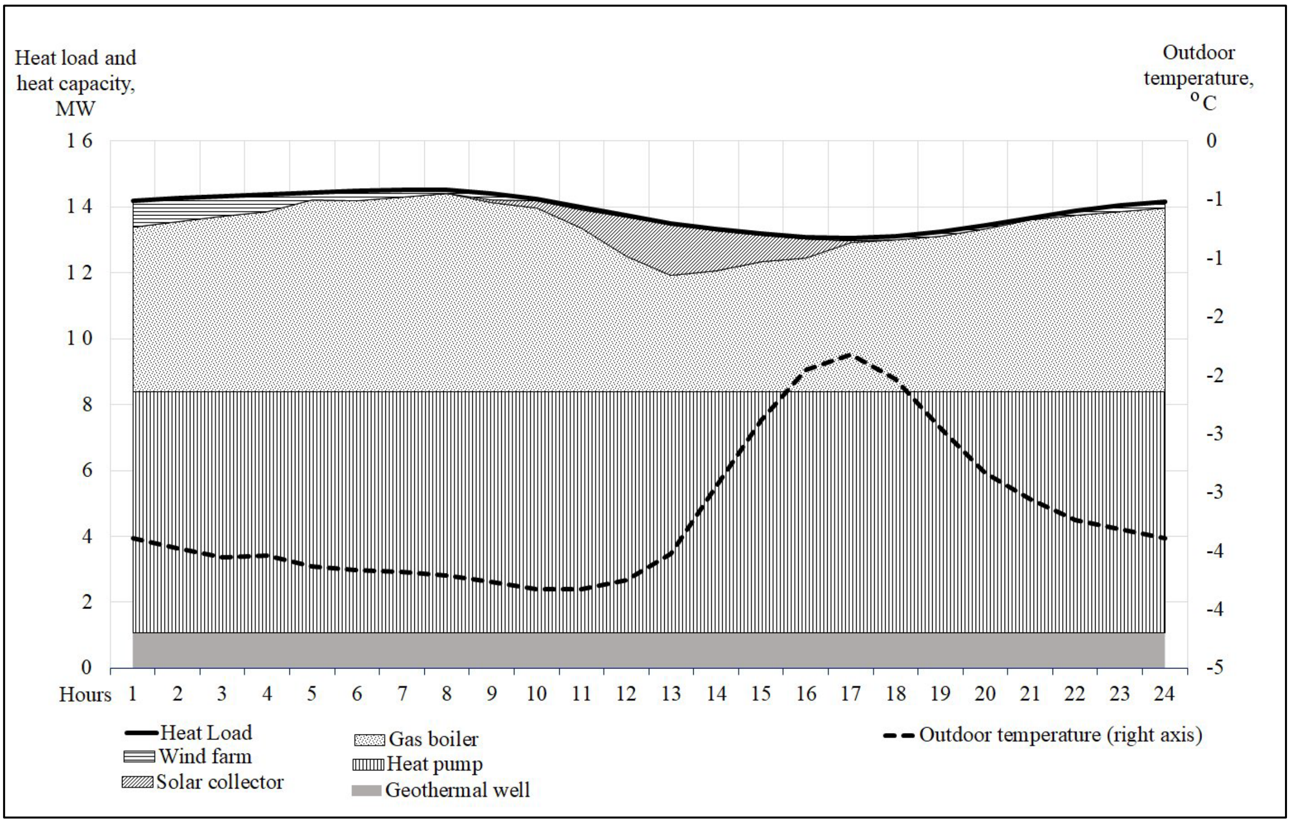

Fig. 2. Hourly thermal load and thermal power (MW) of heating units

Numerical estimates of comparative efficiency due to the use or non-use of renewable energy sources in the autonomous heat supply system are presented in Table 3 and Fig. 3 and 4.

Table 3. Numerical evaluations of comparative efficiency due to the use or non-use of RES in the autonomous heat supply system

	Total generation, MWh	Total cost of heat supply, only gas boiler, Euro	Selfcost of heat supply, only gas boiler, Euro/MWh	Total cost of heat supply, gas boiler and RES, Euro	Selfcost of heat supply, gas boiler and RES, Euro/MWh	Ratio of the selfcost of heat supply of gas boiler and RES / gas boiler, %
January 10	333.32	12 331	36.99	9 351	28.05	76
January 20	343.88	12 724	37.00	9 346	27.18	73
February 10	357.73	13 236	37.00	10 299	28.79	78
February 20	338.46	12 525	37.01	9 113	26.92	73
March 10	249.68	9 239	37.00	6 525	26.13	71
March 20	181.35	6 710	37.00	4 164	22.96	62
November 10	79.01	2 924	37.01	2 213	28.01	76
November 20	134.69	4 983	37.00	2 567	19.05	52
December 10	241.15	8 920	36.99	6 003	24.89	67
December 20	284.02	10 509	37.00	6 642	23.39	63

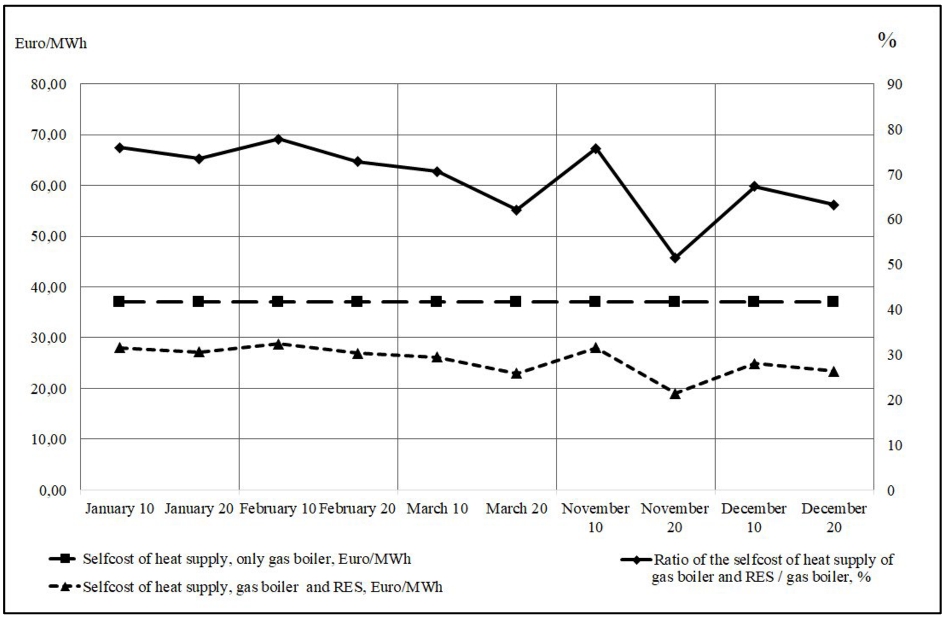

Fig. 3. Numerical cost estimates in an autonomous heat supply system for typical days of the heating season due to the use of RES

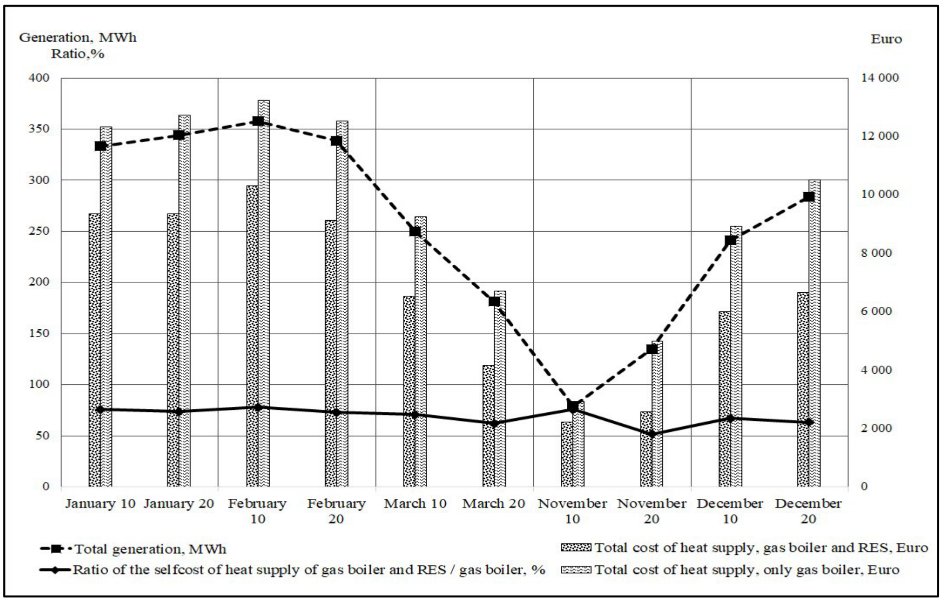

Fig. 4. Numerical evaluations of the comparative effectiveness of RES use in the autonomous heat supply system for typical days of the heating season

The obtained results indicate a decrease in the specific cost of hourly heat supply with an increase in the part of thermal energy supplied at the expense of RES, and accordingly, a decrease in the part of gas, and in the general case of any other generation based on fossil fuel technologies, in the total volume of heat supply. Thus, the effectiveness of the use of RES based on local energy resources as part of the heat supply system of the cottage village was confirmed.

4. Conclusions

Projects based on the integrated use of RES allow for the creation of autonomous heat supply systems with minimal use of external energy sources.

A new software and information complex for modeling autonomous heat supply systems with minimal use of external energy sources were developed. It allows investigating parameters of the heating units use, to identify the permissible limits of their operation, to ensure the optimal and stable functioning of the heat supply system under the condition of ensuring the production and redistribution of energy in accordance with the consumption schedule, and to evaluate the efficiency of the use of RES in the system.

With help of the developed software and information complex, hourly modeling and research of optimal modes of operation of thermal units of an autonomous heat supply system with minimal use of external energy sources performed, and numerical estimates of the efficiency of the use of renewable energy sources in the system were obtained.

Overall, the article provides valuable insights into the use of renewable energy sources for autonomous heat supply systems. The analysis made and the proposed model contributes to the development of more efficient and environmentally friendly heating systems. The article would be of interest to researchers and professionals working in the field of renewable energy and sustainable development.

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ЕФЕКТИВНІСТЬ ЗАСТОСУВАННЯ ВІДНОВЛЮВАНИХ ДЖЕРЕЛ ЕНЕРГІЇ ДЛЯ АВТОНОМНОЇ СИСТЕМИ ТЕПЛОПОСТАЧАННЯ

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Анотація. *Надано опис розробленого програмно-інформаційного комплексу для моделювання автономних систем теплопостачання, що дозволяє забезпечити оптимальний вибір агрегатів та режимів їх експлуатації, які забезпечуватимуть вироблення та перерозподіл теплової енергії відповідно до графіка споживачів. Виконано моделювання оптимізованих режимів експлуатації автономної системи теплопостачання для котеджного селища на базі місцевих енергоресурсів та з мінімальним використанням сторонніх джерел енергії. Використання програмно-інформаційного комплексу дозволило розрахувати параметри, що забезпечують оптимізоване покриття графіка теплового навантаження котеджного селища на базі місцевих енергоресурсів, на прикладі прогнозованих значень встановленої теплової потужності енергоагрегатів та фактичного графіку температури навколишнього середовища. Розроблений новий програмно-інформаційний комплекс дає можливість погодинного моделювання та дослідження оптимальних режимів функціонування теплових агрегатів автономних систем теплопостачання. В розробленому програмно-інформаційному комплексі застосована модель оптимізації режимів експлуатації, яка належить до класу задач оптимального завантаження генеруючих потужностей енергосистем із критерієм мінімізації витрат на виробництво, накопичення і споживання теплової та електроенергії. Наведено приклад результатів моделювання з використанням графіка теплового навантаження для обраної характерної доби. Отримані результати свідчать про зниження питомої вартості погодинного теплопостачання зі збільшенням частини теплової енергії, що поставляється за рахунок відновлюваних джерел енергії, і, відповідно, зниженням частини газової, а в загальному випадку будь-якої іншої генерації на технологіях викопного палива, в загальному обсязі теплозабезпечення. Таким чином, підтверджується ефективність використання відновлюваних джерел енергії на базі місцевих енергоресурсів у складі системи теплопостачання котеджного селища.*

Ключові слова: автономне теплопостачання, ефективність відновлюваних джерел енергії на базі місцевих енергоресурсів.

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