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IMPROVEMENT OF METHODS OF COMPREHENSIVE ASSESSMENT OF THE OPERATION EFFICIENCY OF CENTRALIZED HEAT SUPPLY SYSTEMS IN MUNICIPAL HEAT POWER ENGINEERING

Igor Kozlov
Doctor of Technical Sciences, Professor*
E-mail: kozlov_i.l_@ukr.net
Vyacheslav Kovalchuk
PhD, Associate Professor*
E-mail: kvi43@ukr.net
Oleksandr Klymchuk
Doctor of Technical Sciences, Professor
Department of Thermal Power Plants and Energy-saving Technologies**
E-mail: aaklymchuk@gmail.com
Katerina Sova
Postgraduate Student*
E-mail: sovaekaterina2@gmail.com
Inna Aksyonova
PhD, Associate Professor***
E-mail: a7631308@gmail.com
Krystyna Borysenko
PhD, Professor***
E-mail: nefertichevo@ukr.net
*Department of Water and Fuel Technology**
**Odessa National Polytechnic University
Shevchenko ave., 1, Odessa, Ukraine, 65044
***Department of Water Supply and Drainage
Odessa State Academy of Civil Engineering and Architecture
Didrihsona str., 4, Odessa, Ukraine, 65029

The possibility of a comprehensive assessment of the efficiency of the operation of a district heating system based on the indicator of the overall efficiency of the equipment OEE (overall equipment efficiency) and its extension to the system as a whole is considered. The disunity of the direction of existing approaches in assessing the efficiency of operation of district heating systems does not allow a comprehensive assessment of the overall efficiency of the functioning of the technological sequence of the entire system.

It is proposed to consider efficiency as the probability of full functioning of all elements of the heat supply system.

It is shown that the heat output of the boiler house is proportional to the power consumption of the boiler house and is approximated by a periodic function.

It is shown that the main element of the heat supply system, which determines its efficiency, is the heat-generating source. As a result of the study, it is determined that the efficiency of the heat-generating source functioning increases as the maximum value of its efficiency is reached.

Numerical modeling has shown that the flexible use of the installed heat generator capacity contributes to an increase in the efficiency factor from 0.53 to 0.70 and the overall efficiency of the heat supply system can be increased by more than 30 %. When designing a boiler house, it was recommended to provide for the installation of capacities with gradation 1; 0.5; 0.25.

It is shown that the OEE indicator allows one to characterize the efficiency of both the heat supply system as a whole and its individual components, and can be used in the design and analysis of the operation of systems

Keywords: heat supply system, heat supply modes, central boiler houses, efficiency criterion, efficiency assessment

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1. Introduction

Construction trends in recent years clearly indicate the chosen course of decentralization of heat supply systems [1]. Almost every second new building constructed is equipped with an autonomous heating system. As a rule, these are gas hot water boilers (60–70 %), electric boilers (7–8 %), solid fuel boilers (15–20 %), heat pumps (2–4 %) [2, 3]. As it is possible to see, most of them are gas boiler houses, mainly roof-top. The use of decentralized heat supply has its positive aspects – a lower tariff for the received heat, a wider range of modulation of heat power, no loss of heat and coolant in heating networks. It is also worth noting the possibility of an individual heating schedule, its beginning and end [4, 5].

However, decentralized heating systems also have disadvantages. These include the dispersal of harmful emissions over residential areas and a strong attachment to the source of heat. Also, centralized heat supply systems make it possible to take into account not only the individual modes of operation of buildings, but also the totality of heat supply modes for buildings for various purposes (residential, administrative, educational, others) [6]. The use of combined heat and power plants (HPP) also makes it possible to talk about the parallel generation of electricity.

The experience of organizing heat supply in European countries [2] shows that district heating systems are more environmentally friendly, have the ability to switch to other types of energy, use secondary energy resources (for example, waste heat) [7]. Also, such systems allow solving complex energy and environmental issues: utilization of household waste, combustion of wood waste from forestry and urban farms, etc. [8, 9].

Guided by positive trends in energy efficiency, the European Commission has developed an "Action Plan for Sustainable Energy Development" in the cities of the Eastern Partnership and Central Asia, describing technologies to optimize municipal heating systems [11].

The presence of the previously created building stock in the regions and the existing infrastructure of heat supply systems determined the use as sources of heat in them: boiler houses with a heating capacity of up to 300 Gcal/h (350 MW) and HPP [10].

When designing these systems, heat sources and heating networks were calculated for the maximum load with the prospect of expanding residential areas and microdistricts. Most of the existing heat supply systems do not connect new subscribers, and, therefore, at the moment the estimated capacity is known. When reconstructing centralized heat supply systems, in addition to replacing the main equipment, it is necessary to replace heating networks [12, 13].

The emergence of new energy strategies in heat supply systems in many countries indicates the need to use qualitatively new approaches in assessing the efficiency of the heat supply system.

2. Literature review and problem statement

The most complex indicator of the functioning of a system, including heat supply, is efficiency – a defining property of any purposeful activity, which is expressed by the degree of achievement of the goal, taking into account the cost of resources and equipment time.

In work [14] it is noted that the degree of perfection of the functioning of the system, that is, its efficiency, can be assessed by the ratio of products produced and expended resources. The heat supply system, like any technological sequence, is designed to produce the final product – heat, which provides comforTable conditions for the consumer. For production, resources are consumed: fuel, water, air, electricity and others. A quantitative assessment of the effectiveness of such a system requires the expression of correlated quantities in one dimension, which is associated with difficulties in transforming diverse quantities.

With the joint production of heat and electricity at HPPs, to assess the efficiency of the work, it is proposed to use the specific consumption of equivalent fuel for the joint production of both types of energy [15]. The analysis of this method showed its insufficient consistency due to the impossibility of a clear determination of the shares of the total fuel consumption for the production of electricity and heat.

The method for assessing the efficiency of the operation of district heating systems in small settlements described in [16] consists in determining the efficiency coefficient as the sum:

$$E_{hs} = \alpha_1 \cdot E_1 + \alpha_2 \cdot E_2 + \alpha_3 \cdot E_3, \tag{1}$$

where E_{hs} – efficiency coefficient of the heat supply system;

E_1 – efficiency coefficient of heat energy generation at the source;

E_2 – efficiency coefficient of transportation of heat energy from the source to the consumer;

E_3 – efficiency coefficient of heat energy consumption;

α_1, α_2, α_3 – weighting factors for each of the efficiency factors.

The resulting value of the efficiency coefficient E_{hs} is compared with the conventionally ideal option, when the maximum efficiency coefficient is or with other existing systems. The disadvantage of this technique is the absence of functional dependencies for the coefficients included in (1) and their weightings.

The efficiency coefficient of the heating network, proposed in [17], was selected based on the principle of completeness of coverage of different aspects of the rational use of the thermal energy potential of all circulating network water:

$$k_{ef} = f\left(t_r, t_s, t_{oa}\right), \tag{2}$$

where t_r, t_s, t_{oa} – the temperatures of the return and supply network water and the outside air, respectively.

The limitation of this indicator is associated with an assessment of the efficiency of only the heating network, which reduces the usefulness of the information received.

A similar approach was proposed in [18], where three parameters are used to describe the efficiency of heat energy transportation. For each of them, standards (class) are established and a correlation is performed with existing or applied calculation methods.

The need for systematic measurements of heat energy losses and the use of subjectively established indicators, with the localization of application only by the energy transportation section, does not allow assessing the efficiency of operation of heat supply systems as a whole and making forecasts.

The foregoing allows to assert that the existing approaches are aimed at assessing individual factors of operational efficiency and does not reflect the general level of assessing the efficiency of the technological sequence of the heat supply system.

The performed analysis [14–18] convinces of the relevance of a comprehensive assessment of efficiency for improving the circuit design and technological characteristics of such systems and the absence of a tool to ensure its implementation.

A variant of the solution to the problem under consideration can be the use of the *OEE* (overall equipment effectiveness) complex proposed by Seichi Nakajima, as a central component of the methodology for determining the possibilities of increasing the efficiency of the process performance and ways to achieve this improvement [19].

By the end of the 1980s, the *OEE* concept became widely known in the Western world [20]. Its provisions have been adapted to various spheres of the economy, allowing at a new level to assess the overall efficiency of various systems.

In the 2000s, *OEE* is used all over the world in almost all production processes [21].

3. The aim and objectives of research

The aim of research is to assess the possibility of using the *OEE* indicator as an indicator of the efficiency of district heating systems in the context of a component complex: heat source – transport networks – consumers.

To achieve this aim, it is necessary to solve the following objectives:

– choose an integral criterion for assessing the effectiveness of the system and propose a method for determining it;

– determine the range of the efficiency criterion for existing heat supply systems;

– to carry out a comprehensive assessment of the operation efficiency of the district heating system.

4. Materials and methods of research

For modeling, as an object of observation, a typical district heat supply system was considered, consisting of:

$$\underbrace{\text{heat supply source} \Rightarrow \text{heating network} \Rightarrow \text{consumer}}_{\text{control}},$$

the operational characteristics of which are given in Table 1. Each component of the system is a set of equipment, real estate and personnel that transform the initial raw materials (fuel) into the final product (heat, comfort).

The source of heat supply is a boiler house with an installed capacity of 300 Gcal/h (2×100+2×50)/(350 MW). The duration of the heating season is 5.5 months.

Table 1

Initial data for modeling

The length of the heating network for heating in a one-pipe version, m		103,520
Heating network section length, m		158,521
Heat losses for own needs, %		2.2
Heat losses in networks, %	Estimated	9.78
	Admissible	10.13
	Actual	11.22
Mass flow rate of water, kg/s		8.15
Number of accidents per year		179
Heat production, Gcal/year	2014	234,013
	2015	207,316
	2016	212,454
	2017	186,890
	2018	196,723
	2019	167,855
Estimated time, hours	Year	8,766
	month	730.5

Heat supply systems, according to the mode of operation, belong to the operating intermittently-periodically. Such a regime is clearly represented by graphs of electricity consumption (Fig. 1).

The frequency of changes in electricity consumption is represented by a ratio of the form:

$$N_e = N_{av} \cdot \left(0.9526 + 0.5392 \cdot \sin(\tau) + 0.8119 \cdot \cos(\tau)\right), \qquad (3)$$

where τ – time, day; N_{av} – average value of consumed energy, kW·h; N_e – calculated value of the consumed energy, kW·h.

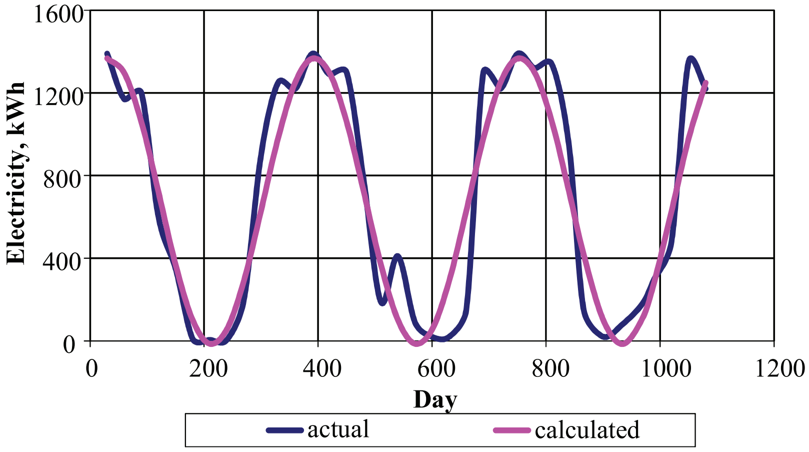

Fig. 1. Electricity consumption by the heat generating module of the boiler room

Assuming that the electricity consumption of the boiler house is proportional to its thermal energy productivity, the values of the monthly and hourly thermal energy productivity in the heating season were calculated (Table 2):

Table 2

Monthly and hourly productivity of the boiler room, (Gcal/month)/(Gcal/hour)

Years	Months						
	October	November	December	January	February	March	April
2014	27214	32399	39634	41794	38269	30036	24667
	50	60	73	77	71	56	46
2015	24109	28703	35112	37026	33903	26609	21853
	45	53	65	69	63	49	40
2016	24707	29415	35982	37944	34743	27269	22395
	46	54	67	70	64	50	41
2017	21734	25875	31653	33378	30563	23987	19700
	40	48	59	62	57	44	36
2018	22877	27237	33318	35134	32171	25250	20737
	42	50	62	65	60	47	38
2019	19520	23240	28429	29978	27450	21544	17694
	36	43	53	56	51	40	33

5. Results of evaluating the efficiency of the heat supply system

5. 1. Features of determining the efficiency indicator

Based on the results of the analysis performed, to assess the efficiency of the heat supply system, the *OEE* efficiency indicator was selected, which makes it possible to study each link of the technological chain and consider the system as a whole.

The evaluation procedure took into account the fact of intermittent operation during the year. Only the period of time corresponding to the heating season was taken into account. Fluctuations in the heat load during this period were assumed to be proportional to electricity consumption.

When determining the availability criterion, along with the scheduled maintenance time, shutdowns due to possible equipment failures were taken into account.

The most important asset in these complexes is equipment. Production assets, and above all equipment, must work for the maximum time with the maximum allowable load indicators [21, 22]. Effective asset management implies regular preventive maintenance and systematic elimination of losses associated with changeovers, raw materials supply and other processes.

The general equipment maintenance (*TPM*) concept, based on an integrated equipment performance metric *OEE*, is used to monitor, measure and process specific performance indicators [23–25].

The *OEE* indicator is constructed as the product of three criteria:

– availability (readiness) of equipment, *A* (Availability);
– productivity, *P* (Performance);
– quality, *Q* (Quality).

Availability criterion *A* analyzes the loss of time, excluding planned shutdowns (*PSD* – planned shut down), unscheduled stops (*DTL* – down time loss): equipment breakdowns and failures, stops due to a lack of raw materials, lack of storage space, etc. .Calculated as the ratio of the operating time (*OT* – operating time), when the equipment worked and released products, to the planned production time, or the planned production time (*PPT* – planned production time)

$$A=\frac{OT}{PPT}. \qquad (4)$$

The operational time is defined as the difference between the planned *PPT* production time and the *DTL* unscheduled shutdown times:

$$OT=PPT-DTL. \qquad (5)$$

The performance criterion *P* (Performance) takes into account the losses associated with the loss of the rate of release of units of production (for example, in our case, units of quantities of heat) *SL* (speed loss) due to wear of equipment, the quality of raw materials, the influence of the human factor. It is determined by the ratio of the actual number of units of production *TP* (total pieces) produced during the operating time *OT* and the maximum possible number of products per unit of time IRR (ideal run rate):

$$P=\frac{TP}{OT\cdot IRR}. \qquad (6)$$

The quality criterion *Q* takes into account the losses associated with poor product quality and is determined by the ratio of the number of good *GP* products to the total amount of *TP* products produced during the operating time *OT*

$$Q=\frac{GP}{TP}. \qquad (7)$$

All considered criteria are ratios of one-dimensional quantities. In mass trials, the ratio of positive outcomes to the total number of trials is likely. Therefore, the criteria can be considered the probabilities of availability, productivity and quality, and the efficiency indicator, respectively, the probability of an event occurring is the efficiency of a system element.

For the system as a whole, efficiency is defined as the product of this indicator of all its elements. This approach is given in [26]. The ineviTable heat losses on each of the elements of the heat supply system are determined by the corresponding efficiency coefficients, and the overall system indicator is represented by the product:

$$\eta_{co}=\eta_p\cdot\eta_d\cdot\eta_e\cdot\eta_c, \qquad (8)$$

where η_p – coefficient of the heat generating unit;
η_d – coefficient of heat distribution efficiency;
η_e – coefficient of heating device efficiency;
η_c – coefficient of system regulator efficiency.

To determine the values of the coefficients, graphical dependencies are proposed (Fig. 2), which are approximated by polynomials:

$$\eta_c=0.0141\gamma^2+0.0133\gamma+1.9129; \qquad (9)$$

$$\eta_e=0.0291\gamma^2+0.0178\gamma+1.8459; \qquad (10)$$

$$\eta_d=-0.0522\gamma^4+0.1564\gamma^3-$$
$$-0.0148\gamma^2-0.1311\gamma+1.8846; \qquad (11)$$

$$\eta_p=0.0678\gamma^3-0.4858\gamma^2+1.2728\gamma+0.8265; \qquad (12)$$

where γ – thermal load of the system, % of the nominal.

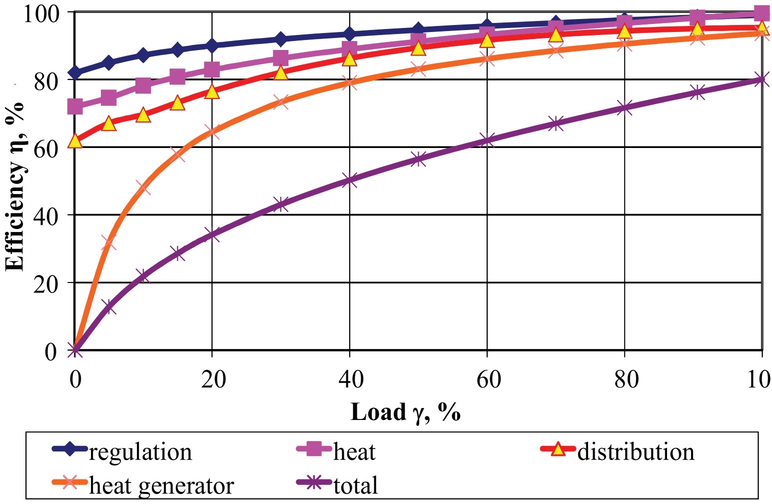

Fig. 2. Influence of relative load on efficiency ratios

5. 2. Estimates of the values of efficiency criteria for components of heat supply systems

Calculated estimates of the values of the efficiency indicator criteria for the elements of the heat supply system showed that the greatest fluctuations are characteristic of the performance criterion of the heat-generating element (0.32–0.95), depending on its productivity, efficiency, auxiliary needs, etc. (Fig. 3).

With seasonal heat generation by a boiler with a nominal capacity of 100 Gcal/h in the initial and final months, the performance criterion does not exceed 0.5, the use of a 50 Gcal/h boiler in these months raises the performance criterion to 0.75.

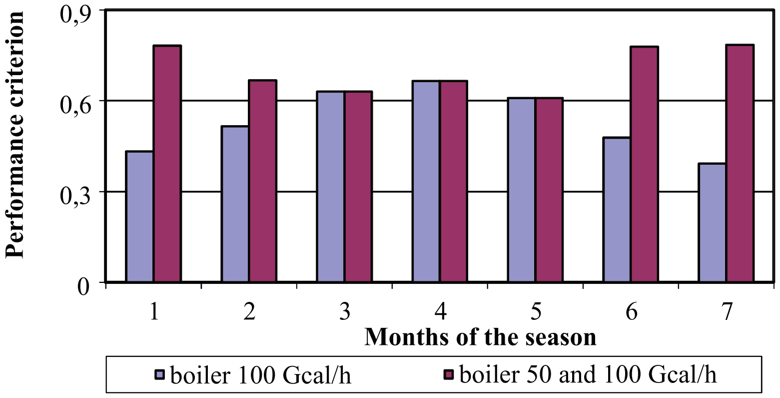

Fig. 3. Influence of the stepwise use of the heat generator's power on the performance criterion

The affordability criterion remains virtually unchanged at 0.936. The quality criterion ranges from 0.82 to 0.9.

5. 3. Comprehensive assessment of the operation efficiency of the heat supply system

The efficiency indicator of the heating main is determined mainly by the criterion of accessibility, and, depending on the duration of operation, does not go beyond 0.83–0.89.

Evaluation of the efficiency of heat consumption causes difficulties due to the condition of the consumer. Thermal insulation, infiltration, wetting of fences, etc. factors significantly affect the values of the criteria. According to estimates, fluctuations in *OEE* for the consumer are 0.98–1.0.

The combined efficiency indicator of the heat supply system is shown in Fig. 4.

Calculations have shown that the use of staged heat production, when the actual performance of the heat generator is close to its nominal, contributes to an increase in the efficiency of the heat supply system.

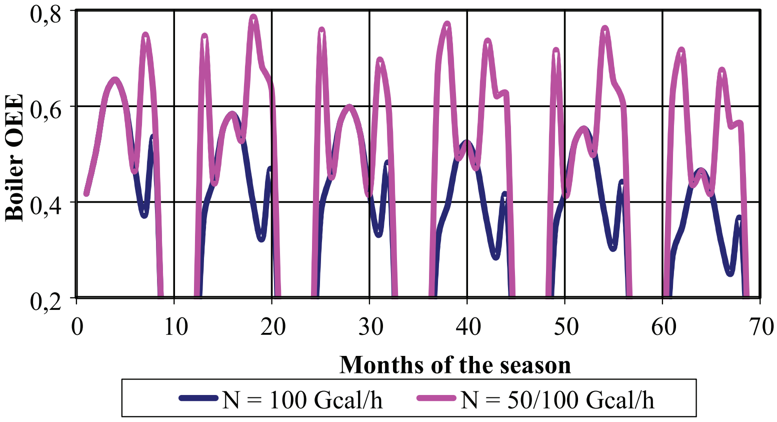

Fig. 4. Efficiency of the heat supply system

Comprehensive assessments of efficiency indicators using approximated efficiency factors of the technological chain of the heat supply system [26] and based on the *OEE* criterion are shown in Fig. 5.

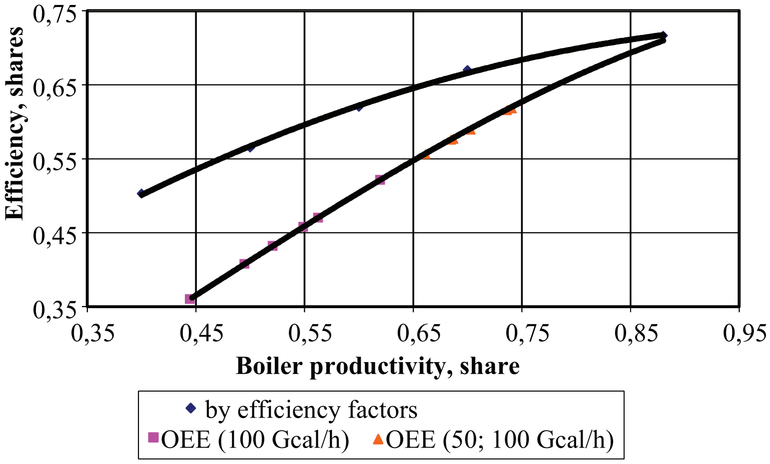

Fig. 5. Assessment of the heat supply system by efficiency factors and by an integrated efficiency indicator

6. Discussion of the results of the study of the overall efficiency indicator in the district heating system

Comparison of the estimates of the indicators of the efficiency coefficients calculated by the relations (8)–(12) and the integrated indicator of the efficiency *OEE* (Fig. 5) shows that in the first case, overestimated values were obtained. To a greater extent, this is manifested at low powers, in comparison with the nominal performance of the heat generator. The efficiency of a heat generator follows its efficiency, which reaches a maximum at 70–75 % of productivity, and then slightly decreases [27].

During the operation of complex systems, a complex intertwining of heterogeneous physical processes arises, which form internal feedbacks that cause a destabilizing effect [28]. Taking into account such impacts to a greater extent ensures the calculation of the criteria included in the *OEE* efficiency indicator.

The results obtained (Fig. 5) make it possible to reduce the total capacity of the heat source during the reconstruction of existing central boiler houses (provided that there is no prospect of building up the serviced residential area) by almost 20 % without reducing the quality of services. Reconstruction of the existing boiler house should take into account the distribution of the total load over the boilers with a step of 0.25, for more efficient operation of the heat source.

It also becomes possible to reduce the diameters of the main highways by taking into account the mutual influence of operating modes for buildings of various functional purposes.

Within the framework of the above material, the possibilities of assessing the effectiveness of the integration of renewable heat sources into existing heat supply systems have not been considered.

It is advisable to develop the results obtained in the direction of building a methodological basis for an analytical audit of heat supply systems by various heat sources, systems of its delivery and consumption modes.

7. Conclusions

1. To assess the efficiency of the heat supply system, it is proposed to use the equipment efficiency indicator *OEE* (overall equipment effectiveness), which makes it possible to evaluate the efficiency of the technological chain of the heat supply system as a whole and its components separately.

2. The results of numerical modeling showed that the interval of the integral indicator of the efficiency of the *OEE* of the heat supply system is 0.3...0.85, while the decisive factor is the efficiency of the heat-generating source.

3. When designing and reconstructing heat supply systems, it is recommended to provide for the possibility of flexible use of installed capacities in order to increase their efficiency. Using the power of boilers in a mode close to optimal ensures an increase in the efficiency factor of the heat generation section from 0.53 to 0.70, and the overall efficiency of the heat supply system increases by more than 30 %. It is necessary to provide for the installation of the power of heat sources with a gradation of 1:0.5:0.25, which can significantly increase the performance of the system.

References

1. Zhou, Y., Yu, W., Zhu, S., Yang, B., He, J. (2021). Distributionally robust chance-constrained energy management of an integrated retailer in the multi-energy market. Applied Energy, 286, 116516. doi: https://doi.org/10.1016/j.apenergy.2021.116516
2. Zhirkova, M. V., Kolodeznikova, A. N. (2017). Performance indicators of the heat supply system's operational condition. International Research Journal, 1 (55), 67–69. doi: https://doi.org/10.23670/IRJ.2017.55.164
3. Mazurenko, A., Klimchuk, A., Yurkovsky, S., Omeko, R. (2015) Development of the scheme of combined heating system using seasonal storage of heat from solar plants. Eastern-European Journal of Enterprise Technologies, 1 (8 (73)), 15–20. doi: https://doi.org/10.15587/1729-4061.2015.36902
4. Zaytsev, O. N., Lapina, E. A. (2017). Increasing the efficiency of the condensing boiler. Journal of Physics: Conference Series, 891, 012158. doi: https://doi.org/10.1088/1742-6596/891/1/012158
5. Wang, Z., Luo, M., Geng, Y., Lin, B., Zhu, Y. (2018). A model to compare convective and radiant heating systems for intermittent space heating. Applied Energy, 215, 211–226. doi: https://doi.org/10.1016/j.apenergy.2018.01.088
6. Klymchuk, O., Denysova, A., Balasanian, G., Ivanova, L. (2020). Enhancing efficiency of using energy resources in heat supply systems of buildings with variable operation mode. EUREKA: Physics and Engineering, 3, 59–68. doi: https://doi.org/10.21303/2461-4262.2020.001252
7. Schlosser, F., Jesper, M., Vogelsang, J., Walmsley, T. G., Arpagaus, C., Hesselbach, J. (2020). Large-scale heat pumps: Applications, performance, economic feasibility and industrial integration. Renewable and Sustainable Energy Reviews, 133, 110219. doi: https://doi.org/10.1016/j.rser.2020.110219
8. Pan, E., Li, H., Wang, Z., Peng, D., Zhao, L., Fan, L. et. al. (2020). Operation optimization of integrated energy systems based on heat storage characteristics of heating network. Energy Science & Engineering, 9 (2), 223–238. doi: https://doi.org/10.1002/ese3.842
9. Klymchuk, O., Denysova, A., Shramenko, A., Borysenko, K., Ivanova, L. (2019). Theoretical and experimental investigation of the efficiency of the use of heat-accumulating material for heat supply systems. EUREKA: Physics and Engineering, 3, 32–40. doi: https://doi.org/10.21303/2461-4262.2019.00901
10. Bertoldi, P., de Raveschoot, R. P., Paina, F., Melica, G., Janssens-Maenhout, I. G. G. et. al. (2014). How to develop a Sustainable Energy Action Plan (SEAP) in the Eastern Partnership and Central Asian cities. EUR 26741. Luxembourg: Publications Office of the European Union. doi: https://doi.org/10.2790/33989
11. Savchenko, O., Voznyak, O., Myroniuk, K., Dovbush, O. (2020). Thermal Renewal of Industrial Buildings Gas Supply System. Proceedings of EcoComfort 2020, 385–392. doi: https://doi.org/10.1007/978-3-030-57340-9_47
12. Ganzha, A. M., Zaiets, O. M., Marchenko, N. A., Kollarov, O. J., Njemcev, E. M. (2018). Methodology of calculation of multiplex heat exchang apparatus with cross flow and mixing in heat carriers. Journal of new technologies in environmental science, 2 (1), 26–35.
13. Myroniuk, K., Voznyak, O., Yurkevych, Y., Gulay, B. (2020). Technical and Economic Efficiency After the Boiler Room Renewal. Proceedings of EcoComfort 2020, 311–318. doi: https://doi.org/10.1007/978-3-030-57340-9_38
14. Lutsenko, I. A. (2012). Osnovy teorii effektivnosti. Altaspera Publishing & Literary Agency Inc., 71. Available at: https://ua1lib.org/book/3031189/438b46?id=3031189&secret=438b46
15. Li, X., Gui, D., Zhao, Z., Li, X., Wu, X., Hua, Y. et. al. (2021). Operation optimization of electrical-heating integrated energy system based on concentrating solar power plant hybridized with combined heat and power plant. Journal of Cleaner Production, 289, 125712. doi: https://doi.org/10.1016/j.jclepro.2020.125712
16. Rachkov, M. R., Melnikov, V. M. (2017). Development of the method of operational efficiency assessment for centralized heat supply systems in small towns. Vestnik IGEU, 4, 13–20. doi: https://doi.org/10.17588/2072-2672.2017.4.013-020

17. Ryabtsev, G. A., Ryabtsev, V. I. (2003). Noviy obschiy pokazatel' effektivnosti raboty teploseti. Novosti teplosnabzheniya, 9, 56–59.
18. Kuznik, I. V. (2011). Otsenka effektivnosti transportirovaniya teplovoy energii. Energosberezhenie, 3, 42–47.
19. Nakajima, S. (1988). Introduction to TPM: Total Productive Maintenance (Preventative Maintenance Series). Productivity Pr, 129.
20. De Ron, A. J., Rooda, J. E. (2006). OEE and equipment effectiveness: an evaluation. International Journal of Production Research, 44 (23), 4987–5003. doi: https://doi.org/10.1080/00207540600573402
21. de Ron, A. J., Rooda, J. E. (2005). Equipment Effectiveness: OEE Revisited. IEEE Transactions on Semiconductor Manufacturing, 18 (1), 190–196. doi: https://doi.org/10.1109/tsm.2004.836657
22. Morozyuk, L., Sokolovska-Yefymenko, V., Gayduk, S., Moshkatiuk, A. (2018). Entropybased methods applied to the evaluation of a real refrigeration machine. Eastern-European Journal of Enterprise Technologies, 6 (8 (96)), 49–56. doi: https://doi.org/10.15587/1729-4061.2018.147710
23. OEE. Available at: https://ru.wikipedia.org/wiki/OEE
24. Chernousenko, O., Butovsky, L., Rindyuk, D., Granovska, O., Moroz, O. (2017). Analysis of residual operational resource of high-temperature elements in power and industrial equipment. Eastern-European Journal of Enterprise Technologies, 1 (8 (85)), 20–26. doi: https://doi.org/10.15587/1729-4061.2017.92459
25. Monitoring effektivnosti ispol'zovaniya proizvodstvennogo oborudovaniya. Available at: http://www.up-pro.ru/library/information_systems/toir/monitoring-effektivnosti.html
26. Narula, K., De Oliveira Filho, F., Chambers, J., Romano, E., Hollmuller, P., Patel, M. K. (2020). Assessment of techno-economic feasibility of centralised seasonal thermal energy storage for decarbonising the Swiss residential heating sector. Renewable Energy, 161, 1209–1225. doi: https://doi.org/10.1016/j.renene.2020.06.099
27. Klymchuk, A. A., Lozhechnikov, V. F., Mykhailenko, V. S., Lozhechnikova, N. V. (2019). Improved Mathematical Model of Fluid Level Dynamics in a Drum-Type Steam Generator as a Controlled Object. Journal of Automation and Information Sciences, 51 (5), 65–74. doi: https://doi.org/10.1615/jautomatinfscien.v51.i5.60
28. Zhong, J., Li, Y., Cao, Y., Tan, Y., Peng, Y., Zeng, Z., Cao, L. (2020). Stochastic optimization of integrated energy system considering network dynamic characteristics and psychological preference. Journal of Cleaner Production, 275, 122992. doi: https://doi.org/10.1016/j.jclepro.2020.122992