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 the elements of the heat supply system.
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 micro-districts. 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:

\[ E_{th} = \alpha_1 \cdot E_1 + \alpha_2 \cdot E_2 + \alpha_3 \cdot E_3, \]

where \( E_{th} \) – 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; \( \alpha_1, \alpha_2, \alpha_3 \) – weighting factors for each of the efficiency factors.

The resulting value of the efficiency coefficient \( E_{th} \) 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:

\[ k_t = f(t_r, t_s, t_{out}). \]

where \( t_r, t_s, t_{out} \) – 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:

heat supply source ⇒ heating network ⇒ consumer,

current

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.

4.1. 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 regime is clearly represented by graphs of electricity consumption (Fig. 1).

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):

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)

\[ A = \frac{OT}{PPT}. \]

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

\[ OT = PPT - DTL. \]

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):

\[ P = \frac{TP}{OT \cdot IRR}. \]

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

\[ Q = \frac{GP}{TP}. \]

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:

\[ \eta_{so} = \eta_p \cdot \eta_d \cdot \eta_c \cdot \eta_e. \]

where \( \eta_p \) — coefficient of the heat generating unit;
\( \eta_d \) — coefficient of heat distribution efficiency;
\( \eta_c \) — coefficient of heating device efficiency;
\( \eta_e \) — coefficient of system regulator efficiency.

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

\[ \eta_p = 0.0141\gamma^2 + 0.0133\gamma + 1.9129; \]
\[ \eta_d = 0.0291\gamma^2 + 0.0178\gamma + 1.8459; \]
\[ \eta_c = -0.0522\gamma^2 + 0.1564\gamma - 0.0148\gamma^2 - 0.1311\gamma + 1.8846; \]
\[ \eta_e = 0.0678\gamma^2 - 0.4858\gamma + 1.2728\gamma + 0.8265; \]

where \( \gamma \) — thermal load of the system, % of the nominal.

![Fig. 2. Influence of relative load on efficiency ratios](image-url)

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.
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.

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 distri-
bution 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.

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