Assessment of the energy efficiency of heat supply systems in the arctic zone of Russia

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Abstract. One of the main tasks of recent years is the development of the Arctic region of Russia. This is due to the economic, political and defense interests of the country. The Arctic zone is characterized by harsh climatic conditions and, as a consequence, high consumption of energy resources to ensure uninterrupted operation of heat supply systems. Taking into account the fact that fuel oil, supplied from other regions, is used as the main type of fuel, the issue of energy efficiency of heat supply systems is quite acute. The proposed methodology for assessing energy efficiency is based on several mathematical methods, including the method of correlation analysis, the method of ranking of indicators and the method of expert criterion evaluation. Generalization of these methods as applied to the heat supply system allowed to create a methodology of criteria assessment of energy efficiency of heat supply systems, allowing with minimal time and with high accuracy to evaluate the effectiveness of the entire system and its individual components. In addition, the application of criteria assessment makes it possible to determine the most relevant areas of energy saving of heat supply systems and to assess the technical and economic effect from the implementation of a particular energy saving measure, taking into account a wide range of external factors and the characteristics of specific heat supply systems.

1 Introduction

The issue of quality energy supply, in particular thermal energy, becomes especially relevant during the development of regions with harsh climatic conditions. The Arctic zone of Russia can be referred to such regions. The air temperature of the coldest five days in this region ranges from -14 ºC to -61 ºC. Under such conditions the questions of quality and cost of heat supply as well as the search for the ways to reduce fuel consumption come to the foreground. Problems of heat supply in the Arctic zone and ways of their solution, including energy saving, are reflected in works [1-3]. The approach proposed in the article will significantly simplify and accelerate the implementation of these measures.

The main purpose of the study is to create a unified and universal methodology of criterial assessment of energy efficiency of heat supply systems, based on which the analysis of system operation is carried out and promising areas of energy saving are selected. The

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peculiarity of such methodology, in particular, is a possibility to set target energy efficiency indicators for a wide range of heat supply systems of various devices under specific operating conditions.

2 Materials and methods

The mathematical methods used in the developed criterion evaluation methodology can be divided into three enlarged blocks, as shown in Fig. 1.

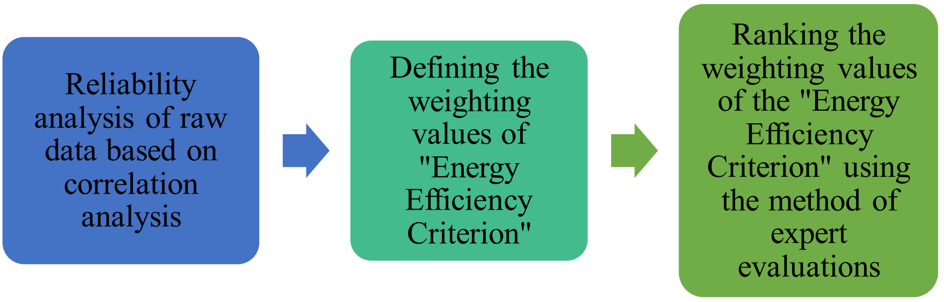

Fig. 1. Mathematical methods used

Analysis of reliability of initial data is performed to determine the usable information about the operation of the heat supply system that does not require additional research, as well as to determine the possibility of obtaining additional information required for the calculations. A similar approach outlined in [4] is used for predicting heat consumption. The authors have developed a method for assessing the reliability of initial data using the Cheddock scale and dividing the results into three groups: data fully suitable for further calculations, partially suitable (incomplete or partially incorrect information) and completely unsuitable for use in further calculations. Correlation analysis, which is used at this stage, is described in [5]. Information about equipment operation schedules, information about outdoor air temperature, useful heat supply, etc. are used as factor attributes. The developed and substantiated list of control and control and balance tests allows to provide completeness of the initial data in the volume necessary for further research.

Analysis of reliability of initial data plays an important role in assessing the energy efficiency of the heat supply system, as it allows at the initial stage to exclude the parameters that artificially over or underestimate the efficiency of the entire system. As an example, we can give the energy characteristics of boiler units, used to determine the weighting values of the criterion of energy efficiency. Fig. 2 shows the energy characteristics of the boiler unit, built on the basis of data of the incorrectly made operation map and the results of control and balance tests of the steam boiler unit.

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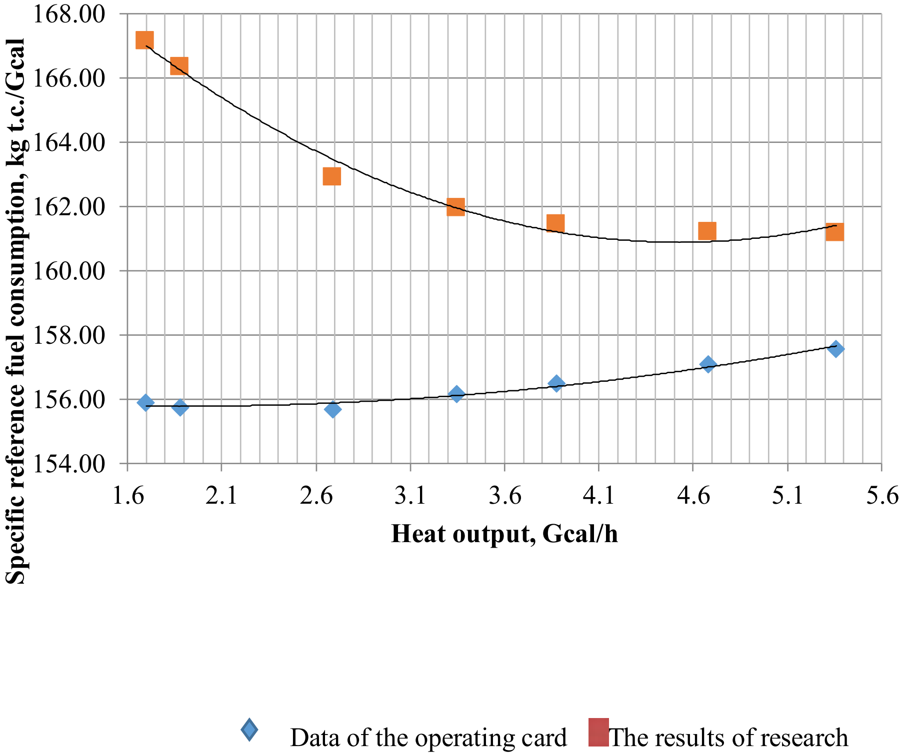

Fig. 2. Energy characteristics of the Viessman Witomax200 steam boiler unit

The use of data from the operation map in this case leads to an artificial underestimation of the specific fuel consumption for heat production by the boiler unit by 3-11 kg c.e./Gcal, depending on the load and, consequently, to a significant underestimation of the calculated fuel consumption by the heat supply source.

Many works, such as [6, 7], are devoted to the issues of criterion evaluation. However, the approach described in these works is of an aggregate nature or focuses on a narrow range of issues. The authors of this article consider determination of weight values of the coefficient of energy efficiency is made for a particular structure of heat supply system and factors, affecting its operation. Weighting values are taken in a range from 0 to 1 and are based on indicators of heat supply system operation, which can include specific fuel consumption for production and supply of heat energy, costs of own needs of the heat supply source, losses during transmission through heat networks, etc. Generalized energy efficiency factor is determined as a weighted average value of weighting coefficients of energy efficiency of individual elements of the heat supply system. Using as the main criterion for assessing energy efficiency of the specific consumption of fuel equivalent is possible, but inconvenient because of the fairly wide range of the resulting numerical values. Bringing all values to a dimensionless scale allows not only to simplify further data processing, but also to introduce target indicators, both for individual elements of the heat supply system, and for the whole system as a whole. An example of application of the energy efficiency factor is illustrated by Fig. 3. In this case there is a graphic form of recording the results of research.

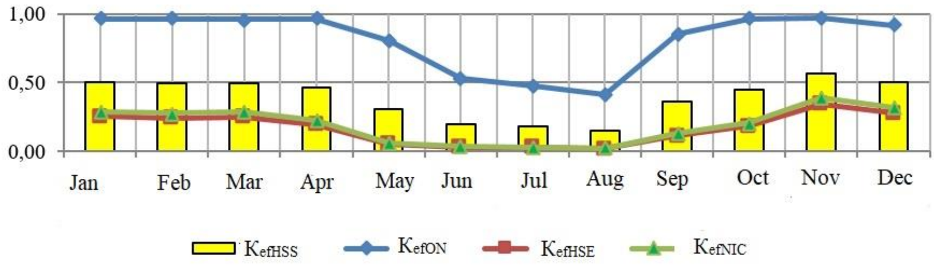

Fig. 3. Energy efficiency coefficients of the heat supply source K_{efHSS} is the coefficient of energy efficiency of the heat supply source; K_{efON} is the coefficient of energy efficiency of heat consumption for own needs; K_{efHSE} is the energy efficiency coefficient of heat source equipment load; K_{efNIC} –is the coefficient of energy efficiency of installed power

Further work with the data obtained involves the use of the method of expert evaluations (ranking method), which is widely used in various fields of science and technology [8 - 9]. The method is based on the ranking of a number of indicators by a group of experts. In the case of considering the heat supply system performance as "experts", it is advisable to apply a period (year, quarter, month, etc.), for which the assessment of energy efficiency of the heat supply system is performed. Such decision is conditioned by the fact that indicators of heat supply system operation are built on the basis of balances, which are recommended to be drawn up on a monthly basis. Energy efficiency coefficients *k* are taken as the evaluation object. The numerical value of the rank in a series of increasing order scale increases from 1 to m. Then the sums of ranks N_i of each of the objects of expert evaluation are determined, on the basis of which a generalized ranked series is constructed. Generalized expert evaluations of the quality of the group - weighting coefficients are calculated by the formula:

$$Q_i = \frac{\sum_{j=1}^{m} N_{i,j}}{\sum_{i=1,j=1}^{n,m} N_{i,j}},$$

where *m* is the number of experts (periods under consideration);*n* is the number of estimated energy efficiency coefficients; $\sum_{j=1}^{m} N_{i,j}$ is the total number of ranks obtained by the i-th object from all j-experts (periods); $\sum_{i=1,j=1}^{n,m} N_{i,j}$ is the largest number of ranks of all evaluated coefficients.

The accuracy of expert evaluations is determined in accordance with the concordance coefficient:

$$W = \frac{12 \cdot S}{n^2 \cdot (m^3 - m)},$$

where *S* is the sum of squares of deviations of ranks from the arithmetic mean of ranks.

$$S = \sum_{i=1}^{n} (\sum_{j=1}^{m} N_{i,j} - N_{av})^2,$$

where N_{av} is the arithmetic average of the ranks.

The values of the concordance coefficient lie in the range $0 \leq W \leq 1$, where 0 means complete disagreement, and 1 means complete agreement of expert assessments.

As a result, according to the ranking series obtained, it is possible to evaluate the most promising areas in terms of energy and resource saving and make a reasonable decision about the feasibility of implementing certain measures.

3 Results and discussion

The heat supply system located in St. Petersburg with a boiler house with installed capacity of 15 Gcal/h and heat networks with a length of 700 m in two-pipe calculation was selected for experimental research. Table 1 shows the main stages of the calculations and the results of the experiment.

Table 1. Experimental results

Evaluated indicator	**Energy efficiency factor**	**Period (month)**											
		I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
Specific fuel consumption	$K_{efcoef.1}$	0,96	0,96	0,961	0,956	0,00	0,00	0,00	0,00	0,94	0,95	0,96	0,96
	$K_{efcoef.2}$	0,00	0,00	0,00	0,00	0,93	0,93	0,93	0,92	0,00	0,00	0,00	0,00
Own needs of the boiler room	K_{efON}	0,97	0,97	0,962	0,964	0,81	0,53	0,48	0,42	0,85	0,96	0,97	0,92
Boiler room load level	K_{efHSE}	0,26	0,24	0,25	0,20	0,055	0,031	0,027	0,019	0,11	0,18	0,35	0,28
Installed capacity utilization	K_{efNIC}	0,29	0,28	0,28	0,22	0,063	0,035	0,031	0,021	0,13	0,21	0,39	0,32
Losses in heating networks	K_{efHN}	0,89	0,89	0,89	0,89	0,91	0,91	0,91	0,91	0,91	0,89	0,89	0,89
		Ranking of energy efficiency coefficients based on "expert" evaluations											
Specific fuel consumption	$K_{efcoef.1}$	2	2	2	2	6	6	6	6	1	2	2	1
	$K_{efcoef.2}$	6	6	6	6	1	1	1	1	6	6	6	6
Own needs of the boiler room	K_{efON}	1	1	1	1	3	3	3	3	3	1	1	2
Boiler room load level	K_{efHSE}	5	5	5	5	5	5	5	5	5	5	5	5
Installed capacity utilization	K_{efNIC}	4	4	4	4	4	4	4	4	4	4	4	4
Losses in heating networks	K_{efHN}	3	3	3	3	2	2	2	2	3	3	3	3
		Determining the sum of the ranks $\sum_{j=1}^{m} N_{i,j}$											
Specific fuel consumption	$K_{efcoef.1}$	38			3			0,15		**The arithmetic mean of the ranks *Nav***			42
	$K_{efcoef.2}$	52			6			0,21					
Own needs of the boiler room	K_{efON}	23	**Construction of a generalized rank series**		1	**Determination of the weighting coefficients of the generalized rank**		0,09	**Determination of the correlation coefficient**	**The sum of the squares of the deviations of the ranks *S***			570
Boiler room load level	K_{efHSE}	60			5			0,24					
Installed capacity utilization	K_{efNIC}	48			4			0,19		**Concordance**			0.23

Evaluated indicator	Energy efficiency factor	Period (month)											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Losses in heating networks	K_{efHN}	32			2			0,13		**coefficient *W***			

Analysis of the results allows us to draw the following conclusions:
1. Constructed generalized series of ranks provides an opportunity to assess the areas of high energy efficiency (in this case the cost of heat energy for own needs and losses in heating networks) and the most promising areas of activity (the degree of loading of the boiler house and the efficiency of boiler number 2) in the field of energy conservation;
2. The weighting coefficient of the generalized ranking series allows to evaluate the importance of a particular indicator in relation to others, in other words, its energy saving potential;
3. It is possible to increase the value of the concordance coefficient by increasing the number of "experts", i.e. reducing the time interval to a week / days / hours.

Using the approach described above contributes to accelerating the main task, namely the right choice of energy-saving measures and saving fuel and energy resources.

Considering the specifics of the Arctic regions, the most promising areas for energy saving are:
1. Decentralization of heat supply systems and introduction of modern cogeneration units. Decentralization or localization of heat supply systems leads to the reduction of the length of heat networks and as a consequence, to the reduction of losses of heat energy during transportation. Application of cogeneration units as sources of heat energy is the most expedient for provision of power supply of small and medium-sized industrial enterprises, as well as blocks of residential development. Coverage of peak loads in decentralized heating systems allow heat accumulators, the use of which is described in [10];
2. Introduction of alternative energy sources, taking into account the peculiarities of fuel supply, can play a significant role in the development of the economy of the region. Application of this kind of energy sources will create conditions for reducing the volume of harmful emissions into the atmosphere and will give an opportunity to maintain the "cleanliness" of the Arctic zone with its active use;
3. Use of modern heat-insulating materials to reduce heat losses during transportation through heat networks. With the impossibility of creating local sources of energy, taking into account geophysical features, above-ground (air) laying of pipelines requires separate attention in terms of the effectiveness of heat insulating materials [11 - 13];
4. Use of modern heat insulating materials in construction to reduce heat losses through enclosing structures of buildings and constructions. This will reduce the cost of heat energy for heating needs, which occupy a significant proportion of the total consumption of thermal energy.
5. Since power consumption in heat supply systems plays an important role, in some cases by modernization of its individual elements it is possible to achieve significant energy savings. Modern approaches to determine the priority areas and ways to reduce electricity consumption are reflected in the works [14 - 16].

4 Conclusion

The developed methodology of criteria assessment of the energy efficiency of heat supply systems makes it possible to promptly and with a high degree of accuracy assess the efficiency of the heat supply system. This is especially relevant when operating systems in the special climatic conditions of the Arctic zone of Russia. Considering the fact that in this region the most common types of fuel are diesel fuel and fuel oil, the issue of energy and resource saving in a number of cases comes to the fore.

Using the developed methodology allows not only to competently determine the directions of energy resources saving, but also to conduct a technical and economic assessment of the implementation of energy-saving measures.

Prospects of this development lies in the possibility of its wide application, both in transport and industrial facilities, and in the sphere of housing and communal services, and the use of energy efficiency coefficients as target indicators allows to substantiate and attract investments for long-term projects in the field of energy saving.

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