E3S Web of Conferences **461**, 01019 (2023) https://doi.org/10.1051/e3sconf/202346101019
RSES 2023

Methodological issues for the formation of reliable and efficient district-distributed heating systems

Ivan Postnikov[1,*]

[1]Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences, Laboratory of Heat Supply Systems, 664033 Irkutsk, Russia

Abstract. The general methodological issues for the formation and operation of district-distributed heating systems are formulated, including determining the areas of economic efficiency of district and distributed (prosumer sectors) heat supply to consumers, reliability analysis and synthesis, as well as economic analysis of failed conditions of the system (determination of damage from undersupply of thermal energy). Methodological provisions for solving these problems are proposed, structured in the form of a general algorithm with connection of problems, methods and results.

1 Introduction

The formation and operation of district heating systems (DHS) in the process of their development involves solving a wide range of scientific and methodological problems. The book [1] provides a fairly extensive methodological basis for solving main issues for existing DHSs. However, at the stage of the current energy transition in heat supply, quite transformations are taking place, considered first of all on the technological level of 4th and 5th generation of DHS [2–5].

One of the general directions of DHS development is associated with the formation of integrated energy systems [6], which involves the effective comprehensive use of various energy technologies (multi-resource systems), and on the other hand, the formation of a fundamentally different concept of development a system based on rational (in theory, optimal) application district heating with active demand for thermal energy. Active consumers or *prosumers* form subsystems (sectors) of distributed heating. Thus, at the present stage of their development, DHS are transformed into *district-distributed heating systems* (DDHS), effectively combining district and distributed generation of thermal energy [7, 8]. The implementation of prosumers with their own heating sources (HS) determines new properties of studied systems which requires the development of methodological support for solving the problems of their functioning and development.

This paper briefly provides number of methodological provisions for solving some problems of formatting and operating a DDHS with prosumers: scaling systems with determining zones of efficiency of district and distributed heating, the reliability analysis both stochastic and economic accounting damages from undersupply of thermal energy, some approaches to ensuring reliability when using prosumer reserves. Brief results of the computational experiment is considered.

2 Methodology

2.1 Scaling DDHS: determining the areas of district heating efficiency

The problem of effective scaling of DHSS (as well as traditional DHS) is to determine the boundaries of district heating efficiency based on the *effective heating radius* (EHR) criterion [9]. Constrains of many methods is the assumption of territorial uniformity of heat load distribution. The main principle of the proposed approach is that for each HS of studied system, the operating costs for the production and distribution of thermal energy are calculated for each section of transmission pipeline to consumers connected to it. The result of the analysis of the entire system is a map of district efficiency areas, which determines the scale of the necessary reconstruction and possible implementation of distributed sectors at these boundaries (prosumer subsystems). Methods and models to solve the problem of effective scaling of DDHS are discussed in detail in [9, 10].

2.2 Stochastic reliability analysis of DDHS based on the nodal indices

A comprehensive approach to the reliability analysis of the DDHS is proposed, which consists of determining the integral impact of all system objects (or subsystems) on the reliability of heating to consumers. The set of problems of reliability analysis and methods for solving them is divided into two main blocks: probabilistic and physical modeling of the functioning of the system. The set of system states is formed as a combination of states of its district and distributed subsystems accounting the technological possibility of their implementation. State probabilities are assessed accounting the specified reliability parameters of components (failure and restoration rates of facilities) based on a *markov random*

*Corresponding author: postnikov@isem.irk.ru

process model. Physical modeling consists of calculating the corresponding thermal-hydraulic conditions in the heat network using models of the theory of hydraulic circuits (THC) [11]. The final result is *nodal reliability indices* (RI), calculated using previously obtained results of probabilistic and physical modeling of states. The methodology for a comprehensive analysis of the reliability of heating systems and its practical applications are described in detail in [12–14].

2.3 Economical reliability analysis of DDHS

The purpose of the economical reliability analysis of DDHS is to assess the emergency conditions while minimizing operating costs accounting *expected damages* (economic losses from possible undersupplies of thermal energy) in the event of failures of system components (facilities). To obtain the parameters of the desired conditions, a methodological approach is proposed, which consists in the joint calculation of nodal prices for thermal energy and damage in the studied system based on the *Lagrange multiplier method*. This method with test calculations in relation to DHS is discussed in detail in [15]. The developed methods and models make it possible, based on the obtained indicators, to identify the most "bottleneck" points in the system, corresponding to the maximum economic losses from interruption of heating to consumers.

2.4 Ensuring the reliability of DDHS accounting the prosumer reserves

Achieving and maintaining a certain standard level of reliability for DDHS is ensured by means of redundancy both in the district and distributed (prosumer) sectors. Based on this, the research problem is formulated as the development of methods for ensuring the reliability of DDHS accounting the additional functional reserve of own prosumer HS (passive time redundancy, active thermal power). The formulation of the scientific and methodological problem consists in determining the optimal relation of reliability parameters of system components (failure and restoration rates) and the capacity of distributed HS of prosumers, which provide the required level of reliability of heating to consumers with minimal total costs for reliability and operation of prosumers within the acceptable parameter values. The study is a development of previous work [16].

3 General algorithm for formation reliable and effective DDHS

The methods discussed above are combined into a general algorithm presented in Fig. 1. The scheme is divided into three categories (problems, methods and results) and four stages corresponding to the previously discussed sections. The first stage (P1) corresponds to the problem of scaling of DHS (sect. 2.1), as a result of which the implementation areas of distributed heating are determined according to the EHR criterion.

In this case, the decision on the localization of the distributed sector is made under a combination of two conditions:

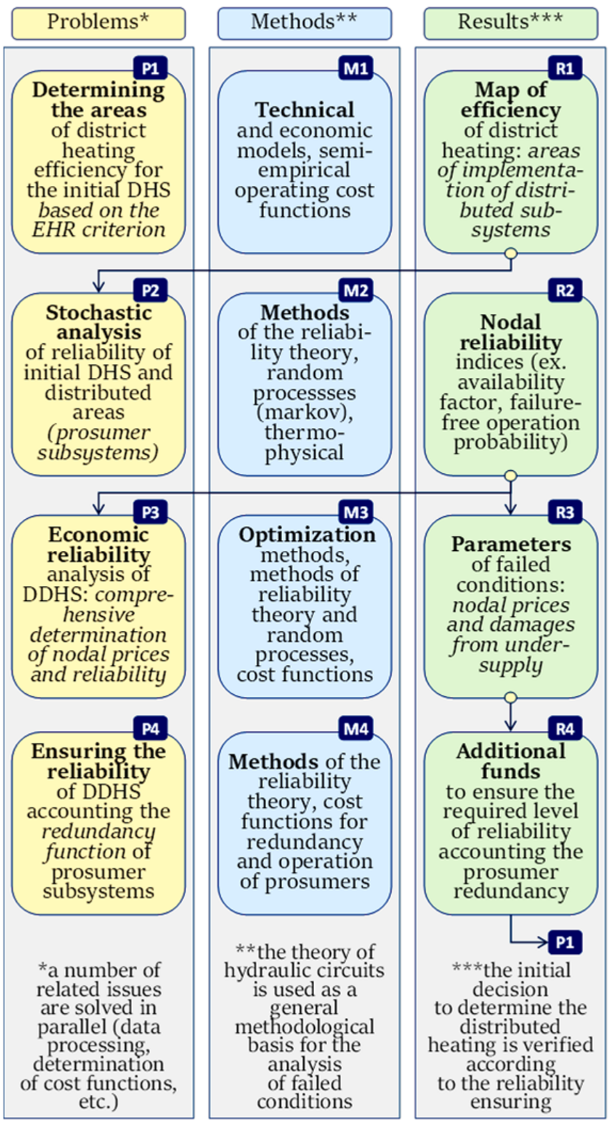

Fig. 1. Shorted diagram of the general algorithm for formation reliable and effective DDHS

1) part of the DHS scheme is located outside the boundaries of the EHR;
2) there is no possibility of structural solutions to expand the HER areas within the existing district system.

For a certain localized distributed sector, a prosumer subsystem is formed with a choice of HS type and heat supply parameters (temperature curve, heating period, etc.), subject to increased economic efficiency within this subsystem compared to the initial connection diagram. This problem is not considered here, but some results of such an analysis are given in [9].

At the second stage (P2), the transition to solving the problem of reliability analysis for the prosumer subsystem is carried out (sect. 2.2). The nodal RI obtained at this stage are used in next two stages. If there are unreliable part an economic assessment of the consequences of failures is carried out (stage P3), as a result of which the economic damages from undersupply of thermal energy are determined (sect. 2.3). To assess their possible reduction, the problem of ensuring (increasing) reliability is solved (sect. 2.4).

Increasing the reliability of the prosumer subsystem can be carried out both through internal redundancy (within the subsystem) and taking into account the possibility of using the reliability potential of the district system. The second option is possible in the case when the prosumer HS operates in parallel with district HS, covering part of the load of its consumer group. At stage P4 (see Fig. 1), the volume of additional funds is determined to ensure the required level of reliability in the considered distributed subsystem. The initial solution along the EHR boundaries is corrected according with the conditions for ensuring reliability (in the case of a partial increase, it is necessary to additionally take into account the expected damage from undersupply).

4 Brief results of computational case example study

Here are the main brief results of the application of the methodological support developed for solving the problems of effective and reliability of DHS accounting their transformation to DDHS with implementation of prosumers. The main issues were to determine areas of efficiency of district heating based on the EHR criterion, technical and economic assessment of the implementation of distributed HS of prosumers at the boundaries of EHR, analysis and ensuring the reliability.

For the studied DHS, the boundaries of the EHR were assessed in accordance with the given standard value of specific operating costs. It was determined that beyond the boundaries of the efficiency of district heating there are 14 branches (sectors) of the network with a total length of 14.8 km (38%) and 42 (46%) nodes of the initial system diagram with a total heat load of 357 GJ/h (39 %).

Next, to evaluate the effectiveness of implementing a prosumer with its own HS (distributed sector), one of the subsystem is selected, remaining actually connected to the district system, while having its own generation. Calculation of operating costs within the studied prosumer subsystem showed that specific cost at nodes within the subsystem is significantly reduced compared to the initial heating scheme from a district HS: the average cost reduction was 25%. The reliability level of the localized system when connecting a prosumer also increases significantly compared to the initial scheme: the increase is 44%. The distribution of the reliability effect on subsystem nodes is shown in Fig. 2. The total economic effect of introducing the prosumer subsystem is shown in Fig. 3 and is estimated at 93.85 million rub/year, which is 48.1% of the operating costs corresponding to the initial scheme. The main part of the effect is associated with a reduction in the cost of thermal energy and amounts to 87.53 million rub/year (44.8%) and only 6.32 million rub/year (3.2%) with a reduction in expected damage from undersupply thermal energy to consumers.

It is also important to note here that the effect is achieved with optimal control of the joint functioning of district and distributed sources. This problem represents the subject of a special study using bi-level programming methods (one level corresponds to the district system, the other to the distributed heating subsystem).

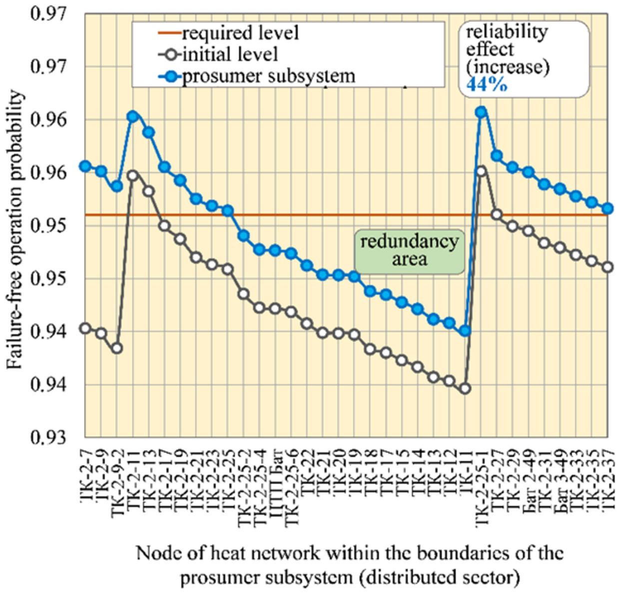

Fig. 2. Distribution of reliability effect on nodes of the prosumer subsystem (distributed sector in DHS)

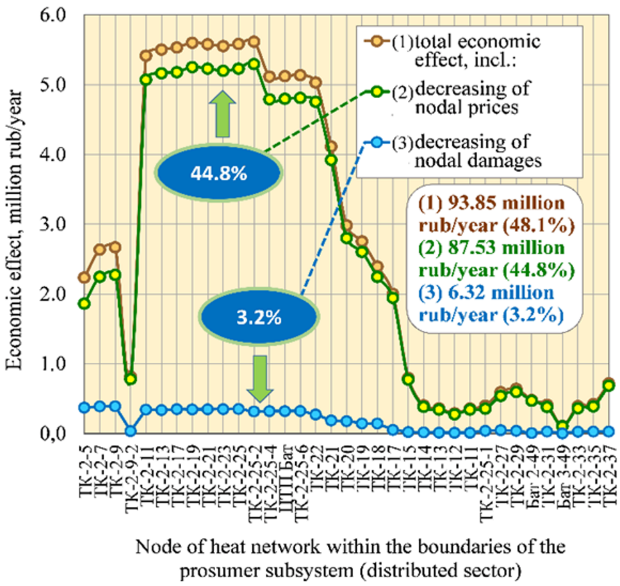

Fig. 3. Distribution of economic effect on nodes of the prosumer subsystem (distributed sector in DHS)

5 Conclusions

A possible version of the methodological basis is proposed to justify decisions on the transition of existing DHS to systems of a district-distributed type with the implementation of prosumers as sources of localized subsystems formed on the boundaries of the technical and economic efficiency of district heating. A number of methodological provisions are presented aimed at solving the problems of substantiating the effectiveness and reliability of decisions made. It is important to note that in addition to the considered issues, there are a number of related and quite complex problems associated with obtaining and analytical processing of data, allowing them to be used as objective functions (mainly, operating costs). As a result of the decision, DDHS should be formed with a higher level of efficiency and reliability of heating to consumers compared to the initial scheme. An important property of the proposed approaches is the ability to adjust the economic efficiency of the system according to reliability conditions accounting the technical and economic consequences of possible heat shortages and the creation of the necessary reserves to reduce them. The resulting solutions can be useful both in the design of heating systems and in justifying their development accounting the reliability factor.

Further development of the proposed methodology involves the solution of many methodological and applied problems. At this stage, we focus on the following priority direction: determination of the feedback for decisions obtained at different levels of the district and distributed heating system. A change in the specific cost of production and distribution of heat in a localized system of a prosumer (or several prosumers at once) will affect the value of the system-wide criterion for determining the EHR boundaries. In this case, the more load will be transferred to the distributed heating part, the more significant will be the deviation of the EHR from its initial value. According to the adjusted criterion, in turn, the previously obtained boundaries of the efficiency of district heating should be revised. When adjusting these boundaries, a reassessment of the technical and economic indices of the distributed sectors will also be required, which will again update the value of the EHR. As a result, to obtain the optimal district-distributed structure of the system, an iterative procedure with a “floating” EHR criterion is required, which is implemented up to some equilibrium solution with acceptable accuracy.

Acknowledgements

The study was supported by the Russian Science Foundation grant No. 22-29-01252, https://rscf.ru/project/22-29-01252/.

References

1. E. Sennova, V. Sidler, *Mathematical modeling and optimization of developing heat supply systems* (Nauka, Novosibirsk, 1987) [in Russian]
2. N. Novitskii, Z. Shalaginova, A. Alekseev, et al., Thermal Engineering **69** (2022)
3. H. Lund, P. Østergaard, M. Chang, et al., Energy **164** (2018)
4. I. Pakere, A. Gravelsins, D. Lauka, et al., Energy **234** (2021)
5. A. Revesz, P. Jones, C. Dunham, et al., Energy **201** (2020)
6. N. Voropai, A. Makarov, eds., *Systems studies in energy: energy transition* (ESI SB RAS, Irkutsk, 2022) [in Russian]
7. L. Brange, J. Englund, P. Lauenburg, Applied Energy **164** (2016)
8. M. Pipiciello, M. Caldera, M. Cozzini, et al., Energy **223** (2021)
9. V. Stennikov, E. Iakimetc, Energy **110** (2016)
10. V. Stennikov, E. Mednikova, I. Postnikov and A. Penkovskii, Environmental and Climate Technologies **23(2)** (2019)
11. A. Merenkov, V. Khasilev, *The theory of hydraulic circuits* (Nauka, Moscow, 1985) [in Russian]
12. V. Stennikov, I. Postnikov, Power Technology and Engineering **47(6)** (2014)
13. I. Postnikov, V. Stennikov, E. Mednikova and A. Penkovskii, Applied Energy **227** (2018)
14. I. Postnikov, Environmental and Climate Technologies **24(3)** (2020)
15. I. Postnikov, A. Penkovskii, Energy Reports **8(13)** (2022)
16. I. Postnikov, Energy Reports **9(1)** (2023)