Reliability Challenges of District Heating Systems in the Context of Technological and Organizational Innovations

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Abstract **This paper reviews current trends in the evolution of district heating systems and some emerging areas of their technological transformation related to the reliability of operation. It also contributes insights into advancing the methodology for reliability analysis and synthesis for these systems. The study highlights the issues of the heat network infrastructure health through a case study of the Irkutsk region, which elucidates their severity. We conclude by noticing an imbalance in the reliability issues of evolving district heating systems: on the one hand, the technological changes and structural transformations are irreversible, on the other hand, a range of major unresolved issues hinder and slow down the adoption of innovations and advancement of the systems.**

Index Terms **— District heating system, transformation of energy systems, energy transition, reliability, reliability analysis and synthesis, equipment health, equipment wear and tear, prosumer, hybrid district and distributed heating system.**

I. Introduction

The reliability of district heating systems (DHSs) becomes an increasingly critical issue with each year. The significant loss of heat, substantial wear of equipment, annual failures of heating mains resulting in prolonged interruptions in heating supply highlight the urgent need to address the issues of heating systems, even in the face of limited resources. The primary areas of confronting the above challenges aim to better equipment health, whereas further evolution of DHS involves the adoption of new technologies, principles of construction, design, and operation; mass digitalization of technological processes; and others.

All these trends, when viewed through the lens of the overall paradigm of transformation of energy systems (ES) as part of the energy transition [1], require more advanced production facilities and up-to-date theoretical foundations. Implementation of technological, structural, and organizational innovations leads to the emergence of new facilities and links, changes in properties, and introduction of new functions of DHSs. These transformations need to be considered in the analysis and synthesis (optimization, assurance) of their reliability and when formulating strategies to ensure it. Based on the literature review [2], we have compiled a systematized list of current methodological research on solving DHS reliability problems [3–34]. This list is shown in Table 1 (it, however, does not claim to be an exhaustive representation of the current research in the field).

The co-occurrence graph of keywords of research papers shown in Fig. 1 provides an overview of the state-of-the-art of DHS reliability studies (received using the service VOSviewer). The cluster that stands out from the rest of the graph links the term *district heating system* to the reliability-related concepts such as *reliability*, *reliability analysis*, *reliability assessment*, and *nodal reliability indices*. The relative isolation of this cluster indicates weak interconnections between reliability issues and other areas of research, in particular, those related to energy efficiency, adoption of renewables, and new principles of systems

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TABLE 1. Published Research On the Design of Methods for Analysis and Synthesis of DHS Reliability (Compiled Based On the Data Reported in [2])

Reliability problem	Level of detail	Methods	References
DHS reliability analysis	System (overall solutions)	Probabilistic, stochastic processes	Valinčius et al., 2015 [3]; Badarai et al., 2018 [4]; Postnikov, 2023 [5]
		Statistical	Rasoulian, 2022 [6]; Gilski et al., 2014 [7]; Marx et al. [8]; Postnikov & Mednikova, 2022 [9]
	Components (node-specific solutions)	Probabilistic	Mortensen et al., 2022 [10]; Ziganshin et al., 2016 [11]; Khoshgoflar Manesh et al., 2018 [12]; Losi et al., 2024 [13]; Mao el al., 2024 [14]; Mao et al., 2022 [15]
		Deterministic	Maliavina et al.,2022 [16]
DHS reliability analysis and risk assessment	Components	Probabilistic	Žutautaite et al., 2017 [17]; Shan et al., 2017 [I8]; Postnikov & Stennikov, 2020 [19]
		Statistical analysis	Sernhed & Jönsson, 2017 [20]
		Hybrid (Weibull model + Monte Carlo methods + failure mode and effects analysis)	Palakodeti, 2016 [21]
		Machine learning methods	Mortensen el al., 2022 [22]
DHS reliability forecasting, predictive analysis	Components	Hybrid (probabilistic + machine learning)	Mortensen & Shaker, 2024 [23]
		Weibull model	Kovacs et al., 2021 [24]; Langroudi & Weidlich, 2020 [25]
		Deterministic	Sun et al., 2009 [26]
DHS reliability optimization	System	Statistical analysis	Dai et al., 2022 [27]; Pan et al., 2024 [28]; Li et al., 2021 [29]
		Machine learning methods	Mao et al., 2021 [30]
	Components	Probabilistic	Postnikov et al., 2017 [31]; Stennikov & Postnikov, 2013 [32]; Postnikov et al., 2018 [33]; I. Postnikov, 2023 [34]

design in general. This situation may result in an inconsistent approach to the overall development of DHSs, lacking well-informed and balanced decisions and failing to consider conflicting multiple criteria for economic performance, efficiency, and reliability. The theory of hydraulic circuits [35] laid out a solid theoretical groundwork for DHS reliability: it contributed a method for *nodal reliability assessment* of consumer heating supply, a system of criteria and requirements for reliability based on the current standards, as well as methods of synthesis of optimal DHSs that consider their reliability [36]. This line of research was further elaborated in [31–34].

II. RELIABILITY OF EMERGING DHS TECHNOLOGIES

The array of modern technologies used for development and transformation of DHS to ensure and enhance their reliability is diverse both in the scope of application (subsystems, facilities, equipment) and in the scale of modernization of the systems. The production level involves the use of efficient heat sources (HSs), secondary thermal energy resources, and renewables. The distribution level focuses on addressing such urgent issues as efficient control of thermal-hydraulic states of heat networks (HNs), reduction in heat loss, reconstruction of pipelines, and, in some systems, transition to low-temperature parameters of heat carrier. It is envisioned that the consumption subsystems will be provided with a set of energy efficient systems and technologies for residential heating, cooling,

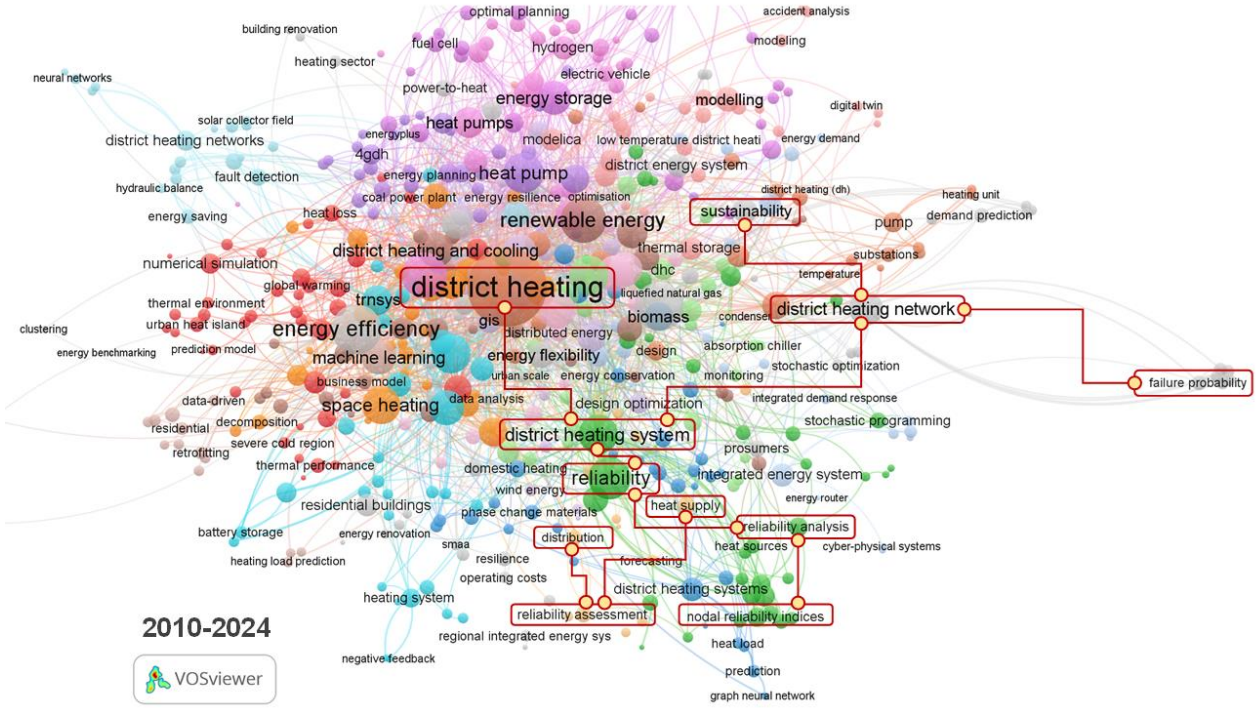

Fig. 1. The co-occurrence graph for reliability studies within research on various aspects of DHS; generated by querying the Scopus database for the search term "district heating + reliability" (based on over 1 000 items published in 2010–2024).

TABLE 2. Reliability Throughout the Stages of Technological Evolution of DHSs

1st generation of DHS (1880–1930)	2nd generation of DHS (1930–1980)	3rd generation of DHS (1980–2020)	4th generation of DHS (2020–2050)
		Key technologies	
Localized steam systems, steam pipes in concrete ducts, condensate lines, expansion joints, pressurized condensate tanks	Hot water pipes in concrete ducts, high pressures, metal-intensive and heavy equipment of heat networks, weak system of monitoring and control of operating conditions	Pre-insulated buried pipelines, efficient compact heating substations, metering and monitoring, control of operating conditions parameters	Integrated energy technologies with intelligent control, full digitalization of processes, prosumers, high energy efficiency, environmental friendliness
		Reliability aspect	
Low reliability due to intensive corrosion damage of condensate piping; high heat loss induced by higher steam parameters, exposure to high risks in case of incidents	Improved reliability due to reduced heal transfer medium parameters, more reliable equipment, energy-saving technologies, as well as systems design with built-in functional and structural redundancy	Still higher reliability due to lower heat transfer medium parameters; integration of various sources (including renewables) which provides a wider safety margin but complicates operating conditions, hence the need for fundamentally new intelligent control systems to back the further evolution	High reliability and controllability of systems; multiple options for multi-resource redundancy due to integration with other energy systems; high level of operational reliability at the level of prosumer-based demand-response subsystems due to optimization of consumption and local thermal capacity redundancy; further improvement of reliability of individual components

and hot water supply, and prosumers will be introduced there to form hybrid district and distributed heating systems (as detailed below).

According to a well-established conception of district heating evolution, the technological change in DHSs is tentatively divided into 4 stages or generations of systems [37] (currently the 5th generation is also being considered). It should be noted that this classification is provisional, which is due to the continuity of the evolutionary process itself and, as a consequence, the impossibility of clearly delimiting the systems of "adjacent" generations by the features unique to them. For example, the DHSs operating

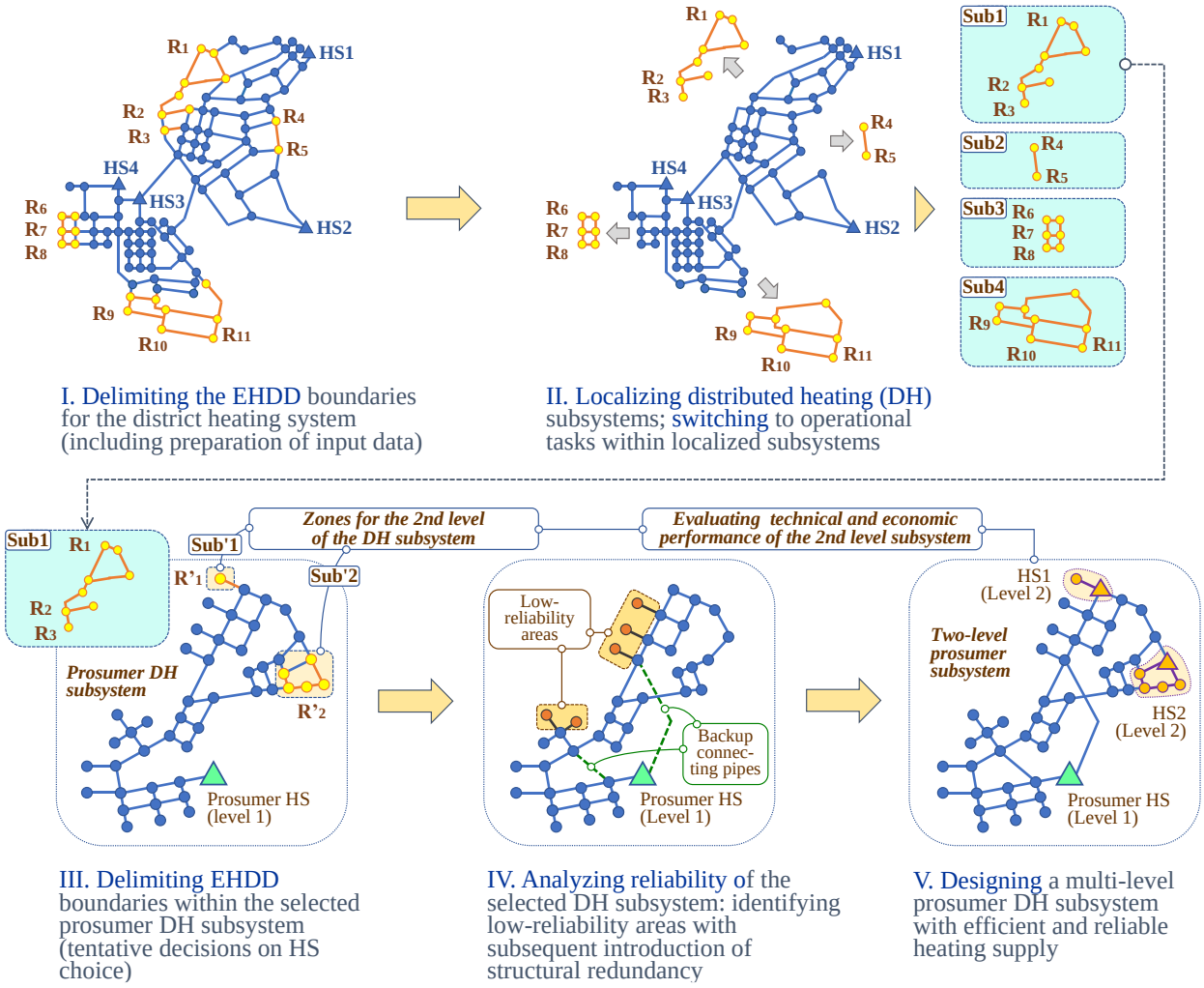

Fig. 2. Formation of reliable hybrid district and distributed heating systems with a multi-level prosumer distributed heating subsystem [35, 39].

in Russia correspond to the 2nd generation, although many of them are unique in scale and structure; most systems in European countries, as well as the new systems operating in China, correspond to the 3rd generation, and only a small number of systems in some European countries (Denmark is a recognized leader in this group) belong to the 4th generation.

An overview of the historical background, structure, and basic properties of these stages is detailed in [37]. Based on the technological features specific to DHSs of different generations we have formulated the corresponding reliability aspects and presented them in Table 2. In the foreseeable future, DHSs will focus on achieving the properties of the 4th and 5th generation systems, which involves: high system reliability and controllability; a variety of options for multi-resource redundancy as part of integration with other ESs; high operational reliability at the level of subsystems run by prosumers due to optimization of consumption and local thermal capacity redundancy at their own DHSs; increased technical reliability of system components, and others. The key parameter that affects the DHS efficiency within the framework of the above conception is the heat carrier temperature, whose decrease leads to a lower heat loss. Furthermore, the transition to low-temperature operating conditions enhances operational reliability, extending service life of pipelines while reducing their thermal stress and deformation. This decreases the thermal expansion of pipelines, enabling the use of more compact compensators and streamlining their installation and replacement. The above factors facilitate cutting costs incurred for maintenance repairs and overhauls of HN equipment, as

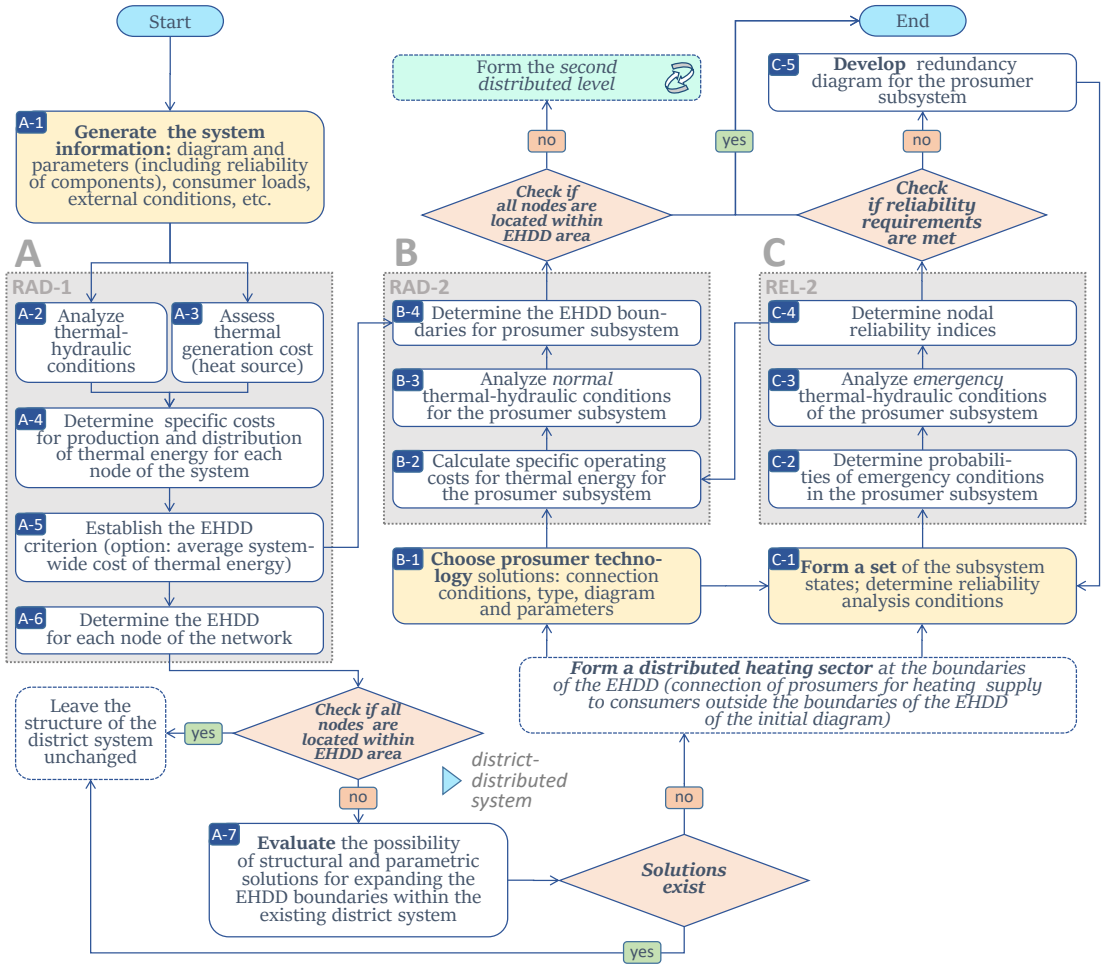

Fig. 3. Algorithm for HDDHS formation (corresponds to the main stages shown in Fig. 2).

well as for the means of rectifying incidents at the facilities that use higher parameters of the heat carrier. However, it is also crucial to consider higher material intensity of HNs due to larger diameters needed to increase the flow rate for compensating for the decrease in the temperature drop.

III. Ensuring Reliability in the Transition to Hybrid District and Distributed Heating

Studies [35, 39] have contributed a promising conception of DHS development that prioritizes reliability assurance. At the core of this conception is the transformation of existing systems or establishment of new ones that are built in line with the principles of synergistic integration of district heating and distributed heating. Such systems, which we refer to as hybrid district and distributed heating systems (HDDHS) have a multi-level hierarchical structure formed by hydraulically independent heating circuits. The circuits implement distributed sources run by prosumers at each level of heat generation to serve the heat load at the nodes of the original layout where reliability goes beyond the acceptable range of nodal reliability indices and efficiency lies outside the acceptable range of economic heat distribution distances (EHDD).

Figure 2 shows the overall flowchart of the algorithm for the design of hybrid district and distributed heating systems with a multi-level structure of distributed heating (DH) subsystems based on HSs run by prosumers. *Stage I* identifies the range of efficient operation of district heating of the original HS layout in terms of its EHDD. *Stage II* localizes DH subsystems so that the problems of their operation are solved within these subsystems. *Stage III* delimits the EHDD boundaries within the selected DH subsystem. If there are consumers outside these boundaries, they are assumed to be connected to the source of the second-level DH: thus, a bi-level (or, generally, multi-level) hierarchical structure is formed with each level having its own prosumers. *Stage IV* focuses on reliability analysis within the efficient operation range obtained for

the selected subsystem and identifies low-reliability nodes to ensure their required redundancy. *Stage V* forms a multi-level HDDHS with efficient and reliable heating supply. Figure 3 shows an algorithm for HDDHS formation, including all the main stages discussed above. This algorithm is capable of accomplishing a wide range of scientific and methodological tasks, including stochastic modeling of the studied system operation (to determine the probabilities of emergency states) and thermal-hydraulic modeling of emergency conditions corresponding to failures of system components. The set of reliability problems corresponding to stage C-5 (see Fig. 3) includes, in addition to stochastic modeling of states, the use of optimization procedures to find solutions for structural and parametric redundancy of the system.

A detailed description of the HDDHS formation algorithm, as well as the methods and models used are presented in [38]. The application of the developed methods to the real-life DHS is considered in the paper [39], which also discusses the achieved reliability and economic effects. Thus, the formation of the considered distributed heating subsystem connected to the prosumer source improves reliability by 44%, while structural redundancy in the system increases reliability to 62% (based on the adopted key reliability indices – availability factor and failure-free operation probability). The total economic benefit is estimated at about RUB 94 million per year, or 48% of the operating costs corresponding to the initial heating system diagram. The economic benefit derived from localizing the distributed heating subsystem based on the prosumer can be attributed to two reasons: 1) a reduction in the thermal energy cost through a decrease in operating network costs for pumping at a reduction in the heating supply distance; 2) a reduction in damage from shortages due to increased reliability. An additional economic benefit can be gained in the district system by lowering operating costs through the integration of distributed heat sources to meet part of the heating demand. The optimal distribution of the load of district and prosumer sources over the calculation period demonstrates the economic effect that can be obtained [40]. For example, the effect can be achieved by changing thermal energy output from the prosumer distributed source and the corresponding operating costs. The greater the part of the load covered by the subsystem self-generation, the smaller the correction required to the resulting effect. However, this factor does not affect the value of the economic effect from damage reduction.

IV. Further Development of the Methodology for Analyzing DHS Reliability

As noted above, the transformations of heating systems entail not only the establishment of new facilities and incorporation of additional links but also the development of the theoretical foundations for solving the reliability problems of these systems. Simultaneously, it is crucial to enhance both production facilities and technologies.

For example, modeling the heating systems with a hybrid district and distributed heating structure which assumes parallel operation of district heating sources and distributed heating sources run by prosumers within a single interconnected heat network infrastructure, should be based on the hierarchy of technological processes capturing both physical and stochastic parameters of the

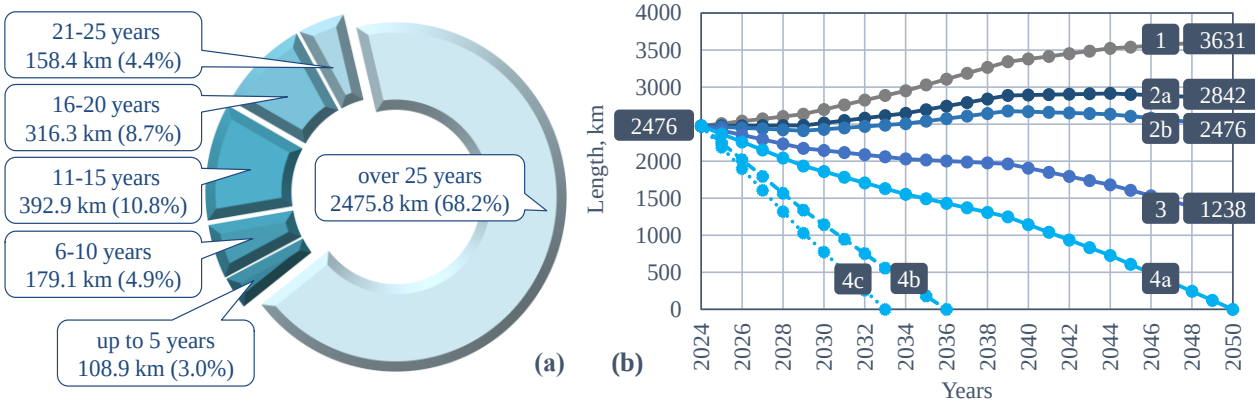

Fig. 4. Current state and projected wear and tear of heat networks in the Irkutsk region to 2050: (a) "age" structure of pipelines; (b) projected wear dynamics under different replacement rates: 1 – no re-laying, 2a – current rate (30.36 km/year), 2b – compensating rate (44.45 km/year), 3 – a 50% reduction in wear (92.06 km/year), 4a, 4b, 4c – complete elimination of wear by 2050 (139.67 km/year), by 2036 (258.97 km/year), and by 2033 (320.81 km/year), respectively.

system and their coordination at the upper level of system control [34]. In this context, the use of logical-probabilistic, stochastic, or statistical models deemed suitable for conventional district heating systems may lead to faulty results that leave out of consideration the concurrent and dependent failures of components operating at different critical facilities and levels of district heating and distributed heating segments of the system. It is important to note that subsystems of different levels are not autonomous, but rather function together to make load redistribution and redundancy possible. On the other hand, this also complicates the failure effects analysis, which relies on emergency thermal-hydraulic conditions in the heat network combined with modeled HSs failures. The design of a hierarchical control system of the heating system with a multi-level generation structure is a research problem in its own right, which involves accomplishing a number of technological (creation of production facilities), theoretical, applied, information-related, and regulatory tasks. The above methodological aspects are equally important for the reliability synthesis of systems being examined and for the establishment of regulatory standards aimed at ensuring high reliability and quality in heating supply.

V. Wear and Tear of the Heat Network Infrastructure in Heating Systems

The key factor hindering the implementation of the majority of promising solutions for heating system development is poor equipment health, mainly that of heat network equipment. For example, there were 4 203 documented incidents in the heating systems operating in Russia in 2022, of which 497 (12%) were in heat sources and 3 706 (88%) were in heat networks [41]. There were 1 327 600 people affected by these incidents in 2022. In this context, the Irkutsk region is an illustrative example (Fig. 4).

The total length of HNs in the region is 3 631 km, whereas the worn out part is 2 476 km (68.2%), of which about 37% is dilapidated, being a priority for replacement to ensure that the incident rate at least does not exceed its current level. Figure 4-b shows projected changes in the length of worn-out HN pipelines for different rates of their restoration. The projection method relies on the following input data: a) the current wear of heat networks (as of 2024); b) the age structure of operating networks in terms of length (Fig. 4-a); c) the current rate of replacement (restoration). These data allow us to estimate the length of pipelines to be worn out annually, according to their service life (over 25 years). Thus, a wear curve is calculated without factoring in renewal. Changing the rate of pipeline replacement can impact the resulting trend either decelerating it or transforming it into a trend of restoration. The existing rate of renovation (curve 2a) fails even to maintain the current level of wear during the projection period. A 50% reduction in wear would require a 3-fold rise in the re-laying rate (curve 3), and more than a 4.5-fold increase to eliminate it completely (curve 4a).

VI. Conclusion

The above review of published research on theoretical and applied reliability problems of heating systems undergoing technological and structural changes has revealed that these problems are either understudied or weakly connected to other lines of research. This may result in inconsistent policies that hinder the development of the systems, as these policies may lack deliberate and balanced decision-making that considers conflicting multiple criteria of economic performance, efficiency, and reliability.

The array of modern technologies used for development and transformation of district heating systems to ensure and enhance their reliability is diverse both in terms of the scope of application (subsystems, facilities, equipment) and the scale of modernization of the systems. As heat generation and distribution technologies continue to evolve, the vision of energy sector development shifts to embracing the trend towards the establishment of integrated multi-energy complexes. These complexes suggest integrating heating systems with various other systems (electricity, gas, and oil systems, as well as those based on renewables), which, along with other effects, leverages interchangeability of energy resources, thereby increasing the redundancy at different levels within the system. In line with this conception, it can be argued that there is much promise in the transition to hybrid district and distributed heating systems with a multi-level hierarchical structure based on prosumer subsystems implemented at each generation level to serve the heat load of the nodes of the original scheme, whose reliability and efficiency go beyond the acceptable limits. In terms of methodological development, a number of assumptions deemed appropriate for modeling conventional district heating systems become restrictive when applied to hierarchical layouts of hybrid district and distributed heating systems, which prompts the development of a

methodological framework for reliability analysis and synthesis.

Another important reliability aspect of heating systems is equipment health. The current level of wear and tear of heat networks necessitates a multiple-fold increase in renovation rates, along with a significant rise in funding, which is currently beyond reach. As a result, there is a growing imbalance in ensuring the reliability of heating systems in the process of their evolution: on the one hand, the technological change and structural transformation are irreversible, on the other hand, a number of major unresolved issues greatly hinder the adoption of innovations. Addressing top-priority issues of reliability of the existing systems to achieve, first of all, their normal (i.e., to specifications) and reliable operation is critical for the effective transition to the future stages of their evolution.

The main developments of the study are a methodology and an algorithm for the formation of district-distributed heating systems. The key limitations assumed in the development of the methodology are as follows: a) for stochastic modeling, we assumed the simplest failure flow of components characterized by typical behavior, independence, and an exponential distribution; b) for thermal-hydraulic modeling, we assumed the main parameters of steady-state conditions in the system (temperature, pressure, flow rates, and others) would remain constant. A number of practical limitations associated with the implementation of district-distributed heating facilities concern the technical level of existing heating systems for innovative transformations. First of all, these are current high wear of heat network, system misalignment, as well as a low level of digitalization and process control.

Advancing the proposed methodology involves addressing many scientific, methodological, and applied problems. At this stage, the priority ones are as follows:

1) Determining the feedback loop of solutions obtained at various levels of the district-distributed heating system (achieving an optimal multi-level system structure necessitates an iterative procedure with “floating” efficiency and reliability criteria to be implemented until some equilibrium solution is reached with acceptable accuracy);

2) Developing methods for optimal loading (based on technical and economic criteria) of district and distributed heat sources in accordance with the thermal load curve during the design period (possible approaches include two-level programming methods, game approaches, and others);

3) Improving the methods designed to ensure reliability of the district-distributed heating system by expanding the use of various functional and structural redundancy methods in prosumer subsystems, including the ability to supply thermal energy into the district network to compensate for emergency shortages;

4) Detailing prosumer circuits, considering the technological and operational factors of their connection to the district system, the conditions and requirements for the reliable operation of the system throughout the entire period, and the range of possible emergency states and events.

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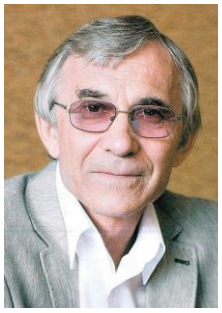

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