Reliability and efficiency of heat supply systems in the Leningrad region

Yu V Andreev 1, M A Grekov 2, V M Proskurin 2 and O V Novikova 2

1 Leningrad region government
Russia, 191311 St.Petersburg, Suvorovskuy, 67
2 Peter the Great St. Petersburg Polytechnic University,
Russia, 195251 St.Petersburg, Polytechnicheskaya, 29

novikova-olga1970@yandex.ru

Abstract. Currently, Russian heat supply system is at the stage of not just organizational, but also technological changes. Any decisions are based on determining priority criteria. The goal of our research is to develop a set of organizational and technical solutions improving the efficiency of production and supply of heat to end consumers, taking into account the criterion that will be defined as the main one for a particular system. Current feasibility of the "generation" subsystem depends on the condition of its main generating equipment, the degree of its load, as well as the efficiency of the distribution of heat load between sources; "transportation" depends on the state of heat supply grids and the extent of their load; "consumption" depends on the state of thermal protection of buildings, losses of consumers, as well as the degree of automation of district heating substations. The criteria may be:
1. Minimum time for the renewal of fixed assets: important in the conditions of disruption of the quality of heat supply. However, research did not confirm any significant violations[1]
2. Minimum variable costs: impact on the formation of tariffs for the population and the price for the industrial consumer;
3. Minimum grid transmission losses: for most systems, they are determined by regulations, not by actual measurements on heat supply grid sites. Not only the radius of effective heat supply and revised production technologies are important, but also the location of facilities and their capacity. However, confirmation of this version calls for implementation of a system for monitoring the state of heat supply grids, for example, based on optical fiber. This can lead to the development of distributed heat energy industry at the level of house heating substations;
4. Economic and budgetary efficiency, taking into account different project financing solutions.

1. Introduction
Managing a regional heat supply system at the level of such territory as the Leningrad Region (LR) is characterized not only by the presence of large industrial and heating facilities such as boiler houses and CHPs, but also by the development of individual heat supply systems. While until the beginning of the 21st century these sources were using wood or coal fuel, in recent years this development has been happening in parallel with the gasification of the countryside and introduction of gas boiler plants in households.

The current feasibility of the "generation" subsystem depends on the state of its main generating equipment, including the concept of "reliability," the efficiency of the installed capacity utilization, as well as the efficiency of the distribution of heat load between sources, if there are alternative ones, which
is rare in the LR. The efficiency of the "transportation" subsystem depends on condition of heat supply grids and their load; "consumption" one depends on the state of thermal protection of buildings, losses of consumers, as well as the degree of automation of district heating substations.

In Western Europe, individual heating systems are predominantly widespread. For example, in Western Germany, the Netherlands, Switzerland, Sweden, Norway, Finland, France and the United Kingdom, more than 80% of apartments are heated autonomously. In Italy, this figure is above 70%, where individual heating is installed in about 20 million dwellings. On the basis of the world expertise in heating, Denmark applied with some amendments the practice adopted in the USSR, and built a system of central heating on the basis of enlarged thermal power plants. The country has chosen the policy aimed at modernizing and consolidating existing heat supply grids. By the mid-1990s, the share of centralized heating systems accounted for about 60% of total heat consumption, while fuel consumption was halved. The cost-effectiveness of Danish centralized heat supply grids is caused by low losses in pipelines due to the introduction of new materials and technologies. Unlike in most countries, in Denmark centralized heat supply systems are governed not by changes in the temperature of the heat carrier, but by changes in the rate of circulation, which automatically adjusts to consumer demand. At the same time, the use of pumps with frequency regulation is widespread, which can significantly reduce energy consumption. Due to this, the heat losses of the main and distribution pipelines of Denmark are less than 4%, and the efficiency of CHPPs reaches 90%.

2. Analysis of characteristics of heat supply systems

The balance of power of heat sources (Table 1) shows significant differences in the sources themselves, as the structure of the LR fuel and energy complex: it includes nuclear power plants, hydroelectric power plants, thermal power plants, combined heat and power plants, and boiler houses. The following table presents the coefficients of heat supply grid upgrade by areas of the LR. They range from 3 to 10%, and the absolute leader in total thermal power is the Vsevolozhsky district.

| LR districts   | Baksitogorsky | Volosovsky | Volkhovsky | Vyborgsky | Gatchina | Kingisepp | Kirishi | Kirovsky | Lodeinopolsky | Lomonosovsky | Luzhsky | Podporozhsky | Pogostsky | Sianino | Tikhvin | Tonskoe | Sosnovy Bor |
|---------------|---------------|------------|------------|-----------|----------|-----------|---------|---------|---------------|--------------|---------|-------------|-----------|---------|---------|---------|-----------|
| Power balance of heat sources | > 1 | 1 | 4 | 43 | 6 | 10 | 3 | 1 | 4 | > 1 | 5 | 3 | 3 | 2 | 6 | 3 | 7 | 1 |
| Heat supply grid upgrade coefficient | 4 | 3 | 6 | 4 | 4 | 9 | 4 | 3 | 7 | 3 | 10 | 6 | 10 | 5 | 7 | 3 | 10 | 3 |

As of the end of 2019, the centralized heat supply system of municipal boiler houses in the LR contains 681 facilities. Of these, 414 are using gas, 163 – coal, 68 – fuel oil and 22 – pellets and wood chips. Analysis of the connected capacity of gas boiler houses in municipal districts showed that on average it makes up only 65% of installed capacity, and in some areas even less than 15%.

Our analysis of the "heat source upgrade ratio" parameter showed that the highest value was observed in the Baksitogorsky district, 0.286, when the average for this factor is 0.017. In the Priozersky district and in the Tikhvin district this indicator is negative, which is due to the fact that more sources were eliminated than new ones introduced. The largest number of upgraded sources of heat supply was in Baksitogorsky district.

As of 2020, more than 70% of gas boilers in the LR have thermal capacity of less than 10 Gcal/h. For such boiler houses, domestic and foreign manufacturers offer modern gas boilers. The market for boiler equipment for private houses is characterized by sales volumes and a list of manufacturing companies. In addition, the number of gasified private households (including gardening) is growing in the LR territory, which has increased the demand for wall-mounted low-power boiler equipment.
According to our market analysis, in 2018 in the region, the structure of the leading holdings offering floor condensing boilers is as follows:

| Manufacturer                  | Market share, % |
|-------------------------------|-----------------|
| Group BDR Thermea            | 28              |
| Vaillant Group               | 23              |
| Ariston Thermo               | 23              |
| Viessmann                    | 12              |
| Cenergasservice              | 3               |
| Other                        | 1               |

Table 2. Market balance by share of key participants.

Table 3. Market turnover in retail prices of 2018, million euro.

| No | Brand       | wall | gas | G+LF | LF | SF | pellets | electric | Total |
|----|-------------|------|-----|------|----|----|---------|----------|-------|
| 1  | Baxi        | 59.11| 15.61| -    | -  | -  | -       | -        | 74.72 |
| 2  | Protherm    | 26.21| 20.02| 2.00 | -  | 0.37| -       | -        | 19.36 |
| 3  | Navien      | 53.40| 2.22 | -    | 1.23| -  | -       | 0.94     | 57.79 |
| 4  | Lemax       | 2.02 | 42.68| -    | -  | 0.43| -       | -        | 45.13 |
| 5  | Vessmann    | 18.05| 5.32 | 20.12| -  | 0.05| -       | -        | 43.60 |
| 6  | Bosch       | 25.4 | 0.14 | 11.91 | -  | 0.18| -       | 0.13     | 37.76 |
| 7  | Zota        | -    | -    | -    | -  | 14.96| 6.50    | 14.13    | 35.60 |
| 8  | Buderus     | 19.17| 5.45 | 5.51 | -  | 1.63| 0.03    | 0.24     | 32.02 |
| 9  | Ariston     | 25.76| 0.12 | -    | -  | -  | -       | -        | 25.88 |
| 10 | Vaillant    | 16.64| 1.41 | -    | -  | -  | -       | 1.67     | 19.72 |
| 11 | Rostovgasapparate | - | 19.45| -    | -  | -  | -       | -        | 19.45 |
| 12 | Evan        | -    | -    | -    | -  | -  | 0.01    | 12.16    | 12.17 |

*G stands for gas, LF – liquid fuel, SF – solid fuel

Statistics on the turnover of boilers indicates a high share of imported equipment purchased in private households. However, in the cities and large towns of the LR, the majority of consumers are provided by municipal boiler houses. Analysis of the structure of consumers of heat energy in the LR indicates the predominance of manufacturing industry.

According to statistics for the period from 2011 to 2019, the planned values of heat loss during transmission through heat supply grids changed from 4.17% to 2.97%. At the same time, actual losses remain higher not only because of deterioration of the grid equipment, but also because of the operational nature. At the moment, a significant part of the boiler houses, including those in the LR, continues to operate according to the temperature schedule with a "cut-off", which entails non-design modes of operation of the plants due to violations of hydraulic modes of the heat supply grids and a decrease in the actual temperatures of the heat transfer fluid. The inertia of heat supply systems and the low level of automation of heat-consuming installations of consumers is accompanied by the shortcomings of the centralized quality regulation of heat loads. Under these conditions, transitioning to a more advanced way of regulating heat dissipation when actual heat loads deviate from the design ones can also be considered as a direction for increasing efficiency and reliability of heat supply systems. In principle, a number of parameters can be used to control the heat supply: the heat transfer coefficient of heating devices, the area of the switched on heating surface, the temperature of the heating medium at the inlet to the device, the equivalent of the consumption of the heating medium, and the operating time of the device. In practice, for a heat supply source, it is realistic to affect only 2 parameters among them: temperature and water equivalent of the heat transfer fluid.

Of course, it is worth mentioning that even regulating these quantities is somewhat limited. For example, the temperature of the heat transfer fluid at the inlet to a heat-consuming installation cannot be less than required for hot water supply (usually 60 °C) and not higher than the limit determined by the permissible pressure of the water in the heat carrier supply line. At the same time, the flow equivalent...
is limited by the available pressure at the heat point and the hydraulic resistance of consumers’ equipment.

Considering this, it is important to determine what are the criteria for assessing reliability and efficiency of the object under study – a heat supply system.

At the moment, both types of heat supply systems – open and closed – are present in the LR. Inside the centralized heat supply system in its various components, many physical and chemical processes simultaneously proceed and closely interact: combustion, flows of liquids and gases, heat and mass transfer, etc. [2, 3]. From domestic and foreign experience of their operation, it follows that there is a significant potential for improvement. Global trends in this area include activities related to improving the economic, energy and environmental efficiency of heat supply systems. At the same time, the potential opportunity to increase total efficiency is naturally connected with the development of the technosphere as a whole. This is manifested in the development and application of new, more advanced methodological and technical solutions at the level of improving technological functions and developing management functions and planning of heat supply systems [4].

Calculations using the example of individual boiler houses have demonstrated that the actual load of consumers can be lower than the calculated one by up to 50%. This result allows us to argue that a decrease in the temperature of the water in the supply lines of heat supply grids does not adversely affect the quality of the heat supply of customers and makes it possible to provide required temperature at the indoor premises.

Based on the recommendations of regulatory documents and the analysis made, two alternative options are possible: quantitative regulation at a temperature schedule of 110/70 °C and qualitative-quantitative regulation while maintaining the existing temperature schedule.

Often situations arise when the actual flow rate of the heat transfer fluid into the supply line is significantly lower than one calculated according to the contractual load. We have calculated heat supply schedules for individual boiler houses and analyzed the effect of their application. We found out that depending on whether the current load is being maintained or if an increase is planned, the most promising approach may be the use of qualitative-quantitative regulation and quantitative one in the case of maintaining the existing load.

The main result of the analysis on the example of individual boiler houses is to identify the actual load of consumers connected to the boiler house, the value of which averaged about 56% of the contractual. Actual regulation of heat supply is somewhat different from the one approved according to the temperature schedule with a "cut-off" of 110 °C. In this case, the actual method of regulating heat supply, which is close to the qualitative one from the point of view of constancy of the heat transfer fluid flow, is not optimal [9].

According to the analysis of the coefficient of heat supply grids upgrade (Table 1), it was revealed that the largest number of replaced heat supply grids was observed in Kingisepsky, Tosninsky and Gatchinsky districts. The average value for this coefficient among the LR districts is 0.02. This is not a criterion for qualitative evaluation, but only indicates the dynamics of upgrading.

3. Assessing the reliability and effectiveness of heat supply systems

There is a number of technical reliability indicators described in [5]. They can be classified by types of resources used in the heat supply systems: electricity supply, water supply and fuel supply of heat energy sources (HES); the indicator of compliance of HES thermal power and the capacity of heat supply grid (HSG) with the estimated heat load of consumers; the indicator of the level of redundancy of sources and elements of the HSG through looping and bridging devices; the indicator of the technical condition of the HSG, characterized by the presence of dilapidated pipelines; the indicator of the failure rate of HSG systems; the indicator of relative emergency undersupply of heat; final indicator of readiness of heat supply organizations for emergency recovery work; the indicator of staffing with repair and operational-repair personnel; the indicators of availability of machines, equipment and mobile emergency power sources.

Also, there is a list of reliability indicators for assessing technical effectiveness, defined by the Ministry of Energy and the Ministry of Regional Development, described in the requirements for heat supply schemes:
1. number of failures in supplying heat energy to consumers;
2. given duration of interruptions in the supply of thermal energy;
3. given volumes of undersupply of heat due to interruptions during supplying heat energy;
4. weighted average value of deviations of the heat transfer fluid temperature, corresponding to deviations of its parameters as a result of violations in the supply of heat energy.

A great contribution to the development of the assessment of the functioning of heat supply systems was made by such scientists as I. A. Bashmakov, V. N. Papushkin, A. S. Nekrasov. By analyzing the works of these scientists, we can identify several groups of performance indicators:
1. nature-climatic, influencing the temperature mode and heat sources functioning;
2. institutional, reflecting the degree of development of the heat supply system, presence of investment programs in the industry;
3. municipal, demonstrating the degree of satisfaction of interests of local budget bodies;
4. consumer, influencing solvency in the field of heat supply, connection to the central heating system, subsidies for heat supply companies;
5. economic, assessing efficiency of the heat supply system;
6. reliability, evaluating possibility of uninterrupted supply, accident rate and amount of losses;
7. technological.

However, reliability indicators consist of just four elements: accident rate of public infrastructure systems, disruptions in the supply of consumers, duration of delivery of goods and services to consumers, and readiness of the heat supply system for the heating season.

Potential problems of consumer solvency, which may increase the risk of disruption of return on investment and limit the use of public-private partnership mechanisms are reflected in consumer indicators:
1. share of the cost of heat supply services in the total income of the population;
2. percentage of families receiving subsidies for utilities;
3. level of collection of payments for heat supply services from the population;
4. rate of growth or decline of degree of payments for heat supply services from the population;
5. portion of the population with incomes below the subsistence level;
6. ratio of changes in tariffs and population incomes;
7. ratio of the cost of heat supply services in the settlement and the regional average;
8. decrease of complaints from the population;
9. cost of centralized heating services compared with autonomous heat supply.

Nature-climatic indicators traditionally characterize the influence of external factors:
1. air temperature of the environment;
2. evaluation of severity of the local climate;
3. average wind speed;
4. assessment of humidity of the local climate;
5. number of sunny days during the heating period.

Technological indicators:
1. ratio of actual specific fuel consumption to regulatory one;
2. ratio of actual water consumption to regulatory one;
3. ratio of actual electricity consumption to regulatory one;
4. ratio of actual losses to regulatory ones;
5. wear of heating sources;
6. wear of heat supply grids.

Economic indicators:
1. profitability change;
2. cost change;
3. net profit;
4. investment recovery rate.

To evaluate the effectiveness of the system, these indicators can be compared with the indicators of the "model" heat supply system. This technique is controversial, but its main advantage is that it assesses all factors affecting the efficiency of heat supply systems.
In Russia, each heat supply system is unique; therefore, it is not possible to develop a unified plan increasing economic and technical efficiency of heat supply systems. But the approaches to boosting the efficiency of heat supply systems are often associated with the analysis of models of the heat supply market, identifying surplus and unprofitable producers according to the results of inventory, development of energy services, ensuring the flow of investments, introducing a closed resource cycle using the energy potential of waste, increasing digitalization of control and regulation of the heat supply system [10].

In the Regulations for Assessing Readiness for the Heating Season, there is a paragraph requiring availability of a monitoring system to check the status of the heat supply system. One of its significant potentials is the reduction of losses due to the implementation of heat supply grid monitoring. The average loss is about 10% of the heat released. Although the reports on the heat supply grids of the LR did not allow us to estimate the actual losses, implementation of monitoring allows to:

- locate defects before an emergency arises;
- evaluate the condition of heat supply grids;
- determine whether pipelines can be used during their lifetime and after it;
- assess the timeliness of withdrawal of heat supply system facilities for repairs.

The authors analyzed the modern systems used to monitor heat supply grids and identified their main advantages and disadvantages.

**Table 4. Advantages and disadvantages of monitoring systems under consideration.**

| Method                        | Accuracy | Range            | Advantages                                                                 | Disadvantages                                                                                           |
|-------------------------------|----------|------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Acoustic diagnostics          | about 80%| Up to 300 m      | Fairly high data interpretation speed and accuracy.                        | Short range, low examination speed.                                                                      |
| Acoustic emission             | about 60%| About 480 m of pipes | One of the most common methods; monitoring itself is fast enough.           | Hard to use on a large number of pipeline sections; low accuracy; difficulties in preparing sections for monitoring |
| Metal magnetic memory         | about 90%| 10–15 cm         | Can be used on coupling sites and bends and for all pipeline arrangements. | Very low accuracy of measurements.                                                                     |
| Ultrasonic thickness measure- | about 95%| 10–20 cm         | High accuracy of locating defects in the heat supply grid.                  | Has to be done together with visual measuring control; time consuming; qualification requirements.        |
| Targeted ultrasound           | about 90–95% | Up to 30 m       | High accuracy; can provide a complete picture of the condition of the pipeline with defects by categories. | Requires restoring damaged thermal insulation of the pipeline; lengthy preparations for the launch of the monitoring equipment. The wavelength is not fit for investigating long pipelines. |
| Thermal imaging               | 85–90%   | Visible range    | No direct contact with the heat conduit and equipment required, which allows to not change the mode of operation of the system. Safe for the monitoring specialist, as there is no contact with pipelines and heat transfer fluid. | It is desirable that the coating is uniform; the specialist must be qualified, possess accurate executive documentation and knowledge of the device. |
| Thermal aerial photography    | 100%     | Area of about 1 km² | The ability to see the big picture; track all the defects in a small amount of time. | Difficulties in obtaining permissions; limitations on weather conditions; only heat losses can be detected, but not the condition of the pipeline. |

An expert assessment of monitoring methods was carried out in the following areas:

1. Specific costs per 1 km of the heat supply grid – $Y_1$;
2. Monitoring efficiency – $Y_2$;
3. Employees present at the monitoring site and the possibility of harming them – $Y_3$;
4. Specific time spent for monitoring 1 km of the heat supply grid – $Y_4$;
5. Accuracy of the information obtained – $Y_5$.

The assessment is made for each of these factors on a scale from 1 to 5 points, where the minimum score (1 point) corresponds to the most unfavorable situation, and the maximum (5 points) – to the most favorable. The cumulative score took into account the weight factor.

The following formula is used for the final result:

$$I = Y_1 \times K + Y_2 \times K + Y_3 \times K + Y_4 \times K + Y_5 \times K$$

(1)

We present the results in the following table.

| Monitoring type                  | Acoustic diagnostics | Acoustic emission | Metal magnetic memory | Ultrasonic thickness measurement | Targeted ultrasound | Thermal imaging | Thermal aerial photography |
|---------------------------------|----------------------|------------------|-----------------------|----------------------------------|---------------------|----------------|---------------------------|
| Final result                    | 3.4                  | 2.6              | 3.2                   | 3.6                              | 2.6                 | 3              | 4                         |

Table 5. Final expert assessment.

On the basis of fiber optic technology, a new type of monitoring has been developed, which can include all the advantages of these types of monitoring, as well as address all the shortcomings. This system does not require complex preparations, disruption of heat transfer fluid supply and large amounts of time. The system is unique, its speed and accuracy of information transmission are the best among all types of technical monitoring.

Table 6. Advantages and limitations of fiber optic monitoring technology.

| Advantages                                                                 | Limitations                                           |
|---------------------------------------------------------------------------|-------------------------------------------------------|
| Determines types of leaks: damage to the outer shell or damage to the pipe due to temperature changes; | Lack of legal framework for the production of pipes with integrated optical fiber; |
| Monitors pipe temperature and heat loss;                                   | Pipes with integrated fiber not available.            |
| Immune to electromagnetic interference;                                    |                                                       |
| Length of controlled pipes up to 60 km;                                   |                                                       |
| Possibility of expanding controlled parameters with the development of fiber technology; |                                                       |
| Ability to transfer information over existing fiber.                       |                                                       |

This method of monitoring has not yet been applied to heat pipes, but this area is considered very promising, therefore OJSC St. Petersburg Heating Grid has launched a pilot project for the introduction of fiber optic monitoring of heat supply grids and their experience can be used in the LR.

The cost-effectiveness of heat supply systems will be affected by tariffs. Since 2018, the maximum levels of tariffs for heat energy supply to consumers, heat transfer services and hot water in an open heat supply system are subject to state regulation. In each price zone, Unified Heat Supply Organizations (UHSO), which appeared since 2013, are responsible for the management of heat supply. UHSOs have been determined for individual localities of the LR, for example, among them is a branch of OJSC Gazprom Teploenergo, which was provided with a unified economically sound tariff throughout the district.

4. Conclusions

The presence of both centralized and distributed heating systems in the small LR settlements implies the need to select strategies for managing reliability and efficiency. The introduction of modern monitoring systems allows to virtually eliminate technical inventory checks and improve reliability of the system.

The results of the studies showed the potential for improving reliability and efficiency of heat supply systems in terms of generation through the use of modern gas boilers, regulating regimes with "cut-offs" and developing monitoring systems of heat supply grids in the centralized and distributed energy systems, close to the final consumer.

Tariffs for heat supply for the population of the LR significantly depend on the operating organization and the connection scheme. Most municipal districts provide heat generated in gas and gas-oil boiler...
houses. The structure of the fuel balance confirms that 83% of fuel needs of boiler houses of the LR are covered by natural gas. Already about 10% in the balance is biofuel (sawdust). This is where the options for technological solutions associated with the use of modern gas boilers and local fuels are formed. The nature of the formation of technical solutions based on biofuels is mainly due to the presence of significant amounts of wood processing enterprises in the region. However, at the moment, switching to using waste of a different origin is not of interest from an economic point of view. The environmental aspect of this issue can still change the fuel balance.

References
[1] ETS-Project 2017 Report on the implementation of work on the topic: Development of the scheme and program for the development of electricity in the Leningrad region for 2017-2021 (in terms of heat supply) (Moscow: ETS-Project, LLC)
[2] Popyrin L S et al. 1989 Research of heat supply systems: A monograph (Moscow: Nauka) p 215
[3] Sednin V A 2005 Theory and practice of creating automated heat supply management systems: A monograph (Minsk: BNTU) p 190
[4] Sednin V A and Sednin A V 2017 Tendencies of development of centralized heat supply systems Energy conservation in urban economy, energy, industry: Seventh International Science and Technology Conference, April 21-22, 2017 (Ulyanovsk : UlGTU) pp 55–58
[5] Order of the Ministry of Regional Development of Russia, dated 26.07.2013 N 310
[6] 2019 SP 131.13330.2018 "SNIP 23-01-99* Construction climatology" (Moscow: Standardinform) p 110
[7] Karlov K R and Baibakov S A The need for ongoing control of parameters of modes and state of heat supply grid pipelines: https://www.rosteplo.ru/Tech_stat/stat_shablon.php?id=3001, accessed on 14.01.2020
[8] Methods of comprehensive determination of the feasibility indicators of heat supply systems … (with changes from 10.04.2020)
[9] Aleshina A, Vladimirov I and Kozhukar E 2018 The values of specific consumption of energy in the assessment of the level of future demand 2018 International Multi-Conference on Industrial Engineering and Modern Technologies, FarEastCon 2018 8602833
[10] Sapozhnikov S Z, Mityakov V Y, Mityakov A V, Babich A Y and Zainullina E R 2019 The study of heat flux measurement for heat transfer during condensation at pipe surfaces Technical Physics Letters 10.1134/S1063785019040163

Acknowledgments
This research work was supported by the Academic Excellence Project 5-100 proposed by Peter the Great St. Petersburg Polytechnic University.