Pathways for sustainable development of urban heat supply systems

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Abstract. Our paper focuses on the development of effective pathways for ensuring sustainable development of urban heat supply systems in the context of liberalization of economic relations in the energy sector. Using the example of the Moscow region, we reveal regularities in the change in the structure of heat sources and the organization of the main elements of the heat supply system. In addition, we propose an improved method for the formation of the marginal tariff for heat taking into account the structure of heat sources and allowing to eliminate the existing disadvantages of introducing market-based pricing methods. Moreover, we develop a mechanism for the sustainable development of centralized heat supply systems based on the organization of competitive selection of heat suppliers and the method of forming the maximum heat tariff.

1 Introduction

In the conditions of a planned economy, the supply of heat to residential neighborhoods and industrial facilities in Russia was carried out through the centralized systems based on the district heating, liquidating small-scale energy facilities, where possible, and transferring them to centralized sources. Thus, it was possible to achieve substantial energy savings and reduce the cost of heat energy and the tariff for consumers [1, 2, 3].

During the transition to a market economy and the liberalization of the country's energy sector, the production, transmission and distribution of energy turned out to be in different ownership, a lot of intermediaries appeared between generating facilities and end users. Today, the outcomes of these deep institutional changes significantly affect the final cost of heat for consumers, ensuring the reliability of heat supply and creates a threat for sustainable development of the industry [4, 5].

The restructuring of the district heating system has led to a change in the structure of heat sources. On the one hand, the development of district heating leads to the enlargement of heat sources and the elimination of district heating stations and small boiler houses. On

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the other hand, technologies of individual heat supply are spreading, for example, roof-top boiler houses, which in some cases turn out to be more efficient for urban and housing and communal services due to the absence of costs for maintenance of heating networks [6, 7, 8].

Market mechanisms contribute to the introduction of energy-saving solutions, in particular, the transfer of equipment for preparing hot water for domestic needs in buildings, that is, the gradual abandonment of central heating points in favor of individual ones.

The liberalization of economic relations in the heat and power industry continues, due to the adopted law "On Heat Supply". This leads to the complication of economic principles and models of organizing heat supply for urban and housing and communal services of the country. An economic model of a unified heat supply organization is considered as a promising development of centralized heat supply, which sells heat energy at fixed tariffs for end users, collects payments, and has the authority to optimize capacity utilization. At the same time, it concludes unregulated contracts with organizations - sources of heat supply, based on the principle of "alternative boiler room" [9, 10].

The above-described changes in the development of urban heat supply, due to the integration of market principles of heat management, require the development of effective organizational mechanisms for their implementation and tools for economic assessment. Our paper is devoted to the proposal of new mechanisms for managing the development of urban heat supply systems, taking into account the latest achievements in the field of energy efficient production and transmission of heat energy, which make it possible to increase the efficiency of urban heat supply management when introducing market pricing mechanisms.

2 Analysis of patterns in the development of urban heat supply systems: a case of the Moscow region

Heat supply includes three main processes: the transfer of heat to the heat carrier, heat transport, and the use of thermal potential. To organize the heat supply process, a heat supply system is designed, consisting of heat sources (CHP, thermal stations, small boiler houses), pipeline systems, heat consumption systems with heating devices.

The following features can be distinguished that allow for the classification of heat supply systems:

- by power (characterized by the range of heat transfer and the number of consumers),
- type of heat source (CHP, thermal power plants (TS), small boiler houses),
- type of heat carrier (saturated steam, hot water, various high-temperature heat carriers).
- At the same time, for each class of heat supply systems, there are two options for organizing the scheme for the production and transmission of heat energy:
- scheme of centralized heat supply from CHPPs or from large boiler houses (RTS, KTS), when heat for several buildings is supplied from one source,
- individual heat supply scheme, when the heat source is located in a heated building or annex.

In a planned economy, heat supply to Russian cities was carried out through centralized systems based on district heating. Thus, it was possible to achieve energy savings and reduce the cost of heat energy and the tariff for consumers [2, 3, 5].

During the transition to a market economy, the production, transmission, and distribution of energy turned out to be in different ownership, a lot of intermediaries

appeared between generating facilities and final consumers, which affected the final cost of consumed heat.

The adoption of the Law "On Heat Supply" in 2010, designed to regulate the developing market relations, led to a gradual transition in the tariff setting system from state regulation of all tariffs to setting only the maximum level of prices for heat energy for the end user [9, 11, 12].

As a promising development of urban district heating, the model of a unified heat supply organization is considered, which sells heat energy at fixed tariffs to end users, collects payments, and has the authority to optimize capacity utilization. At the same time, it concludes unregulated contracts with organizations - sources of heat supply, based on the principle of "alternative boiler room". The price of an "alternative boiler house" is determined by the price of heat supply from an alternative source that replaces centralized heat supply [7, 13].

Furthermore, with the development of market mechanisms and an increase in the efficiency of small heat sources, there is a spread of technologies for individual heat supply, for example, roof-top boiler houses which in some cases turn out to be more efficient for urban and housing and communal services due to the absence of costs for servicing heating networks.

In addition, market mechanisms contribute to the introduction of energy-saving solutions, in particular, the transfer of equipment for preparing hot water for domestic needs in buildings, that is, the gradual abandonment of central heating points in favor of individual ones.

The above-described trends in the development of urban heat supply, due to the integration of market principles of heat management, lead to a change in the structure of heat sources. To a large extent, this process is determined by the advantages and disadvantages of organizing centralized and individual heat supply systems. The identified advantages and disadvantages of centralized and individual heat supply systems are presented in Table 1.

In order to identify patterns in the development of urban heat supply systems in the country, we will consider the heat supply system of the Moscow region. The overwhelming majority of the city's heat sources are included in the centralized heating system, which is the largest in the world. The total length of heating networks in one-pipe calculation is about 15 thousand km. Taking into account the seasonal unevenness of heat consumption, the average annual power utilization rate of heat sources is 21% [7, 14, 15].

Table 1. Comparative analysis of centralized and individual heat supply systems

Heating system	Advantages	Disadvantages
Centralized	<ul style="list-style-type: none">• saving heat and fuel due to district heating;• environmental friendliness through the use of more efficient cleaning systems and construction of high chimneys;• improvement of planning solutions for the area development.	<ul style="list-style-type: none">• additional costs for CHPPs for the construction of heat supply installations, an increase in electricity consumption for own needs;• limitation of the unit capacity of installations due to the small value of the heat load of the consumer (in comparison with the electrical load);• small radius of heat transfer.
Individual	<ul style="list-style-type: none">• small (short) heating networks;• reduction of heat carrier losses;• reduction of heat losses.	<ul style="list-style-type: none">• environmental pollution (since it is economically inexpedient to build high chimneys);• high initial capital costs.

The Moscow region has the highest heat load in the world. The average heat load in the city per person is 3 thousand kcal / h (3.5 kW) (4 times more than the electric one) [7, 14, 16]. Moscow's energy supply is mainly provided by powerful CHPPs and heating systems from them, created on the basis of PJSC Mosenergo (TGK-3). The district heating system covers 96% of consumers.

Another large city energy supply company is PJSC MOEK, which provides about 27% of the city's heat load. The sources of Mosenergo PJSC and MOEK PJSC are connected to 87% of the city's heat load.

The unit heat capacities of the Moscow CHPPs reach 4,900 Gcal / h. The five largest CHPPs in Moscow provide more than 50% of the city's heat load. PJSC Mosenergo accounts for about 70% of the total heat generation in the city, PJSC MOEK - 25%.

The main heat sources in Moscow are 13 CHPPs of PJSC Mosenergo (including regional CHPP-22 and CHPP-27) and 196 sources of PJSC MOEK: 36 regional thermal power plants (RTS), 25 quarterly thermal power plants (KTS), small boiler houses (MK).

The basis of the generating capacities of the CHPPs of PJSC "Mosenergo" are steam turbine CHPPs with steam power equipment. Currently, the city has significant reserves of thermal power sources - about 16.7 thousand Gcal / h. The total heat capacity of the CHPPs supplying consumers in the city of Moscow is 40,000 Gcal / h. The average service life of the steam power equipment of the CHPP is 26 years. Average specific fuel consumption for heat supply is 165.5 kg of fuel equivalent / Gcal (according to the physical method of cost sharing) [7, 11].

The total thermal capacity of power sources of PJSC MOEK is 18,000 Gcal / h. The average specific fuel consumption for heat energy supply from the power sources of PJSC MOEK is 156.3 kg of fuel equivalent / Gcal, for small boiler houses - 168.1 kg of fuel equivalent / Gcal, which corresponds to a boiler house efficiency of no more than 85%. For 45 boiler houses with the most worn-out equipment, the average specific fuel consumption was 270.6 kg of fuel equivalent / Gcal (efficiency 53%).

Since 2007, in accordance with the order of the Moscow Government, a program has been implemented to reconstruct RTS and KTS with the installation of gas turbines on them, which significantly increases their competitiveness relative to CHP.

The following patterns can be distinguished in changing the structure of heat sources in the Moscow region:

- Despite the significant role in the power supply of CHPPs, the use of small and medium-sized boilers is growing every year, which is achieved by reducing the cost and timing of construction and installation works, increasing the efficiency and reliability of equipment.
- District heating plants (RTS) provide heat supply to individual residential areas of the city. Only thermal energy is produced. However, the installation of a gas turbine plant allows RTS to produce electricity with relatively low operating costs. Thus, the role of RTS and, consequently, sources of average power and distributed generation, in urban power supply is growing.
- Quarter thermal power plants (KTS) supply heat to individual quarters of the city. Having less capacity than RTS, they ensure greater decentralization of heat supply. Nevertheless, KTS, along with small thermal power facilities, are economically less efficient than CHP and RTS. This circumstance leads to the gradual elimination of small boiler houses and the implementation of the transfer of consumers to centralized sources of heat supply.
- Despite the tendency towards centralization, the rate of elimination of small heat sources is decreasing, which is explained by an increase in the efficiency of decentralized heat supply systems based on individual heating points and roof-top boiler houses.

3 Methods of forming the cost of heat energy in urban heat supply systems

The Russian Federal Law "On Heat Supply" introduces the right to choose from five methods of regulating the cost of heat energy [5, 17, 18]:

- method of economically justified costs (costs);
- method of indexation of established tariffs;
- method of ensuring the return on invested capital (Regulatory Asset Base, RAB);
- method of comparison of analogs;
- alternative boiler house method (since 2019).

The applied pricing method is set at the regional level and determines the marginal tariff for heat for consumers, taking into account the required gross revenue of the heat supply company. A generalized description of the methods for the formation of marginal prices for heat energy is shown in Figure 1.

Fig. 1. Characteristics of methods for the formation of marginal prices for heat

According to the method of economically justified costs, the required gross revenue of the heat supply company is calculated as the sum of production, repair, administrative and depreciation costs, as well as standard profit.

According to the method of indexation of the established tariffs, the required gross revenue includes operating expenses, depreciation, standard and estimated profit of the enterprise.

Under the RAB method, the gross revenue required for tariff setting is defined as the sum of operating costs, return on invested capital and return on investment capital.

According to the method of comparison of analogs, long-term tariffs are established based on the analysis of the costs of other heat supply enterprises, the fixed assets and operating conditions of which are characterized by similar physical and technological parameters. The required gross revenue is calculated by indexing the baseline expenditure using the cost reduction index and the consumer price index.

In the coming years, within the framework of the plan for the liberalization of economic relations in the heat power industry, a massive transition of regions to the use of the

alternative boiler house method is planned in order to attract investments in the modernization of heat supply systems, characterized by a high wear rate. At the same time, it is planned to form a single heat supply organization in the district heating systems, which sells heat at fixed tariffs to end consumers, collects payments, and has the authority to optimize capacity utilization. It also enters into unregulated contracts with heat suppliers based on the principle of "alternative boiler house".

An alternative boiler house is understood as a set of standard technical and economic parameters for the operation of a model heat source, set for a certain price zone. In accordance with this concept, an alternative boiler house is a local source of heat supply, which consumers can replace by third-party heat supply organizations. At present, an alternative boiler house is understood as an object with a capacity of 25-50 Gcal / h. The price of heat is supposed to be set at a level that does not exceed the cost of heat generated in this boiler house, including investment costs for its construction. The cost of thermal energy of an alternative boiler house is determined in the process of modeling an investment project in accordance with the payback period and rate of return acceptable to the investor [5, 18, 19].

For CHPPs, in accordance with the method, the marginal tariff is assumed to be equal to the boiler house tariff minus the cost of heat transportation through the main pipelines. The final tariff for the consumer is defined as the tariff of the boiler house with a surcharge for transportation through distribution networks:

$$Tariff_{CHP} = Tariff_{Boiler} - C_{lines}^{magistral} + C_{lines}^{distribution}, \quad (1)$$

where $Tariff_{CHP}$ - marginal tariff for thermal energy generated at CHP, $Tariff_{Boiler}$ - ideal boiler room tariff, $C_{lines}^{magistral}$ - the cost of transporting heat through the main networks to the heating point, $C_{lines}^{distribution}$ - the cost of transporting heat energy through distribution networks to the consumer.

At the same time, the alternative boiler house method has many disadvantages. Thus, model calculations show that the inclusion of capital costs of the boiler house in the calculation of the marginal price leads in many regions to a significant increase in the tariff for thermal energy. Also, the monopoly of a single heat supply company will not allow independent heat producers to develop.

In order to reduce the impact of these shortcomings, it is proposed to take into account the structure of heat sources operating in a single price zone when forming the maximum tariff for thermal energy (see Figure 2 below).

Fig. 2.An improved method of forming the maximum heat tariff

According to the method, the key costs of heat producers are considered as a set of production and investment costs. Production costs are primarily determined by fuel costs. Investment - expenditures on programs for the modernization of fixed assets.

The limiting tariff is determined by the closing costs of the last switched on heat source. The “ideal boiler room” model is involved in pricing.

Finding the closing costs (the last included heat source with the highest total costs when generating a volume of heat not provided by other sources) requires solving the dynamic programming problem:

$$TC(Q) = \min [TC_1(Q_1) + TC_2(Q_2) + \dots + TC_n(Q_n) + TC_{IB}(Q_B)] \quad (2)$$

$$\begin{cases} TC_i(Q_i) = I_i + kbQ_i \\ TC_{IB}(Q_{IB}) = I_{IB} + kbQ_{IB} \\ Q_1 + Q_2 + \dots + Q_n + Q_{IB} = Q \\ Q_i^{\min} \leq Q_i \leq Q_i^{\max} \\ Q_{IB}^{\min} \leq Q_{IB} \leq Q_{IB}^{\max} \end{cases} \quad (3)$$

where Q - required thermal power of the heat supply system to meet the needs of the consumer, Q_i - thermal power of the i -th heat source, Q_B - heat output of an ideal boiler room, $TC_i(Q_i)$ - total costs of the i -th heat source, $TC_{IB}(Q_B)$ - total costs of an ideal boiler room.

4 Results and discussion

Figure 3 that follows shows the results of calculating the marginal pricing for large cities in Russia according to the proposed method for forming the marginal heat tariff. The results are compared with the current tariff and calculations using the "alternative boiler house" method.

Fig. 3. The results of calculating the marginal pricing according to the proposed method and the method of "alternative boiler room"

As one can see from the above calculation results, the proposed method of marginal pricing when organizing centralized heat supply to consumers on the basis of a single heat supply company allows to reduce the upper price limit obtained by the "alternative boiler house" method. But at the same time, the cost of heat turns out to be higher than the current tariff. To prevent tariff growth, it is necessary to further improve the organizational model of the unified heat supply company by developing mechanisms to increase market competition between heat sources.

Nowadays, one of the most common models of a unified heat supply company is the consolidation of the entire heat supply business in one organization, which provides favorable conditions for optimizing the functioning and development of heat supply systems, and also contributes to the capitalization of a heat supply company and the growth of its investment attractiveness. A significant drawback of this model is lack of competition between heat sources, which does not stimulate a single heat supply company to form the cost of heat energy below the limit for a given price zone [19, 20].

One of the mechanisms for introducing a competitive environment in the heat supply market is the organization of a single purchaser of heat energy (Figure 4).

Fig. 4. Single Buyer Organization Model

All heat sources of the city are connected to a single loop-back heating network, and to provide technological and commercial dispatching, an independent heating network operator - a heating network company - is created. Heat transfer activities are separated from production.

The heating grid company purchases heat from heat sources with the lowest tariffs, and then sells it to consumers. This model is an organizational and economic mechanism that ensures the competitive selection of heat suppliers for the district heating system, taking into account technical constraints. The application of the model is advisable in the restructuring of the heat economy and the transition to market pricing.

Minimization of fuel costs for heat production can be described in the form of a mathematical programming problem:

$$B^h(Q) = \min \left[b_{CHP}^{hh} \cdot Q_{CHP} + b_{boiler} \cdot Q_{boiler} \right] \quad (4)$$

$$\begin{cases} Q_{CHP} + Q_{boiler} = Q \\ (b_{CPP} - b_{CHP}^{he}) N_{CHP}^h(Q_{CHP}) - (b_{CHP}^e - b_{CPP}) N_{CHP}^e(Q_{CHP}) \geq 0 \end{cases} \quad (5)$$

where Q - annual heat load, b_{boiler} - specific fuel consumption for heat production by boiler plants, b_{CHP}^e - specific fuel consumption for electricity generation at CHP in condensing mode, $b_{CHP}^{hh}, b_{CHP}^{he}$ - specific fuel consumption for heat and electricity production in district heating mode, b_{CPP} - specific fuel costs of condensing power plants, N_{CHP}^h, N_{CHP}^e - electricity generation by CHPP in heating and condensing mode, Q_{CHP}, Q_{boiler} - heat load of CHP and boiler house.

In the case of consolidation of the entire heat supply business to consumers in one organization, there are no price control mechanisms in the heat market, and from here it will strive to its maximum value. Most of the fuel costs will be related to heat. The limiter

of the allocation of costs to heat will be the marginal price determined by the method of the alternative boiler house:

$$\frac{b_{CHP}^{hh} \cdot Q_{CHP} + b_{boiler} \cdot Q_{boiler}}{Q} \leq b_{boiler}^a \quad (6)$$

where b_{boiler}^a - unit costs of an alternative boiler house, taking into account the investment component.

In the case of a single customer, due to competition between heat sources, most of the fuel costs will be attributed to electricity. The limiting factor for attributing costs to electricity will be the specific fuel costs of condensing power plants, the excess of which will lead to the displacement of CHP from the electricity market:

$$b_{CHP}^{he} \leq b_{CPP} \quad (7)$$

The results of a comparative assessment of the effectiveness of the mechanisms for organizing a single heat company and a single buyer for a heat supply system with two heat sources are presented in Figure 5 that follows.

Fig. 5. Analysis of the comparative efficiency of the mechanisms for organizing a single heat company and a single buyer

As one can see from Figure 5, the lowest price for heat energy can be formed by a single customer model. Thence, market organizational and economic mechanisms have a greater potential to reduce the cost of heat energy than the formation of a single heat company and contribute to the sustainable development of urban heat supply systems.

5 Conclusions

Overall, our paper reveals some regularities in the change in the structure of heat sources and the organization of the main elements of the heat supply system on the example of the Moscow region. It appears that despite the significant role in the power supply of CHPPs, the use of small and medium-sized boilers is growing every year, which is achieved by reducing the cost and timing of construction and installation works, and increasing the efficiency and reliability of equipment.

Moreover, we developed an economic and mathematical model and a cost-effective scenario for the introduction of a market pricing mechanism in centralized heating systems based on the "alternative boiler house" method has been compiled.

Furthermore, the paper proposes an improved method for the formation of the marginal tariff for heat taking into account the structure of heat sources and allowing to eliminate the existing disadvantages of the pricing of the alternative boiler house method.

In addition, the paper describes the mechanisms that ensure sustainable development of urban heat supply systems on the basis of increasing market competition between heat sources in the formation of a single heat supply company. Our results stemming from the model calculations show that the formation of a single buyer of heat energy on the basis of a heat grid company when organizing a competitive selection of heat suppliers for a district heating system can reduce the price of heat energy for consumers.

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