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Bi-level modeling of district heating systems with prosumers

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Abstract

The paper deals with the actual problem of the functioning and development of district heating systems in the framework of the transition to intelligent energy, in which the active consumers (prosumers) holds the key place. The paper proposes an optimization mathematical model for management the operation of district heating systems taking into account prosumers based on the bi-level modeling method (bi-level programming). The proposed mathematical model allows taking into account the technical and economic characteristics of heat sources and heat networks, the interests of participants in the process of heat supply to consumers and determining the optimal conditions for management the operation of district heating systems.

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Keywords: District heating system; Heat sources; Prosumer; Optimal development; Bi-level programming; Mathematical modeling; Optimization

1. Introduction

Currently, in many countries around the world, along with the development of district heating systems (DHS), the trend of a large-scale transition to individual heat supply based on decentralized sources (DS) is increasingly being observed. The refusal of DHS in favor of DS is due to the need to move to a new technological paradigm of heat power development in Russia and is due to the exhaustion of the efficiency potential of DSH. The introduction of the DS is primarily determined by their competitiveness (acceptable one-time capital investments, the absence of a fee for connection to heat networks, a transport component for transferring heat carrier and a payment for heat losses, etc.) relative to DHS. Under these conditions, the problem of developing theoretical and practical bases for solving problems of managing the development and operation of DHS, taking into account the DS is of particular relevance. This is due to the need to move to the creation of integrated centrally distributed DHS with adaptive control of the modes of their functioning of a new generation, in which the consumer acquires a new property associated with its “activation”, i.e. providing consumers with the opportunity to independently manage the amount of heat energy received (prosumers), as well as its functional properties (quality, reliability, etc.). Under these conditions, a sufficiently new type of control for heat supply appears — management of demand for heat energy.

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Researchers in many countries conduct theoretical and practical studies on the prosumer. The investigations to be emphasized are presented in Zhang et al. [1], Perkovic et al. [2], Yang et al. [3], Zafar et al. [4], Ottesen et al. [5], Vergados et al. [6], Prakash et al. [7], Brange et al. [8]. They are focused on various aspects of prosumer operation and control within power supply systems. In Brand et al. [9] and Kauko et al. [10] the authors consider some issues of prosumer operation in the DHS.

Based on the analysis of publications on the prosumer topic, which is part of a more general theory of the establishment of intelligent and integrated energy systems (Smart Grid), we can conclude that almost all these investigations concern electric power systems. At the same time, these technologies are also relevant for DHS which are the largest fuel consumers, especially in Russia, where fuel consumption for heating needs exceeds 45% of the total fossil fuel consumed in the country.

One of the main goals of involving the prosumer (hereinafter we mean heat prosumer) in the DHS is to enhance the efficiency and cost-effectiveness of system operation by managing optimal distribution of sources supplying heat loads. The methodological problems which need to be solved to achieve this goal are various and traditional for energy systems on the whole and DHS in particular. The involvement of prosumer in the DHS, however, brings about new aspects in these problems and calls for new methodological approaches to solve them. The development of these methods is a subject of the presented paper.

2. Bi-level organization model for management the operation of DHS

Modern DHS, like other energy systems (electric power, oil, gas, etc.) have a hierarchical (vertically integrated) system of organization of operation and development management, which can be represented as a bi-level model. The first (upper) level of the bi-level model of the heating market is represented by the regional tariff service, whose duties include regulation of the tariff for heat energy for consumers, and the second (lower) is the district heating system, which is part of the heat supply company (HSC), which performs the functions of heat supply to consumers and prosumers.

The main idea of such an approach to constructing a scheme for management the district heating systems of consumers and prosumers is to single out the corresponding subsystems into aggregated participants, which makes it possible to specify the goals that each of them pursues. The relationship between the participants of heat supply is as follows. The HSC, based on consumer demand for heat energy, generates heat energy and sells it to consumers from the condition that heat sources produce such amount of heat energy that would maximize their profits, while collectively they should cover the amount set by consumers demand for heat energy, taking into account the physico-technical limitations and optimal flows in the heat network. The regional tariff service, protecting the rights of consumers, sets a level of heat tariff that, on the one hand, would stimulate heat sources to satisfy a given demand from consumers, and on the other hand, would allow them to get maximum profit from the sale of heat energy at observance of the optimum modes in heat networks.

Modeling of such a system is carried out using bi-level programming. The transition to the one-level optimization problem is carried out by replacing the extremal problem of the lower level on their optimality conditions in Dempe [11].

3. Mathematical formalization of the bi-level model of DHS with prosumers

DHS can be described by a hydraulic network with m nodes and n branches, represented by a directed graph $G = (J, I)$, where $J = J_{HS} \cup J_{CON} \cup J_0$ — a set of nodes, consisting of a sets of heat sources, consumers and branching nodes without heat sources and consumers; I — a set of branches. According to Merenkov and Khasilev [12], the optimal flow distribution in hydraulic network can be represented by the following set of equations:

$$\mathbf{A} \cdot \mathbf{x} = \mathbf{Q} \quad (1)$$

$$\overline{\mathbf{A}}^T \cdot \overline{\mathbf{P}} = \mathbf{y} \quad (2)$$

$$\mathbf{y} + \mathbf{H} = \mathbf{S} \cdot \mathbf{X} \cdot \mathbf{x} \quad (3)$$

where $\mathbf{A} = \{a_{ij}\} - (m - 1) \times n$ incidence matrix for linearly independent nodes, which is obtained on the basis of complete matrix by deleting any of its rows; $\mathbf{x} = (x_1, \dots, x_n)^T$ — vector of flow rates, t/h; $\mathbf{Q} = (Q_1, \dots, Q_{m-1})^T$ — vector nodal sources or sinks, t/h; $\bar{\mathbf{A}}^T$ — transposed complete matrix $\bar{\mathbf{A}}$; $\mathbf{P} = (P_1, \dots, P_m)^T$ — vector of pressures at nodes, Pa; $\mathbf{y} = (y_1, \dots, y_n)^T$ — vector of differences between the pressures at branch nodes, Pa; $\mathbf{H} = (H_1, \dots, H_n)^T$ — vector of heads, Pa; $\mathbf{S} = \text{diag}(s_1, \dots, s_n)$ and $\mathbf{X} = \text{diag}(|x_1|, \dots, |x_n|)$ — diagonal matrices of hydraulic resistances and flow rates, respectively.

Part of nodes in the hydraulic network is represent of heat sources. The maximum and minimum level of heat production at heat sources is expressed through Q_{j_min} and Q_{j_max} , and is written in the form of system constraints, GJ/h:

$$Q_{j_min} \leq Q_j \leq Q_{j_max}, \quad j \in J_{HS} \tag{4}$$

Denote by $Z_j(Q_j)$ the costs of heat production by the j th heat source (EUR). In the market conditions behavior of heat source (lower level) is dictated by its intention to maximize profit $P_j(Q_j)$. Let $c_j, j \in J_{HS}$ be the price per heat unit (EUR/GJ), then the problem of the lower level is written as follows, EUR:

$$P_j(Q_j) = c_j \cdot Q_j - Z_j(Q_j) \rightarrow \max, \quad j \in J_{HS} \tag{5}$$

$$Q_{j_min} \leq Q_j \leq Q_{j_max}, \quad j \in J_{HS} \tag{6}$$

Costs in the heat networks is determined by the well-known dependence in Merenkov and Khasilev [12], EUR:

$$Z^{HN}(x) = F_1 + F_2 \cdot \sum_{i \in I} x_{i\tau}^2 \cdot |x_{i\tau}| \cdot s_i, \quad x \in \mathbb{R}^n \tag{7}$$

where F_1 — semi-fixed costs of heat network, EUR; F_2 — coefficient at semi-variable costs of heat network; \mathbb{R} — a set of real number.

Consumers of heat energy consist of two sets. The first set J_{CON}^{HH} is household consumers with fixed loads $Q_j^{HH} = \text{const}, j \in J_{CON}^{HH}$, GJ/h. The second set J_{CON}^{PR} is prosumers. The behavior of the prosumer is described by the demand function, which was obtained on the basis of real calculations and can be represented as a linear relationship in Penkovskii et al. [13], GJ/h:

$$Q_j^{PR} = w_j - v_j \cdot c_j^{PR}, \quad j \in J_{CON}^{PR} \tag{8}$$

where $w_j > 0, v_j > 0$ — coefficients obtained from the approximation of the factual data on the heat volume purchased by an prosumer, depending on price; c_j^{PR} — purchase price, EUR/GJ.

To simulate the upper level, it is necessary to formalize of the regulator criterion. As noted earlier, the duties of the regulator include the regulation of tariff for household consumers (c^{HH} , EUR/GJ). Next, we will assume that the regulator, defending the interests of household consumers, seeks to determine the minimum tariff for them. Consider the economic balance of the district heating system:

$$\sum_{j \in J_{HS}} c_j \cdot Q_j + Z^{HN}(x) = c^{HH} \cdot \sum_{j \in J_{CON}^{HH}} Q_j^{HH} + \sum_{j \in J_{CON}^{PR}} c_j^{PR} \cdot Q_j^{PR} \tag{9}$$

Let us express from (9) the tariff of heat energy for household consumers:

$$c^{HH} = \frac{\sum_{j \in J_{HS}} c_j \cdot Q_j + Z^{HN}(x) - \sum_{j \in J_{CON}^{PR}} c_j^{PR} \cdot Q_j^{PR}}{\sum_{j \in J_{CON}^{HH}} Q_j^{HH}} \tag{10}$$

Thus, the mathematical model of the district heating system management with prosumers will be written in the following form:

$$c^{HH} = \frac{\sum_{j \in J_{HS}} c_j \cdot Q_j + Z^{HN}(x) - \sum_{j \in J_{CON}^{PR}} c_j^{PR} \cdot Q_j^{PR}}{\sum_{j \in J_{CON}^{HH}} Q_j^{HH}} \rightarrow \min \tag{11}$$

subject to

$$Q_j = \arg \max\{P_j(Q_j) : Q_{j_min} \leq Q_j \leq Q_{j_max}\}, \quad j \in J_{HS} \tag{12}$$

$$\mathbf{A} \cdot \mathbf{x} = \mathbf{Q} \tag{13}$$

$$\bar{\mathbf{A}}^T \cdot \bar{\mathbf{P}} = \mathbf{y} \quad (14)$$

$$\mathbf{y} + \mathbf{H} = \mathbf{S} \cdot \mathbf{X} \cdot \mathbf{x} \quad (15)$$

$$Z^{\text{HN}}(x) = F_1 + F_2 \cdot \sum_{i \in I} x_{i\tau}^2 \cdot |x_{i\tau}| \cdot s_i, \quad x \in \mathbb{R}^n \quad (16)$$

$$Q_j^{\text{HH}} = \text{const}, \quad j \in J_{\text{CON}}^{\text{HH}} \quad (17)$$

$$Q_j^{\text{PR}} = w_j - v_j \cdot c_j^{\text{PR}}, \quad j \in J_{\text{CON}}^{\text{PR}} \quad (18)$$

Unlike the flow distribution problem with lumped-parameters Dempe [11], in this case the volumes production of heat energy will be variable.

The costs of heat production by a heat source have the form of a squared relationship. They were obtained by approximating actual heat supply data depending on the heat source costs by the method of least squares Stennikov et al. [14], EUR:

$$Z_j(Q_j) = \alpha_j \cdot Q_j^2 + \beta_j \cdot Q_j + \gamma_j, \quad \alpha_j > 0, \quad \beta_j > 0, \quad \gamma_j > 0, \quad j \in J_{\text{HS}} \quad (19)$$

Due to the fact that the coefficients α_j , β_j , γ_j are positive, the cost function is a strongly convex, monotonically increasing function that takes positive values at $Q_j \geq 0$, $j \in J_{\text{HS}}$.

Thus, the problem corresponding to expressions (5)–(6) will have the form:

$$-\alpha_j \cdot Q_j^2 + (c_j - \beta_j) \cdot Q_j - \gamma_j \rightarrow \max, \quad j \in J_{\text{HS}} \quad (20)$$

$$Q_{j.\text{min}} \leq Q_j \leq Q_{j.\text{max}}, \quad j \in J_{\text{HS}} \quad (21)$$

Dependence of optimal solution to problem of lower level (20)–(21) on heat price is determined by the following relations:

$$Q_j^* = \begin{cases} Q_{j.\text{min}}, & c_j < 2 \cdot \alpha_j \cdot Q_{j.\text{min}} + \beta_j \\ \frac{c_j - \beta_j}{2\alpha_j}, & 2 \cdot \alpha_j \cdot Q_{j.\text{min}} + \beta_j \leq c_j \leq 2 \cdot \alpha_j \cdot Q_{j.\text{max}} + \beta_j \\ Q_{j.\text{max}}, & c_j > 2 \cdot \alpha_j \cdot Q_{j.\text{max}} + \beta_j \end{cases} \quad (22)$$

From the set of Eqs. (22) it follows that if the heat prices vary within the values corresponding to the expression

$$2 \cdot \alpha_j \cdot Q_{j.\text{min}} + \beta_j \leq c_j \leq 2 \cdot \alpha_j \cdot Q_{j.\text{max}} + \beta_j \quad (23)$$

the volume of the produced heat providing the maximal profit depends on the price linearly, GJ/h:

$$Q_j = \frac{c_j - \beta_j}{2 \cdot \alpha_j}, \quad j \in J_{\text{HS}} \quad (24)$$

In this case the problem (11)–(18) will be written in the following form:

$$c^{\text{HH}} = \frac{\sum_{j \in J_{\text{HS}}} c_j \cdot Q_j + Z^{\text{HN}}(x) - \sum_{j \in J_{\text{CON}}^{\text{PR}}} c_j^{\text{PR}} \cdot Q_j^{\text{PR}}}{\sum_{j \in J_{\text{CON}}^{\text{HH}}} Q_j^{\text{HH}}} \rightarrow \min \quad (25)$$

subject to

$$Q_j = \frac{c_j - \beta_j}{2 \cdot \alpha_j}, \quad j \in J_{\text{HS}} \quad (26)$$

$$\mathbf{A} \cdot \mathbf{x} = \mathbf{Q} \quad (27)$$

$$\bar{\mathbf{A}}^T \cdot \bar{\mathbf{P}} = \mathbf{y} \quad (28)$$

$$\mathbf{y} + \mathbf{H} = \mathbf{S} \cdot \mathbf{X} \cdot \mathbf{x} \quad (29)$$

$$Z^{\text{HN}}(x) = F_1 + F_2 \cdot \sum_{i \in I} x_{i\tau}^2 \cdot |x_{i\tau}| \cdot s_i, \quad x \in \mathbf{R}^n \quad (30)$$

$$Q_j^{\text{HH}} = \text{const}, \quad j \in J_{\text{CON}}^{\text{HH}} \quad (31)$$

$$Q_j^{\text{PR}} = w_j - v_j \cdot c_j^{\text{PR}}, \quad j \in J_{\text{CON}}^{\text{PR}} \quad (32)$$

It is easy to see that, unlike (11)–(18), problem (25)–(32) is a traditional problem of mathematical programming.

4. Case study and an analysis of results

The developed mathematical model was tested on the real district heating system with two heat source and one prosumer. The design scheme is shown in Fig. 1.

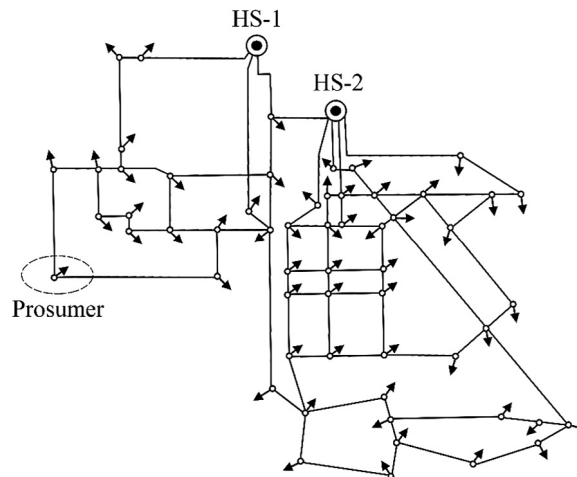


Fig. 1. The design district heating system scheme.

The simulation of the DHS depicted in Fig. 1 was carried out in GAMS/Conopt computing environments. Table 1 presents the technical and economic indicators of DHS obtained in the process of performing optimization calculations.

From Table 1 it can be seen that, heat energy sources produced a total of 7375 GJ/h of heat energy, of which 52% comes from heat source 1 and 48% from heat source 2. Prices for heat energy production were 8.8 EUR/GJ and 7.8 EUR/GJ for heat source 1 and heat source 2, respectively. Such prices make it possible to profit from the sale of thermal energy in the amount of 1503 EUR for the first and 1741 EUR for the second heat sources. The proposed mathematical formulation of the problem of finding the optimal tariff for household consumer allowed determining its minimum value — 18.5 EUR/GJ. In turn, the prosumer purchases heat energy from the district heating system in the amount of 655 GJ/h at a price of 24.2 EUR/GJ.

Table 1. Technical and economic indicators.

Heat supply organization	
Heat production volume, GJ/h including:	7 375
HS-1	3 882
HS-2	3 493
Heat production costs of HS-1, EUR	6 626
Heat production costs of HS-2, EUR	4 754
Profit of HS-1, EUR	1 503
Profit of HS-2, EUR	1 741
Heat energy price of HS-1, EUR/GJ	8.8
Heat energy price of HS-2, EUR/GJ	7.8
Heat consumption by household consumers, GJ/h	6 720
Heat consumption by prosumer, GJ/h	655
Heat energy price for household consumer, EUR/GJ	18.5
Heat energy price for industrial consumers, EUR/GJ	24.2

5. Conclusion

At present, there is virtually no methodological support for the process of “activating” the consumer under the conditions of the heat market model valid in Russia. This requires new research in this area. The paper considers the organizational model of heat supply to consumers in the form of a heat supply company in bi-level system, when the regulator (regional tariff service) manages tariffs for consumers, and sources of heat energy meet specified demand on the part of consumers from the condition for obtaining maximum profit. A criterion for optimizing the regional tariff service is proposed. Using bi-level approach, technical and economic indicators of the DHS with prosumers are calculated, ensuring the rational organization of the heating energy market. The proposed mathematical bi-level model to the greatest extent reflects the conditions emerging in the local market for thermal energy. This model reasonably takes into account the established “rules of conduct” in the heat market, as well as the physico-technical and economic constraints of the system under consideration.

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