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Article

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Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Stennikov, Valery; Penkovskii, Andrey (2020) : The pricing methods on the monopoly district heating market, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 2, pp. 187-193,
<https://doi.org/10.1016/j.egyr.2019.11.061>

This Version is available at:

<https://hdl.handle.net/10419/243877>

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The 6th International Conference on Power and Energy Systems Engineering (CPESE 2019),
September 20–23, 2019, Okinawa, Japan

The pricing methods on the monopoly district heating market

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Received 3 October 2019; accepted 22 November 2019

Abstract

District heating plays an important role in many countries with cold climates. District heating are local systems and in most cases, they organized as natural monopoly markets. This article examines the three variants for the formation of prices for household consumers on monopoly district heating market: market equilibrium of supply and demand for heat energy (liberalized district heating market) and forming the price of heat energy based on average total and marginal costs (regulated heating market). To perform calculations, a mathematical model of the district heating market is developed. It is based on the classical model of monopoly market. The model was applied to conduct the studies on a heat supply system with three heat sources.

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Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

Keywords: Heat supply system; Monopoly district heating market; Heating pricing; Market equilibrium; Regulation; Mathematical modeling

1. Introduction

District heating plays an important role in the heating market. Main consumption share of heat energy in district heating are household and industrial consumers. The total number of district heating markets has been estimated to 80 000 systems in Frederiksen and Werner [1], thereof about 50 000 in Russia in Stennikov et al. [2], 6000 in the Europe in Werner [3] and the remaining 24 000 are in China and the countries of the former Commonwealth of Independent States (such as Kazakhstan, Ukraine, Georgia, Belarus, etc.). There are two main forms organization of district heating market: competition and monopoly. Competition model on the district heating market is an important element of a market economy, since it contributes to the growth of heat energy efficiency production, improving its quality and, as a result, reducing its price, which can have a favorable effect on the development of district heating. In condition of competitive market, the purchase price for heat energy is not regulated due to the possibility of a market choice of supplier (heat source). Among the main countries where currently operates a competitive model in the district heating market can be identified Sweden in Werner [3], Finland in Paiho and Saastamoinen [4], Germany in Wissner [5]. Another type of heat market that is most prevalent in countries with developed of district heating is

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<https://doi.org/10.1016/j.egy.2019.11.061>

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Nomenclature

J_{hs}	Set of heat sources
J_{con}^{hh}	Set of household consumers
$J_{con}^{ic,hn}$	Set of industrial consumers connected to heat networks
$J_{con}^{ic,hs}$	Set of industrial consumers located on collectors of heat source
I	Set of branches
Q_j^{hs}	Volume production of heat energy of j th heat source
Q_j^{hh}	Heat energy demand of j th household consumer
$Q_j^{ic,hn}$	Heat energy demand of j th industrial consumer connected to heat networks
$Q_j^{ic,hs}$	Heat energy demand of j th industrial consumer located on collectors of heat source
$Q_j^{(H)}$	Design heating load of j th household consumer
$Q_j^{(HW)}$	Design hot water supply load of j th household consumer
$\tau_{(HP)}$	Duration of heating period
P^{HSC}	Profit of Heat Supply Company
w^{HSC}	Price on the heat energy of Heat Supply Company
Z_j^{hs}	Costs on the production heat energy of j th heat source
Z_i^{hn}	Costs in the i th section of the heat network
x_i	Heat carrier flow rate in the i th section of the heat network
s_i	Coefficient of hydraulic resistance of the i th branch
\bar{A}	Complete incidence matrix
A	$(m-1) \times n$ incidence matrix for linearly independent nodes, which is obtained on the basis of complete matrix \bar{A} by deleting any of its rows
\bar{A}^T	Transposed complete matrix \bar{A}
P	Vector of pressures at nodes
y	Vector of differences between the pressures at branch nodes
H	Vector of heads
S	Diagonal matrices of hydraulic resistances
X	Diagonal matrices of flow rates
x	Vector of flow rates
Q	Vector of nodal sources or sinks
$Q_{j,min}^{hs}$	Minimum level of the j th heat source productive capacity
$Q_{j,max}^{hs}$	Maximum level of the j th heat source productive capacity
w^{hh}	Final heat energy price for household consumers
$w^{gen,hh}$	Price for generation of heat energy for household consumers
$w_j^{ic,hn}$	Purchase price of heat energy of the j th industrial consumer connected to heat networks, which includes production and transportation of heat energy
$w_j^{gen,ic,hn}$	Purchase price of heat energy of the j th industrial consumer connected to heat networks, which includes only production of heat energy
$w_j^{gen,ic,hs}$	Purchase price of heat energy of the j th industrial consumer located on collectors of heat source, which includes only production of heat energy
w^{hn}	Price for transportation of heat energy

a natural monopoly with tariff regulation on the heat energy for consumers. These are the large heating markets of some countries European Union (Netherlands in Osman [6], Poland in Wojdyga and Chorzelski [7], Lithuania in Heating and Cooling [8], Latvia in Sarma and Bazbauers [9], Norway in District Heating in Norway [10], Estonia

w^{HSC}	Equilibrium heat energy price of production and transportation of Heat Supply Company
$w^{\text{gen.HSC}}$	Equilibrium heat energy production price of Heat Supply Company
θ	Number of considered categories of heat energy consumers
Θ^{hh}	Share of heat energy consumption of household consumers
$\Theta_j^{\text{ic.hn}}$	Share of heat energy consumption of the j th industrial consumer connected to heat networks
$\Theta_j^{\text{ic.hs}}$	Share of heat energy consumption of the j th industrial consumer located on collectors of heat source

[11], etc.), Russia in Dyomina [12], China in Zhang et al. [13] and other. In these countries the regulator, whose duties include the management of the tariff for heat energy, are the different bodies of government management.

The monopoly model of district heating system provides for the integration of all heat supply aspects, including production, transportation and sales of heat energy in the unified Heat Supply Company (HSC). The organizational model of HSC can be represented by the scheme shown in Fig. 1.

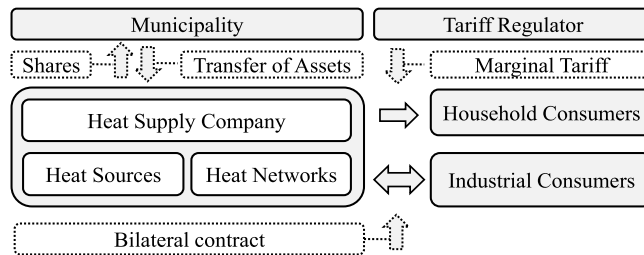


Fig. 1. The organization model of regulated monopoly district heating market.

In the organizational model of heat supply management (see Fig. 1), simultaneous control over the production, transportation and sales of heat energy is justified in the context of maintaining system reliability [14], reducing technical and economic risks, and sustainable functioning of DH.

Within the framework of this model, there is no competition among heat sources, and heat networks are a monopoly structure.

In this monopoly model, the HSC should become the owner of all the municipal assets including heat sources and distribution heat networks. Such a merging of the main assets and heat supply control processes shapes the HSC as a single seller in the heat market, i.e. a monopolist. Thus, the HSC will have a total control of heat supply in the market and market heat price.

The relationships among the market participants in the form of the monopoly model of the HSC develop according to a certain pattern and imply the following. Based on the forecasts of demand and optimal variants of heating system expansion, the HSC delivers heat (under medium-term and long-term contracts) to consumers at a price calculated as a sum of a price of heat source heat production and a price of heat transportation from the heat source to the consumer. In this case, the HSC produces the volumes of heat that on the one hand would maximize its profit, given physical–technical constraints on heat sources and heat networks, and meet the demand for heat specified by the consumer, and on the other hand would correspond to the consumer wish to pay for this demand.

Currently, among the most common approaches for modeling medium-term (or long-term) forecasting of possible situations in a monopoly heating market, we can distinguish the classical microeconomic model of monopoly in Tirole [15]. It is one of the universal models for analyzing the functioning and development of various markets, including those that are adequate to the heat business.

There are many possible variants for the formation of prices for heat energy for household consumers of in the context of the HSC model, the most common of which are:

- Free pricing based on market equilibrium of demand and supply for heat energy
- Regulation tariff for household consumers at the level of average total costs

- Regulation tariff for household consumers at the level of marginal costs

To perform the analysis of models of prices heat energy formation for in the conditions of the market the corresponding mathematical model of district heating system which will allow to carry out multivariate calculations on optimization of the heating market according to the established economic criteria and taking into account the available technological restrictions of the district.

2. A mathematical model of monopoly district heating market

In the market conditions, the HSC behavior is described by the classic mathematical model of natural monopoly in Belleflamme and Peitz [16], that is, it is necessary to determine the maximum profit P_τ^{HSC} in meeting this demand from consumers:

$$P_\tau^{\text{HSC}} = \sum_{j \in J_{\text{hs}}} w_\tau^{\text{HSC}} \cdot Q_{j\tau}^{\text{hs}} - \sum_{j \in J_{\text{hs}}} Z_{j\tau}^{\text{hs}} - \sum_{i \in I} Z_{i\tau}^{\text{hn}} \rightarrow \max, \quad (1)$$

subject to

$$Q_{j\tau}^{\text{hs}} \leq Q_{j\tau}^{\text{hs}} \leq Q_{j\tau}^{\text{hs}}, \quad j \in J_{\text{hs}}, \quad (2)$$

demand of consumers (household and industrial)

$$Q_{j\tau}^{\text{hh}} = [1 - (1 - r) \cdot (\tau/\tau_{\text{HP}})^a] \cdot Q_j^{(\text{H})} + Q_j^{(\text{HW})}, \quad j \in J_{\text{con}}^{\text{hh}}, \quad (3)$$

$$Q_{j\tau}^{\text{ic.hn}} = \xi_j - \psi_j \cdot w_{j\tau}^{\text{ic.hn}}, \quad j \in J_{\text{con}}^{\text{ic.hn}}, \quad (4)$$

$$Q_{j\tau}^{\text{ic.hs}} = \mu_j - \pi_j \cdot w_{j\tau}^{\text{gen.ic.hs}}, \quad j \in J_{\text{con}}^{\text{ic.hs}}, \quad (5)$$

costs of HSC

$$Z_{j\tau}^{\text{hs}} = \alpha_j \cdot (Q_{j\tau}^{\text{hs}})^2 + \beta_j \cdot Q_{j\tau}^{\text{hs}} + \gamma_j, \quad j \in J_{\text{hs}}, \quad (6)$$

$$Z_{i\tau}^{\text{hn}} = F_1 + F_2 \cdot x_{i\tau}^2 \cdot |x_{i\tau}| \cdot s_i, \quad i \in I, \quad (7)$$

model of optimal flows distribution in the heat network

$$\begin{bmatrix} \mathbf{A} \cdot \mathbf{x} - \mathbf{Q} \\ \mathbf{y} - \overline{\mathbf{A}}^T \cdot \overline{\mathbf{P}} \\ \mathbf{y} + \mathbf{H} - \mathbf{S} \cdot \mathbf{X} \cdot \mathbf{x} \end{bmatrix} = 0 \quad (8)$$

ratio among prices

$$w_\tau^{\text{gen.hh}} = w_\tau^{\text{hh}} - w_\tau^{\text{hn}}, \quad (9)$$

$$w_{j\tau}^{\text{gen.ic.hn}} = w_{j\tau}^{\text{ic.hn}} - w_{j\tau}^{\text{hn}}, \quad (10)$$

$$w_\tau^{\text{hn}} = \sum_{i \in I} Z_{i\tau}^{\text{hn}} / \left(\sum_{j \in J_{\text{hs}}} Q_{j\tau}^{\text{hs}} - \sum_{j \in J_{\text{con}}^{\text{ic.hs}}} Q_{j\tau}^{\text{ic.hs}} \right), \quad (11)$$

$$w_\tau^{\text{gen.HSC}} = w_\tau^{\text{gen.hh}} \cdot \theta_\tau^{\text{hh}} + \sum_{j \in J_{\text{con}}^{\text{ic.hn}}} w_{j\tau}^{\text{gen.ic.hn}} \cdot \theta_{j\tau}^{\text{ic.hn}} + \sum_{j \in J_{\text{con}}^{\text{ic.hs}}} w_{j\tau}^{\text{gen.ic.hs}} \cdot \theta_{j\tau}^{\text{ic.hs}}, \quad (12)$$

$$w_\tau^{\text{gen.HSC}} = \left(\sum_{j \in J_{\text{hs}}} w_\tau^{\text{HSC}} \cdot Q_{j\tau}^{\text{hs}} - \sum_{i \in I} Z_{i\tau}^{\text{hn}} \right) / \sum_{j \in J_{\text{hs}}} Q_{j\tau}^{\text{hs}}, \quad (13)$$

$$\theta_\tau^{\text{hh}} = \sum_{j \in J_{\text{con}}^{\text{hh}}} Q_{j\tau}^{\text{hh}} / \sum_{j \in J_{\text{hs}}} Q_{j\tau}^{\text{hs}}, \quad (14)$$

$$\theta_{j\tau}^{\text{ic.hn}} = \sum_{j \in J_{\text{con}}^{\text{ic.hn}}} Q_{j\tau}^{\text{ic.hn}} / \sum_{j \in J_{\text{hs}}} Q_{j\tau}^{\text{hs}}, \quad (15)$$

$$\theta_{j\tau}^{\text{ic.hs}} = \sum_{j \in J_{\text{con}}^{\text{ic.hs}}} Q_{j\tau}^{\text{ic.hs}} / \sum_{j \in J_{\text{hs}}} Q_{j\tau}^{\text{hs}}, \quad (16)$$

$$w_{\tau}^{\text{gen.hh}} = \begin{cases} w_{\tau}^{\text{gen.HSC}} - w_{\tau}^{\text{gen.HSC}} \cdot (1 - \Theta_{\tau}^{\text{hh}}), & \text{if } \Theta_{\tau}^{\text{hh}} > 1/\theta_{\tau} \\ w_{\tau}^{\text{gen.HSC}} + w_{\tau}^{\text{gen.HSC}} \cdot (1 - \Theta_{\tau}^{\text{hh}}), & \text{if } \Theta_{\tau}^{\text{hh}} < 1/\theta_{\tau}, \\ w_{\tau}^{\text{gen.HSC}}, & \text{if } \Theta_{\tau}^{\text{hh}} = 1/\theta_{\tau} \end{cases}, \quad (17)$$

$$w_{j\tau}^{\text{gen.ic.hn}} = \begin{cases} w_{\tau}^{\text{gen.HSC}} - w_{\tau}^{\text{gen.HSC}} \cdot (1 - \Theta_{j\tau}^{\text{ic.hn}}), & \text{if } \Theta_{j\tau}^{\text{ic.hn}} > 1/\theta_{\tau} \\ w_{\tau}^{\text{gen.HSC}} + w_{\tau}^{\text{gen.HSC}} \cdot (1 - \Theta_{j\tau}^{\text{ic.hn}}), & \text{if } \Theta_{j\tau}^{\text{ic.hn}} < 1/\theta_{\tau}, \\ w_{\tau}^{\text{gen.HSC}}, & \text{if } \Theta_{j\tau}^{\text{ic.hn}} = 1/\theta_{\tau} \end{cases}, \quad (18)$$

$$w_{j\tau}^{\text{gen.ic.hs}} = \begin{cases} w_{\tau}^{\text{gen.HSC}} - w_{\tau}^{\text{gen.HSC}} \cdot (1 - \Theta_{j\tau}^{\text{ic.hs}}), & \text{if } \Theta_{j\tau}^{\text{ic.hs}} > 1/\theta_{\tau} \\ w_{\tau}^{\text{gen.HSC}} + w_{\tau}^{\text{gen.HSC}} \cdot (1 - \Theta_{j\tau}^{\text{ic.hs}}), & \text{if } \Theta_{j\tau}^{\text{ic.hs}} < 1/\theta_{\tau}. \\ w_{\tau}^{\text{gen.HSC}}, & \text{if } \Theta_{j\tau}^{\text{ic.hs}} = 1/\theta_{\tau} \end{cases}. \quad (19)$$

The search for an optimal solution to the developed mathematical model of the heat energy monopoly market is based on the univariate relaxation method in Shoup [17] with the of methods of redundant design schemes in Merenkov and Ya Khasilev [18] and simple iteration. The method suggests the reduction of the multidimensional optimization problem to one-dimensional one and the use of a stepwise procedure for the improvement of solutions concerning the volumes of production by all heat sources.

There are two classic methods regulation of tariff on the monopoly market in Gravelle and Rees [19]: marginal cost (MC) method or average total cost (ATC) method.

Consider formation of a mathematical model of a regulated monopoly district heating market, in which the tariff on the heat energy for household consumers is set at the level of the corresponding share of average total costs, which were spent on the production and transportation of heat energy for household consumers. The scheme of construction of such a mathematical model (1)–(19) is fully consistent with the model with the addition of restrictions on the heat energy tariff for household consumers:

$$w_{\tau}^{\text{hh}} = ATC = \frac{\Theta_{\tau}^{\text{hh}} \cdot (\sum_{j \in J_{\text{hs}}} Z_{j\tau}^{\text{hs}}(Q_{j\tau}^{\text{hs}}) + \sum_{i \in I} Z_{i\tau}^{\text{hn}}(x_{i\tau}))}{\sum_{j \in J_{\text{con}}^{\text{hh}}} Q_{j\tau}^{\text{hh}}} = \frac{\sum_{j \in J_{\text{hs}}} Z_{j\tau}^{\text{hs}}(Q_{j\tau}^{\text{hs}}) + \sum_{i \in I} Z_{i\tau}^{\text{hn}}(x_{i\tau})}{\sum_{j \in J_{\text{hs}}} Q_{j\tau}^{\text{hs}}}. \quad (20)$$

In the case of regulation of the tariff on the heat energy for household consumers at the level of marginal costs, the type of mathematical model will be preserved in the same way as in the regulation variant at the average total costs, but with the replacement of heat energy tariff for household consumers at marginal cost. Marginal costs or costs associated with the additional production and transportation of a heat energy unit are the ratio of the total marginal costs for the production and transportation of heat energy to the volume of produced and transportation of heat energy by the HSC. For household consumers, these costs can be represented as follows:

$$w_{\tau}^{\text{hh}} = MC = \frac{\partial(\sum_{j \in J_{\text{hs}}} Z_{j\tau}^{\text{hs}}(Q_{j\tau}^{\text{hs}}) + \sum_{i \in I} Z_{i\tau}^{\text{hn}}(x_{i\tau}))}{\partial Q_{j\tau}^{\text{hs}} \partial x_{i\tau}} = \sum_{j \in J_{\text{hs}}} (2\alpha_j \cdot Q_{j\tau}^{\text{hs}} + \beta_j) + \frac{3 \cdot C_{\text{el}} \cdot \sum_{i \in I} x_{i\tau}^2 \cdot s_i}{367.2 \cdot \eta}. \quad (21)$$

3. Simulation and result

The developed mathematical model was tested on the real district heating system with three heat source. The design scheme is shown in Fig. 2.

Considered three variants formed pricing on the heat energy:

- Variant 1 - free pricing based on market equilibrium of demand and supply for heat energy (EQ)
- Variant 2 - regulation tariff on the heat energy by average total costs method (ATC)
- Variant 3 - regulation tariff on the heat energy by marginal costs method (MC)

Table 1 presents annual technical and economic indices obtained from the calculations for HSs, heat network and consumers.

The calculations showed that in variant 3 are achieved the maximum heat energy production volumes (38.0 million GJ) with the minimum price (1.35 EUR/GJ) on the heat energy of HSC. Minimum level production heat energy (30.9 million GJ) with maximum heat energy price (2.41 EUR/GJ) of the HSC correspond variant 1. The

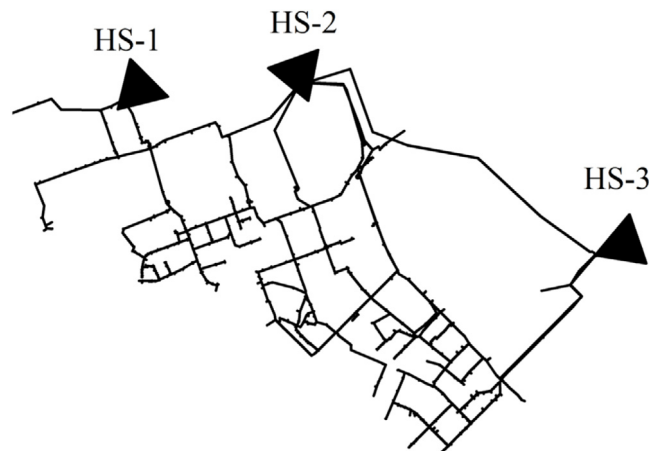


Fig. 2. The design heat supply scheme.

Table 1. Technical and economic indices.

Calculated indices	EQ	ATC	MC
Heat production volume, million GJ, including:	30.9	32.0	38.0
HS-1	4.6	6.3	6.5
HS-2	17.7	17.5	21.8
HS-3	8.6	8.2	9.7
Heat production costs, million EUR	44.8	46.8	54.9
Heat network costs, million EUR	16.9	9.7	11.7
Total costs of the Heat Supply Company, million EUR	61.7	56.5	66.6
Heat consumption by household consumers, million GJ	27.0	27.0	27.0
Heat consumption by industrial consumer, million GJ	3.8	5.1	11.0
Equilibrium heat energy price of the Heat Supply Company, EUR/GJ	2.41	1.84	1.35
Heat energy price for industrial consumers, EUR/GJ	3.07	3.01	2.65
Heat energy price for household consumer, EUR/GJ	2.33	1.63	0.83
Profit of the Heat Supply Company, million EUR	12.80	2.80	-15.04

results obtained for the prices and volumes of heat energy produced by HSO satisfy the market conditions of demand and supply (i.e. the price increases with a decrease in the heat energy production volumes and vice versa).

From the standpoint of the HSC (maximizing profits), variant 1 is beneficial in which it receive the greatest profits. The model with tariff regulation for household consumers at the level of marginal costs (variant 3) HSC incur losses. Since the tariff set for household consumers does not allow to cover relatively fixed costs of HSC.

In variant 2 (regulation of household tariff at the level of average total costs), HSC makes the profit (4.7% of total revenue) at the account of industrial consumer, and tariff for the household consumers and the price for the industrial consumer will be 1.63 EUR/GJ and 3.01 EUR/GJ, respectively.

For household consumers, the best is variant 3, in which the lowest prices for heat energy are obtained - 0.83 EUR/GJ. The most expensive tariff for household and industrial consumers is variant 1.

4. Conclusion

The most common is the monopoly model of the heat energy market operating under two pricing conditions: free (liberalized) pricing and tariff regulation for consumers. The equilibrium mathematical model was developed for the free pricing in the heat energy market based on the microeconomic model of the monopoly market. This mathematical model makes it possible to take into account heat energy production and transportation costs as part of a single economic criterion. For the equilibrium pricing for consumers, the method based on market pricing principles was proposed. For the regulated heat market model, the methods of heat energy pricing for household consumers with allowance for average total costs and marginal costs was proposed. The practical studies carried

out on the example of the district heating system with three heat sources showed that the transition from regulated tariffs to the free pricing model in the heating market would lead to a sharp increase in the heat energy tariffs for household consumers (by 30%) and gaining of excess profit by HSC (more 17%).

Acknowledgments

The research was performed at Melentiev Energy Systems Institute of Siberia Branch of the Russian Academy of Sciences under the support of Russian Science Foundation (Grant No. 17-19-01209).

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