Optimization of the Effective Heat Supply Radius for the District Heating Systems

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Abstract – The problem of determining the effective (optimal) heat supply radius is considered. Heat supply radius is transportation distance of heat energy in the district heating systems (DHS), under which the highest indices of economic efficiency of district heating to consumers are respected. To solve this difficult and multifactorial problem, a bi-level approach has been proposed. This approach allows finding the optimal frameworks of territorial areas of district heating while fulfilling the necessary requirements for thermal-hydraulic modes in heat networks and for reliability of heating to consumers. Methodology for solving the formulated problem is based on bi-level programming methods, models of Theory of hydraulic circuits, nonlinear optimization methods, nodal reliability indices (availability factor, failure-free operation probability), Markov random processes models and other methods and models. A case study has been conducted using the developed methodological apparatus for the actual DHS scheme of the Irkutsk city (Russia, Siberia).

Keywords – Connection charge; district heating system; effective heat supply radius; energy management; nodal reliability indices; optimization; reliability of heat supply; specific cost

Nomenclature

Sets

i	number of district heat source
I	set of district heat sources
j	number of heat consumer
J	set of heat consumers
n	number of heat network section (branch)
N	set of heat network sections
$N(i)$	subset of heat network sections which included in the supply area of i -th district heat source
$N(m)$	subset of heat network sections from district heat source to node m
$N(s)$	subset of heat network sections failure or restoration of which corresponds to transit from state s to some other state z

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$N(z)$	subset of heat network sections failure or restoration of which to transit from state z to some other state s	
$N'(s)$	subset of heat network sections failure of which corresponds to transit to some state s	
M	number of heat network nodes	
M	set of heat network nodes	
M_{ef}	subset of heat network nodes located in the zone of effective heat supply radius	
s, z	numbers of system state	
E	complete set of system states	
$E(s)$	subset of system states from which the system can transit to state s	
Functions		
F_{obj}^1	objective function of the first level: heat supply radius	m
F_{obj}^2	objective function of the second level: cost on production and distribution of thermal energy in the system	EUR
R_{ef}	effective heat supply radius	m
φ	variable coefficient depending on type of heat source	—
B	average number of consumers per 1 km ²	number/km ²
Δt	temperature difference of heat carrier in supply and return pipes	°C
c_t	thermal capacity of the heat carrier	MWh/(t °C)
ΔH	total pressure drop in the supply pipe from the heat source to the most peripheral substation	Pa
l_n	length of n -th section of heat network	m
d_n	diameter of n -th heat network section	m
x_n	heat carrier flow rates in n -th network section	t/h
k_n	specific investment cost for n -th heat network section (re)construction	EUR/m
ψ_n	specific pressure drop in n -th section	Pa/m
τ_0	duration of the heating period	h
τ_p	hours of pump operation under design load	h
τ_{sj}	part of the heating period within which state s is a failed state for consumer j	h
Q_i^0	total (maximum) heat load of i -th heat source	MWh/h
Q_i	connected heat load of the i -th district heat source	MWh/h
Q_j	heat load of the j -th consumer connected to the considered heat source	MWh/h
Q_{los}	heat losses	MWh/h

Z_m	cost on production and distribution of thermal energy in node m	EUR
Z_{av}	average cost on production and distribution of thermal energy in system	EUR
s_{hi}	heat production cost of the i -th heat source	EUR/MWh
s_e	electricity cost	EUR/MWh
α	annuity rate	
k_i	specific capital investment in i -th heat source capacity expansion	EUR/MW
f	share of heat network depreciation, repair and maintenance charges	
η_p	pump efficiency	
p_s, p_z	probability of system state s and z respectively	
p_0	probability of totally operable system state	
k_{ef}	connection effectiveness coefficient	
$\mathcal{E}$	ratio of the total network length to the length of the heat transmission networks	
l_j	length of the designed heat network from connection point to consumer j	m
q_L	linear heat density	MWh/m
L_{ef}	total length of heat transmission networks at boundaries of effective heat supply radius	m
l_{jmax}	maximum connection distance for consumer j	m
Q_{jmin}	minimum necessary load level of consumer j for its connection at a fixed point of the heat network	MW
Matrices and vectors		
A	incidence matrix with linearly independent m nodes and n sections (branches) of the heat network (dimension $(m-1) \times n$)	
x	vector of heat carrier flow rates in the network sections	t/h
G	vector of mass flow rates at nodes	t/h
$\overline{A}^T$	transposed node-branch incidence matrix	
P	vector of pressures at nodes	Pa
h, H	vectors of losses and pressure heads	Pa
S	diagonal matrix of hydraulic resistance coefficients	mh ² /t ²
X	vector of flow rates in the network sections	t/h
$ x $	vector of absolute values of flow rates in the network sections	t/h
Q	vector of thermal energy flow rates at nodes	MW
Reliability indices and parameters		
λ_n	failure rate of heat network sections n	1/h

μ_n	restoration rate of heat network sections n	1/h
K_j	nodal availability factor	
K_j^0	standard value of availability factor	
R_j	nodal failure-free operation probability	
R_j^0	standard values of failure-free operation probability	

1. INTRODUCTION

The main goal of the expansion and upgrading of district heating systems (DHS) of towns and cities is to meet the demand for heat and provide reliable heat supply at minimum economic and environmental cost. Moreover, it is also important to economically incentivize the development and adoption of energy saving technologies, and provide a system approach to the DHS designing. Optimal planning of DHS, their scale, and distance of heat transmission largely determine the efficiency of heat supply development and modernization. Rational construction of DHS based on innovative technologies and energy efficient equipment considerably reduce investment and annual operating costs, and enhance the efficiency and reliability of these systems.

In the European countries, especially in the Scandinavian countries, the active development of the DHS began after the oil crisis of 1973 [1]–[3]. In Russia, large-scale construction of district (centralized) heat sources began as part of the plan «GOERLO» in the 1970s [1], [4]. According to classification presented in [5] DHS of that time are 1st generation systems. Currently Russian DHS mainly are second generation systems. Some large cities have 3rd generation heating systems. In the European countries, today most DHS are 3rd generation systems. The main goal of energy strategies of Europe and Russia is to improve energy efficiency, reliability and comfort of heat supply like it suggests 4th generation [5], [6]. Recently many researchers are discussing the transition to intelligent energy systems [5], [7]. In the case of Russia achieving this goal is complicated not only by the large size of systems but also by its number. The construction of new 4th generation DHS requires significant investment in upgrading equipment for both DHS and heat-consuming installations. Today consumers and heating companies are not ready to incur increased costs.

It also seems important to note the problem of sustainable energy planning in general is comprehensive and very important for a social, economic and environmental point of view [8]. For example, methods to provide the effective energy policy and legislative aspects of this problem are considered in [9]–[11].

In the current situation, problems of determining the criteria for the efficiency of connecting new consumers are of great importance to optimal development of DHS. As a rule, economic criteria are used: if the cost of heating the consumer from a centralized source is lower than from an individual source, then its connection to DHS is considered as economically feasible [12]. This problem becomes even more topical when implementation the technology of parallel consumption wherein the heat consumer connected to the DHS also consumes heat produced by other energy sources [13], [14]. Heat supply planning is usual and legislated in Europe. However, each country has its own features in the organization of heat supply. Scandinavian countries are developing municipal energy plans that include territory-zoning maps by type of heat supply or levels of heat density [15]–[19]. The Heat roadmap Europe states that DHS will be suitable in dense urban areas, while local heat pumps and biomass

boilers will be suitable in other areas [20]–[23]. In Denmark, connection to DHS for consumers with sufficient level of heat density is obligatory. To expand the district heating area, new technologies are introducing that allow to improve energy-efficiency of heating with low heat demand. Authors [24]–[26] pay attention to pipe design methods and proposed improved methods for distribution pipes design to reduce heat losses. Economic feasibility of low temperature DHS in areas with low heat density was analyzed in [27], [28]. The issue of integration of decentralized thermal storages within DHS is discussed in [29]. Also in Sweden, economic feasibility of connection of new consumers is estimated by linear heat density and additionally by effective width for areas with detached houses [30]. In Finland, consumers have the right to choose a way of heating and the connection charge is determined by the building sizes and the location of consumer [31], [32]. The organization of heat supply in Russia and China has some similarities. Generation of heat is based on large combined heat and power plants (CHPP), Government regulation of the heat tariffs is carried out, the consumer can choose between district and individual heating. At the same time, in China since 2007, and in Russia since 2009 DHS and construction of CHPP are priorities within energy policy [33], [34].

In many considered cases and also according to the Russian law “About Heat Supply” the effectiveness of decisions made on the expansion of DHS can be assessed according to the criterion of an effective heat supply radius (EHSR) or in other words the extension of heat network from heat source to consumer. The parameter EHSR is unique and used only in Russia. European researchers use other criteria, for example, heat density and linear heat density [17], [18]. EHSR and linear heat density have similar patterns, but it's not the same. EHSR is the distance from a heat source to a node, behind which the connection of new consumers is not economically feasible. Linear heat density is a criterion, which we can use to estimate EHSR and local radius, for example. It is also important to add that development existing DHS should be rational to make it more efficient. Optimal planning, determination of EHSR and conditions of new consumers connection will help to improve current situation in Russian. We consider, that it's first and important step on the way to the main goal of energy strategy – intelligent heating systems or 4th generation DHS. Within the framework of this area, researches related to the prosumer and the use of low-temperature modes in DHS are especially perspective [28], [35]–[37].

The search for EHSR represents an important problem for designing and development of DHS. An analysis of scientific and technical literature shows that the calculation of EHSR has been paid sufficiently great attention to, since the time of district heating emergence. The research shows that EHSR and heat source service areas depend greatly on specific features of systems and location of heat sources [38]–[41]. The studies on the determination of effective district heating zones have been recently restarted [42]–[44]. It is worth noting that the considered techniques do not take into account the reliability requirements in the calculation of EHSR, this can result in severer consequences of failures in system.

The basic principle of heat supply planning for Russia was presented in [41], [45]. At the same time, currently there is no regulatory documents to provide a technique for the calculation of EHSR. Thus, the objective of determining an optimal size of DHS requires the development of a new methodological basis, which will enable us to decide on connection of new consumers to the system, based on the calculation of EHSR. Thus, we can conclude that it is necessary to calculate the EHSR for each heat source of DHS for all directions of transmission pipelines, assess the heat supply reliability indices and, additionally, assess each new connection in zone of effective district heating according to an additional criterion – a

local effective heat supply radius (LHSR). We propose techniques for the assessment both of EHSR for the heat transmission pipelines and LHSR.

2. METHODOLOGY

2.1. General Optimization Model for Search of Effective Heat Supply Radius

The considered problem is formulated as determine to maximum EHSR at minimum cost price on production and distribution thermal energy in DHS. Moreover, should be taken into account requirements to reliability heat supply to consumers. This optimization problem can be solved by the bi-level programming methods [46]–[48]. Thus, the considered problem is represented by the following set of expressions.

Objective functions are:

$$F_{obj}^1 = \sum_{n \in N(i)} l_n \rightarrow \max, i \in I, \quad (1)$$

$$F_{obj}^2 = \sum_{i \in I} \left[(s_{hi} + \alpha k_i) + \left(\frac{(f + \alpha) \sum_{n \in N(i)} (k_n d_n l_n)}{Q_i^0} + \frac{s_e \tau_p \sum_{n \in N(i)} (x_n \psi_n l_n)}{367.2 \eta_p Q_i^0} \right) \right] \rightarrow \min. \quad (2)$$

Cost for nodes of system and average cost in system are:

$$Z_m = (s_{hi} + \alpha k_i)_m + \left(\frac{(f + \alpha) \sum_{n \in N(m)} (k_n d_n l_n)}{Q_i^0} + \frac{s_e \tau_p \sum_{n \in N(m)} (x_n \psi_n l_n)}{367.2 \eta_p Q_i^0} \right), \quad (3)$$

$$Z_{av} = \frac{1}{\sum_{i \in I} Q_i} \sum_{i \in I} \left[Q_i (s_{hi} + \alpha k_i) + Q_i \left(\frac{(f + \alpha) \sum_{n \in N(i)} (k_n d_n l_n)}{Q_i^0} + \frac{s_e \tau_p \sum_{n \in N(i)} (x_n \psi_n l_n)}{367.2 \eta_p Q_i^0} \right) \right]. \quad (4)$$

Thermal energy balance in the system is:

$$\sum_{i \in I} Q_i = \sum_{j \in J} Q_j + Q_{los}. \quad (5)$$

Flow distribution model is [49]:

$$Ax = G, \quad (6)$$

$$\bar{A}^T P = h - H, \quad (7)$$

$$h = SX|x|, \quad (8)$$

$$Q = Gc_t \Delta t. \quad (9)$$

Nodal reliability indices are [50]:

$$K_j = \sum_{s \in E} p_s ((\tau_0 - \tau_{sj}) / \tau_0), \quad (10)$$

$$R_j = \exp \left(-p_0 \sum_{s \in E} \sum_{n \in N'(s)} \tau_{sj} \lambda_n \right). \quad (11)$$

Markov random process of the evolution of events (failures and restorations of heat network sections) [50]–[52]:

$$p_s \left(\sum_{n \in N(s)} \lambda_n + \sum_{n \in N(s)} \mu_n \right) = \sum_{z \in E(s)} \left(\sum_{n \in N(z)} p_z \lambda_n + \sum_{n \in N(z)} p_z \mu_n \right), s \in E. \quad (12)$$

Constraints on variables and parameters are:

$$Z_m \leq Z_{av}, m \in M_{ef}, \quad (13)$$

$$Z_m > Z_{av}, m \notin M_{ef}, \quad (14)$$

$$0 \leq Q_i \leq Q_i^0, i \in I, \quad (15)$$

$$K_j \geq K_j^0, j \in J, \quad (16)$$

$$R_j \geq R_j^0, j \in J. \quad (17)$$

The objective function of the first level (1) is maximizing of EHSR as sum of heat network sections which included in the supply area of i -th district heat source. The objective function of the second level (2) is minimizing of general cost on production and distribution of heat energy in the system. The numerical coefficient of 367.2 is necessary to convert expression parameters to correct dimension. Flow distribution in the heat network determine with use the thermal-hydraulic model (6)–(9) which present basic system equations of Theory of hydraulic circuits [49] and consist on the Kirchhoff laws and closing equations. Reliability of heat supply to consumers is estimated on nodal reliability indices: availability factor (10) and failure free operation probability (11). These indices determined with use equation system of Markov random process (12). In more detail the issues of applying the Markov random processes in the problems of DHS reliability are considered in [50]–[52].

Solution of formulated nonlinear problem is based on method of coordinate-wise relaxation (or method of coordinate-wise descent) with reduce the multidimensional optimization problem to one-dimensional one and use of simple iteration method within solve cycle with step-by-step procedure for improvement solutions according to the heat production output by all the sources.

2.2. Technique for the Effectiveness Assessment of New Heat Consumer Connection Based on Local Effective Heat Supply Radius

The LHSR represents the maximum length of a heat network section between a connection point and a consumer, whose construction and operation does not lead to an increase in the specific costs in the system. In doing so, the capital investment in the construction of a new

heat network section and its operating costs are taken into account. Indices and criteria characterizing the effectiveness of consumer connection and in fact limiting its capabilities can include the following: a constraint on heat network losses, a constraint on the level of connection charge, a load connection effectiveness coefficient (CEC) – k_{ef} . CEC represents a relative value determined as a ratio of heat load of an applicant to the length of a new branch and linear load density of the entire heating system from the heat source to be connected to a new consumer, considering the length of the whole heat network:

$$k_{ef} = \varepsilon Q_j \tau_0 / (l_j q_L). \quad (18)$$

Index q_L is a ratio of heat load connected to a heat source i to the total length of heat transmission networks at boundaries of EHSR (L_{ef} , m):

$$q_L = Q_i \tau_0 / L_{ef}. \quad (19)$$

With the value k_{ef} below 1 the connection is considered to be ineffective. Consequently, the maximum (at $k_{ef} = 1$) connection distance for consumer j is determined by the expression:

$$l_{jmax} = \varepsilon Q_j \tau_0 / q_L. \quad (20)$$

The minimum necessary load level (at $k_{ef} = 1$) of consumer j for its connection at a fixed point at some distance l_j from the heat network is calculated by the expression:

$$Q_{jmin} = q_L l_j / (\varepsilon \tau_0). \quad (21)$$

To make a decision on whether or not the new consumer connection to the heating system is economically viable, we developed an algorithm consisting of the following stages.

- Collect and process the initial information;
- Determine the boundaries of EHSR for the heat network (a set of points on the network, «cutting out» a part for which the heat cost exceeds an average cost in DHS). The radius is determined by model presented in the part 2.1;
- Calculate the maximum length of heat pipelines from the connection point on the existing heat network to a new consumer by Eq. 20;
- Determine consumer charge for connection to DHS according to the following rules:
 - If a point of new consumer connection to the existing network lies in the zone of EHSR and the length of a new heat pipeline does not exceed the maximum length obtained in step 3, the connection charge corresponds to an established level approved by the government,
 - If a point of new consumer connection to the existing network lies in the zone of EHSR, but the length of a new heat pipeline exceeds the maximum length obtained in step 3, the connection charge is agreed individually and normally exceeds the established level approved by the government. If the consumer connection leads to a rise in specific heat production and transportation costs throughout the system, then an individual heat tariff is established for the consumer, which allows compensation for the increase in the costs,
 - If a point of new consumer connection to the existing network lies beyond the zone

of EHSR, the connection charge is agreed individually, and an individual heat tariff is considered to compensate for an increase in specific heat production and transportation costs.

3. CASE STUDY

A scheme of the DHS on Irkutsk city map is presented in the Fig. 1. The heat transmission and distribution heat network in this large system have two pipes. The supply-return temperature of heat supply is 150/70 °C. The pipelines are laid above ground on low and high support beams, and underground in no-passage and passage ducts. The total length of heat network from the Novo-Irkutskaya combined heat and power plants (NICHPP) makes up 474.3 km, including 112.9 km of transmission pipelines (TP). The installed electric capacity of the NICHPP is 708 MW, the installed heat capacity is 2010 MW. The service area of this plant covers three city districts. All of them are either completely or partially supplied with heat from this heat source along three TP: TP-1, TP-2, and TP-4. TP-3 supplies heat to consumers in suburban settlement.

Fig. 1. DHS of Irkutsk on the city map.

According to methods presented in the part 2.1, EHSR was calculated for the NICHPP in Irkutsk. The GAMS (General Algebraic Modeling Systems) software package is used as a

solver. An aggregate scheme of the considered heating system with decisions on EHSR is presented in the Fig. 2. Its values for the NICHPP (disregarding reliability requirements) along the transmission pipelines and their branches are limited by nodes highlighted in red in the Fig. 2. The values of the radius vary from 2 km (the least distance between the consumer and source) to 15.5 km in the direction of pumping station PS 4–7.

Fig. 2. Aggregate scheme of the DHS (NICHPP) with decisions on EHSR.

An analysis of heating system reliability shows that the standard values of availability factor and probability of failure-free operation, set according to [51], [52], are not met for some nodes that belong to the zones of EHSR. According to the reliability indices obtained, we adjusted EHSR in the considered system. In the Fig. 2, the boundaries of EHSR, considering reliability, are shown in blue color and dashed lines. Thus, the maximum EHSR for the NICHPP, considering the reliability requirements, will decline from 15.5 km to 14.6 km and the total length of the heat transmission networks in the zone of EHSR will shrink by 4.2 km and make up 67.7 km. According to the obtained results, considering reliability requirements, the zone of EHSR embraces 284.3 km of heat network out of 474.3 km, i.e. 40 % of the networks are beyond EHSR zone. Connection of new consumers (according to the technique presented in the part 2) within the boundaries of EHSR with the existing technical feasibility does not lead to an increase in the heat cost.

Specific heat cost for the longest branches of TP and average specific heat cost for the system are presented in the Fig. 3. Correlation between the heat load and a material

characteristic of the heat network has a significant influence on the specific heat cost for each node. The greater the specific material characteristic of the heat network (per heat load unit), the higher the specific heat cost and vice versa. All network sections have different specific material characteristic and EHSR depends on it.

The maximum length of a heat pipeline from the point of new consumer connection to the existing heat network is calculated according to the technique proposed in the part 2.2. Fig. 4 presents the maximum length of the pipeline from the point of connection to the existing heat network to a new consumer, which was calculated according to Eq. 20. The obtained values are recommended to be updated annually or when EHSR changes due to a considerable change in the connected heat load and total length of the heat network. Fig. 4 shows that the connection of a new consumer is justified if a heat pipeline is constructed on the basis of 156 m per 1 MW at a supply/return temperature of 150/70 °C (or at a temperature difference in supply and return pipelines equal to 80 °C). A lower temperature difference in supply and return pipelines in the network section is characterized by an uplift in capital and operating costs. Therefore, the maximum length of the heat pipeline declines.

Fig. 3. Specific heat cost for the longest branches of transmission pipelines (TP) of the DHS of Irkutsk city on based NICHPP: crossing of line with average level (dashed line) corresponds to decision on EHSR.

Fig. 4. The maximum length of a heat pipeline from the point of new consumer connection to the transmission pipeline of DHS based on NICHPP.

In the event that the applicant is located in the zone of effective heat supply radius and wants to connect a 1.16 MW (1 Gcal/h) load to the heating system at a supply/return temperature of 120/70 °C, DHS company, based on connection effectiveness coefficient, assesses the connection feasibility, and makes pipeline routing from a connection point to a consumer. If the obtained value is either above or equal to 1, the connection of this consumer will not increase the specific costs in the system. However, if CEC is below 1 the construction and operation of a new heat network section will cause non-standard costs and consequently a rise in the connection charge and heat tariffs. Therefore, the connection charge should be agreed individually according to the real costs of the network construction. Moreover, the consumer must compensate for the non-standard annual operating costs of heat network section.

4. CONCLUSIONS

The paper proposes a technique for the calculation of EHSR for a heat source in the DHS. The radius is determined as a set of nodes in a heat network scheme. The cost of heat production and transportation at these nodes does not exceed its average values throughout the considered DHS. The considered problem is formulated as determine to maximum effective heat supply radius at minimum cost price on production and distribution thermal energy in DHS taking into account requirements to reliability heat supply to consumers. Proposed methods are universal for any type of DHS. It takes into account individual features of territories and can be successfully applied in design of heat supply schemes.

Connection of new consumers within the boundaries of EHSR, considering reliability requirements, will restrain the cost rise in the DHS, decrease heat losses and ensure the required level of system reliability. Heat supply to consumers situated beyond the zone of EHSR requires a plan for the construction of a new heat source. At the same time, the boundaries of the expansion zone of an optimal DHS (i.e. connection of new consumers) cannot be determined by a single value of EHSR, since the heat loads are non-uniformly

distributed throughout the system. It seems sensible to resolve the question of consumer connection, taking into account both EHSR and the distance between the consumer and connection point to the heat network in the zone of radius (LHSR).

We propose a technique to assess the economic viability of new connections. This technique can be used by DHS company and regulators to assess the cost-effectiveness of the connection, and the costs required for each new consumer. In the first stage, we estimate whether or not the section of the transmission pipeline where the consumer connection is planned belongs to the zone of EHSR. In the second stage, we calculate the maximum heat pipeline length from the connection point to a new consumer (LHSR). The consumers located beyond the zone of EHSR or within this zone but beyond the limits of admissible distance from the connection point, should be connected individually and under an individual tariff, provided there is an available heat capacity of the heat source and available transmission capacity of heat network.

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