Comparative analysis of heat supply options for small and middle-sized settlements of Eastern Siberia by using uncertain and fuzzy information

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Abstract. The problems of heat supply in small and medium-sized settlements of Eastern Siberia are considered. Variants of using cogeneration heat plant (CHP) or boiler plant on coal or wood waste, the use of liquid petroleum gas (LPG) and liquid natural gas (LNG) as a fuel, the use of electric boiler plant or stand-alone electric boilers, applications of solar collectors and heat pump installations are considered based on a systems approach and fuzzy modelling, by taking into account the uncertainty of some factors.

1. Introduction

One of the most important tasks facing the national economy of Russia is to increase the efficiency of heat supply for small and medium-sized settlements in Eastern Siberia. The low efficiency of heat supply systems is due to quite complex problems: considerable distance from fuel sources, centralized electricity and heat supply; long distances between settlements; the duration of the heating period (2/3 of a year); low outdoor temperatures. Traditionally, it is considered that the centralized heating systems are the most efficient [1]. Moreover, East Siberia is characterized by the presence of relatively cheap coal reserves, therefore coal heat sources are most prevalent in this region.

In large cities, due to the combined generation of heat and electricity and the use of highly efficient technologies, the use of coal-fired CHP plants ensures a relatively low cost of thermal energy and an acceptable degree of purification of combustion products. In small and medium-sized settlements, coal-fired boiler houses are mainly used, which are less efficient than CHP plants and, as a rule, are less environmentally friendly. All these factors lead to a high cost of thermal energy and an increase in tariffs for the population and business. Attempts by the tariff service to restrain the rise in prices for thermal energy lead to the fact that the resource supplying organizations lack the motivation to modernize and increase the energy efficiency of equipment [1-3]. The low level of remuneration, the shortage of funds for the necessary materials does not make it possible to ensure quality equipment operation. This, in turn, leads to significant losses due to low equipment efficiency and high wear of heat networks. This vicious circle needs to be broken. At present, it becomes obvious that the existing methods of state regulation in heating systems require serious changes. One of the most important points of the heat market liberalization planned by the Ministry of Energy is the so-called principle of
“alternative boiler house”[1]. On the one hand, it is assumed that the development of the market will lead to the introduction of the most efficient technologies. On the other hand, the “alternative boiler house” tariff should set a limit price for heat at the level of the amount that a consumer could spend on heating using his own gas boiler room, taking into account the cost of its purchase, installation and operation. It will be prohibited to sell heat at a price that exceeds this level. Thus, the key criterion for choosing the ways and means of modernization of heat supply systems is the economically reasonable tariff [3, 4].

The modern level of development of technology creates the possibility of applying a wide variety of methods and means to the organization of heat supply to populated areas. In small and medium-sized settlements cogeneration can be effectively used in mini-CHP. In such settlements low population density and low level of operation increase losses in the transport of thermal energy which leads to low efficiency of the centralized heat supply from boiler plants. The analysis shows that in many cases autonomous energy sources using local types of fuel, as well as secondary and renewable energy sources are more profitable.

In determining the paths for the development of heat supply schemes, the final decision is made not only on the basis of the criterion of an economically reasonable tariff. When making a decision, a multi-criteria system analysis is necessary, taking into account the uncertainty of a number of parameters and the lack of clarity of judgment. Environmental constraints are becoming increasingly important. Many areas of Eastern Siberia, in particular, the southern Baikal region, are among the specially protected natural territories, where strict regulations are imposed on the emissions of harmful substances and even moderate risk of man-made disasters are unacceptable [5].

The experience of developing heat supply schemes shows that along with economic, environmental criteria, danger of emergencies, risks of interruptions in fuel supply, a significant role is played by such criteria as the attitude of the government and the population to particular technologies, prospects for the development of the settlement, etc. Such criteria are of a fuzzy nature. Often they are expressed in the following way: "the population will not accept it .."; "..this is not tested ....", "there is not enough experience." Such different nature of factors that must be considered when deciding on the direction of development of the heating system, the technical impossibility of measuring some indicators, and the fundamental unclearness of others led to the choice of fuzzy logic and optimization methods in this study. Inherent in the estimates of the operation of heating systems, fuzziness has led to the widespread use of fuzzy logic and probabilistic approaches in their analysis and the development of automated control systems [6,7].

2. Models and research methods

When making decisions on the future development of heat supply systems for small and medium-sized settlements in the southern part of the Baikal region, the determining factors are the factors influencing the formation of economically sound tariffs. When assessing the cost of fuel and materials, it is necessary to take into account systemic factors, including climatic conditions, environmental restrictions, logistics, etc. [2–4]. When choosing the direction of development of the heat supply system of populated areas, the main role is given to such criteria as: the cost of production and transportation of thermal energy, energy efficiency, environmental friendliness, safety and investment.

The algorithm for selecting the option of heating the settlement is divided into three main stages. At the initial stage, all possible sources of energy are analyzed. For further analysis, only those are selected whose use is possible without violating environmental restrictions and is expedient from a logistics point of view. At the second stage, heat supply schemes for the selected sources are formed taking into account the corresponding technologies. At the third stage, the choice of the heat supply scheme is carried out, based on the criterion of the minimum cost.

This paper uses materials obtained in the development of a heat supply scheme for the Baikal urban settlement [9], which was conducted with the participation of the authors of the article. During the development and subsequent updating of the heat supply scheme, special attention was paid to the choice of heat sources and the degree of centralization of the system. Options for centralized and
decentralized heat supply and fuels such as coal, LNG, LPG, renewable and secondary energy sources were considered. The following options were investigated as possible heat supply schemes: modernization of the existing CHP plant; construction of a heat source focused on the use of various types of fuel (LNG, LPG, coal, biofuel) using cogeneration (mini CHP); construction of a boiler plant designed to use various types of fuel (LNG, LPG, coal, biofuel); construction of electric boiler; the device of the autonomous heat sources working at electric energy (EE); use of renewable and secondary energy sources.

The first stage of the research is the collection of information on each of the possible variants. The second stage is the selection of options that meet the restrictions on harmful emissions, and are accepted by the population and government officials. The final stage is the selection of options for which the cost of heat produced does not exceed a certain threshold value. The criterion for selecting an acceptable heat supply option at the second stage is as follows:

$$\text{MAX}(R_{\text{NOX}}, R_{\text{SOX}}, R_{\text{ash}}, R_{\text{ac}}, 0.5 R_{\text{pop}}, R_{\text{gov}}) < 0.5,$$

where $0 < R_i < 1$ is the value of the membership function of the class of solutions that violate the $i$th constraint. $R_{\text{NOX}}, R_{\text{SOX}}, R_{\text{ash}}$ show the degree of violation of standards for emissions of nitrogen oxides, sulfur oxides and ash content, respectively; $R_{\text{ac}}, R_{\text{pop}}, R_{\text{gov}}$ are numerical representations of the linguistic parameters reflecting the danger of an emergency, the attitude to the heat supply variant of the population and the government, respectively. A coefficient of 0.5 reflects the relative importance of the indicator: from the population the absence of pronounced protest is enough while the options that are not accepted by the government cannot be accepted in principle. At the first stage, ten possible heat supply options for the city of Baikalsk are presented for consideration. At the second stage, options based on the use of coal are excluded due to environmental constraints, options based on the use of gas are excluded for high risks of accidents; heat pumps and solar collectors are excluded for negative attitudes of population and government. As a result, biofuel-related options, electric boiler houses and autonomous electric boilers were found to satisfy all the limitations and pass to the third stage of selection.

The main results of the study on heat supply of Baikalsk city are summarized in table 1. In columns 6-11, the indicators of compliance with the restrictions are given in the form of fractions: in the numerator the absolute or linguistic values are given, and in the denominator the degrees of violation of the restrictions are given. In the derivation of the thermal energy cost when using LPG and LNG the fuel price of 20 thousand rubbles per ton is assumed. It should be noted this price might be higher if we take into account the trends of the world market and the positions of leading Russian companies towards the prospects for gas supply in Eastern Siberia.

The high risk of using LPG and LNG is due to the possible consequences of the gas release in case of accidents during transportation or storage. The government distrust of heat pump technology and solar collectors is due to previous negative experiences. The biofuel-based technologies meet no confidence because of the lack of experience of large-scale use of the technology. The options based on the use of LNG and LPG are excluded due to the lack of confidence in the reliable gas supplies at reasonable prices. Serious concern regarding the construction of the electric boiler plant is the likelihood of a significant increase in electricity tariffs.

The negative attitude of the population towards heat pumps and solar collectors is caused by the need for serious reconstruction of building heating systems and increasing personal responsibility for the operation of the systems. A significant part of the population does not want to take any responsibility for their dwelling heating and express the position of the mere user: "the government must provide ...". However, increasing the degree of a consumer control over the consumption of energy resources increases his/her motivation to save energy. Owners of houses with autonomous heat sources and energy accounting are much more thrifty about their consumption. From this point of
view, the use of autonomous heat sources (house electric boilers and/or heat pump installations) should stimulate consumers to save energy.

3. Results and discussion
Comparative analysis of the cost of heating options and the required investment is given in figure 1. From the point of view of economic and energy efficiency, the most attractive are options for the use of biofuels, heat pumps and solar collectors, that is, options using secondary and renewable energy resources. The cheapest energy give options with solar collectors. However, considering other criteria, including the amount of necessary capital investments, this option cannot be accepted as a base case. However, the use of solar energy as a supplement to other heat supply options can improve the efficiency of heating systems.

The lowest cost of production of heat energy is provided by CHP due to the joint production of heat and electric energy and due to the low cost of fuel. But due to severe environmental constraints [5], the use of CHP as a base case has also been rejected. As a result, for Baikalsk city, the base option was chosen for heating from boiler houses operating on biofuel such as dry chips and/or pellets [9]. The use of combined heat and power generation using local biofuels provides a lower cost of energy supply than the boiler houses, but requires higher investments. The choice of a cheaper option with regard to investments was influenced by the low assessment of the development prospects of Baikalsk city. At the same time, from the standpoint of energy efficiency, environmental friendliness, as well as in terms of investment volumes, heat sources using electricity are more preferable. In this case, the rejection of options associated with city electric boiler or with autonomous electric boilers is caused by a high estimate of the risk of increase to an unacceptable level of electricity tariffs. When evaluating a variant using heat pump installations, the lack of experience in large-scale use of heat pumps in Russia has played a decisive role. In addition, several years ago in Baikalsk city, a heat pump of 500 kW was installed. The decision to introduce this installation was made in a purely bureaucratic way, without taking into account the fact that the wastewater treatment plant, where the heat pump was installed, was remote from consumers. As a result, the use of the heat pump installation did not justify itself, and, apparently, this formed a long term negative attitude towards innovation on the part of decision makers.

Figure 1. Comparison of options for the cost of production and transport of heat energy and the required investment
| Option | Fuel and/or technology | Investments, million rubbles | Cost price, rubbles/Gcal | Results of restrictions violation assessment | Constraint violation indicators a |
|--------|------------------------|-----------------------------|-------------------------|-----------------------------------------------|-------------------------------|
|        |                        |                             |                         |                                               | NOx emission, R_{\text{NOx}} ton/year | SOx emission, R_{\text{SOx}} ton/year | Ash emission, R_{\text{ash}} ton/year | Accident danger, R_{\text{ac}} | Population attitude, R_{\text{pop}} | Government attitude, R_{\text{gov}} |
| 1      | LNG                    | 3650                        | 3527                    | declined because of accident danger          | 121/0.5                        | 0.0                          | 0                                | high/0.9                       | neutral/0.2                     | neutral/0.2                             |
| 2      | LPG                    | 3150                        | 3736                    | declined because of accident danger          | 121/0.5                        | 0.0                          | 0                                | high/0.9                       | neutral/0.2                     | neutral/0.2                             |
| 3      | Biofuel (CHP)          | 3004                        | 1288                    | declined because of investments             | 6.50.03                        | 25.0/0.1                     | 30.5/0.4                        | low/0.1                        | neutral/0.2                     | neutral/0.2                             |
| 4      | Biofuel (boiler plant) | 2474                        | 1446                    | accepted                                      | 6.50.03                        | 25.0/0.1                     | 30.5/0.4                        | low/0.1                        | neutral/0.2                     | neutral/0.2                             |
| 5      | Coal (boiler plant)    | 2768                        | 1595                    | declined because of ecology                 | 231/1.0                        | 251.7/1.0                    | 35/0.5                          | medium/0.5                     | neutral/0.2                     | positive/0.0                             |
| 6      | Coal (CHP)             | 9100                        | 1020                    | declined because of ecology                 | 320/1.0                        | 380/1.0                      | 51/1.0                          | medium/0.5                     | neutral/0.2                     | positive/0.0                             |
| 7      | City electrical boiler plant | 1300                        | 4275                    | declined because of high risk of EE price growth | 0                              | 0.0                          | 0                                | low/0.1                        | positive/0.0                     | neutral/0.2                             |
| 8      | Autonomous electrical boilers | 209                         | 3012                    | declined because of high risk of EE price growth | 0                              | 0.0                          | 0                                | low/0.1                        | positive/0.0                     | neutral/0.2                             |
| 9      | Heat pumps             | 2100                        | 1209                    | declined because of population and government attitude | 0                              | 0.0                          | 0                                | low/0.1                        | negative/1.0                    | negative/1.0                             |
| 10     | Solar collectors       | 8000                        | 505                     | declined because of population and government attitude | 0                              | 0.0                          | 0                                | low/0.1                        | negative/1.0                    | negative/1.0                             |

a Indicators of violation of restrictions are given in the form of fractions, where the numerator shows the value in its original representation, and the denominator - the value of the corresponding membership function.
4. Conclusions
Given the full range of system factors, coal-fired boilers in the short term are no longer the cheapest heat sources for many small and medium-sized settlements in the Baikal region. It is advisable for small and medium-sized settlements to individually optimize heat supply schemes. Inflated risk assessments are caused by lack of experience. This, in turn, is due to the lack of pilot projects. To reduce the negative impact of overestimated risk assessments, it is important to intensify pilot projects on the use of heat pumps, solar collectors, biogas, mini CHP.
As for Baikalsk city, finally the biofuel boiler plant was found to be the optimal choice considering all constraints.

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