

Optimization of energy sources structure to minimize environment pollution

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Abstract. The paper gives a general statement of the problem of choosing the structure of energy sources of urban heat supply systems to meet technical, economic and environmental constraints. One of the effective approaches to solve such a problem is the construction and optimization of redundant schemes of technological structures of energy sources. A model based on the theory of energy hubs is presented as one of the methods for constructing the redundant scheme. The application of the theory of energy hubs for selecting the types of energy sources allows, in an enlarged form, selecting the main equipment of energy sources, and evaluating technical and economic indices, and the degree of negative impact on the environment (at the level of gross emissions of harmful substances into the atmosphere). A case study of modeling a redundant system for selecting the optimal structure of energy sources, considering the minimum atmospheric pollution, is illustrated.

1 Introduction

A significant adverse impact of energy facilities on the environment is the pollution of atmosphere. In Russia, power plants and boiler houses burn about 390 million tons of fuel equivalent a year, throwing into the atmosphere about 3.67 million tons of pollutants, which is 21% of the total volume (17.35 million tons) of atmospheric emissions for all stationary sources of the Russian Federation as of 2016 [1, 2].

One of the key mechanisms of environmental protection in our country is the assessment of the caused damage and the corresponding payment for emissions of air pollutants. However, as practice shows, the existing algorithm for calculating damage from environmental pollution [3] leads to inadequate compensation for the damage. The operating costs of existing plants for complex chemical purification reach 10% of the company's annual income, and relative size of penalties is 0.05%. As a result, domestic polluting enterprises do not have effective economic incentives to implement environmental protection measures. To change the situation, it is necessary to clarify the concept of environmental damage, as well as penalties for it. It is important that effective measures for the prevention of harmful emissions

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are justified and taken into account already in the design stage.

An analysis of the domestic scientific and methodological literature, as well as the available methodological tools for the influence of heat supply systems on air pollution, allows

us to draw a number of conclusions. The proposed approaches to solve the problems of reconstruction and development of heat supply systems are mainly focused on improving their reliability, controllability and economy. Normally, in these approaches, the activities aimed at reducing the negative impact on the environment are determined for already selected options of the system development, which is not always the best solution [4-8]. The greatest effect on reducing emissions can be achieved when the measures are considered for all compared options [9].

The search for the most profitable composition of energy sources in the urban heat supply systems is a complex problem of scheme-and-structure optimization. Under energy source structure optimization we understand the optimal choice of its type, location and configuration of equipment. The problem has a nonlinear character and is difficult to formalize for practical implementation. The objective is to determine the energy source types, location and configuration of its equipment, including a variety of technical and economic conditions, environmental and territorial restrictions. Solution to such a problem depends on a large number of external and internal factors, such as compliance with the heat and electricity balance conditions; reliability, environmental and other constraints. The environmental constraints that stand out in terms of the degree of impact are the requirements of reducing harmful emissions of pollutants into the atmosphere. Heat power industry is one of the industries that most negatively affect the surface layers of the atmosphere.

A methodological approach based on the construction of redundant schemes, developed both in Russia and other countries, proved rather effective in the optimization of structure of energy sources in urban heat supply systems [10,

11].

The methodological approach to the construction of redundant schemes is also developed at Melentiev Energy Systems Institute SB RAS. It implies that a researcher constructs a redundant design calculated scheme of a heat supply system as a set of all admissible configurations of the heat network and the location of heat sources, considering constraints related to obstacles on the terrain and sites chosen for placement of the sources [12]. The idea of the approach is that when choosing the heat sources, the redundant scheme is supplemented by a fictitious node and a subset of fictitious links connecting it with those nodes where the optimal heat power of a source is selected. The number of fictitious links for each source node depends on how many alternatives of source types are considered at a given node. The local optimization of various trees of initial approximation is carried out by the directional enumeration of trees. This allows obtaining solutions close to optimal ones. The redundant scheme when prepared includes all possible alternatives, which eliminates the risk of excluding an optimal solution from consideration.

The authors of [13, 14] propose such an approach to construct a structural scheme of an energy source based on a redundant scheme. According to this approach, various options of energy source equipment are considered in a single scheme, which contains a finite number of components with their possible interrelationships.

2 The mathematical statement of the problem

The mathematical statement of the problem of selecting the structure of energy sources of urban heat supply systems considering technical, economic and environmental constraints can be presented as follows. A set of urban sources I consists of subsets of existing I_1 and new I_2 energy sources. For each energy source $i \in I$, set M_i is formed. Each component m of this source describes an option of reconstruction and/or modernization of an existing energy source or installation of a new energy source.

The objective function is the sum of costs determined by the composition, type and performance of the system components, USD:

$$S = \sum_i^I s_i \cdot Q_i - S_{out}^{eps} \cdot W_{out}^{eps} + S_{in}^{eps} \cdot W_{in}^{eps} + \sum_k^K S_k \cdot F_{ik} \Rightarrow \min, \quad (1)$$

In this case, the following constraints are met:
 Urban heat balance, Gcal/year:

$$\sum_i^I Q_i = Q^{city}, \quad (2)$$

urban electricity balance, MWh/year:

$$\sum_i^I W_i - W^{city} - W_{out}^{eps} + W_{in}^{eps} = 0. \quad (3)$$

The condition for competition in options for the reconstruction and/or modernization of existing energy source $i \in I_1$ is as follows:

$$\sum_m^{M_i} V_i^m = 1, \quad (4)$$

the competition condition in the options for each new energy source $i \in I_2$ is:

$$\sum_m^{M_i} V_i^m = G_i, \quad (5)$$

where V_i^m determines the implementation / non-implementation of an option of equipment $m \in M_i$ of an energy source i that has a certain set of technical and economic characteristics.

Heat generation by the i -th energy source, Gcal:

$$Q_i = \sum_m^{M_i} Q_i^m \cdot V_i^m, \quad (6)$$

power generation by source i , MWh:

$$W_i = \sum_m^{M_i} W_i^m \cdot V_i^m, \quad (7)$$

dependence of heat output on the fuel type:

$$Q_i^m = f(B_i^{m,h}, \dots, B_i^{m+1,h+1}), \quad (8)$$

dependence of electricity output on heat output:

$$N_i^m = f(Q_i^m), \quad (9)$$

dependence of electricity output on installed capacity:

$$W_i^m = f(N_i^m), \quad (10)$$

dependence of gross emissions of harmful substance k on the fuel type:

$$F_{ik}^m = f(B_i^{m,h}, \dots, B_i^{m+1,h+1}), \quad (11)$$

constraints on the amount of fuel used:

$$B_i^{m,h} \leq B_{i,max}^{m,h}, \quad (12)$$

gross emissions of harmful substance k from the i -th energy source, t/year:

$$F_{ik} = \sum_m^{M_i} F_{ik}^m \cdot V_i^m, \quad (13)$$

urban heat supply system should meet the standards of the protection of the atmosphere:

- the maximum permissible emissions (MPE) of harmful substances, t/year:

$$F_{ik} \leq F_{ik}^{\max}, \quad (14)$$

- the maximum permissible concentrations (MPC) for the dispersion of these emissions, mg/m³:

$$C_{kp} - \Delta C_{kp} \leq C_k^{\max}, \quad (15)$$

$$\sum_i^I \sum_m^{M_i} (C_{kpi}^m \cdot V_{im}) = C_{kp}, \quad (16)$$

$$C_{kpi}^m = f(F_{ik}^m). \quad (17)$$

where i is energy source from set I ; h is type of burned fuel; m is the number of option by type and configuration of the energy source equipment; Q^{city} is urban heat consumption, Gcal/year; W^{city} is urban electricity consumption, MWh/year; W^{eps} is the need for electricity in the electric power system, which can be covered by electricity from CHP, MWh/year; $B_i^{m,h}$ is consumption of fuel type h , it is burned by source i when option m is implemented, $B_i^{m,h}, \dots, B_i^{m+1,h+1}$, t/year; $B_{\max}^{m,h}$ is the maximum possible volume of burned fuel, t/year; W_i is electricity supply from source i , MWh/year; Q_i is heat generated by source i , Gcal/year; Q_i^m is heat generated by source i when option m is implemented, Gcal/year; W_i^m is electricity generated by source i when option m is implemented, MWh/year; N_i^m is electric power of source i when option m is implemented, MW/year; V_i^m is implementation of option m of reconstruction and/or expansion and/or modernization of source i or installation of new source i ; G_i is an auxiliary variable of Boolean type, if new source is not installed, then $G_i = 0$, if it is installed, then $G_i = 1$. G_i depends on V_i^m , for example, if $V_i^m = 1$, G_i becomes automatically $G_i = 1$; F_{ik} is gross emission of harmful substance k of source i , t/year; F_{ik}^{\max} is the MPE of harmful substance k into the atmosphere, established by calculation for source i , t/year; C_k^{\max} is the maximum

concentration of substance k in the atmosphere in the territory under consideration, which is relatively safe for the human and the environment (usually the MPC values established in legislation are taken as a sanitary and hygienic standard), mg/m³; C_{kp} is the calculated concentration of harmful substance k in the atmosphere at point p , mg/m³; p is the point from set P_k of points of the territorial dispersion of harmful substance k ; C_{kpi}^m is concentration resulting from implementation of option m for source i , mg/m³; ΔC_{kp} is a change as a result of implementation of option m for source i , mg/m³; S is costs of urban heat supply system, USD; s_i is unit cost at source i , USD/Gcal (USD/kW); W_{in}^{eps} is volume of electricity purchased from electric power system, MWh/year; W_{out}^{eps} is volume of electricity sold to the power system, MWh/year; S_{in}^{el} is tariff for purchase of electricity from electric power system, USD/kWh; S_{out}^{el} is tariff for sale of electricity to power system, USD/kWh; S_k is penalty for exceeding MPE of substance k , USD/t.

Figure 1 presents a graphical interpretation of a variety of options for the structure of energy sources of urban heat supply system in the form of a redundant scheme.

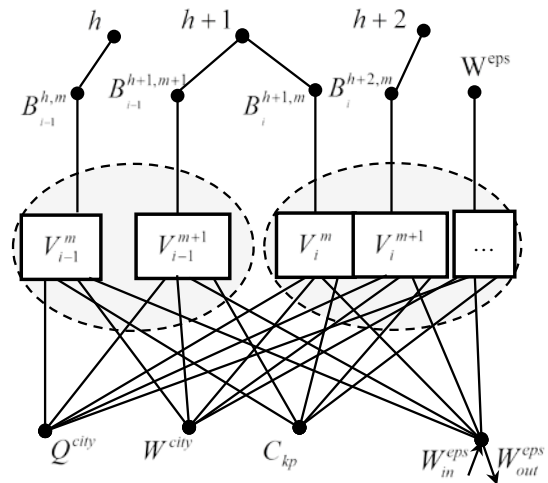


Fig. 1. Redundant scheme of a structure of energy sources of the urban heat supply system.

Rectangles V_i^m indicate the implementation/non-implementation of m options of equipment of energy source i . The lines going from them to point Q^{city} are the graphical reflection of heat balance equation (2), lines going to W^{city} and W^{eps} correspond to electricity balance equation (3), and the lines directed to point C_{kp} show the concentration of harmful substance at point p in terms of substance k .

Dotted lines in Figure 1 show possible competing options

for each energy source.

The above mathematical formulation is a mixed integer nonlinear programming (MINLP) problem. It is nonlinear, which in particular is explained by the presence of integer variables V_i^m , and nonlinear dependences (8)-(11).

Therefore, to solve it, we propose decomposing it into simpler subproblems that are solved in stages. In the first stage, subproblem (1)-(14) is solved, where the types of energy sources are determined, the composition of the main equipment is selected, and the negative impact on the environment is assessed (at the level of gross emissions).

In the subsequent stages, equations (15)-(17) are taken into account, that is, for the energy sources chosen in the first stage, the equipment is determined, given the MPC of harmful substances in the surface layer of the atmosphere.

3 Modelling of redundant scheme of energy source structure

Optimization of a structure of energy sources as the first stage problem can be solved using the theory of energy hubs [15], which is widely used in modern practice [16].

The energy hub is an intermediate link between energy producers and the transport infrastructure, on the one hand, and consumers, on the other. It ensures the transfer, conversion, production and storage of various types of energy carriers. The energy hub transforms the energy carrier, changing its potential, which allows integrating any consumer into the system.

The technological model of the hub includes four structural components [17]:

1. Input flows of energy carriers supplied directly from producers or from the system of energy transport infrastructure (fuel supply systems, from renewable energy sources (wind and solar energy), for example, electricity from centralized electricity supply system or heat from district heating system, etc.

2. Energy converters ensure the conversion of some types of energy carriers into their other types (boiler room, chiller, heat pump, etc.), or responsible for a change in physical parameters of energy carriers (electrical transformer, network pump, pressure regulator, etc.).

3. Energy storage (accumulator, battery) designed to store fuel, energy accumulation (for example, heat accumulator, power storage, gas tank, coal storage, etc.).

4. Output flows of energy carriers sent to consumers loads (heat, cooling, power consumption, etc.).

The energy carriers in the energy hub can be transferred from the input to the output with changing parameters (for example, electric voltage) or with a significant transformation changing the form of the energy carrier (for example, the cogeneration unit can convert gas into electricity and heat).

The modeling of hubs is based on three assumptions [18]:

1. There are no losses in the hubs, except for conversion and storage losses;

2. The simulated system is in a stable, steady state;

3. The energy flow is always directed from input to outputs of the hub.

The main idea of applying the energy hub methodology is to model the structure of option $m \in M_i$ of energy source i

in the form of an energy hub whose existence is determined by variable V_i^m . General structure of the energy source, shown in Figure 2, consists only of energy converters, since energy storage components are not provided in the energy source structure. Figure 2 shows converters R_γ , inputs P_α and outputs L_β , where $1 \leq \gamma \leq z$, $1 \leq \alpha \leq \omega$, $1 \leq \beta \leq \mu$, z is the number of converters, ω is the number of inputs, μ is the number of outputs. The energy flows going through converters R_γ can be described in a vector form:

$$\mathbf{L} = \mathbf{C} \cdot \mathbf{P}, \quad (18)$$

where \mathbf{L} – the vector of outputs, i.e. energy supply (heat and electricity production), harmful emissions, etc.; \mathbf{P} – vector of inputs, i.e. consumption of primary energy (fuel, electricity); \mathbf{C} – input-to-output coupling matrix.

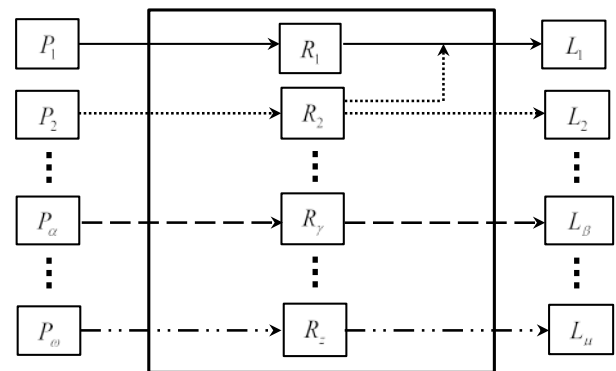


Fig. 2. Representation of the energy source structure in the form of an energy hub.

Matrix \mathbf{C} describes mapping of the input flows of converters to the output flows. Components \mathbf{C} are the coupling coefficients of converters $c_{\alpha\beta}$, each connecting one input P_α with output L_β :

$$L_\beta = c_{\alpha\beta} \cdot P_\alpha, \quad (19)$$

where α , β are the input and output energy carriers, respectively.

The coupling coefficient $c_{\alpha\beta}$ of converters characterizes the efficiency of conversion of fuel α into energy β and depends on the fuel type (coal, gas, etc.), equipment types and capacities (boiler, turbine, etc.) and its operating conditions.

If P_α is common for several converters, then $c_{\alpha\beta}$ will also depend on the distribution of the input energy flows, which is described by the distribution coefficients v_α^γ . Each of the coefficients determines the proportion of input flow P_α coming to converter γ :

single energy source equipment, that has an industrial heat load of 1.32 Gcal/h. Technical, economic and cost indices for the options of energy source equipment are given in Table 1.

Table 1. Plant options for one energy source

Parameter name	Value		
Option number (source structure)	1	2	3
Plant type	E-1/9-1M	3516 HR SITA54	DG98M KUV-30
Number of plants	3	2	2
Fuel type	fuel oil	gas	gas
Consumption of fuel by one plant, kgce/h	81.4	464.7	471.2
Annual costs of fuel purchase by one plant, thousand USD/year	152.28	124.84	125.68
Heat capacity of one plant, Gcal/h	1.965	1.64	1.34
Electrical capacity of one plant, MW	-	1.03	1
Electricity purchase, MW	2	-	-
Annual costs of electricity purchase, thousand USD/year	1051.2	-	-
The cost of a set of plants, thousand USD	20.1	11	12
The cost of laying a gas pipeline, thousand USD	-	9	9

Option 1 suggests the installation of oil fuel-fired boilers E-1/9-1M. Option 2 suggests the installation of a Mini-CHP based on low-power gas-fired plants SITA54 manufactured in France. Option 3 includes a Mini-CHP based on gas plants DG98M with a low-power gas-fired waste heat boiler KUV-30. All the options have equal heat and electricity output. To this end, when the energy source equipment does not produce electricity, it is purchased from an external electric power system (Table 1, Option 1).

Figure 4 demonstrates the gross emissions of harmful substances by energy source option.

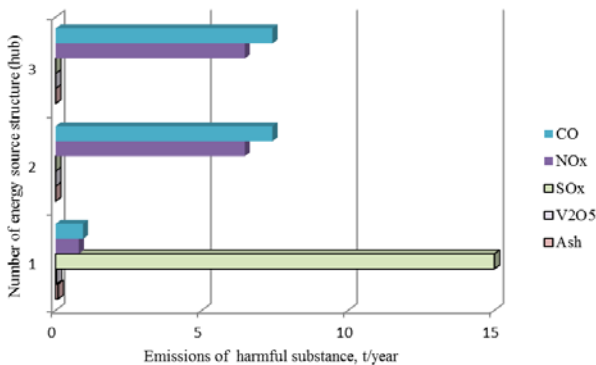


Fig. 4. Gross emissions of harmful substances by option of energy source.

Table 2 indicates the sizes of penalties for harmful substance emission, taken according to [21].

Table 2. Sizes of penalty for negative impact on the environment, 2018

Name of harmful substance	Thousand USD/t
Nitrogen dioxide, NO _x	0.0021
Benzopyrene	84.19
Vanadium Pentadioxide, V ₂ O ₅	0.042
Ash	0.034
Sulfur dioxide, SO _x	0.00069
Carbon oxide, CO	0.000025

Figure 5 shows the models of power plants in the form of hubs created according to the options of equipment presented in Table 1.

The outputs of hubs, in addition to heat and electricity are the annual emissions of harmful substances.

Comparison of the considered options of the energy source structure in terms of technical and economic indices, as well as emissions of harmful substances into the atmosphere with the help of the method proposed above, made it possible to obtain the optimal solution, which corresponds to option 2 (Figure 5, hub 2).

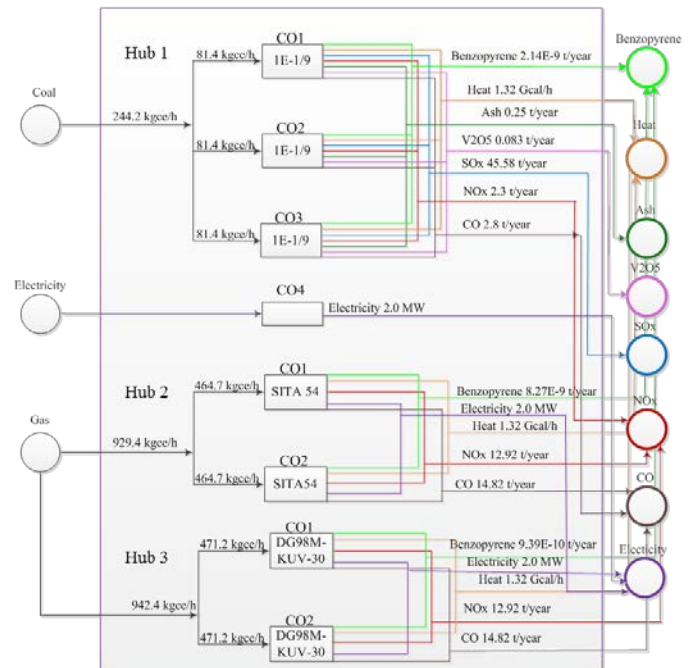


Fig. 5. Options of energy source equipment.

This option of the structure suggests installing a natural gas - fired Mini CHP of type 3512HR SITA54 with a heat capacity of 1.64 Gcal/h and a maximum electric power providing the needs of an industrial enterprise of 2.06 MW. The gross emissions of harmful substances when operating at the design heat load in this option of the energy source structure are minimal and will be: NO_x – 12.92 t/year, CO – 14.82 t/year, benzopyrene – 8.27E-9 t/year.

5 Conclusions

The choice of the energy sources optimal structure is a complex nonlinear problem due to the presence of discrete variables, non-linear functions, for example, power

generation, dependence of pollutant emissions on fuel consumption, etc. We propose solving this problem in stages. In the first stage, the types of energy sources are determined, the composition of the main equipment is selected, the negative impact of energy sources on the environment is assessed (at the level of gross emissions). In the second stage, for the selected areas of energy sources development, the equipment composition is specified considering the MPC of harmful substances in the surface layer of the atmosphere.

The problem of the first stage can be solved by constructing redundant schemes of energy source structures by the methodology of energy hubs. This provides the following advantages:

- the flexibility of the model as a result of considering more connections and types of equipment for energy supply to consumers;

- the opportunity to optimize the types of power plants, the cost of generated energy, levels of environmental pollution and tackle other problems by selecting different combinations of input vectors;

- the relative ease to take into account environmental constraints, because gross emissions of harmful substances as well as technological indices are considered as output parameters.

The considered case study demonstrates that, in the first stage of optimizing the energy sources structure, the equipment characteristics can be linearized, which allows solving the problem of choosing the directions of energy sources development as a linear programming problem with integer variables.

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