DECISION SUPPORT SYSTEM USED TO IMPROVE THE COMPETITIVENESS OF A POWER GENERATING COMPANY UNDER CONDITIONS OF UNCERTAINTY

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ABSTRACT

In real life energy problems that do not contain uncertainties are more of an exception than the rule. Solving the problems of analyzing the state and development of energy systems, including power generating companies, is seriously complicated by the uncertainty of initial information observed when describing the current and future level of competitiveness, as well as the uncertainty of criteria on quality of the state and of decisions on effective development being made. The difficulties in analyzing the state of energy systems caused by the influence of objective factors are such that, despite numerous researchers working in this area, they are still far from being overcome. Therefore, studies on improving the decision-making system to improve the competitiveness of a power generating company, taking into account the uncertainty factors in solving the tasks considered in this article, are relevant. The article proposes a scheme for elaborating a system of informational support for decision-making pertaining to development of a power generating company. Methods for determining results of operations on fuzzy parameter values have been developed. We present here methods for solving selection problems with fuzzy values of criterion assessments on a finite set of alternatives and classification problems with a fuzzy description of classes and values of indicators characterizing the power generating companies' competitiveness. An algorithm for informational support of the process of generation and selection of development alternatives for power generating companies in a high economic risk environment has been developed. In the course of this study we have reviewed the directions for increasing the level of competitiveness of a power generating company, taking into account any peculiarities of the use of innovative technologies in the area of energy generation in an environment where uncertainty and multiple criteria are present.

Keywords: power generation industry, efficiency, competition, strategy, reliability, risks, mathematical economic models, uncertainty, centralized energy sources.

1 INTRODUCTION

High volatility of the economy results in an increased interest towards the use of various mathematical methods for analyzing patterns of development and behavior of electric power systems, and the main difficulties in applying these methods are associated with the uncertainty of the external environment's parameters. Often one has to deal with the need to effect calculations while some of the equations' parameters are unclearly defined or reflect inaccurate process information. However, in the case of elaborating formal models, they most often use deterministic methods and bring certainty into those situations where it does not really exist. The inaccuracy of defining certain parameters in calculations is practically not accounted for, or based on certain assumptions and admissions, inaccurate parameters are replaced by expert estimates or average (weighted average) values. The violations of equalities and balance ratios that arise in this case lead to the need to vary some parameters in order to accurately satisfy the given equations and produce an acceptable result. The peculiarity of electric power systems is that a significant part of information required for their mathematical description exists in the form of ideas or wishes of experts. However, the language of traditional mathematics contains no concepts that would make it possible to

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accurately reflect the fuzziness of their representations. Conventional quantitative methods of system analysis are inherently of little use and ineffective for such systems. This is determined by the incompatibility, consisting in the fact that the more complex the system, the less we are able to give accurate and at the same time practical judgment about its behavior, as applicable to systems whose complexity exceeds a certain threshold, and where accuracy and practical significance become almost mutually exclusive. It is in this sense that an accurate quantitative analysis in real economic, social or other systems associated with human participation does not have the required practical value [1], [2].

The objective nature of presence of uncertainty in specific energy problems implies the use of special methods for their solution, which make it possible to operate with fuzzy categories. The practice of applying the theory of fuzzy sets demonstrates two approaches: the use of fuzzy algorithms for solving problems with uncertainties and the application of previously developed, tested algorithms to fuzzy source data. The first way is most often used for problems where there is a large number of uncertainties of various kinds, the second one is most often used for well-thought-out problems with uncertainty in the form of fuzzy values of parameters and coefficients.

The methods proposed in the article are most applicable to control operation of electric power systems. These methods use to the fullest extent the opportunities and advantages of the direction of mathematics under consideration for modeling uncertain, inaccurate, fuzzy or incomplete data, as well as for obtaining solutions based on such data [3].

Taking into account the above, it is proposed to apply the theory of fuzzy sets to solve the problems of development of power generating companies and their facilities – power plants and power grids. This theory's application provides an opportunity to describe the state and patterns of operation of reviewed object using information in its original form.

At present, there seem to be two approaches for applying the theory of fuzzy sets to energy sector's issues. The first is to generate fuzzy algorithms for obtaining fuzzy solutions based on fuzzy data. The other one is to create a fuzzy topology based on the definition of a fuzzy parameter value and the use of well-known algorithms to find a solution to the problem, which, due to the fuzzy topology, will also be fuzzy. Both of these approaches are intensively used in handling applied problems. As applicable to energy problems, the algorithmic approach is developed in cases where uncertainty leads to new formulations of the problem itself. It should be noted that the tasks of qualitative assessment of the state of a system and the choice of competitive development options for a power generating company and, in particular, the power plants, are a striking example of the algorithmic direction of applying the theory of fuzzy sets when the objective is not clearly defined [4], [5].

2 THEORETICAL AND METHODOLOGICAL FOUNDATIONS FOR SOLVING THE PROBLEM OF CHOOSING ALTERNATIVES FOR THE DEVELOPMENT OF ENERGY SYSTEMS IN AN ENVIRONMENT WHERE UNCERTAINTY AND MULTIPLE CRITERIA ARE PRESENT

The topological approach for application of the theory of fuzzy sets is typical for solving problems that have already been successfully solved via deterministic methods, but where systems have now, due to the external environment's changed conditions, acquired uncertainty in the source data and in the mathematical model's formulation. This applies mainly to the tasks of developing electric power systems. The problem's definition does not suffer any major changes, and therefore it is tempting to use the old solution algorithm. The peculiarity lies in the need to take into account the fuzzy values of the source data and of the model's parameters [6], [7].

Further, the basic concepts of the theory of fuzzy sets, main features of topology in terms of determining a fuzzy number and a fuzzy arithmetic operation, theoretical foundations for solving problems of choice and classification with fuzzy source data will be considered, and a model for elaborating a system of decision-making support aimed at increasing the competitiveness of a power generating company will be presented [8].

In order to describe the fuzzy values, it is proposed to use the following exponential membership function (*MF*) with an infinite domain of definition and a limited range of values:

$$\mu(x) = exp[-b(x-c)^2], \tag{1}$$

where b and $\boldsymbol{c}$ are coefficients that determine the degree of fuzziness and the position on the numerical axis.

In order to determine the values of coefficients we used the starting point of the fuzzy boundary ($\mu(a) = 1$) and the width of the significant uncertainty range ($\mu(a \pm d) = \alpha$). In this case, the values of coefficients are determined according to the following expressions:

$$c = \alpha;\ b = -\frac{\ln(\alpha)}{d^2}. \tag{2}$$

The fuzzy value of the parameter can be described using four coefficients: c_L = start of the fuzzy left border; b_L = degree of fussiness of the left border; c_R = start of the fuzzy right border; b_R = degree of fussiness of the right border. The membership function has a single value within the range from the beginning of the left border to the beginning of the right border. Thus, you can write the fuzzy value of any parameter as a sequence of four numbers: $R = \{c_L;\ b_L;\ c_R;\ b_R\}$.

For example, if the fuzzy predicted value of the installed capacity of a power plant is defined by the statement "from 12 to 14 MW with uncertainty margins of five percent", then the coefficients for the alpha level equal to 0.1 ($\boldsymbol{a}$ = 0.1) are defined as follows:

$$c_L = 12;\ b_L = -\frac{\ln 0.1}{(12*0.05)^2} = 6.40;\ c_R = 14;\ b_R = -\frac{\ln 0.1}{(14*0.05)^2} = 4.70. \tag{3}$$

In the case of installed generating capacity of the power plant under consideration, the fuzzy value is written as a sequence of numbers N={12; 6,40; 14; 4,70}.

When solving the problems of choosing a development option and classifying states according to the levels of competitiveness of a power generating company, in most cases, the values of parameters have to be obtained as a certain estimated value based on fuzzy data. In order to perform calculations, it is necessary to determine the arithmetic operations on fuzzy values. In general, these operations are specified as follows:

$$\mu_{A^\circ B}(z) = \sup_{Z=x^\circ y} \{min(\mu_A(x), \mu_B(y))\}, \tag{4}$$

where the ° character defines mapping rules or denotes an operation.

The algorithm for solving the choice problem is based on the following conditions: n alternatives are given, and the choice must be made according to m criteria. In this case, the set of criteria K are clear and finite, and the criterion estimates of alternatives are fuzzy subsets of universal sets of estimates that represent a formalization of fuzzy concepts.

The starting point for solving the choice problem consists in formulating the binary preference relations. In view of the finite number of alternatives, they can be written in the form of a matrix. The maximum degree to which one alternative can be better than another according to the criterion under consideration is an element of such a matrix.

The values of elements of the matrix of fuzzy preference relation are calculated according to the following equation:

$$r_{ij}^k = \sup_{x,y \in X} \left[min\{\mu_i^k(x), \mu_j^k(y), \mu_R^k(x,y)\} \right], \tag{5}$$

where $\mu_i^k(x), \mu_j^k(y)$ – are membership functions of estimates of alternatives *i* and *j* according to criterion *k*; $\mu_R^k(x,y)$ = value of membership function of preference relation of *k* criterion.

In energy sector's problems, the preference relation is usually a total ordering relation. Then the eqn (5) appears as:

$$r_{ij}^k = \sup_{\substack{x,y \in X \\ x \geq y}} \left[min\{\mu_i^k(x), \mu_j^k(y)\} \right]. \tag{6}$$

According to this equation, the value of an element of the matrix of a binary preference relation is defined as the maximum degree under which alternative *i* can be better than alternative *j*. It follows from this that if the abscissa of the beginning of the right fuzzy boundary of the *i* alternative is greater than or equal to the abscissa of the beginning of the left fuzzy boundary of the *j* alternative $(c_{iR} \geq c_{jR})$, then the value of the element of the binary preference relation is equal to one ($r_{ij} = 1$). In other cases, the value of the element of the matrix of binary preference relation is defined as the ordinate of the intersection point of membership functions of alternatives. This is shown graphically in Fig. 1.

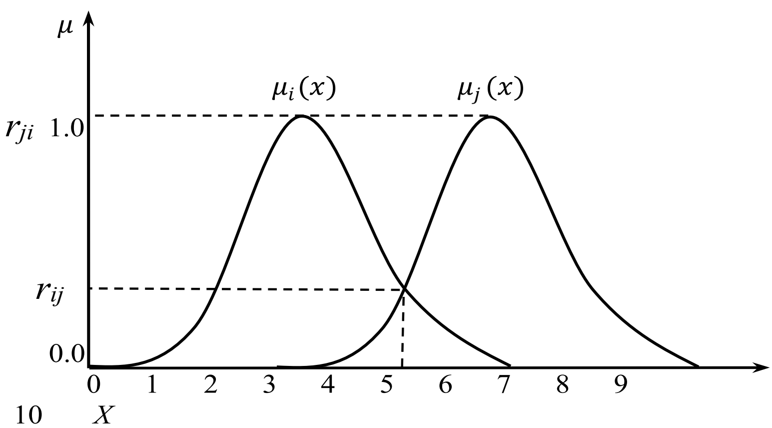

Figure 1: Graphical interpretation of definition of value of an element of a binary preference relation.

Based on this, the rules for calculating the values of an element of the binary preference relation matrix have been developed:

$$r_{ij} = \begin{cases} 1, if\ c_{iR} \geq c_{jR}; \\ \exp\left(-b_{iR} b_{jL} \frac{(c_{jL} - c_{iR})^2}{b_{jL} + b_{iR} + 2\sqrt{b_{jL} b_{iR}}}\right), if\ c_{iR} < c_{jR.} \end{cases} \tag{7}$$

Their use enables one to obtain matrices of fuzzy preference relations for all criteria.

Further, an algorithm consisting of four stages for selecting a rational alternative is proposed:

1. Based on the initial binary preference relations, fuzzy relations F and Q, which determine the set of effective alternatives and the ranking of alternatives in this set, are elaborated, taking into account the importance of respective criteria:

$$\mu_F(x,y) = \min\{\mu_i(x,y), \dots, \mu_m(x,y)\}, \tag{8}$$

$$\mu_Q(x,y) = \sum_{i=1}^{m} \lambda_j \mu_j(x,y). \tag{9}$$

2. These relations are used to define the fuzzy subsets of non-dominated alternatives:

$$\mu_F^{UD}(x) = 1 - \sup_{y \in X}[\mu_F(y,x) - \mu_F(x,y)], \tag{10}$$

$$\mu_Q^{UD}(x) = 1 - \sup_{y \in X}\left[\mu_Q(y,x) - \mu_Q(x,y)\right], \tag{11}$$

3. The degree of non-dominance of each alternative as an intersection of the sets $\mu_F^{UD}(x)$ and $\mu_Q^{UD}(x)$ is found:

$$\mu_F^{UD}(x) = \min\left\{\mu_F^{UD}(x), \mu_Q^{UD}(x)\right\}, \tag{12}$$

4. The alternatives with the greatest degree of non-dominance are considered as rational.

With the help of the proposed methodological approach it was possible to solve a number of practical decision-making problems pertaining to the increase of competitiveness of power generating companies and their facilities (power plants) when only fuzzy source data is available.

3 RESEARCH OF COMPETITIVE APPROACHES TO THE RE-EQUIPMENT OF POWER PLANTS

Due to no new power plants being commissioned and to the steady deterioration of existing power generating facilities in Russia, the relevance of re-equipment of thermal power plants keeps rising.

The concept of “re-equipment” corresponds to a set of measures aimed at increasing the competitiveness of existing electric power facilities. Based on this, the re-equipment of thermal power plants comprises the following measures [9], [10]:

1. Replacement of assemblies and parts of the main and auxiliary equipment that has exhausted its useful life;
2. Replacement of physically worn-out or obsolete equipment with new units;
3. Changes in the heat grid of thermal power plants;
4. Upgrading of thermal power plants to higher steam parameters;
5. Recycling of energy resources corresponding to redundant parameters;
6. Conversion of condensation power plants or individual turbines to heating mode;
7. Conversion of electric power equipment to a mode that manages the daily and weekly schedules of electrical loads;
8. Conversion of power plants to combustion of non-standard fuels;
9. Environmental protection measures such as replacement or installation of flue gas or wastewater treatment facilities, installation of higher chimneys, disposal of industrial waste, etc.

10. Replacement of existing or implementation of new means of mechanization and automation;
11. Special measures to improve the labor and safety conditions.

The structuring of these types of re-equipment was carried out according to the targeting of activities and the nature of work performed at the electric power facility. The following principal tasks were identified at the time of analyzing the targeting of measures aimed at re-equipment of thermal power plants:

1. Extension of the service life of electric power equipment;
2. Increase in production capacity and in production of energy products – electrical and thermal energy;
3. Significant improvement of principal system parameters – stability of parallel operation, etc.;
4. Improving the efficiency of the use of energy, labor and material resources;
5. Improving the efficiency of environmental protection and safety of facilities;
6. Diversification of production, mainly based on recycling of industrial waste (waste heat, ash and slag residues)
7. Enhancement of efficiency of investment processes in a self-financing environment;
8. Improving the social efficiency of the electric power industry (employment growth, personnel training, etc.).

It should be noted that only the upper layer is highlighted in the process of this structuring of goals. Down the line, it became necessary to conduct a more detailed analysis of the "tree" of goals, leading to a set of indicators for a quantitative assessment of alternative options and to generation of a system of performance criteria. Table 1 shows the correspondence of re-equipment types to the goals.

Table 1: Structuring of re-equipment types to the goals.

Types of re-equipment	Targeting of activities							
	1	2	3	4	5	6	7	8
1. Replacement of components and assemblies	+	–	+	–	–	–	+	+
2. Installation of new equipment	+	+	+	+	+	–	+	+
3. Heat grid change	–	+	–	+	+	–	+	+
4. Conversion to enhanced steam parameters	–	+	–	+	–	–	+	+
5. Recycling of energy resources	–	–	–	+	–	+	+	+
6. Conversion to heating mode	–	+	–	+	+	–	+	+
7. Conversion to the load following mode	–	–	+	–	–	–	+	–
8. Conversion to a different fuel type	–	–	–	+	+	–	–	+
9. Environmental activities	–	–	–	–	+	+	–	–
10. Mechanization and automation	–	–	+	+	–	–	–	+
11. Labor conditions improvement	–	–	–	+	–	–	–	+

Note: The goal of re-equipment is defined as: 1 = extension of service life; 2 = increase of energy production; 3 = improvement of system parameters; 4 = improving the efficiency of resource use; 5 = improving the efficiency of environmental protection; 6 = diversification of production; 7 = increasing the efficiency of investments; 8 = increasing social efficiency.

In the process of generalizing the possible approaches to re-equipment, three competing options for restoring the capacity of power plants were identified, which are subject to consideration at the stage of pre-design engineering:

1. Extending the service life of electric power facilities by upgrading auxiliary and main power equipment with replacement of physically worn out elements, mainly operating in areas experiencing high temperatures and high pressure.
2. Replacement of existing equipment with new units while maintaining the previous standard sizes.
3. The same is based on new energy generation technologies (environmental, energy and resource saving).

A multi-criteria analysis of these re-equipment options was implemented on the basis of the example of a coal-fired condensing power station with an installed capacity of 2,000 MW composed of four power plants with a single plant capacity of 500 MW (C-500-240). Construction of a new power station of the same type was accepted as a general alternative to re-equipment (Option 4).

The comparison of options under consideration was carried out according to the three “synthetic” criteria – energy, economy and environment criteria – each of which was presented in the form of sets of particular criteria (subcriteria) (Table 2). Multicriteria analysis employs as its source data the quantitative estimates assumed for the subcriteria being considered. Possible intervals of ambiguity of these estimates were taken into account.

Calculations were made for various combinations of weighting factors in the range of 0 to 1 with a step of 0.25. The results of the multicriteria analysis are given in Table 3.

Table 2: Parameters of criteria system for analysis of power plants re-equipment options.

Criteria	Subcriteria
1. Energy	1.1. Specific reference fuel consumption
	1.2. Availability coefficient
	1.3. Facility service life
	1.4. Average annual electricity generation during the initial operation period (15 years)
2. Environment	2.1. Specific atmosphere emissions of hazardous substances
	2.1.1. Nitrogen oxides
	2.1.2. Sulfur oxides
	2.1.3. Ashes
	2.2. Need for land assets
3. Economy	3.1. Relative capital investment
	3.2. Multiplicity factor of investment cycle
	3.3. Integrated economic benefit (net present value)
	3.4. Integrated costs

Subject to a relatively wide range of weighted estimates by groups of criteria (0.25–0.5), which includes the case of equivalence of these groups (all weights are equal to 1/3), the most competitive option is a power plant’s re-equipment based on new electricity generation technologies (Option 3). The same option has the highest degree of non-dominance in comparison to other alternatives in terms of energy and environmental criteria (with their weights equal to 1). Under these conditions, a new condensing power plant’s construction is the second most preferable option (Option 4). The lower rank of the latter, as the analysis shows, is due to: according to the energy criterion – significantly lower volumes of electricity

Table 3: Results of a multi-criteria analysis of re-equipment options.

Weights of criteria, %			Estimates of non-domination			
1. Energy	2. Environment	3. Economy	Option 1	Option 2	Option 3	Option 4
0.0	50.0	50.0	0.75	0.70	1.0	0.70
25.0	37.0	37.0	0.79	0.75	1.0	0.77
50.0	25	25.0	0.77	0.76	1.0	0.84
75.0	12.5	12.5	0.74	0.78	1.0	0.91
100.0	0.0	0.0	0.71	0.80	1.0	0.98
50.0	50.0	0.0	0.58	0.65	1.0	0.87
37.0	37.0	25.0	0.74	0.73	1.0	0.81
25.0	25.0	50.0	0.87	0.80	1.0	0.75
12.5	12.5	75.0	1.0	0.85	0.99	0.69
0.0	0.0	100.0	1.0	0.75	0.86	0.50
50.0	0.0	50.0	0.93	0.88	1.0	0.79
37.0	25.0	37.0	0.82	0.78	1.0	0.80
25.0	50.0	25.0	0.65	0.69	1.0	0.78
12.5	75.0	12.5	0.45	0.59	1.0	0.77
0.0	100.0	0.0	0.25	0.50	1.0	0.75

generation at the initial stage (due to an increase in the time of energy construction) and according to the environmental criterion – the need for an additional land acquisition for a new power plant. With an increased weight of the economic criterion (from 0.75 to 1.0), the option of extending the power plant's service life (Option 1), which has more favorable investment parameters, becomes more competitive.

Thus, according to the results of the multicriteria analysis, options for extending the service life of energy facilities by upgrading equipment (Option 1) and replacing existing equipment with new units based on new technologies (Option 2) fall into the zone of higher competitiveness.

4 CONCLUSION

As a result of the research, a software package for multicriteria analysis of options for the development of an electric power system with fuzzy source data was developed. This complex implements the possibilities of using the mathematical apparatus of the fuzzy sets theory for solving problems of choosing from a finite set of alternatives according to a finite number of criteria.

1. Four practical tasks for the development of the electric power system were solved. When solving them, the broad possibilities of applying multicriteria analysis algorithms in a fuzzy information environment to various aspects of the development problem have been demonstrated.
2. Solving the problem of choosing a competitive option for the technical re-equipment of coal-fired condensing power plants has shown the effectiveness of the option providing for the introduction of new technologies at the sites of old power plants. With limited investment resources, the most preferable option is to extend the service life of existing equipment.

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3. The information obtained will be useful to the management of power generating companies in the process of making decisions on optimizing resources and using competitive advantages by improving the structure of generating capacities of power plants.

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