METHODOLOGICAL APPROACH TO CHOOSING ALTERNATIVES FOR THE DEVELOPMENT OF ENERGY SYSTEMS IN CONDITIONS OF UNCERTAINTY AND MULTI-CRITERIA

A. DOMNIKOV, M. KHODOROVSKY & L. DOMNIKOVA
Academic Department of Banking and Investment Management, Ural Federal University named after the First President of Russia B.N. Yeltsin, Russia.

ABSTRACT

Power engineering is one of the most dynamic industries in the modern world; it applies specific production and management technologies and also assumes a complex structural transformation of power systems and transition of power engineering business to a qualitatively new level providing sustainable power supply. Within the context of existing situation, the electric power industry, which is currently actively developing, is an important element of power infrastructure that requires a long-term and continuous solution of the challenges the industry faces. These are the circumstances of the development of methodological tools and decision-making procedures based on multi-criteria analysis, since the tasks of developing energy systems in modern conditions represent the most typical class of tasks where the problem of taking into account multi-criteria and uncertainty is most acute. The purpose of the study is to develop methods for the formation and comparison of options for the development of electric power systems in conditions of uncertainty and multi-criteria. The use of fuzzy set reporting models and new decision-making procedures based on fuzzy relations are proposed to address the development challenges. When addressing them, a considerable room for applying multi-criteria analysis algorithms to various aspects of the problem of power systems development in the fuzzy information environment was demonstrated. The results of the study are presented in the form of an analysis of the rational concentration of power plant capacities, which made it possible to identify the most effective way to reduce the plant's installed capacity while increasing the role of environmental criteria.

Keywords: competition, ecology, efficiency, fuzzy sets, mathematical economic models, power industry, reliability, strategy, uncertainty.

1 INTRODUCTION

In the modern sense, energy systems are defined as open systems designed to involve extraction, production, transformation (processing), transportation, storage and distribution of energy resources and energy carriers, and supply these products to consumers. Such systems comprise interconnected parts: fuel supply (by type of fuel), heat supply, and electricity supply.

Energy systems should function in accordance with the concept of sustainable development, which appears in the process of combining three main points of view: economic, social, and environmental. It implies the adoption of measures aimed at the optimal use of limited resources and the use of environmentally friendly, nature-, energy-, and material-saving technologies, maintaining the stability of social and cultural systems, as well as ensuring the integrity of biological and physical natural systems.

In accordance with the subject of ongoing research, the results obtained in the development of energy systems in conditions of uncertainty and multi-criteria will be most consistent with the following sustainable development goals that were adopted at the UN General Assembly (2015): (1) Goal 7: Affordable and clean energy (SDG 7 is to "Ensure access to affordable, reliable, sustainable and modern energy for all") and (2) Goal 9: Industry,

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Innovation and Infrastructure (SDG 9 is to "Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation") [1–3].

The new conditions for the development of energy systems revealed a significant limitation of the available methods of system research, which were mainly focused on the stable and predictable development of the global economy. The situation in the world is dynamic, it is therefore necessary to solve non-standard tasks with many unknowns and to respond to challenges in which the factor of uncertainty is large. The priority of the study is strategic forecasting of the development of energy systems, and such an analysis should be realistic, objective, based on reliable information and the widest range of reliable sources of information.

Currently, the operation of energy systems can be characterized by a significant increase in the uncertainty of the operating conditions and development goals; this uncertainty is associated with changes taking place in the global economy towards sustainable development. The issues of energy systems development include a broad scope of tasks, which, in one way or another, may be formulated as the state classification and rational options selection tasks. Provision of high-power systems reliability, in essence a mathematical formulation, is a task of pattern recognition [4, 5]. In real life, energy problems that do not contain uncertainties are rather a rare exception than the rule [6]. Most often, the following types of uncertainties are recognized: uncertainty of goals, uncertainty of nature (conditions for development or operation), and uncertainty of actions of decision-making subjects. That is why, the uncertainty of goals in power industry is related to their unclear wording or with the multi-purpose situation. Whereas, the uncertainty of situation reflects the level of information insufficiency on the object of interest and its environment, as well as non-existence of a definitive knowledge for the forecasted period.

Special fuzzy mathematical methods based on fuzzy set theory are well suited to adequately describe the uncertainties. This theory was suggested by Zadeh [6–8] and was designed specifically to represent uncertain concepts, analysis, and modelling of systems in which humans are involved. The essential difference between uncertainty and randomness leads to the fact that mathematical fuzzy set methods are absolutely different from probability theory methods [6]. They are simpler in many respects because the notion of a probability measure in the probability theory corresponds to the simpler notion of a membership function in the fuzzy sets theory [7].

In the field of power systems development, the choice is extremely diverse both formally and in terms of contents. Therefore, their solution methods also vary. There is a number of approaches to the selection process: criterial description of choice, choice description based on binary relation, group choice description, as well as choice description as optimal management task solution.

Based on the above, it seems possible to apply the fuzzy set theory methods for description of uncertainties and development of assessment methods for conditions and development options for power systems with the purpose of improving their reliability and environmental performance.

Methods are proposed for determining the results of operations on fuzzy parameter values, as well as for determining the choice tasks using fuzzy values of criterial assessments of the finite set of alternatives and classification with fuzzy description of classes and values of condition indicators. At present, there seem to be two approaches for applying the theory of fuzzy sets to the issues of power sector. The first one is about generating fuzzy algorithms for obtaining fuzzy solutions based on fuzzy data. The other one is about creating a fuzzy topology based on the definition of a fuzzy parameter value and the use of well-known algorithms for finding a solution to the problem, which, due to the fuzzy topology, will also be fuzzy [8, 9]. Both of these approaches are intensively used in handling applied problems. As applicable to power problems, the algorithmic approach is developed in cases where uncertainty leads to new formulations of the problem itself. The tasks of qualitative assessment of the system conditions and the choice of development options for power systems and power plants are a perfect example of the algorithmic trend in applying the theory of fuzzy sets when the objective is not clearly formulated. Thus, the presence of various types of uncertainties may be noted as their main distinctive feature.

The topological approach in applying the fuzzy sets theory is typical for solving problems that already were successfully solved with the use of deterministic approaches, but due to the changed conditions of external environment, have currently acquired uncertainty in the source data and in the mathematical model formulation. This applies mainly to the problems of power systems development. Since the problem statement does not undergo any major changes, it is therefore attractive to apply a solution algorithm specifically focused on accounting of fuzzy values in the input information and in the model parameters [6, 10].

Thus, the main goal of the study is to develop methods for the formation and comparison of options for the development of electric power systems and other energy systems interacting with them and their facilities, primarily power plants, under conditions of uncertainty and multi-criteria.

2 METHODOLOGICAL ASPECTS OF MULTI-CRITERIA ANALYSIS OF POWER SYSTEMS IN FUZZY ENVIRONMENT

The objective nature of the 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 fuzzy sets theory demonstrates two approaches: the use of fuzzy algorithms for solving problems with uncertainties and the application of previously developed and tested algorithms to fuzzy source data. The first approach is more often used for the problems with a large number of various uncertainties, the second one – for elaborated problems with an uncertainty in the form of fuzzy parameters and coefficients values.

The starting point for solving the choice problem consists in formulating the binary preference relations. In view of the finite number of alternatives, these relations 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 [11–13].

The values of elements of the matrix of fuzzy preference relation are calculated according to the following formula [10, 12]:

$$r_{ij}^{k} = \sup_{x,y \in X} \left[min\left\{ \mu_i^k(x), \mu_j^k(y), \mu_R^k(x,y) \right\} \right], \tag{1}$$

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

In decision-making problems on the development of energy systems, the preference relation is usually a non-strict order relation [12]. Then, eqn (1) appears as follows:

$$r_{ij}^{k} = \sup_{\substack{x,y \in X \\ x \geq y}} \left[min\left\{ \mu_i^k(x), \mu_j^k(y) \right\} \right] \tag{2}$$

According to this formula, 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.

The point of intersection of membership functions is determined from the condition $\mu_i(x) = \mu_j(x)$, which, for the accepted form of writing a fuzzy value, corresponds to the equation:

$$\exp\left(-b_{iR}\left(x - c_{iR}\right)^2\right) = \exp\left(-b_{jL}\left(x - c_{jL}\right)^2\right). \quad (3)$$

This equation is converted to the standard form of a quadratic equation as follows:

$$(b_{iR} - b_{jL})x^2 + 2(b_{jL}c_{jL} - b_{iR}c_{iR})x + (b_{iR}c_{iR}{}^2 - b_{iL}c_{iL}{}^2) = 0. \quad (4)$$

To solve a quadratic equation, it is necessary to find its discriminant:

$$D = 4b_{jL}b_{iR}\left(c_{jL} - c_{iR}\right)^2. \quad (5)$$

Then the root of the discriminant of the quadratic equation will be equal to $\sqrt{D} = 2\left(c_{jL} - c_{iR}\right)\sqrt{b_{jL}b_{iR}}$, and the solution will be written as follows:

$$x_{1,2} = \frac{-\left(b_{jL}c_{jL} - b_{iR}c_{iR}\right) \pm \left(c_{jL} - c_{iR}\right)\sqrt{b_{jL}b_{iR}}}{b_{iR} - b_{jL}}. \quad (6)$$

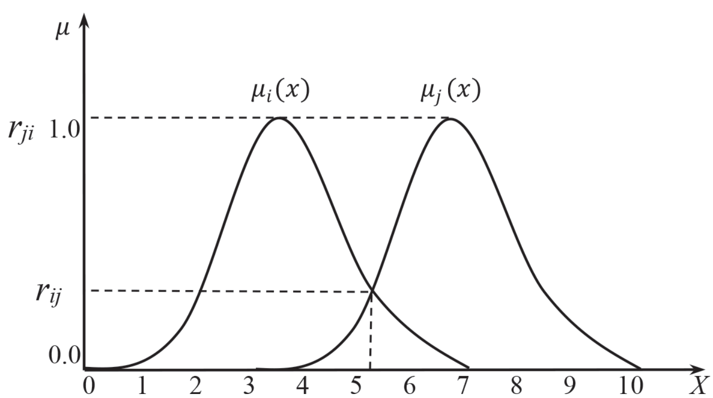

Figure 1: Graphical interpretation of definition of value of an element of a binary preference relation [12].

By substituting this expression into the left side of eqn (3), the value of the matrix element of the binary preference relation is determined, which is written as follows:

$$r_{ij} = \exp\left(-b_{iR}\left(\frac{-\left(b_{jL}c_{jL} - b_{iR}c_{iR}\right) \pm \left(c_{jL} - c_{iR}\right)\sqrt{b_{jL}b_{iR}}}{b_{iR} - b_{jL}} - c_{iR} \right)^2 \right). \tag{7}$$

As a result of a number of transformations, the right-hand side of eqn (7) is converted to:

$$r_{ij} = \exp\left(-b_{iR}b_{jL}\,\frac{(c_{jL} - c_{iR}{}^2}{b_{jL} + b_{iR} \pm 2\sqrt{b_{jL}b_{jR}}} \right). \tag{8}$$

The resulting expression contains sign uncertainty. The analysis shows that the '-' sign corresponds to the intersection of the membership functions outside the required interval from C_{iR} to C_{iL}, and the '+' sign gives the necessary solution for estimating the value of the binary preference relation matrix element. Thus, the required expression can be written as follows:

$$r_{ij} = \exp\left(-b_{iR}b_{jL}\,\frac{(c_{jL} - c_{iR}{}^2}{b_{jL} + b_{iR} + 2\sqrt{b_{jL}b_{jR}}} \right). \tag{9}$$

As a result, the rule for calculating the binary preference relation is obtained:

$$r_{ij} = \begin{cases} 1, c_{iR} \geq c_{jL} \\ \exp\left(-b_{iR}b_{jL}\,\dfrac{(c_{jL} - c_{iR})^2}{b_{jL} + b_{iR} + 2\sqrt{b_{jL}b_{jR}}} \right), c_{iR} < c_{jL}. \end{cases} \tag{10}$$

Thus, matrices of fuzzy preference relations for all criteria can be obtained:

$$R^k = \begin{vmatrix} 1 & r_{12}^k & \dots & r_{1n}^k \\ r_{21}^k & 1 & \dots & r_{2n}^k \\ \dots & \dots & \dots & \dots \\ r_{1n}^k & r_{n2}^k & \dots & 1 \end{vmatrix}, k = \overline{1, m}. \tag{11}$$

Based on these relations, it is possible to derive scores of non-dominance of the alternatives under consideration.

In view of the above, and using the decision support system in the conditions of uncertainty, developed by the authors for selecting a rational alternative, it is appropriate to use an algorithm, consisting of the following stages [12]:

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 derived, taking into account the importance of respective criteria:

$$\mu_F\left(x, y\right) = \min\left\{\mu_i\left(x, y\right), \dots, \mu_m\left(x, y\right)\right\}, \tag{12}$$

$$\mu_Q(x,y) = \sum_{i=1}^{m} \lambda_j \mu_j(x,y), \tag{13}$$

where λ_j is the assessment of importance of criterion j, $\lambda_j \in [0, 1]$.

2. The fuzzy subsets of non-dominated (*UD*) alternatives in the said sets are defined:

$$\mu_F^{UD}(x) = 1 - \sup_{y \in X}\left[\mu_F(y,x) - \mu_F(x,y)\right], \tag{14}$$

$$\mu_Q^{UD}(x) = 1 - \sup_{y \in X}\left[\mu_Q(y,x) - \mu_Q(x,y)\right]. \tag{15}$$

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

$$\mu_F^{UD}(x) = \min\left\{\mu_F^{UD}(x), \mu_Q^{UD}(x)\right\}. \tag{16}$$

4. Selection of alternatives from the set is assumed as rational:

$$X^{UD} = \left\{\mu^{UD}(x) = \sup_{x' \in X}\left[\mu^{UD}(x')\right]\right\}. \tag{17}$$

Thus, the solution for a problem will be an alternative with the maximal degree of non-dominance. The set problem was solved under the condition that the criteria are of different importance.

After calculating the binary preference relation under both criteria, the intersections of these binary preference relationships *F* and the weighted sum *Q* were determined; this allowed determining the options' non-dominance values [12, 14].

With the help of the developed approach of multi-criteria analysis in fuzzy environment, it became possible to solve a practical task for solving the problem of choosing an option for the development of big power plants.

3 VALIDATION OF RATIONAL POWER PLANTS CAPACITIES CONCENTRATION

Concentration of generating capacities in power systems is of determining importance for the problems related with ecology and investment attractiveness of energy companies; furthermore, their solution shows the rational way of solving the issues of power systems development. It is worth mentioning that the influence of regional factors on structural and technical policy in the development of electrical power systems and power-generating companies is largely evident in the rationale for concentration of electro-generating capacities [5, 15]. The rational levels of electric power plants capacity concentration depend both on the conditions of formation and development of power systems in connection with fuel and energy complex, that is, increase of the demand for capacity, conditions of fuel provision, implementation of advanced production technologies and electrical energy transfer, systemic reliability, among others, and also on the regional factors related to provision of environmental safety and social acceptability of the electric power objects [4, 16, 17].

Out of many problems of decision making related to the development of power systems, the following ones have been considered:

- validation of rational concentration of generating capacities;
- ranking of the points for possible construction of a heating power plant in accordance with ecological criteria;

- taxonomy of the points for possible construction of a heating power plant, taking into account environmental criteria;
- comparison of the technical re-equipment options for a heating power plant;
- ranking of energy supply directions.

These problems were studied using the software developed by the authors for multicriteria analysis in a fuzzy environment and in accordance with the methodological approach presented in Section 2. It is based on the method of selecting from a finite set of alternatives on a finite number of criteria [12].

Four levels of concentration of electro-generating capacity were identified as a result of the task analysis. The first level corresponds to the aggregate capacity concentration, that is, the unit capacity of the power units installed in power plants [5, 18–20]. The second one is related to the power plant concentration, that is, the unit capacity of power plants. The third level shows the capacity concentration conditions within geographic locations (within a radius up to 10–50 km). It is obvious that, in an electro-generating system, such zones belong to separate power hubs. Therefore, this concentration level is called a local level. Finally, the fourth concentration level reflects the conditions of power plants placement within relatively big territorial zones (within a radius of 50–100 km and more).

The multi-criteria analysis of electro-generating capacities concentration was held for the third (local) level, as the interaction of the above-mentioned systematic and regional factors is most obvious on this level [14]. According to the logic of the study, the multi-criteria analysis should be preceded by formation of external conditions for electricity sector development, development of generalized models of electricity generation and transmission indicators, and creation of a simulation model of the spatial structure [21–23].

The multi-criteria analysis of alternative options for capacities' concentration was carried out in relation to fossil-fuel electric power plants on the basis of classical approaches [24] using the methodological tools developed based on the theory of fuzzy sets and described in Section 2.

Coal-fired power plants with units of 400 and 800 MW were taken as the object of the study. Six alternatives for the installed capacity of this type of heat power plant, ranging from 1.6 to 13.6 GW, have been considered. At that, a cluster of power plants, that is, two plants built within the same geographical area, is modelled with a capacity of more than 6.4 GW.

The comparative effectiveness of these options was correlated according to four criteria:

- the dynamic specific fixed costs of electricity generation and distribution (criterion 1);
- specific needs in land resources for electric power plants (criterion 2);
- specific number of industrial and production personnel (criterion 3);
- damage from environmental pollution (criterion 4).

The initial values of the alternatives scores according to the considered criteria are given in Table 1, where γ is an indicator that depends on the local conditions of the power plant construction zone (population density, values of agricultural and forest land, among others) and ranges from 0.5 to 1.5, according to expert opinion.

The uncertainty range of the economic criterion scores is assumed to be based on the above-mentioned developments (taking into account the variation in the densities of incremental generation capacity demand). For criteria 2 and 3, the scores' uncertainty is considered within a 5% interval, while for criterion 4, because of the greater diversity of influencing factors, the uncertainty interval is assumed to be 10%.

Calculation of estimates of non-dominance of alternative options for the concentration of power-generating capacities was performed using a multi-criteria analysis program in a fuzzy environment. During the calculation, the weight estimates of each of the criteria varied in the range from 0 to 1 (1 means the most significant criterion).

Table 2 presents the results of multi-criteria analysis based on three main rated conditions: 1 – at equipoise of criteria; 2 – at increase of weight under criterion 4; 3 – at averaging of non-dominant alternatives values within the whole range of value judgments for criteria. Herewith, the extent of the environmental damage model indicator values were additionally

Table 1: The characteristics of energy-generating capacities alternative concentration options.

Option	Power of an electric power plant, GW	Average score by criteria					
		1	2	3	4		
		Unit costs, $/kW	Land capacity, ha/MW	Personnel coefficient, person/MW	Environmental friendliness, r.u.		
					$\gamma = 0.5$	$\gamma = 1.1$	$\gamma = 1.5$
1	1.6	175.3	0.532	0.76	1.27	1.69	2.01
2	4.0	187.6	0.435	0.51	2.05	4.58	8.02
3	6.4	173.1	0.354	0.47	2.55	7.72	16.18
4	8.8	189.8	0.327	0.45	2.99	10.95	26.12
5	11.2	191.7	0.314	0.42	3.36	14.28	37.47
6	13.6	197.3	0.364	0.39	3.67	17.64	50.14

Table 2: Scores of the non-dominant alternatives for the concentration of electricity-generation capacities.

Option	Power of an electric power plant, GW	Design conditions								
		1			2			3		
		$\gamma = 0.5$	$\gamma = 1.1$	$\gamma = 1.5$	$\gamma = 0.5$	$\gamma = 1.1$	$\gamma = 1.5$	$\gamma = 0.5$	$\gamma = 1.1$	$\gamma = 1.5$
1	1.6	1.000	1.000	1.000	1.000	1.000	1.000	0.785	0.827	0.783
2	4.0	0.932	0.932	0.932	0.748	0.748	0.748	0.623	0.643	0.623
3	6.4	1.000	1.000	1.000	0.831	0.831	0.831	0.778	0.838	0.787
4	8.8	0.255	0.000	0.000	0.255	0.000	0.000	0.223	0.000	0.000
5	11.2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	13.6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

varied for each of the rated conditions. The most rational alternative from the set is the one that has the maximum degree of non-dominance.

As follows from the analysis of the obtained results, if the criterion weights are equal (condition 1), the range of effective solutions in terms of non-dominant capacity concentration is between 1.6 and 6.4 GW. For the observed increase in the weight of the environmental damage criterion (condition 2), the option with a reduced power concentration (1.6 GW) becomes the most efficient one, and when averaging the indicators over the whole interval of weight scores, then the option of a HPP (Heat power plant) with the capacity of 6.4 GW takes the advantage. The influence of choosing the environmental model type in the considered values interval turned out to be insignificant.

The comparative effectiveness of these options was determined under four criteria: (1) dynamic specific fixed costs for generation and distribution of electric power; (2) specific needs in land resources for location of electric power stations; (3) specific production personnel number; and (4) environmental damage from pollution. The comparative scores have shown that when the criterion weights are equal, the options with capacities concentration between 1.6 GW and 6.4 GW fall into the efficient range, and when the environmental effects criterion weight is increased, the option with a lower capacity concentration (1.6 GW) becomes the most efficient.

4 CONCLUSIONS

The use of the developed methodological approach for multi-criteria analysis with the application of mathematical apparatus of fuzzy sets theory made it possible to carry out the analysis of rational concentration of electric power plants capacities, which allowed identification of the most effective option for decreasing a plant capacity when the role of environmental criteria grows. If economic, social, and environmental criteria are of equal importance, then a power plant with higher installed capacity is the most efficient option. Placing several power plants, a so-called ‘power plant cluster’, within the same geographical location does not give sufficient effect for all the variations in the importance of criteria. Thus, the results obtained showed the relevance of the task of multi-criteria zoning, which is related to the fact that the territory of an electric power system is characterized by a great diversity of conditions. These conditions, as a rule, are described by a complex of engineering and geographical factors, among which the environmental factors are of the highest interest. This is explained by the fact that the conditions included in it are in their essence the environmental criteria for selecting the rational locations for placement of electric power plants. This raises the prospective task of differentiating the territory in terms of conditions for power plants construction, first and foremost, in terms of environmental conditions, and identifying the most favorable areas for power plants construction in terms of such conditions.

In further research based on the suggested approach, it is envisaged to study the problem of the influence of management decisions in the development of energy-generating companies on reliability of power systems including the renewable energy sources. Determining the capacity share of renewable sources and selecting their type based on the multi-criteria approach will be of the greatest interest in research on the reliability of such combined power systems.

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REFERENCES

[1] Berg, C., *Sustainable action: overcoming the barriers*. Routledge studies in sustainability: London, 2019. https://doi.org/10.4324/9780429060786

[2] EIB Group Climate Bank Roadmap 2021–2025. *European Investment Bank*, 2020. https://doi.org/10.2867/503343

[3] Horton, S., Financing the sustainable development goals. *Achieving the Sustainable Development Goals*, Routledge: London, pp. 206–225, 2019. https://doi.org/10.4324/9780429029622

[4] Bhattacharyya, S. C., Energy data and energy balance. *Energy Economics*, Springer Verlag: London, 2011. https://doi.org/10.1007/978-0-85729-268-1

[5] Calderóna, C., Underwood, C., Yi, J., Mcloughlin, A. & Williams, B., An area-based modelling approach for planning heating electrification. *Energy Policy*, **131**, pp. 262–280, 2019. https://doi.org/10.1016/j.enpol.2019.04.023

[6] Zadeh, L., Fuzzy sets. *Information and Control*, **8(3)**, pp. 338–353, 1965. https://doi.org/10.1016/s0019-9958(65)90241-x

[7] Zadeh, L., Fuzzy logic – A personal perspective. *Fuzzy Sets and System*, **281**, pp. 4–20, 2015. https://doi.org/10.1016/j.fss.2015.05.009

[8] Zadeh, L., *The Concept of a Linguistic Variable and its Application to Approximate Reasoning*. American Elsever Publishing Company: New York, 1973.

[9] Seising, R., Pioneers of vagueness, haziness and fuzziness in the 20th century. Forging New Frontiers: Fuzzy Pioneers, eds. M. Nikravesh, J. Kacprzyk, & L. Zadeh, *Studies in Fuzziness and Soft Computing*. Springer: Berlin-Heidelberg, pp. 55–81, 2007. https://doi.org/10.1007/978-3-540-73182-5_4

[10] Wang, X., Ruan, D. & Kerre, E., *Mathematics of Fuzziness - Basic Issues*. Springer-Verlag: Berlin-Heidelberg, 2009.

[11] Domnikov, A., Khodorovsky, M. & Domnikova, L., Methodological approach to the research of energy cogeneration systems operational reliability indicators. *International Journal of Energy Production and Management*, **6(3)**, pp. 263–276, 2021. https://doi.org/10.2495/EQ-V6-N3-263-276

[12] Domnikov, A., Khodorovsky, M. & Domnikova, L., Decision support system used to improve the competitiveness of a power generating company under conditions of uncertainty. *WIT Transactions on Ecology and the Environment*, **254**, pp. 15–23, 2021. https://doi.org/10.2495/ESUS210021

[13] Jardine, N. & Sibson, R., *Mathematical Taxonomy*. John Wiley and Sons: London, 1971.

[14] Domnikov, A., Khodorovsky, M. & Domnikova, L., Identification and classification of the states of cogeneration systems by competitiveness levels of power generating companies. *WIT Transactions on Ecology and the Environment*, **254**, pp. 25–32, 2021. https://doi.org/10.2495/ESUS210031

[15] Rada, E. C., Ragazzi, M., Torretta, V., Castagna, G., Adami, L. & Cioca, L. I., Circular economy and waste to energy. *AIP Conference Proceedings*, **1968(1)**, p. 030050, 2018. https://doi.org/10.1063/1.5039237

[16] Goldbach, K., Rotaru, A., Reichert, S., Stiff, G. & Gölz, S., Which digital energy services improve energy efficiency? A multi-criteria investigation with European experts. *Energy Pol*icy, **115**, pp. 239–248, 2018. https://doi.org/10.1016/j.enpol.2017.12.036

[17] Johnstone, P. & Kivimaa, P., Multiple dimensions of disruption, energy transitions and industrial policy. *Energy Research & Social Science*, **37**, pp. 260–265, 2018. https://doi.org/10.1016/j.erss.2017.10.027

[18] Manusov, V. & Ahyoev, J., Technical diagnostics of electric equipment with the use of fuzzy logic models. *Applied Mechanics and Materials*, **792**, pp. 324–329, 2015. https://doi.org/10.4028/www.scientifc.net/amm.792.324

[19] Saaty, T., Relative measurement and its generalization in decision making why pairwise comparisions are central in mathematics for the measurement of intangible factors the analytic hierarchy/network process. *Revista de la Real Academia de Ciencias Exactas, Fisicas y Naturales*, **102**, pp. 251–318, 2008. https://doi.org/10.1007/bf03191825

[20] Scholten, D. & Künneke, R., Towards the comprehensive design of energy infrastructures. *Sustainability*, **8(12)**, pp. 1291–1295, 2016. https://doi.org/10.3390/su8121291

[21] Lombardi, P. & Schwabe, F., Sharing economy as a new business model for energy storage systems. *Applied Energy*, **188**, pp. 485–496, 2017. https://doi.org/10.1016/j.apenergy.2016.12.016

[22] McInerney, C. & Bunn, D., Expansion of the investor base for the energy transition. *Energy Policy*, **129**, pp. 1240–1244, 2019. https://doi.org/10.1016/j.enpol.2019.03.035

[23] Xu, Y., Yang, K., Zhou, J. & Zhao, G., Coal-biomass co-firing power generation technology: current status, challenges and policy implications. *Sustainability*, **12**, 3692, 2020. https://doi:10.3390/su12093692

[24] Celikyilmaz, A., Kacprzyk, J. & Türksen, I., Modeling uncertainty with fuzzy logic. with recent theory and applications. *Studies in Fuzziness and Soft Computing*. Springer: Berlin, Heidelberg, 2009.