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Two-step procedure for multi-criteria choice of generating-capacity structure in remote areas

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Abstract. The paper dwells upon the problem of multi-criteria choice of ways to develop generating capacities to supply power to remote consumers. We herein propose a two-step multi-criteria analysis method: choosing promising power-generation technology first, and then specifying the generating-capacity structure. The paper describes the structure of the proposed multi-criteria methods: the interval TOPSIS method for Step 1; for Step 2, an upgraded analytic hierarchy process based on identifying the structure of the decision maker's preferences. We demonstrate the use of this method with evidence from the Penzhinsky District, Kamchatka Krai. Thermal power plants, hydroelectric power plants, diesel power plants, as well as solar and wind power are analyzed as power sources. Step 1 includes: analyzing the potential power-supply loads in a specific area; formulating alternative power-generation technology; formulating goals and criteria; criterion-based evaluation of alternative options using objective and subjective models; multi-criteria evaluation of alternatives; analyzing the sensitivity of results and the selection of promising technology. Step 2 includes: formulating goals and criteria on the basis of the selected power-generation technologies; formulating the available alternatives; criterion-based evaluation of alternatives; multi-criteria evaluation and final decision-making.

1 Introduction

Supplying power to remote consumers in North-Eastern Russia is still a problem. Remote areas have scattered power sources and an underdeveloped infrastructure in general [1]. When analyzing the development of such areas, one has to assess the feasibility of establishing local power grids using local fuels and renewable energy [2, 3, 4]. Today, there exist multiple different methods for the structural optimization of generating capacities; these methods are based on analyzing techno-economic factors alone [5, 6]. However, comprehensive evaluation reveals various impacts that the available alternatives might bring, which is why multi-criteria analysis of power infrastructure and its development in such areas is imperative.

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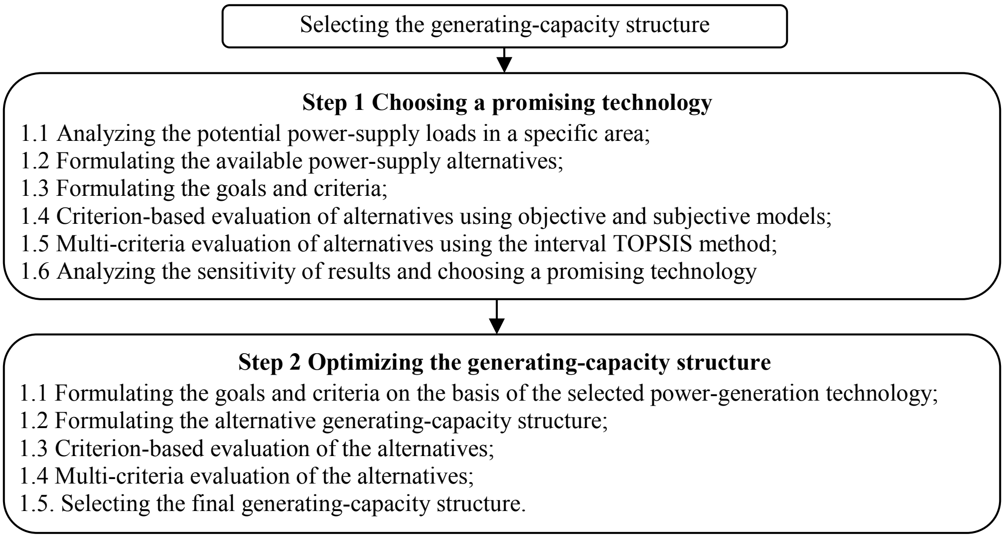
2 Two-step procedures for selecting the generating-capacity structure in remote areas

To solve the problem, we herein propose a two-step procedure for multi-criteria analysis of the structural development of generating capacities; Fig. 1 presents the main points of the procedure.



Selecting the generating-capacity structure

Step 1 Choosing a promising technology

1.1 Analyzing the potential power-supply loads in a specific area;
1.2 Formulating the available power-supply alternatives;
1.3 Formulating the goals and criteria;
1.4 Criterion-based evaluation of alternatives using objective and subjective models;
1.5 Multi-criteria evaluation of alternatives using the interval TOPSIS method;
1.6 Analyzing the sensitivity of results and choosing a promising technology

Step 2 Optimizing the generating-capacity structure

1.1 Formulating the goals and criteria on the basis of the selected power-generation technology;
1.2 Formulating the alternative generating-capacity structure;
1.3 Criterion-based evaluation of the alternatives;
1.4 Multi-criteria evaluation of the alternatives;
1.5. Selecting the final generating-capacity structure.

Fig. 1. Two-step generating-capacity selection procedure: the structure

Step 1 (Fig. 1) included the collection of the necessary data on a power-supply location and its primary power consumers (as planned); multi-criteria assessment of the primary power-generation technologies that can ensure reliable power supply to such consumers. Step1 was first targeted at selecting the best power-generation technology for future use. Step 2 included detailed multi-criteria evaluation of the selected technologies as well as finalizing the generating-capacity structure.

3 Multi-criteria evaluation methods for choosing promising power-generation technologies

For Step-1 multi-criteria evaluation (Fig. 1), we chose such well-known method as the interval TOPSIS method. For Step 2, we chose a modified Analytic Hierarchy Process (AHP).

3.1 TOPSIS

Dealing with uncertainty in the input data and the decision-maker's preferences, we decided to use the interval TOPSIS method.

The method includes the following steps [7]:

- formulating a set of alternatives and criteria;
- vector normalization of data by intervals and weights;
- finding the best and the worst inter-alternative borders;
- finding each alternative's distance to the best and the worst border;
- finding the best alternative.

The method is essentially about recognizing such object as the best alternative that minimizes the distance from the best alternative (by the aggregate of all criteria) and maximizes the distance from the worst alternative [8, 9, 10].

To that end, calculate the total distance D^+_i from each alternative to the best solution; and the total distance D^-_i to the worst solution:

$$D_j^+ = \sqrt{\sum_{i=1}^{I} (\upsilon_{ij}^L - A_i^+)^2 + \sum_{i=1}^{J} (\upsilon_{ij}^U - A_i^+)^2}$$
$$D_j^- = \sqrt{\sum_{i=1}^{I} (\upsilon_{ij}^U - A_i^-)^2 + \sum_{i=1}^{J} (\upsilon_{ij}^L - A_i^-)^2} \qquad (1)$$

Where $\upsilon_{ij}^L, \upsilon_{ij}^U$ are the evaluation criteria in the upper and the lower boundaries of the interval evaluation that include the normalized alternative evaluations and criterion weights; A_i^+, A_i^- are the best- and the worst-alternative levels; I is the set of indices of the parameters to maximize; J is the set of indices of the parameters to minimize.

The assessment criterion C^*_i is calculated as:

$$C_j^* = \frac{D_j^-}{D_j^+ + D_j^-} \quad (j = 1,2,...,n) \quad (0 \le C_j^* \le 1) \qquad (2)$$

Its advantages are as follows: option to configure interval estimates; minimum number of queries to the decision maker; quantitative multi-criteria evaluation of alternatives; using two measures for evaluation of alternatives; simple and easy to use for the decision maker.

3.2 Modified Analytic Hierarchy Process

The original AHP uses pairwise-comparison matrices based on a pairwise-comparison scale so as to evaluate the decision-maker's preferences, see Table 1.

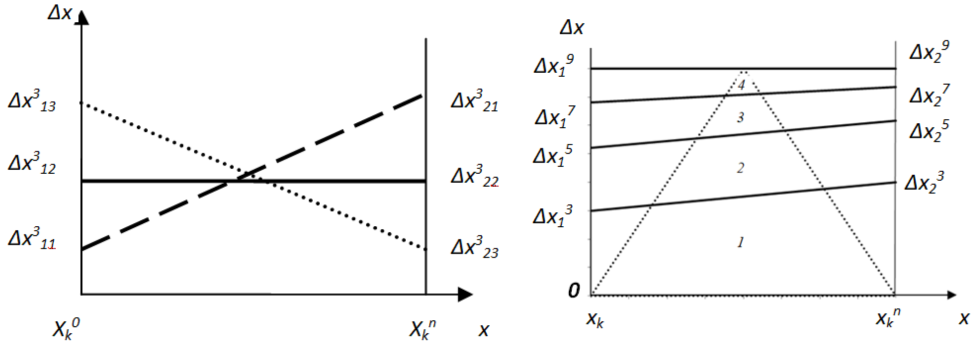
Table 1. Pairwise-comparison scale

Relative importance	Score
Equal importance	1
Moderate importance	3
Strong importance	5
Demonstrated importance	7
Extreme importance	9

Solving a problem with multiple alternatives makes this step quite difficult.

This is why we decided to use an author-modified Analytic Hierarchy Process (AHP) for Step 2, see Figure 1. The structure and upgrades of this method are presented in papers [11, 12]. Upgrades are essentially about identifying the decision-maker's preferences while taking into account the uncertainty caused by the small number of queries to the decision-maker.

To that end, we propose creating a dialog where the decision-maker could help find Level 3 Moderate Importance as a function of criterion-based evaluations, see Fig. 2a. The Figure shows relative-importance evaluations as a function the alterations in the estimates Δx within the estimate range from x_k^0 to x_k^n by the criterion. The dialog is then used to generate the decision-maker's criterion-based preference structure for the pairs of alternatives, see Fig. 2b. The Figure shows the areas that, hitting which the alternatives to compare are scored accordingly, see Table 1.



a b

Fig. 2. Decision-maker's perception of Level 3 Moderate Importance and probable structure of the decision-maker's preferences with respect to the paired alternatives

This enables automated filling of the pairwise-comparison matrices by interpolation. Further steps follow the original AHP.

For practical use, the above model for generating-capacity selection is proposed for tests with evidence from a remote consumer located in the village of Kamenskoye, Kamchatka Krai.

4 Choosing the generating-capacity structure for the Penzhisnky District, Kamchatka Krai

4.1 Selecting the best power-generation technology for future use

4.1.1 Analyzing the potential power-supply loads in the area; formulating the power-supply options, goals, and criteria

For Step 1, one must select the best ways to supply power. To that end, potential power-supply loads specific to the area are analyzed using data from territorial-planning and construction-site charts, as well as mineral-deposit maps [13, 14].

In our case, power-supply load amounted to 100 MW as calculated using data on similar enterprises located in the same region. The following potential power sources were analyzed: thermal power plants (TPP), hydroelectric power plants (HPP), diesel power plants (DPP), solar farms (SF) and wind farms (WF).

Step1 is targeted at selecting the best power-generation technology for future use. Our analysis employed the following criteria: net present value (NPV); required area; environmental impact (hazardous atmospheric emissions, waste generation, biological impact on the ecosystem); social factors (popular attitude to any specific technology, health damage, occupational mortality risks); technological efficiency (maneuverability of, and sufficiency of resources for, the plant). When evaluating the technologies herein proposed for social and biological factors, we used subjective models and expert opinions.

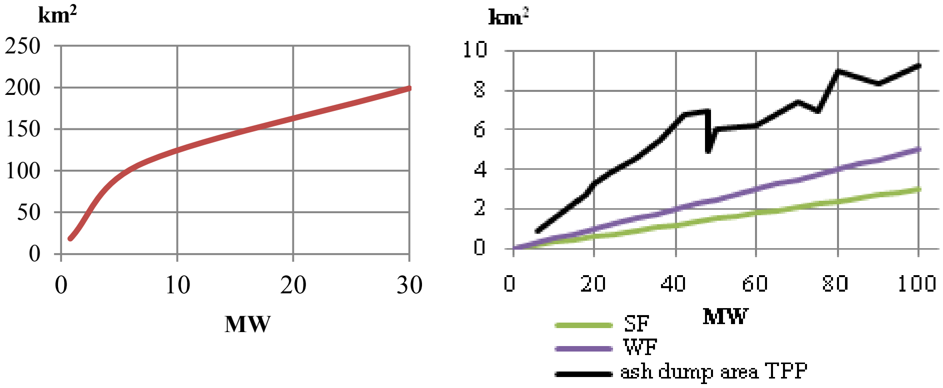
4.1.2 Analysis of land areas required for various power-generation technologies

When evaluating the possible construction of an HPP, we estimated the hydrological potential of the Penzhina River and its tributaries [15]. The Belaya River was selected as the construction site.

Our hydroelectric power calculations were done in the following steps:

1. Find the reservoir-surface area as a function of the reservoir water level.
2. Find the minimum required "dead" reservoir volume.
3. Calculated the minimum necessary water flow to the turbines during low-water years for each alternative normal head-water level of the dam.
4. Calculate the minimum annual HPP productivity rates taking into account the redistribution of runoffs over the year for each alternative normal head-water level of the dam.

Fig. 3a presents the calculated required land areas as a function of the plant capacity.



a b

Fig. 3. Flooding area HPP and land area required for TPP, WF, SF as a function of plant capacity

The area required for WF and SF was calculated on the basis of specific land-intensity rates: 0.001 to 0.006 ha/kW for solar farms; 0.01 ha for wind farms [16]. TPP ash-pond areas are within 0.07 ha/TOE of fuel consumed. Figure 3b shows the land areas required for 25 years of TPP/WF/SF operation as a function of capacity.

4.1.3 Sufficiency of energy resources

Our evaluation of resource sufficiency was based on the wind-speed re-occurrence rates as measured by metrological stations (readings available at rp5.ru); we only took into account such wind speeds that enable consistent wind-farm operation. For SF analysis, we took into account the sunshine periods throughout the year. Table 2 presents the overall evaluations.

Table 2. Sufficiency of solar and wind-power resources

Solar power potential			Wind-power potential		
Period under consideration, h	Duration of sunshine per annum	Rating	Total measurements	Wind exceeding 3 m/s	Rating
8,760	4,488	0.51	22,795	9,993	0.43

4.1.4 Multicriteria analysis of technologies by the TOPSIS method.

When carrying out criterion-based evaluation of alternatives by means of objective and subjective models, the values shown in Table 3 were obtained for further multi-criteria analysis.

Table 3. Criterion-based comparison of alternatives per 1 kW of installed capacity

X	K_1 NPV, RUB	K_2 (Land area required, m^2)	K_3 (Environmental impact)	K_4 (Social factors)	K_5 (Technological efficiency)
TPP	98,529 to 121,279	92 to 165	1	3	4
WF	2,000 to 47,500	50 to 100	4	4	2
HPP	465,000 to 562,500	6,633 to 6,633	3	4	5
SF	28,725 to 96,975	10 to 60	5	5	2
DPP	-799,103 to (-799,643)	0	2	2	5

TOPSIS interval method returned the following results, see Table 4.

Table 4. Final evaluation of alternatives by means of the multi-criteria TOPSIS method

HPP	TPP	SF	WF	DPP
0.737862	0.643679	0.634865	0.606192	0.341608

According to Table 4, technologies were ranked as follows: HPP > TPP > SF. Therefore, these three alternatives were assumed for further analysis. WF and DPP were thus excluded.

4.2 Specifying the generating-capacity structure for the most precise description of the impacts of selected power-generation technologies

Step 2 included a more detailed goal and criterion hierarchy based on the specific conjunction of the selected technology types. For this case, the following subcriteria were proposed for HPP/TPP/SF technologies, see Fig. 4.

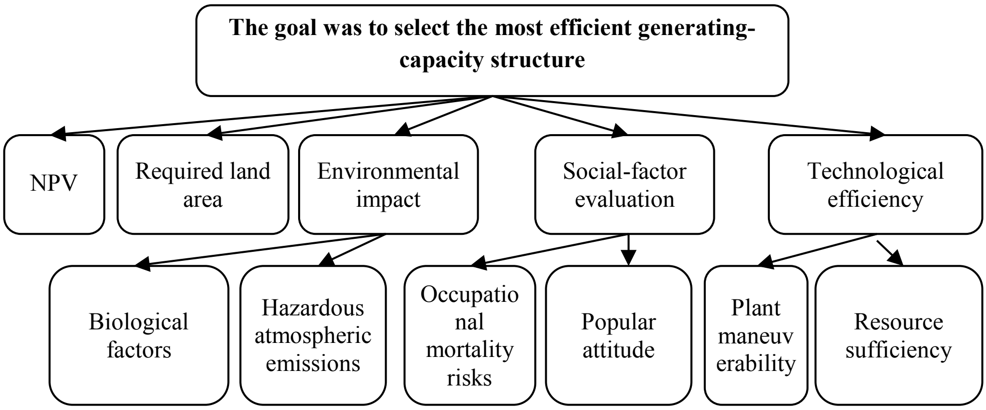


Fig. 4. Specified hierarchy of goals and criteria for the selected technologies

Given these criteria, the alternatives were evaluated as follows, see Table 5.

Table 5. Criterion-based evaluation of the alternatives

	NPV, RUB	Land area required, m^2	Emissions, t/year	Biological impact
Per 1 kW of installed capacity				
TPP	109,904	128.5	9,737	4
HPP	513,750	6,633	0	9
SF	62,850	35	0	2
	Occupational mortality risks	Popular attitude (10-point scoring scale)	Reliability (resource sufficiency)	Maneuverability
Per 1 kW of installed capacity				
TPP	7	4	0.9	3
HPP	4	3	1	10
SF	2	9	0.51	1

We further carried out multi-criteria evaluation by the upgraded analytic hiearchy process. We formulated the set of alternatives given the specific conjunction of various power-generation technologies. Given that there were numerous alternatives, they were pre-selected. As a result, the best solution was found in a limited set of alternatives, see Table 6.

Table 6. Final set of alternatives for finding the best solution

			K_1	K_2	K_3		K_4		K_5		RANK
					K_{31}	K_{32}	K_{41}	K_{42}	K_{51}	K_{52}	
TPP	HPP	SF									
MW											
70	30	0	8.43	652.055	5.5	6,815.9	6.1	3.3	5.1	0.93	0.146597
65	30	5	8.20	652.52	5.4	6,329.05	5.85	3.4	5	0.9105	0.114781
60	30	10	7.96	652.99	5.3	5,842.2	5.6	3.5	4.9	0.891	0.097724
55	30	15	7.72	653.45	5.2	5,355.35	5.35	3.6	4.8	0.8715	0.084648
80	20	0	9.28	651.52	5	7,789.6	6.4	3.2	4.4	0.92	0.095357
75	20	5	9.05	651.98	4.9	7,302.75	6.15	3.3	4.3	0.9005	0.074165
70	15	20	9.32	685.64	4.55	6,815.9	5.9	3.7	3.8	0.882	0.099734
90	10	0	10.13	650.98	4.5	8,763.3	6.7	3.1	3.7	0.91	0.09493
80	10	10	9.66	651.92	4.3	7,789.6	6.2	3.3	3.5	0.871	0.064077
100	0	0	10.9904	650.45	4	9,737	7	3	3	0.9	0.127987

The analysis and ranking of alternatives by modified analytic hierarchy process returned the following final generating-capacity ranks:

Rank #1: 70-MW TPP, 30-MW HPP, rank = 0.146
Rank #2: 100-MW TPP, rank = 0.127
Rank #3: 65-MW TPP, 30-MW HPP, 5-MW SF, rank = 0.114

Analysis of results shows that when taking into account environmental and social criteria, an HPP is a better power source than a TPP; however, its capacity is limited by the economically justified land-area requirement. When taking into account the technological efficiency, which is crucial for the decision maker in this case, solar farms are worse than HPP or TPP. In such cases, the best option is the alternative of HPP and TPP.

5 Implications

Thus, this paper presents the following:

– A two-step methodology for multi-criteria analysis of generating-capacity structure for remote areas;

– Multi-criteria analysis methods for both steps, using which minimizes the number of queries to the decision-maker while allowing to take into account the input uncertainty;

– A modified analytic hierarchy procedure to minimize the number of Step-2 queries to the decision-maker;

– Goal and criteria hierarchies, baseline models for the evaluation of alternatives;

– A test of the proposed method in the case of selecting a generating-capacity structure for the Penzhinsky District, Kamchatka Krai.

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