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The new investing effectiveness evaluation multi-criteria method in modern energy supply systems

Nowa wielokryterialna metoda oceny efektywności inwestowania w nowoczesnych systemach energetycznych

Waldemar Kamrat*)

Key words: *Decision making; Modelling investment process; Multi-criteria method; Effectiveness evaluation;Renewable energy development; Sustainable energy supply systems.*

Abstract
The important problem in the processes of modelling and programming the development of sustainable energy sector is the multi-criteria manner of assessing the effectiveness of investments. The goal of this paper is to show how to take into account the impact of investments in multidimensional modeling decision-making processes. This goal can be achieved through the development, presentation, and use of a new multi-criteria method of evaluating the effectiveness of investing towards to modern renewable energy sector. This innovative method was developed and tested in research for the energy sector carried out by the author. Method consist of a relatively simple way of taking into account the qualitative features of the criteria in the process of evaluating investments in the energy sector. Using the real data of the energy invested in the city of X in Poland, the effectiveness of the project was examined applying the multi-criteria method proposed by the author, and for the same purpose, the well-known ELECTRE method was used. The comparison of the results of the investment effectiveness studies by both methods confirmed the high convergence of the effects obtained in both methods. The achieved results of research very high effectiveness of the analyzed renewable energy technologies.

Słowa kluczowe: *Podejmowanie decyzji; Modelowanie procesu inwestycyjnego; Metoda wielokryterialna; Ocena efektywności; Rozwój energii odnawialnej; Zrównoważone systemy dostaw energii.*

Streszczenie
Istotnym problemem w procesach modelowania i programowania rozwoju sektora energii zrównoważonej jest wielokryterialny sposób oceny efektywności inwestycji. Celem artykułu jest pokazanie, jak uwzględnić wpływ inwestycji w wielowymiarowym modelowaniu procesów decyzyjnych. Cel ten można osiągnąć poprzez opracowanie, prezentację i zastosowanie nowej, wielokryterialnej metody oceny efektywności inwestycji w nowoczesnym sektorze energetyki odnawialnej. Ta innowacyjna metoda została opracowana i sprawdzona w badaniach dla sektora energetycznego prowadzonych przez autora. Metoda polega na stosunkowo prostym sposobie uwzględnienia cech jakościowych kryteriów w procesie oceny inwestycji w energetyce. Wykorzystując rzeczywiste dane dotyczące energii zainwestowanej w mieście X w Polsce, zbadano efektywność projektu, stosując zaproponowaną przez autora metodę wielokryterialną i w tym samym celu wykorzystano znaną metodę ELECTRE. Porównanie wyników badań efektywności inwestycji obiema metodami potwierdziło wysoką zbieżność efektów uzyskanych obiema metodami. Uzyskane wyniki badań bardzo wysokiej efektywności analizowanych technologii energetyki odnawialnej.

1. Introduction

In market economy conditions, in most cases, an analysis of investment effectiveness must now focus on answers to two questions: will investment cost-effectiveness be assured (will the expected profit meet investment expenditure and additional exploitation costs), and will the investment be environmentally friendly. A precise, wide, multi-aspectual technological and economic analysis must be connected with a great number of calculations and the knowledge of various parameters. It must be based on databases regarding particular investment strategies. Therefore, in most economically developed countries, complex computer programs based on mathematical models are used to conduct such analyses. The modeling of multidimensional research on investments or the modernization towards modern sustainable energy systems is a dynamic development field. Its worldwide development is associated with e.g., new norms defining the maximum permissible levels of pollution in the environment. A great number of available technologies for reducing emissions and their various costs result in the necessity of conducting multi-variant studies and analyses to find rational solutions. All these reasons and the development of computer technology have contributed to using methods and computer programs that aid multivariate analyses. In general, the evaluation of the effectiveness of investing towards energy transition should be based on a multiparameter and multivariate analysis, taking into account diverse conditions of execution and exploitation. Whereas technological reasons beyond the expected (projected) level of energy demand are objective, economic situations, however, being of dynamic nature, have a significant impact on the risk and uncertainty of investing in the power energy sector. We must therefore seek such methods that are able to meet modern market demands. In an investment process, the decision-maker usually has to confront a situation in which there is a couple of opposite (discordant) objectives e.g., profit maximization or

* **Waldemar Kamrat** is a full professor at Gdansk University of Technology. His areas of interests are investment effectiveness in the energy sector, risk evaluation, local market development and energy planning. Member of the Committee on Energy Problems Board of the Polish Academy of Sciences, International Association of Energy Economic – Vice president of Polish branch (Polish association of energy economics).

minimization of total direct costs. The essence of a multi-dimensional decision problem lies in the fact that individual investment projects can be evaluated from different viewpoints, using both quantitative and qualitative criteria. The final choice, however, should be in terms of quantity, which means that the decision-maker has to receive answers on which projects are effective from the point of view of different aspects. All multidimensional methods of effectiveness estimation are in general strongly formalized and frequently require mathematical apparatus for which special software is needed. This group comprises appealing application methods for assessing the effectiveness of an investment in power engineering, such as:

- nonparametric boundary estimation,
- hierarchic problem analysis,
- artificial neural networks,
- multi-criteria ranking methods.

These methods, via the decision maker's preference modeling, allow taking into account various decision situations, including risk and investment uncertainty. The methods mentioned above are described in detail in the available literature. In the recent 30 years, the results of many scientific studies in the field of modeling processes in the power industry have been carried out and presented. These were various works, both of a fundamental nature, scientific articles, as well as other studies and analyzes. In these works, various aspects of methods and techniques of multi-criteria analysis, modeling methods, and techniques of multi--criteria analysis were presented. This concerned, among others, such problems as the use of fuzzy set elements to model decisions in planning processes [1],[8],[19],[;numerical taxonomy [15]; artificial intelligence methods[32]; DEA methods[6],[18], [25]; AHP methods[23],[26];ELECTRE methods[2],[17];or the methods of multivariate comparative analysis [9],[20], [31]. Other works, for example [24] describe the use of the Geographic Information System and multi-criteria decision-making methods in the assessment of the location of solar farms. On the other hand, ranking methods such as the hybrid multi-criteria method of analyzing the location of dispersed renewable sources[28], environmental management problems for wind farms and models of multi-purpose investment optimization taking into account costs and environmental impacts[30], and the modeling development issues in energy systems are presented in papers [3],[4],[7],[10],[21],[27],[29]. Reference [16] shows an interesting approach to making decisions in planning the expansion of the power system. It presents an insight into various multiple criteria decision making (MCDM) techniques and progress made by considering renewable energy applications over MCDM methods. Very important researches and studies regarding modeling tools for power systems are presented in the paper [22]. Reference [22] shows a lengthy review of modeling tools for energy systems with large shares of variable renewables, where it describes a thorough review of 75 tools currently used for analyzing sustainable energy systems. Updated and validated key information about the used models is presented. Finally, the author of this paper also contributed to the issues of decision modeling by conducting research on the application of elements of multivariate analysis [11],[12],[13],[14]. In the author's opinion, in the investment evaluation processes, the final choice of a rational investment option should be made on the basis of multi-criteria analysis, as the decision-maker (investor) should understand which projects are effective in terms of many aspects and desired features. It should be noted that the term "investment strategy" should refer both to the construction of a new power plant producing energy, modernization of an existing one, or application of highly-efficient modern technologies and systems of electricity transmission. The introduction of new energy technologies and modernization of existing production facilities or transmission systems require the implementation of a decision-making process based on a variety of partial criteria taking into account various categories e.g., economic, technical, technological, realization, and other. The entire decision-making process is also dependent on the nature of limiting factors: resources, demand, supply, comparability of energy production and transmission technologies. The author proposes a new multi-criteria method of evaluating the effectiveness of investing in a modern energy sector. This innovative method was developed and tested in research for the energy sector carried out by the author. It is effective for planners, analysts, and decision-makers in energy development planning processes.

2.Method essence and basic methodological assumptions

In general, it is assumed that there is a partial criteria set for the evaluation of an investment:
$D = \{dj\}$, where : dj – denotes jth evaluation criterion for j = $1, 2, ..., k$; k-number of criteria.

In order to introduce individual criteria, one needs to eliminate the impact of various characteristic which may alter/modify the true validity priority, being an adverse phenomenon to be reduced with the aid of weight coefficients λj.

The easy manner of defining weight coefficients λj is a method of relative informative value comprising the variability coefficient of number realization of the jth criterion of the ith investment strategy. In this respect the weight of the λj criterion is designated as follows:

$$\lambda_j = \frac{v_j}{\sum_{j=1}^{k} v_j}, \tag{1}$$

where:

$$v_j = \frac{s_j}{\bar{x}_j}$$

whereas sj was the standard deviation of the jth criterion calculated from the following formula:

$$s_j = \left[\frac{1}{k} \sum_{j=1}^{k} (x_{ij} - \bar{x}_j)^2 \right]^{\frac{1}{2}} \tag{2}$$

x_{ij} – number realization of the j^{th} criterion of the i^{th} investment strategy ($i = 1,2, ... , t$),

$\bar{x}_j$ mean values of the jth criterion calculated from the formula:

$$\bar{x}_j = \frac{1}{k} \sum_{j=1}^{k} x_{ij} \tag{3}$$

Since

$$\sum_{j=1}^{k} v_{ij} = 1$$

and $\lambda_j > 0$, thus λ_j may be interpreted as weights defining an informative value of features-criteria.

Besides the weight normalizing condition:

$$\sum_{j=1}^{k} \lambda_j = 1 \tag{4}$$

it is deduced that they can be interpreted as validity rates of respective criteria.

An interesting attempt to formalize the process of weighting appears to be the application of the logic of the fuzzy set. The concept of fuzziness means that an object (component) may have a degree of affiliation between the total membership and non-membership to the set of feasible solutions. In the case of a particular criterion, the membership is substituted by its utility, expressed as a number from the range <0,1>. The means to determine weights of respective partial criteria depend on an expert decision, under the general condition that the sum of the weight coefficients is one. Based on professional experience, an expert usually determines change ranges of weight coefficients, guided by the principle that the most important is economic criteria (range 0,3 ÷ 0,4), technical criteria (range 0,2 ÷ 0,4), and automation criteria (range 0,1 ÷ 0,3). In multi-criteria evaluation methods, partial criteria may be quantifiable or unquantifiable. Should we deal with unquantifiable criteria (quality), one needs to define their corresponding quantities. There is a principal assumption that quality differences are the derivative of quantity differences, thus quality features can be defined via quantitative features.

In the case when in set **D** = {*dj*} we have a subset of unquantifiable criteria, these must be subject to order operation, which is based on a subjective analysis. This yields rank-order scales. In each case, quantifiable scales for quantifiable criteria and rank-order scales for non-quantifiable ones need to be constructed. One must realize that any rank order or an order t of a component set of variants of activities $X_i \in \boldsymbol{X}$ ($i = 1, 2, ..., t$) as well as assigning evaluation $\{d_j\}$, weight vectors $\{w_j\}$ and preferences $\{p_i\}$ are always prone to subjective errors.

For simplified procedures of taking account of preference criteria, regression analysis seems worthy. A qualitative trait has only two variants (0, 1), and acts as a discrete dependent variable. Regression characteristics thus obtained are the quantitative equivalent of the qualitative criterion (non-measurable). After assigning respective values {0, 1} to highlighted quality criteria, they may be treated as if they were measurable criteria (quantitative).

For example for criteria d_1 i d_2 of a common scale (defining unsatisfactory and satisfactory states), one may correspondingly assign numbers 0, 1.

Each evaluated element according to criteria d_1 and d_2 should be on the aforementioned scale. Each element d_1 i d_2 thus corresponds to feasible state sets d_1 and d_2.

Let $\boldsymbol{B} = \{b_i\}$, $i = 1,2,..., t$ be t^{th} an element finite set that represents feasible investment projects. Thus, for a sample evaluation of an element $b \in \boldsymbol{B}$ via criteria d_1 and d_2 one can state that elements br are part of the Cartesian product $d_1 \times d_2$. To generalize this case for k criteria one can state that each element br is part of the Cartesian product $d_1 \times d_2 \times$ …x dk.

The mapping of an element set i.e. set of investment strategy projects in a criterion d_j ($j = 1, 2,..., k$), with the aid of function gj according to the following formula:

allows determining the defined graph G_j:

$$\boldsymbol{B} \xrightarrow{g_j} \boldsymbol{d}_j \tag{5}$$

$$\boldsymbol{G}_j = (B, U_j) \text{ dla } j = 1,...,k \tag{6}$$

whereas:

$$< b_r; b_s > \in U_j \equiv [g_j(b_r) \geq g_j(b_s)], \quad for \quad r \neq s;\ r,s = 1, 2, ..., t \tag{7}$$

The effect of the mapping of a set ***B*** into a criterion dj is thus the type G_j graph. For a project, for each j^{th} criterion there is a corresponding graph G_j.

The comparing of t elements from the point of view of *k* criteria, equivalent to putting a given element br in the Cartesian product $d_1 \times d_2 \times ...x\ d_k$, has been decomposed into *k* independent mappings described by the function g_j. All elements $b_r \in \boldsymbol{B}$ are thus compared and evaluated according to the jth criterion, followed by a criterion *(j + 1)*, *(j + 2)* up to the depletion of the k numbers of criteria. Since an element br evaluated according to particular criteria can take different places on a scale, the final general evaluation should be rendered on the basis of a synthetic evaluation measure for all criteria.

A. 3. Investment effectiveness evaluation measure

An important issue that accompanies the construction of a synthetic measure of assessing investment effectiveness is the choice of feasible investment strategies through formal analysis, and the defining of the k-element set of features-criteria, which facilitate the assessment of the considered projects.

Defining initial databases in the range of energy demand, realization conditions, scope, and financing as well as planned investments are all essential topics. In the initial phase, an observation matrix is constructed $X^o = [x^o_{ij}]$, in which number realizations xoij of investment strategies characterized by the jth feature-criterion (measurable character) are written down, satisfying the condition:

$$x^o \geq 0 \tag{8}$$

where: $i = 1, 2, ..., t$; $j = 1, 2, ..., k$.

The obtained matrix $X^o = [x^o_{ij}]$ contains number realizations of quantitative variables expressed in different units. Variables x^o_{ij} do not meet postulates of normalizing formulas and show various preferences concerning stimulating and destimulating specificity for particular partial feature-criteria.

In the next study phase, normalization using appropriate calculus techniques should be performed , with the key issue being the transformation of number realization images of variables x^o_{ij} into the range <0,1>, thus eliminating the impact of various measurement units. The transformation that allows normalizing (unitizing) the investigated features (stimulants S^x, destimulants D^x) may be described by the following dependence:

$$_S x'_{ij} = \frac{_S x_{ij} - \min\limits_i \{_S x_{ij}\}}{\max\limits_i \{_S x_{ij}\} - \min\limits_i \{_S x_{ij}\}}, \tag{9}$$

$$_D x'_{ij} = \frac{_D x_{ij} - \max\limits_i \{_D x_{ij}\}}{\min\limits_i \{_D x_{ij}\} - \max\limits_i \{_D x_{ij}\}}. \tag{10}$$

The abovementioned normalization procedure is applied here, thus forming a normalized matrix $X' = [x'_{ij}]$ and using formulas modifications:

$$_S x'_{ij} = \left(\frac{_S x_{ij} - \min\limits_i \{_S x_{ij}\}}{\max\limits_i \{_S x_{ij}\} - \min\limits_i \{_S x_{ij}\}} \right)^{z_j} \tag{11}$$

$$_D x'_{ij} = \left(\frac{_D x_{ij} - \max\limits_i \{_D x_{ij}\}}{\min\limits_i \{_D x_{ij}\} - \max\limits_i \{_D x_{ij}\}} \right)^{z_j}. \tag{12}$$

where z_j denotes the power index, playing a specific role in the normalization procedure.

The value of the power index shows either equal ($z_j = 1$) or differentiated ($z_j \neq 1$) absolute feature value change in the entire changeability range.

Feature-criteria whose number realizations have different values for investigated investment strategies undergo the normalizing procedures described by formulas:9,10,11,12. In the case when number realizations of the considered strategies are equal for a feature-criterion *j* ($j = 1, 2, ..., k$), there is a natural elimination of this feature, as all the strategies are equally rated from the feature viewpoint. Thus, the obtained partial evaluations practically do not have an impact on global assessment.

To take into account quality phenomena (defined by non-measurable features) in the investment effectiveness evaluation process, one needs to attribute numeral correspondents {0,1} to them, in accordance with the rule described earlier in this work, and add them to the normalized observation matrix $X' = [x'_{ij}]$. The new matrix $X'' = [x''_{ij}]$, called the ordered matrix, contains transformed variables of measurable character (quantity) as well as non-measurable ones (quality).

The matrix $X'' = [x''_{ij}]$ plays a significant role in the study of investment effectiveness evaluation using the suggested methodology. In order to measure the effectiveness rate of an investment strategy evaluated from the k criteria point of view, an evaluation matrix $M = [m_{ij}]$ of dimensions $t \times k$ is formed.

Elements m_{ij} of the evaluation matrix are obtained via attributing an appropriate point rank to an ith investment strategy, evaluated on the basis of substituting jth criterion., The main rule is to obtain the maximum number of points by the strategy of the highest number realization value x''_{ij}.

In order to differentiate between fuzzy evaluations of respective strategies, it is suggested that a procedure of the division of the changeability range of number realization x''_{ij} into subranges of equal span α_v should be applied. Thus, a set A = $\{\alpha_v\}$ is obtained, where v is the number of division methods (v = 1, 2, ..., N) of the changeability range of number realizations x_{ij} into subranges of equal span α_v defined by the formula presented:

$$\alpha_v = 1 \cdot 10^{-v} \quad (13)$$

In this respect, for the defined v^{th} division method, into δ subdivisions of equal span α_v, it is possible to differentiate respective strategies expressed by number realizations on the accuracy level α_v:

$$\underset{x''_{ij} \in \left((\delta-1)\frac{1}{\alpha_v}, \delta\frac{1}{\alpha_v} \right)}{\forall} m_{ij}^{(\alpha_v)} = \delta - 1 \quad \text{where} \quad \delta = 1, 2, \ldots, \frac{1}{\alpha_v}, \quad (14)$$

$$\underset{x''_{ij}=0}{\forall} m_{ij}^{(\alpha_v)} = 0 \quad (15)$$

The formulae show that investment strategies (tasks) whose number realizations are in the same subranges have the point rank (δ = 1), and strategies whose realizations are x''_{ij} = 0 have the point rank 0.

The chief issue is to check whether strategies of different numbers i, i' ($i' \neq i$, i = 1, 2, ... , t) whose point rank differs by 1 are clearly distinguishable on a level α_v using the procedure given below:

$$\underset{j=1,2,\ldots k}{\forall} \left| m_{i'j} - m_{ij} \right| = 1 \cap \left| m_{i'j}'' - m_{ij}'' \right| < \alpha_v \quad (16)$$

Fulfilling the dependence (17) means that one must go to another division method, that is a number v must be attributed a value $v = v+1$.

In order to designate all elements m_{ij} of an evaluation matrix M, the procedures mentioned above should be iterative for partial criteria j (j = 1, 2, ... , k). It can happen that particular strategies for different criteria will be evaluated on various differentiation level α_v.

Thus, one needs to reduce the values of $m_{ij}^{(av)}$ evaluated on the differentiation level α_v, to a given reference base level αb according to the formula given below:

$$m_{ij}^{(\alpha_b)} = \frac{\left(\frac{1}{\alpha_b} - 1 \right)}{\left(\frac{1}{\alpha_v} - 1 \right)} \cdot m_{ij}^{(\alpha_v)} \quad (17)$$

where:
$m_{ij}^{(ab)}$ – evaluation matrix elements brought to a reference base level α_b,
$m_{ij}^{(av)}$ – evaluation matrix elements according to a differentiation level α_v.

In the author's opinion, the most comfortable solution is to reduce matrix elements $m_{ij}^{(av)}$ to the first level α_1, which means that the formula (16) takes the following form:

$$m_{ij}^{(\alpha_1)} = \frac{\left(\frac{1}{\alpha_1} - 1 \right)}{\left(\frac{1}{\alpha_v} - 1 \right)} \cdot m_{ij}^{(\alpha_v)} \quad (18)$$

The denoted elements of the evaluation matrix M form a new ordered evaluation matrix:

$$\boldsymbol{M}^{(\alpha_1)} = \left[m_{ij}^{(\alpha_1)} \right]$$

It is clear to see that in the calculus procedures of evaluation matrix elements, no partial criteria weights have been taken into account so far. Weight coefficients λj which are designated using the procedures described in the previous subchapter, and which satisfy the condition:

$$\sum_{j=1}^{k} \lambda_j = 1$$

are taken into account in the formula for the global sum of $S_i^{(ab)}$ the obtained rank points, by means of the i^{th} strategy (evaluated according to the j partial criteria on the level $^{\alpha_b}$ in the following way:

$$S_i^{(\alpha_b)} = \sum_{j=1}^{k} \lambda_j \cdot m_{ij}^{(\alpha_b)} \quad (19)$$

With the denoted sum for the ith investment strategy, one designates a evaluation measure fi according to the formula:

$$f_i = \frac{S_i^{(\alpha_b)}}{S_{\max}^{(\alpha_b)}} \quad (20)$$

where S_{max} is the sum of maximum point ranks (possible to obtain in the procedure of establishing the order of variants through the i^{th} strategy) evaluated according to all k criteria calculated using the formula:

$$S_{\max}^{(\alpha_b)} = \left(\frac{1}{\alpha_b} - 1 \right) \cdot k \quad (21)$$

For the assumed way of bringing the value of the evaluation matrix to the first reference arrangement (α_b=α_1) formulas:19,20,21 take the following form:

$$S_i^{(\alpha_1)} = \sum_{j=1}^{k} \lambda_j \cdot m_{ij}^{(\alpha_1)} \quad (22)$$

$$f_i = \frac{\sum_{j=1}^{k} \lambda_j \cdot m_{ij}^{(\alpha_1)}}{\left(\frac{1}{\alpha_1} - 1 \right) \cdot k} \quad (23)$$

$$S_{\max}^{(\alpha_1)} = \left(\frac{1}{\alpha_1} - 1 \right) \cdot k \quad (24)$$

The positions of individual investment strategies on the synthetic effectiveness scale are of a formal character. It means that evaluation measure values f are relative – strategies are the best in the research class set, not absolutely the best. Nevertheless, it is feasible and advisable to divide an evaluation measure on a synthetic effectiveness scale into a few groups, forming i.e. isospheres of effectiveness dependent on differentiation rate α.

Using the differentiation levels assumed earlier, an effectiveness measure fi may be divided into isospheres with f_i boost. The aforementioned operation allows choosing the best strategy, depending on the desired accuracy scale based on an evaluation measure f_i within the range <0, 1>. The presented procedure implies that investment strategies of high effectiveness take values near 1, whereas those of low – take values near zero.

With such effective evaluation measures at hand, one can easily make a rational choice of an investment decision from the viewpoint of various criteria – economical, environmental, and social. It is particularly important in the case of power engineering development under market conditions.

4. Approach to method application

Generally, section 4th presents the algorithm of investment effectiveness evaluation, issues of sets and initial databases determination, and investment effectiveness evaluation, using the proposed methodology. Finally, achieved results and discussion are presented.

4.1.Algorithm of investment effectiveness evaluation method

A general algorithm of investment effectiveness evaluation according to the author's method is outlined in Fig.1.

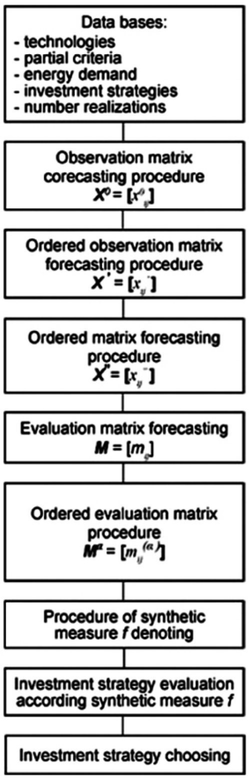

Fig.1. Schematic algorithm of the method for assessing the effectiveness of investment

Ryc.1. Schemat algorytmu metody oceny efektywności inwestycji

For the verification-conceptual purpose, the author's method algorithm (W-1) was applied for investment project evaluation leading to choosing the most effective investment variant for a source of energy generation (this does not exclude using the method in other cases).

The choice made was next compared to the result of the effectiveness evaluation conducted with the aid of the well-known ELECTRE method (W-2).

For comparability reasons, investment effectiveness was studied using the same criteria, under analogically assumed conditions of energy demand and realization of investment venture, based on the same energy technologies.

Moreover, in the ELECTRE method (W-2), which requires arbitral adoption of weight coefficients or the assumption of equivalence of criteria, an analogical approach to the method suggested by the author (W-1) is used. This means that weight coefficients are the same in both methods.

The operation described above allows obtaining the comparability of both methods, the suggested method, and the renowned multi-criteria ELECTRE method, using the same databases on number realizations of investment strategies and partial evaluation criteria.

4.2.Determination of Sets and Initial Databases

In the model research on the evaluation of investment effectiveness (in the sense presented earlier), when the comparability condition was satisfied, specific investment options were analyzed.

These options were chosen from a general set of feasible modern power engineering technologies which are defined in Table 1, on the basis of a formal analysis.

Particular investment strategies are using symbols: ALT01, ALT02, ... , ALT12, in order to best compare model research results obtained by using the author's method (W-1) with those obtained by means of the Electre method (W-2). An analogical principle is applied due to criteria, where the CR denotation is used. In addition, the rule of listing quantity criteria first was applied, followed by quality criteria.

In the model research, number realizations of measurable features: CR01□CR14 of stimulating and destimulating character (a stimulating feature has a positive influence on the investigated phenomenon, contrary to a destimulating feature) were transformed via was applied. previously described unitarization procedures, whereas in the case of quality features: CR15, CR16, CR17 the principle described earlier in this paper was applied.

Table 1. Investment strategies applied in model research

Tabela 1. Strategie inwestycyjne zastosowane w badaniach modelowych

Investment strategy characteristics	Denotation	Specification
Gas turbine power plant	ALT01	with water peak boiler
Cogeneration gas fired plant	ALT02	with water peak boiler
Gas engine blocks	ALT03	gas engines with peak boilers
Modern heating plant	ALT04	high efficiency
Modern coal heating plant	ALT05	with high efficiency boilers
Biomass heating plant	ALT06	reservoir fuel: oil
Solar technology	ALT07	installation for usable water production
Fuel cells	ALT08	high power on natural gas
Technologies applying waste heat or utilized waste	ALT09	heat plant system with a high power heat pump, an engine system with a heat pump, a combined system of energy generation from waste
Geothermal heat plant	ALT10	system for heat generation
Modernization on the supply side	ALT11	chiefly heat network modernization, automation, application of modern technologies and equipment on the supply side
Modernization on the demand side	ALT12	thermo-modernization of housing, recipient installation modernization, using DSM rules

Practically, it means the acceptance of the following realization numbers for quality features: CR15, CR16, CR17:

$$\text{CR15, CR16}: \begin{cases} 0, \text{ when the feature is present,} \\ 1, \text{ when the feature in not present,} \end{cases}$$

$$\text{CR17}: \begin{cases} 0, \text{ when the feature in not present,} \\ 1, \text{ when the feature is present.} \end{cases}$$

Set of feature-partial criteria is outlined in Table 2.

An analysis of investment effectiveness by means of multi-criteria methods shows that the greater the number of partial criteria is, the less impact their weight coefficients exert on the level of global evaluation. Due to the reasons mentioned above and in order to simplify calculations in the model research on 17 partial criteria, identical weight values were assumed, which did not exclude the application of various coefficients, designated on the basis of the procedures described in the previous subsection.

Table 2. Feature – partial criteria applied in modern research

Tabela 2. Kryteria cząstkowe zastosowane w badaniach efektywności

Feature – criterion name	Denotation	Unit	Feature-criterion specification		
			stimulant	destimulant	quality
Investment project costs	CR01	10^6 PLN		+	
Project financial costs with respect to investment costs	CR02	PLN/PLN		+	
Realization cost of heat unit supply	CR03	PLN/GJ		+	
Sulphur dioxide emission	CR04	g/GJ		+	

Nitrogen oxidesemission	CR05	g/GJ		+	
Carbon dioxide emission	CR06	kg/GJ		+	
Dust emission	CR07	g/GJ			
Global thermal efficiency of applied power technology	CR08	–	+		
share of the combined system in heat demand	CR09	–	+		
Required space for investment project	CR10	m^2		+	
Distance of investment project location from potential heat recipients	CR11	m		+	
Investment realization period	CR12	years		+	
Planned exploitation period	CR13	years	+		
Investment risk costs with respect to investment costs	CR14	PLN/ PLN		+	
Environmental burden due to environmental factors (noise, waste, etc.)	CR15	–			+
Main hindrances (technical, location, formal legal, sociological)	CR16	–			+
Technical and technological maturity of power systems and appliances	CR17	-			+

On the basis of source materials [5], [14] regarding the scope and type of planned investment ventures, for each case, a data compilation in the form of an observation matrix was made (Table 3, where number realizations of measurable features for CR01-CR14 were presented).

The raw data compiled in Table 3 underwent further transformations according to the unitarization procedure described in previous subchapter. Next, number realizations of quality features were added to unitarization matrices. As a result, an ordered observation matrix was formed for the investigated case (Table 4).

The ordered observation matrix in Table 4 is the initial database for calculations and a graphical representation of the evaluation measure of investment effectiveness, using a relatively simple MS Excel worksheet (according to the author's W-1 method).

What is more, the database described above was applied in comparative studies conducted according to the multi-criteria method and the ELECTRE program in which equivalence of partial criteria was assumed. The description and model research results can be found in the next subsection.

1) 4.3. Investment Effectiveness Evaluation

In model research, in order to obtain the expected economic effects, an extension of an existing power plant of total heat power 160 MJ/s was analyzed. The combined system of 15 MJ/s heat power which consisted of the following was used:

- gas turbine power plant with peak boilers ALT01,
- cogeneration gas-fired power plant ALT02,
- gas engine blocks on electricity generation with peak boilers ALT03.

In addition. the effectiveness of a modern coal heating plant ALT05 and the effectiveness of a biomass heating plant ALT06 were inspected, assuming that electricity power came from the power station.

Modernization options on the supply side ALT11 and the demand side ALT12 were considered, i.e. the entire effectiveness of 7 investment strategies was analyzed.

When the suggested procedure of investment effectiveness evaluation was applied, the following evaluation matrix was obtained (Table 5).

The considered investment strategies gave the following values of evaluation measures f_i:

- modernization ventures on the supply side ALT11– 0,83;
- ventures on the demand side ALT12 – 0,80;
- biomass heating plant ALT06 – 0,63;
- gas turbine power plant ALT01 – 0,54;
- coal heating plant ALT05 – 0,48;
- gas engine blocks on electricity generation ALT03 – 0,47;
- cogeneration gas fired power plant ALT02 – 0,37.

A graphical representation of investment effectiveness evaluation concerning investment strategies under research is presented in Fig.2.

Table 3. Preliminary observation matrix – case study for the City X

Tabela 3. Wstępna macierz obserwacji – studium przypadku dla Miasta X

CITY X / ALT	Criteria													
	01	02	03	04	05	06	07	08	09	10	11	12	13	14
01	21,50	0,20	22,60	0,00	75,00	54,0	0,00	0,80	0,03	250,0	1200,00	1,50	15,00	0,10
02	27,40	0,36	24,50	0,00	80,00	56,0	0,00	0,86	0,04	500,0	2000,00	2,00	20,00	0,20
03	22,60	0,21	25,00	0,00	240,0	53,0	0,00	0,80	0,05	700,0	1500,00	1,20	15,00	0,12
04														
05	3,70	0,06	20,90	460,0	200,0	92,0	275,	0,82	0,00	150,0	500,00	0,80	10,00	0,05
06	7,50	0,12	21,30	0,00	35,00	50,0	0,00	0,92	0,00	90,00	650,00	1,00	12,00	0,07
07														
08														
09														
10														
11	1,80	0,10	20,60	0,00	0,00	0,00	0,00	0,83	0,00	0,00	1000,00	0,50	30,00	0,05
12	4,70	0,15	16,80	0,00	0,00	0,00	0,00	0,81	0,00	0,00	0,00	0,50	30,00	0,07

Table 4. Ordered observation matrix – case study for the CITY X

Tabela 4. Uporządkowana macierz obserwacji – studium przypadku dla Miasta X

CITY X / ALT	Criteria																
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
01	0,55	0,53	0,29	1,00	0,69	0,41	1,0	0,0	0,6	0,64	0,40	0,33	0,25	0,67	1,0	1,0	1,0
02	0,00	0,00	0,06	1,00	0,67	0,39	1,00	0,50	0,80	0,29	0,00	0,00	0,50	0,00	1,00	0,00	0,0
03	0,19	0,50	0,00	1,00	0,00	0,42	1,00	0,33	1,00	0,00	0,25	0,53	0,25	0,53	1,00	0,00	1,0
04																	
05	0,93	1,00	0,50	0,00	0,17	0,00	0,00	0,17	0,00	0,79	0,75	0,80	0,00	1,00	0,00	1,00	1,0
06																	
07																	
08																	
09																	
10																	
11	1,00	0,87	0,54	1,00	1,00	1,00	1,00	0,25	0,00	1,00	0,50	1,00	1,0	1,0	1,0	1,00	1,0
12	0,89	0,70	1,00	1,00	1,00	1,00	1,00	0,08	0,00	1,00	1,00	1,00	1,0	0,9	1,0	0,00	1,0

Table 5. Evaluation matrix – case study for the CITY X (W-1 method)

Tabela 5. Macierz oceny – studium przypadku dla Miasta X (metoda W-1)

CITY X / ALT	Criteria																		
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	Si	fi
01	23	53	29	9	6	41	9	0	6	64	40	3	25	6	9	0	9	9,11	0,54
02	0	0	6	9	6	39	9	50	8	28	0	0	50	0	9	0	0	6,30	0,37
03	18	5	0	9	0	42	9	33	9	0	25	5	25	5	9	0	9	8,06	0,47
04																			
05																			
06	92	99	50	0	1	0	0	16	0	78	75	8	0	9	0	9	9	8,14	0,48
07	77	80	45	9	8	45	9	99	0	87	67	6	10	8	0	9	9	11,60	0,68
08																			
09																			
10																			
11	99	86	53	9	9	99	9	24	0	99	50	9	99	9	9	9	9	14,15	0,83
12	88	70	99	9	9	99	9	8	0	99	99	9	99	8	9	0	9	13,57	0,80

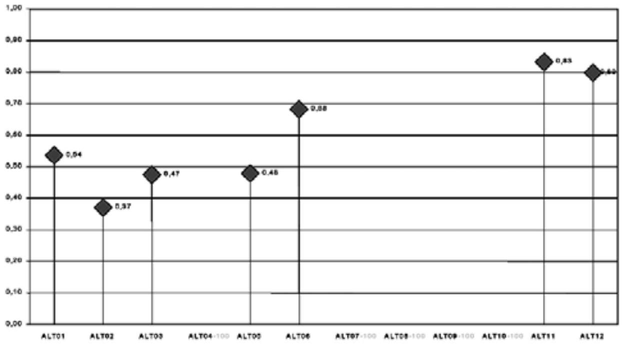

Fig.2. Evaluation measure of investment effectiveness – case study for the CITY X (W-1 method)

Ryc.2. Miara oceny efektywności inwestycji – studium przypadku dla Miasta X (metoda W-1)

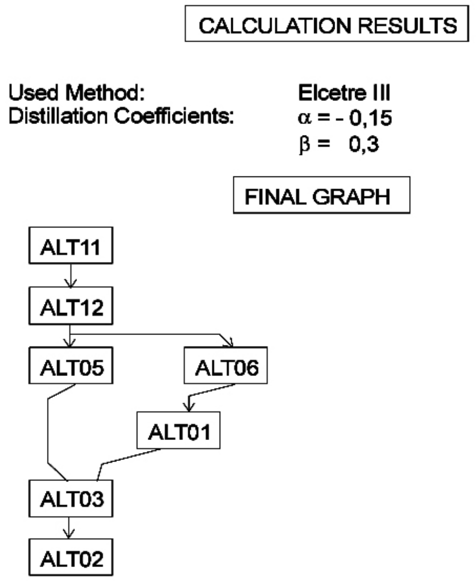

Fig. 3. Investment effectiveness evaluation – case study for the CITY X (W-2 method)

Rys. 3. Ocena efektywności inwestycji – studium przypadku dla Miasta X (metoda W-2)

Modernization activities, as well as a gas power plant and a gas turbine power plant, show high effectiveness as far as supply and demand are concerned ($f_i \in <0,80 \div 0,90)$). The remaining options show lesser effectiveness.

The effectiveness of the considered investment options has also been studied using the ELECTRE method/v. Electre III . The initial data for analysis can be found in Table 6.

The research results with a graphical representation are outlined in Fig.3.

The considered strategies (apart from ALT06, ALT01) have been evaluated in the following order:

- modernization ventures on the supply side ALT11;
- modernization ventures on the demand side ALT12;
- coal heating plant ALT05 ;
- gas engine blocks based on electricity generation ALT03;
- cogeneration gas-fired power plant ALT02.

A biomass heating plant ALT06 was not compared with a coal heating plant (effectiveness on a similar level), but showed more effectiveness than a gas turbine power plant ALT01, than an electricity generating power plant, and then a cogeneration gas-fired plant.

4.4.Results and discussion

In order to verify the validity of the best investment strategy in the considered case study, model research on investment effectiveness was carried out. A comparison of procedure results was made. The applied calculation procedures, using identical assumptions and initial databases according to the author's method (W-1) and the ELECTRE method (W-2), allowed comparing the studied investment options and ranking them from the best to the worst.

Both multi-criteria methods principally stem from different positions, namely:

- W-1 method strives to establish the order of studied investment options on the basis of partial criteria decomposition, followed by a synthesis of partial evaluations, leading to assigning an evaluation measure fi,
- W-2 method establishes the order of studied options without defining a quantity evaluation measure of particular strategies.

For the reasons mentioned above, the verification of the complementarity of results is only qualitative in character. The model research results of investment options (denotations in accordance with table 1) are shown in Table 7, the method quality is denoted by (+) symbol, lack of evaluation is marked with the symbol(·).

Table 6. Initial database – case study for the CITY X (W-2 method)

Tabela 6. Baza danych wejściowych – studium przypadku dla Miasta X (metoda W-2)

CITY X / ALT	Criteria																
	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17
01	21,5	0,2	22,6	0	75	54	0	0,8	0,03	250	1200	1,5	1,5	0,1	1	0	1
02	27,4	0,36	24,5	0	80	56	0	0,86	0,04	500	2000	2	20	0,2	1	0	0
03	22,6	0,21	25	0	240	53	0	0,84	0,05	700	1500	1,2	15	0,12	1	0	1
05	3,7	0,06	20,9	460	200	92	275	0,82	0	150	500	0,8	10	0,05	0	1	1
06	7,5	0,12	21,3	0	35	50	0	0,92	0	90	650	1	12	0,07	0	1	1
11	1,8	0,1	20,6	0	0	0	0	0,83	0	0	1000	0,5	30	0,05	1	1	1
12	4,7	0,15	16,8	0	0	0	0	0,81	0	0	0	0,5	30	0,07	1	0	1

Table 7. Table of results – case study for the CITY X

Tabela 7. Tabela zbiorcza wyników – studium przypadku dla badania Miasta X

No.	W-1 method		W-2 method	Conformity evaluation method
	Investment strategy order	Evaluation measure	Investment strategy order	
1	ALT11	0,83	ALT11	(+)
2	ALT12	0,80	ALT12	(+)
3	ALT06	0,68	ALT05, ALT06	(+)
4	ALT01	0,54	ALT01	(+)
5	ALT05	0,48		(·)
6	ALT03	0,47	ALT03	(+)
7	ALT02	0,37	ALT02	(+)

The analysis of the case study data, using the W-1 and W-2 methods, shows full complementarity (+) in the first, second, third, fourth, sixth, and seventh positions. The strategies ALT06 and ALT01 in the W-2 method were evaluated in the following order: ALT11 → ALT12 → ALT06 → ALT 01 → ALT03 → ALT02, skipping comparisons with the ALT05 option (·).

On the basis of the comparative analysis of the model research results, using both methods, one can notice a high evaluation complementarity of investment strategies. Moreover, the scientific multi-criteria method suggested by the author, apart from being simple and easy to apply, allows evaluating investment strategies using a synthetic evaluation measure *f*.

Practically, it means performing quality and quantity analyses of investment options, i.e. variants of investment tasks in sustainable energy power engineering.

5. Conclusions

The proposed multi-criteria method analyzed in relation to possible investment strategies shows high modernization effectiveness on the supply side (mainly the modernization of transmission systems, distribution, automation of networks and heat distribution centers, application of modern technologies and high-performance power equipment), and on the demand side (thermo – modernization of houses, modernization of recipient installations, application of DSM rules). The high effectiveness of demand options in the investigated case study results also from the fact that the ventures, thermo – modernization, in particular, concern housing districts that were built several years ago using energy-consuming technologies. Lowering energy consumption in houses will require big financial means. On the other hand, ventures on the demand side face the dispersion of financial assets due to the number of recipients being higher than the number of energy producers and distributors.

It is very often the cause of decision-making and project coordination problems connected with potentially highly effective investment options.

Apart from high effectiveness on the supply-demand side, considerable profitability is characteristic for combined systems strategies, utilizing biomass, or natural gas. Their effectiveness will increase even more in the case of an increase in relatively low prices of electricity.

It concerns also non-conventional energy supplying systems such as heat pumps or fuel cells, which have already shown high effectiveness. If various partial criteria are taken into account, investment in traditional coal energy systems has proven to be the least effective.

As the author's studies infer the introduced scientific method can be a good tool to support decision modelling and enables taking rational decisions concerning investment towards sustainable renewable energy in power engineering. ■

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