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Influence of RES Integrated Systems on Energy Supply Improvement and Risks

Wpływ zintegrowanych systemów OZE na zaopatrzenie w energię – aspekty pozytywne i ryzyka

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Abstract
RES (renewable energy sources) plays a very important role in the context of sustainable development, as an alternative to fossil fuels and nuclear power.
This paper presents the description of a RES technology cluster – an integrated system, which consists of equipment using different types of RES. It demonstrates that the stochasticity of renewable energy input influences the energy supply reliability. The work considers the influence of diversification of different RES sources on the improvement of energy supply reliability and reduction of risks connected with energy loss. Based on mathematical simulation using the convex optimization method, the authors propose a novelty solution to determine the most effective equipment configuration of an integrated energy system – a RES cluster. Effective computer programs have been developed and registered in order to calculate the optimal integrated renewable energy system in the Russian Federation.
The optimization criterion is the minimal cost of generating 1kWh of electricity of the whole complex of renewable energy sources. The feature of calculating the optimal combination of renewable energy sources is based on the variance of random variables, climatic characteristics unlike average for the year. This approach improves the accuracy of calculations by 25-40%. This leads to a reduction in capital equipment costs and reducing the cost of production of 1kWh of electricity.

Key words: renewable energy sources, RES technology cluster, renewable power supply system, energy supply reliability

Streszczenie
OZE (odnawialne źródła energii) odgrywają istotną role w kontekście rozwoju zrównoważonego, jako alternatywę dla spalania paliw kopalnych i energetyki jądrowej.
W tym artykule opisano klaster technologiczny OZE – zintegrowany system, na który składają się urządzenia wykorzystujące różne rodzaje OZE. Pokazuje, że nieprzewidywalność dostaw energii odnawialnej ma wpływ na niezawodność dostaw energii. Rozważono wpływ dywersyfikacji OZE na poprawę jakości systemu zasilania i zmniejszenie ryzyka związanego ze stratami energii. W oparciu o symulację matematyczną autorzy proponują innowacyjne rozwiązanie pozwalające określić najbardziej efektywną konfigurację sprzętową zintegrowanego systemu energetycznego – klaster OZE. Opracowano i zarejestrowano programy komputerowe umożliwiające obliczenie zintegrowanego systemu energetycznego na przykładzie Federacji Rosyjskiej.
Za kryterium optymizacji przyjęto minimalny kost wytwarzania 1 kWh energii elektrycznej przez cały system odnawialnych źródeł energii. Obliczenia odnoszącej się do optymalnej kombinacji odnawialnych źródełe energii oparte są na wariancji zmiennych losowych i dokładnych danych odnoszących się do warunków klimatycznych (a więc uwzględniono o wiele więcej, niż średnie dane dla danego roku). Takie podejście pozwala na zwiększenie

dokładności obliczeń I 25-40%. W konsekwencji instalacja będzie mniejsza i lepiej dostosowana do potrzeb, co pozwoli na obniżenie ceny wytwarzania 1kWh energii elektrycznej.

Słowa kluczowe: odnawialne źródła energii, klaster technologiczny OZE, odnawialny system zasilania, niezawodność systemu zasilania

1. Introduction

Sustainable development is a strategy that is concentrated on satisfying basic human needs, both of present and future generations (WCED, 1987). Among them energy issues are especially important, since our civilization cannot function without acquiring energy, in particular electricity. Because of the pollution connected with burning fossil fuels, and fears related to nuclear power renewable sources of energy (RES) seems to be a real alternative. They amounts up to 7-20 % of annual energy production in the developed and developing countries. In the Russian Federation, where the reserves of hydrocarbon are considerable, this index reached the level of 1.2 % in 2014 (excluding Crimea).

Existence of distant settlements and autonomous objects situated throughout the vast territories of the Russian Federation demand reliable independent energy sources. This problem is currently solved mainly by means of diesel generator units powered by the organic fuel. The features of the country's geographical location (middle and high latitudes, severe continental climate, isolated location of the major part of the settled land from seas) induce low-energy wind (3-5 m/s) and relatively low average annual insolation (120-200 W/m^2) on the larger part of the Russian Federation. These factors have determined inadequate reliability and low competiveness of RES (renewable energy sources).

Power supply systems with various types of installations, which use the major part of the energy potential available on a particular territory, can improve the reliability and competiveness of RES for isolated objects. The essential feature of such renewable power supply systems is the use of multiple renewable energy sources and a wide range of different types of equipment: WT (wind turbines), PC (photoelectric converters), SCP (solar collecting panels), sHEPS (small hydro-electric power station), BU (biogas units), HP (heat pumps), etc.

Current approaches to the description of integrated systems are numerous. Their analysis can be presented in a large-scale classification of different production clusters. It determines the object of the research in question – the power supply systemfor isolated power suppliers, or *technology process cluster of RES* or, simply, *RES cluster*.

It is indicated in the diagram that the technology RES cluster is formed by a group of different types of equipment (as a part of power supply system), which are different in sources of energy (sun, wind, water, geothermal heat) but common in their renewable (non-depletable) nature.

The disadvantage of renewable energy sources is their stochasticity; it leads to the risk of energy shortages or essentially reduces the reliability of energy supply.

In this regard, we face the problem of the risk measurement and its influence on power supply.

2. Methods and Results

2.1. Risks connected with the use of the renewable energy sources and RES clusters

Risks in renewable energy are possible loss of energy supply stimulated by an advent of casual unfavorable events (zero wind or sun, low water level). In other fields of activity, risk is also understood as damage (Knight, 1921). The latter may be impersonal, i.e. be determined by an external influence. However, a risk, as a possible loss, can be frequently related with a choice of one or another solution, behavior or alternative. In this case, it is a choice of the RES equipment. It should be noted that a risk is sometimes understood as a possibility of occurrence of an unfavorable event. The higher is the possibility, the greater is the risk.

If direct measurement of losses or their possibility is impossible, risks can be measured via ranking of corresponding objects, processes or events in respect of possible losses, damages, etc. Ranking is usually based on experts' judgments.

A natural reaction to the presence of risks in the field of renewable energy is a will to use different types of energy simultaneously, diversify the RES equipment, i.e. to divide the general problem of energy production among different types of RES installations. Diversification is a conventional instrument to reduce many types of risks. An increase in the number of components (RES equipment) decreases the overall risk.

The second way to reduce the influence of risks is the risk management. Risk management is performed by various methods: for example, through accurate calculation of combinations of installed capabilities for each type of the RES equipment.

However, the risk management obtains a reliable basis and consequences of diversification become analyzable via methods of mathematical statistics only in those cases, where a risk can be measured and represented in a form of a statistical factor (Bendat, Piersol, 1971).

In mathematical analysis, the risk is frequently measured by such ordinary statistical characteristics as dispersion and root-mean square deviation. Both characteristics measure the variation from average values. The bigger are variations, the higher is the

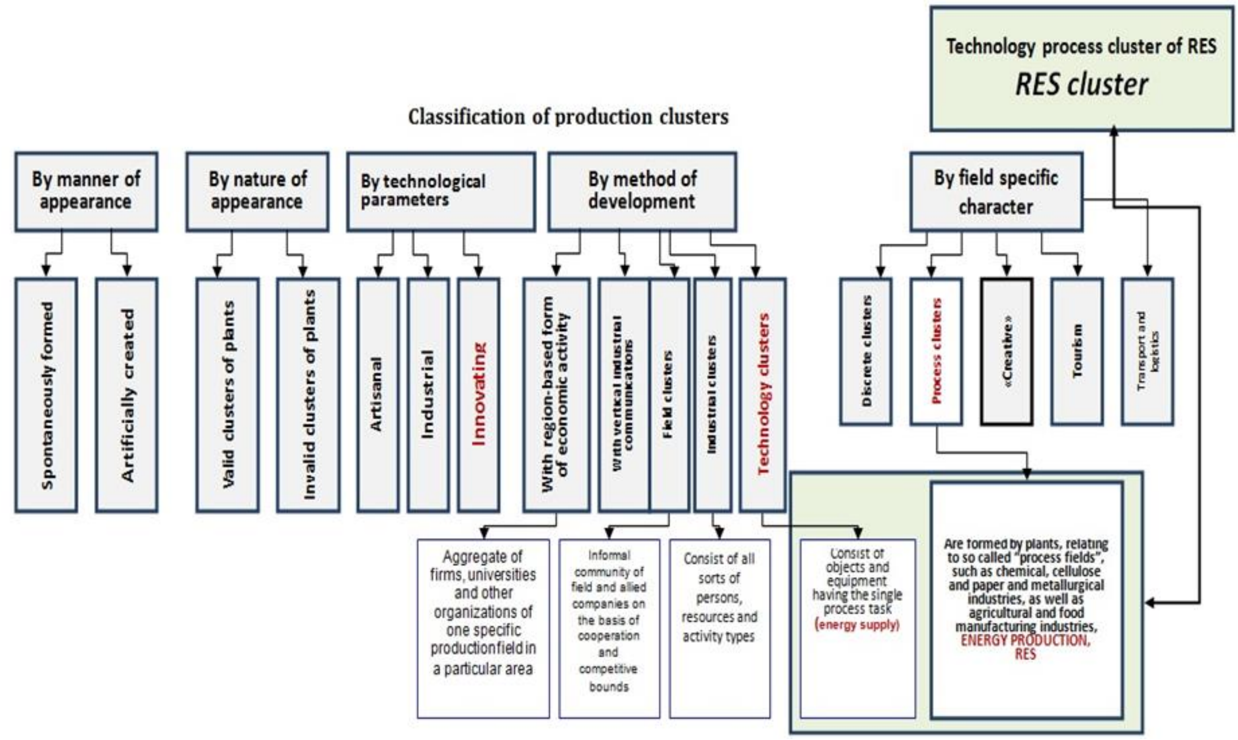

Figure. 1. The place of the power supply system based on RES, as a technology process cluster of RES, within the system of the general classification of production clusters

spread of indexes around the average and, consequently, the greater is the risk level.

The correlation between the dispersion D and the root-mean square deviation is as follows:

$$\sigma = \sqrt{D} .$$

Whereas the sampling variance for the average one is determined as

$$D = \sum \frac{(x_i - \bar{x})^2}{n-1},$$

where:

n is the quantity of observations;

x is the average of the stochastic variable x.

As it is known, the mean-root square deviation has an undeniable advantage: in case real distribution is in close proximity to the normal one (that should be verified statistically, of course), this parameter can be used to determine the range, wherein the value of the stochastic variable is expected to appear with the specified probability. Thus, when speaking about the distribution of production costs of 1 kW*h by a RES technology cluster, it is possible to state that the value of the stochastic variable x (in this case, it is the production cost of 1 kW*h by a RES cluster) is within the limits ~x±s with the probability of 68%; with the probability of 95%, it is within the limits x±2s and so on (Fig. 2).

*2.2. Cost of the energy produced by a RES cluster and the dispersion of 1 kW*h production cost*

Now we specify the impact of diversification on the minimization of risks and elicit conditions, in which this impact is achieved. Let us assume that the test object is some theoretical technology cluster of RES (hereinafter – *RES cluster*). This assumption is caused by methodological advantages – in this case, it is easier to understand the relationship among the basic variables. However, many obtained results can be easily extended to any RES system.

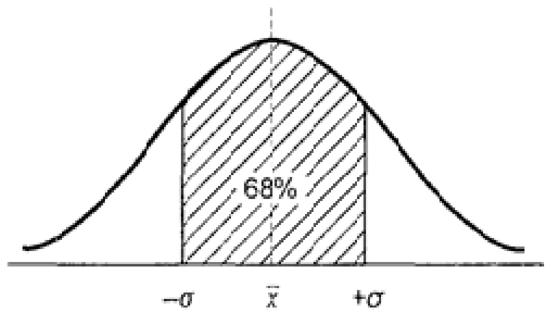

Figure 2. Distribution of the values of the stochastic variable x

The dispersion of 1 kW*h production cost can serve as an instrument to measure the risk during a long-term use of RES. The diversification of the equipment (if applied correctly) leads to a decrease of this dispersion, other conditions being equal. Diversification is based on the simple hypothesis. If each component of a RES cluster is characterized by some dispersion of 1 kW*h production cost, the total dispersion of 1 kW*h production cost is determined by its composition. Thus, changes in the composition of the RES cluster initiate changes in the total dispersion of reliability. In some cases, the total dispersion can be reduced to a minimum (Esipov, 2008).

Let us consider a technology RES cluster consisting of *n* types of energy sources. A type of equipment in the cluster is denoted as *i*, the number of equipment types is a_i. The production cost of 1 kW*h for one *i* makes a *d* value. *A* is the total production cost of 1 kW*h. It is equal to:

$$A = \sum a_i \, d_i \qquad (1)$$

If d_i is the average cost of 1 kWh produced by the equipment, then *A* value characterizes the average production cost of 1 kWh produced by the RES cluster in total.

Let us assume that indexes of the production cost of 1 kWh from different energy sources are statistically independent values (in other words, they do not correlate with each other). In this case, the dispersion of 1 kWh production cost by the entire cluster (represented as D) can be figured as

$$D = \sum a^2_i D_i \qquad (2)$$

Where D_i is the dispersion of cost of 1 kWh produced by the equipment of the *i*-type.

For simplicity (that will by no means affect results of the further discussion), we will change over from absolute measurement of RES equipment quantity to relative measurement. Now, let a_i describe a segment (or share) of an *i*-type in the RES cluster. Consequently, $0 < a_i < 1$; $\sum a_i = 1$.

For indexes of 1 kWh production cost of a RES cluster, which are dependent in a statistical sense, the dispersion of overall reliability is determined in the following way:

$$D = \sum a^2_i D_i + 2 \sum a_i \, a_j \, r_{ij} \, \sigma_i \, \sigma_j \qquad (3)$$

where D_i is the dispersion of 1 kWh production cost for *i*-type of equipment;

r_{ij} is the correlation factor of the cost of 1 kWh produced by the equipment of types *i* and *j*;

s_i and s_j are the root-mean square deviation of the production cost of 1 kWh for the equipment of types *i* and *j*. The evidence of validity of formulas (2) and (3) are not given in this paper as they can be found in textbooks on mathematical statistics (Knight, 1921).

The correlation factor of two stochastic variables *x* and *y* is known; it is determined in accordance with the formula (4):

$$r_{xy} = \sum (x-\overline{x})\,(y-\overline{y}) \,/\, n \, \sigma_x \, \sigma_y \qquad (4)$$

Where *x* and *y* are the average values of two RES types (in this case, the average production costs of 1 kWh).

The correlation factor is frequently calculated according to the following operating formula:

$$r_{xy} = \frac{n\sum xy - \sum x \sum y}{\sqrt{[\sum x^2 - (\sum x)^2]\,[n\sum y^2 - (\sum y)^2]}} .$$

This factor can be a positive or a negative value. With positive correlation, the dispersion of energy production cost of 1 kW*h increases; with negative correlation it decreases. As a matter of fact, with a significant negative correlation, positive deviations from the average production cost of 1 kW*h generated by a RES system are liquidated by the negative deviations of others. Conversely, with positive correlation, the deviations are summarized, which increases the total dispersion and risk.

Specialists are well aware of the following characteristics of correlation factor:

• factor has no dimension; consequently, it is comparable to different data series;

• r_{xy} value lies within the range from -1 up to +1. The value $r = +1$ is a reflection of the existence of full positive correlation between the variables, i. e. there is a functional linear dependence – with increase of x, y increases in a linear manner. When r = -1, the negative linear dependence is observed.

Let us now understand the effect of the size of RES equipment diversification on the risk value. The size of diversification is a number of objects possible for use in one technology cluster of RES. Let us refer to an illustrative example, which will allow us to highlight the influence of the factor mentioned above. Let a RES cluster consists of different types of equipment having the same dispersion of the production cost of 1 kW*h s^2_0. The specific weights of each type of equipment (PC, WT, etc.) are also similar and the total sum of equipment shares (in terms of installed capacity) is equal to 1. Assuming that indexes of the production cost of 1 kWh in individual types of RES equipment are independent, we can use the formula (2). Within this framework, in order to estimate the amount of root-mean square deviation of 1 kWh production cost, we get:

$$D = \frac{1}{n}\sigma_0^2 ,$$

Where *n* is the number of types of RES equipment.

Using the formula mentioned above, we will determine a dispersion of 1 kW*h production cost produced by a RES technology cluster consisting of two or three RES types. For two different sources, we have:

$$D = \frac{1}{2}\sigma_0^2 \text{ and } \sigma = \sqrt{\frac{1}{2}} \times \sigma_0 = 0{,}71\,\sigma_0 .$$

For three types of RES equipment, the square deviation of 1 kW*h production cost is $0.58s_0$. Thus, with an increase in the number of RES cluster equipment, risk decreases, even if the dispersion of constituent elements is the same. However, diversification effectiveness decreases, i.e. the cost of the installed equipment grows. The corresponding dependence is shown in Fig. 3.

Diversification scaling-up has the biggest influence at initial stages – when *n* values are small. For example, in the considered example, a transition from one RES type to four decreases the square deviation by 50%, and from one to eight – by 65%.

The above findings, concerning the tendency of root-mean square deviation change depending on the number of elements, when the dispersions of the elements are equal, are valid for other, more general, cases. However, the dependency of this parameter on the degree of diversification is not so clear then.

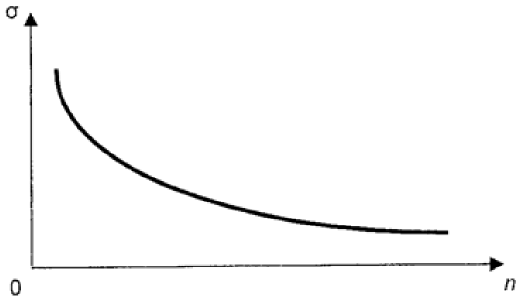

Figure 3. Diagram of diversification influence (growth of different RES types equipment) on risk.

Now let us see the changes in the cost and risk value in a case when the technology cluster of RES is restructured. To do this, formulas (2) and (3) should be written for two RES types: X (WT) and Y (PC). This analysis is of practical importance as these types are most available and understandable for consumers. It helps to illustrate the consequences of *mixing* RES equipment with different production costs of 1 kW*h of energy and different dispersion. For the independent sources:

$$D= a^2_x D_x+a^2_y D_y \quad (5)$$

and for dependent parts of equipment in composition of RES cluster, it is:

$$D= a^2_x \sigma^2_x+a^2_y \sigma^2_y+2a_x a_y r_{xy} \sigma_x \sigma_y \quad (6)$$

Where a_y= 1 - a_x.

In this case, the average value of 1 kW*h production cost is defined as:

$$A= a_x d_x + (1- a_x)d_y \quad (7)$$

If d_y>d_x. and s_y> s_x, then an increase in the share of the most effective type of RES will decrease the 1 kW*h energy production cost. Thus, based on (7), we will obtain:

$$A= d_x + (d_y - d_x) a_x \quad (8)$$

As for the dispersion, it follows from the expression (6) that the proposition is ambiguous and depends on the sign and the degree of correlation. In this regard, let us have a closer look at three situations:

- complete positive correlation of 1 kWh production cost between types of the RES equipment (r_{xy}= +1),
- complete negative correlation (r_{xy}= -1), independence of 1 kWh production cost between types of the RES equipment,
- zero correlation (r_{xy} = 0).

In the first case, the increase of production cost of 1 kWh between two types of the RES equipment, due to the integration of Y in addition to existing X, is followed by the increase of both production cost and the dispersion. For a technology cluster of RES with two types of the equipment, the square deviation is within the limits $s_x < s < s_y$ (Fig. 4).

For a special case, when $s_x = s_y = s$, we will obtain $D = s^2$ – by the formula (6). In other words, *mixing* equipment types in a RES cluster will have no influence on the dispersion value here.

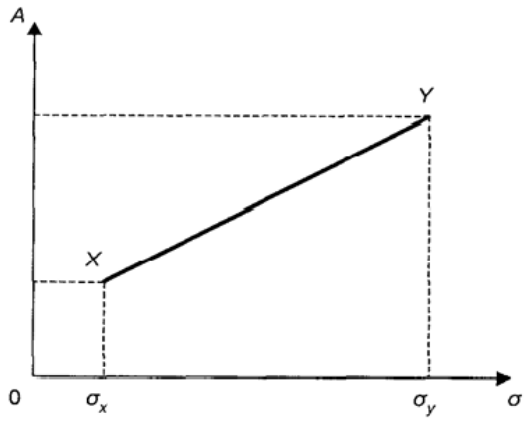

Figure 4. Diagram of values of square deviation for a technology cluster of RES with X and Y types of equipment.

A weak point of the situation with additional components to a RES cluster is a considerable increase of its cost. Therefore, it requires use of methods of the mathematical optimization and their classification in terms of the equipment structure and the installed capacity of the RES cluster.

In a general case, for mathematical analysis, the RES cluster can be presented as a function diagram (see Fig.5). Consideration of the object in the way shown in Fig. 5 is built up on the principle of a *black box*, as a base in performing the optimization task (Esipov et al., 2008).

It was correctly supposed that the perturbation influences W_i cannot be controlled. They are either stochastic or vary in time (wind speed, insolation, temperature). They determine the stochasticity of the mathematical model.

Finding solutions for such a task with the help of a *black box* is carried out through mathematic simulation, using the method of convex optimization (Sharpe, 1963).

The target function for the mathematical model of the RES cluster is a quadratic function from $x_1, x_2, \ldots, x_n$, of the following type:

$$D(Y/a) = \sum_{i=1}^{n}\sum_{j=1}^{n} \sigma_{ij} x_i x_j \Rightarrow \min , \quad (9)$$

Where x_i is quantities of the installed capacity of each type of renewable energy sources of the RES cluster;

Y / a is the energy cost produced by the cluster per unit time;

σ_{ij} is the sample covariance calculated on sampling for Y_i ,Y_j .

The physical meaning of the function is minimization of dispersion for the cost of energy produced by the power supply system (RES cluster) per unit time**.** The problem involves a choice of x_k with a *minimum risk* and minimum production cost of 1 kW*h under the following restrictions:

$x_0 + x_1 + x_2 + \ldots + x_n = 1$; $x_0 r_0 + x_1 m_1 + \ldots + x_n m_n = A$;

$A < r_0$; $x_i \geq 0, \quad i = 0,1,\dots,n$

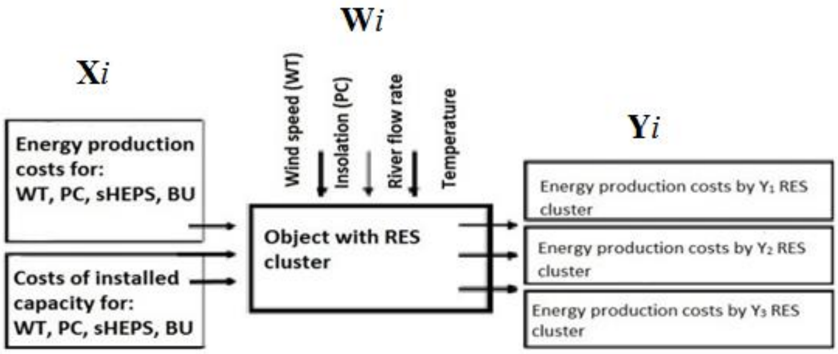

Figure 5. Algorithm of a multifactorial discrete mathematical model of a RES cluster

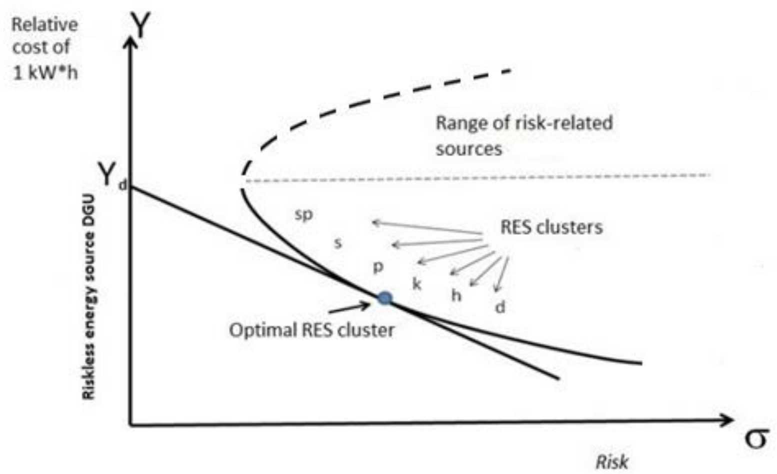

Figure 6. Diagram to define the optimal RES cluster and evaluate the risk of energy supply (%)

It is a convex programming problem, which is solved using the Sover Add-in in Excel. As a result, we will receive a vector (x_0, $x_1, \dots, x_n$) that defines the effectiveness of the RES cluster depending on the equipment structure. With regard to the RES cluster, it is nothing but finding an optimum relation of fraction capacity of x_{DGU}, x_{WT}, x_{PC}, …x_n (DGU is a diesel generator unit).

The visualization algorithm of finding the effective RES cluster is shown in Fig. 6 (Tobin, 1965).

The value evaluates risks, i.e. it is a variation of cost of energy produced by the cluster per unit time. Such an approach is known in investment analysis, where the corresponding model includes risk-related and risk-free financial instruments; it is called *Tobin's portfolio approach* (Tobin, 1965).

The area of the variety of risk values and possible clusters is called the *Markowitz bullet*, as its form resembles a bullet and was described by the Nobel laureate Markowitz in his works on creation of optimal investment portfolio on the base of risk-related valuable securities (in renewable energy, we would say *stochastic* sources) (Markowitz, 1952, 1990).

A single renewable energy installation usually tends to be oversized to accommodate load demand. Combinations with one or more sources of the renewable energy will improve load factors and help to maintain and replace cost as well (Fulzele, Dutt, 2012). Their development is dependent on the improvement of processing, decrease in the cost price of the produced useful energy and increase in the operation comfort. On the side of the resources, the potential of renewable energies could noticeably exceed the needs, but their contribution to the energy balance depends on available surfaces, investments for their equipment and the reduction of consumption (Lakhoua, 2014).

3. Conclusions

1. The use of power delivery systems built on the principles of diversification (variety of sources) of RES technology clusters increases the reliability of energy supply of stand-aloneobjects.
2. Risk management (decrease of probability of object's power failure) is subject to the selection of the optimal equipment structure of RES based on different principles for obtaining the renewable energy.
3. Research of solutions on finding the most effective equipment structure of an

integrated energy system – RES cluster – can be carried out on the base of mathematic simulation, using the method of convex optimization.

4. Scietific literature includes several studies dedicated to energy production cost analysis of renewable energy sources. Compared to them, this study has shown the specific diversified minimization of risks and elicited their conditions; it is quite different in logic and methodological advantages. It has also described a unique process algorithm of a multifactorial discrete mathematical model of a RES cluster.

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