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Trends in the Development of the Global Energy Market

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ABSTRACT

In recent years, there have been some natural and human-made disasters and severe social clashes in globally important energy regions, which has had a negative impact on the environment in general and on the development of the energy market in particular. Therefore, the development of the modern energy industry is aimed at the broad involvement of renewable energy sources (RES) in the energy balance of the world's advanced countries. At the EU level, particular attention is given to increasing the proportion of RES in total energy consumption to 12% with the installed capacity of solar photovoltaic (PV) systems up to 3 GW. The purpose of our study is to propose a mathematical model of the electricity generation processes in renewable solar and wind energy systems by methods of the theory of impulsive, random processes as well as recommendations for the development of RES based on the analysis of the trends in consumption and production of energy resources, their supply-demand proportion, and a model for the development of the energy market. Our findings show that the proposed model will allow to optimize the structure and create adaptive energy systems of RES.

Keywords: Energy Consumption, Active Consumer, Energy Market, Electric Power Industry, Tariffs
JEL Classifications: D24, Q43, M31

1. INTRODUCTION

The world economy in the 21st century is facing a financial and economic crisis, which has led to a reduction in global gross domestic product by about 0.5-0.7% for the first time in more than half a century. This is mainly due to a number of the human-made disasters that have had a negative impact on the environment, as well as some severe social clashes and hotbeds of tension in globally important energy regions. Renewable energy sources (RES) in the energy balance of the highly developed countries have significant potential to contribute to their economic, social and environmental energy sustainability. At the EU level, particular attention is given to increasing the share of RES in total energy consumption to 12% with the installed capacity of solar photovoltaic (PV) systems up to 3 GW. According to the scholars, solar and wind energy will then be the world's largest RES in 2040. The capacity of solar PV systems is expected to range from 300 GW to 450 GW at 1000 euro/kWh and an electricity price at 0.05-0.12 euro/kWh (Bezrukih and Strebkov, 2005).

The structure of energy consumption in Europe is heterogeneous and is determined by various conditions such as the availability of natural resources, transport opportunities and the specifics of domestic needs. The natural resource such as oil is a universal source of energy for many oil-producing countries, for example, Saudi Arabia - 62%, Mexico - 52%, Indonesia - 43%, Iran - 40%, etc. (Renewables 2016 Global Status Report, 2016).

Some countries focus on the use of domestic primary energy sources, which determine the priorities of industrial and domestic consumption (%): China (70%), South Africa (73%), India (53%), Poland (57%), Kazakhstan 50% and Australia (37%), where the main primary energy source is coal. Hydropower resources are present in Norway (64%), Brazil (35%), Sweden (30%), Switzerland (28%) and Canada (26%). Natural gas is the main primary energy source in Turkmenistan (78%), Algeria (63%), Azerbaijan (59%), Iran (58%), Russia (54%), Argentina (51%), Great Britain (35%) and USA (27%). The countries that consume natural gas from imported sources are Belarus (73%), Ukraine (40%), Hungary 42%), Italy (40%) and Germany (23%) (BP Statistical Review of World Energy June 2017, 2017).

A number of countries, with limited inland energy resources, focus on nuclear energy: France (38%), Sweden (26%), Finland (18%), Switzerland (21%), Ukraine (17%), Belgium (16%), the Republic of Korea and Japan (13%), and West Germany (10%) (BP Statistical Review of World Energy June 2017, 2017).

Despite this, RES have become the priority in the energy market. 2015 was the start of the renewable energy sector with the largest installed capacity. Currently, RES are the dominant energy source in the world, which led to a change in the energy market, whose consequence was the decline in oil prices and the growing price competitiveness of renewable energy technology. Also in 2015, the United Nations General Assembly adopted the document "Sustainable Energy for Everyone" within the framework of achieving common sustainable development goals.

Over the past 10 years, RES have gained momentum and outstripped the traditional energy sector by investing in new capacity inputs. Large banks are involved in financing renewable energy, there having appeared new investment such as "green" bonds, crowdfunding and yieldcos.

This paper is organized as follows. Section 2 gives a brief review of the literature. Section 3 provides a brief analysis of the energy market. Section 4 considers a method of the theory of impulsive random processes when developing mathematical models for the electric power generation. Section 5 proposes recommendations for the use of the RES clusters.

2. LITERATURE REVIEW

Energy efficiency and renewable energy are the main aspects of the cooperation of the International Energy Agency with Russia. In 2017, this agency published a global energy forecast, which highlights an exemplary scenario of the dynamics of energy demand and supply by 2030 (World Energy Outlook 2017, 2017).

Challenges and prospects of reforming the electric power industry have been widely investigated by Chubais (2016) and Global Wind Statistics (2017).

Modeling of RES was proposed in the works by Smerdov and Brikun (2009); Firsova et al. (2018).

There is a vast amount of literature on simulation, as a special case of mathematical modeling (Bogatyrev and Kreymer, 2003; Fedyanin and Meshcheryakov, 2010; Belyakov and Ryabov, 2007; Mitrofanov and Semenova, 2015; Lapaeva and Dedeeva, 2017). As the authors note, the principle of simulation modeling allows evaluating the characteristics of the system. Simulation modeling can be used as the basis for structural, algorithmic, and parametric synthesis of large systems, when it is required to create a system with specified characteristics under certain restrictions, which will be optimal according to specific criteria for evaluating efficiency. Vel'kin et al. (2013) were among the first to describe the mathematical modeling of RES clusters. The simulation model was calculated in the general form, which allows optimizing the RES cluster by the equipment composition and the minimum cost criterion for generating 1 kWh.

In recent years there has been considerable interest in the development scenarios of the global and Russian energy markets, in particular, RES (Doukas et al., 2012; Chumakov, 2015; Fedorenko et al., 2015; Elistratov, 2016). The study was based on the analysis of the development scenarios of the global and Russian energy markets, in particular, RES, which were presented in public reports of WWEA (WWEA Publishes World wind resource assessment Report, 2014). The review of the Russian electric power industry was given by Ernst and Young (Review of the Russian electric power industry for 2017, 2018). The first set of the analyses investigated the structure of the global energy market, the structure of the volumes of electricity generation and the distribution of investments in various types of energy sources. The current situation in the Russian energy market was examined. The development scenarios of the renewable energy market in Russia was proposed (Four scenarios for the development of renewable energy for Russia, 2016).

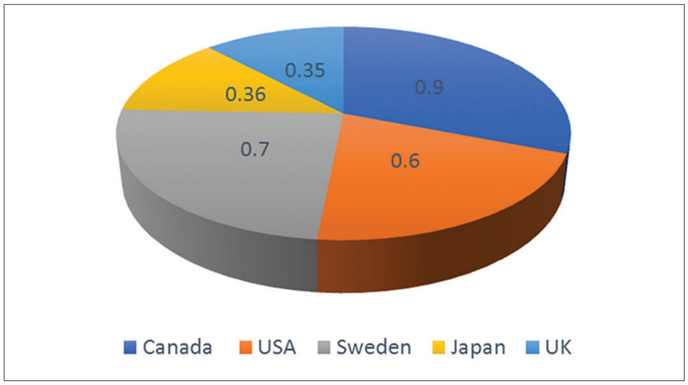
One issue that needs to be raised is the development of energy supply to consumers through the simultaneous widespread use of various energy sources, including RES. A mathematical simulation model for the electric power generation is proposed to solve this problem.

3. DESCRIPTION OF DATA

The achievements of the 20th century were primarily obtained through the use of fossil energy. At the same time, its consumption increased exponentially. During our study from 2013 to 2017, we performed an analysis of the trends in the development of electric power industry based on public reports of WWEA, EY, and review of the Russian electric power industry. As noted in the analytical reports, the developed countries succeeded in reducing the specific energy consumption in industry and household by 30-50% in the following decades. As a result, these countries see an increase in production with a constant value of energy consumption (Figure 1).

Analyzing the indicators of the energy report prepared by Renewable Energy Policy Network for the 21st century (REN21) (Key points of REN 21 report – 2017, 2018) over the past decade, some key points can be pointed out. For example, 2017 saw an increase of 6% in the capacity of solar collectors with a thermal insulation coating. The development of the RES market in different countries is not substantially steady. It has significantly increased in Denmark, Mexico, Poland, and Turkey while in Europe it has weakened. The total global generation capacity of concentrating solar thermal power in 2017 is 4.8 GW, whose 10% was installed

Figure 1: Specific energy consumption rate



Source: https://wwindea.org/wp-content/uploads/2017/06/170612-FES-Windenergie-rus-print.pdf.

in 2015 in Morocco (160 MW), South Africa (150 MW) and in the USA (110 MW), Israel (121 MW), Chile (110 MW), Saudi Arabia (100 MW), China (50 MW) and India (25 MW).

It should be noted that since 2015 wind energy has been a leading source of the new renewable energy facilities in Europe, China, and the USA. Wind generation with a total installed capacity of 63 GW was introduced between 2015 and 2017. In 2018 the entire global installed wind energy capacity is 433 GW. RES markets are emerging in Africa, Asia, and Latin America. Currently, wind energy meets electricity needs in many countries, such as Denmark (42%), Germany (more than 40%), Uruguay (15.5%) in 2017.

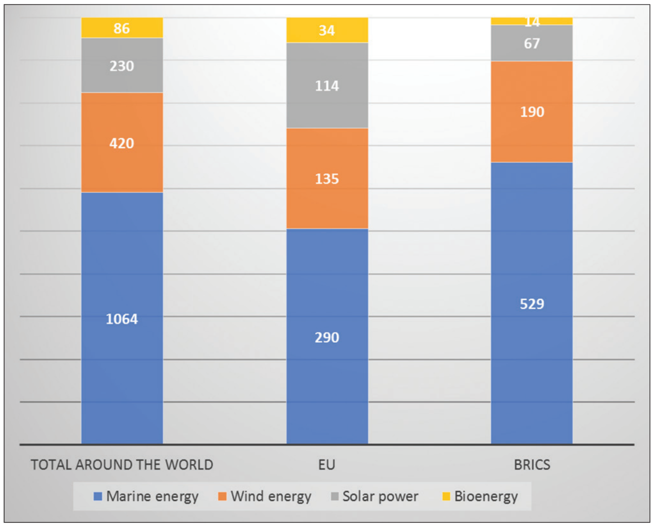
There has been a growth in biomass heat markets by 3% as compared with 2014. The use of such RES is rapidly gaining momentum in China, Japan, Germany, and the United Kingdom, by 8% per year on average. 2017 saw the development of biofuels in thermal and biological ways, which allows increasing capacity and volume.

Figure 2 shows the renewable energy installed capacity throughout the world, in the EU, and the BRICS at the end of 2017. The total renewable energy installed capacity (without hydropower) was 921 GW in 2017. The total renewable energy installed capacity:

- Hydropower -1090 GW
- Bioenergy - 112 GW
- Geothermal energy - 13.5 GW
- Solar power - 303 GW
- Wind energy - 487 GW.

So, as practice shows, the global renewable energy resources are enormous. Their involvement in the energy balance will make it possible to solve the energy problems with a complete abandonment of fossil fuel extraction. Exact quantitative estimates for renewable energy resources are hardly likely. Figure 3 shows the projected values of the expected growth in installed capacity for the heat and electricity production based on RES, (GW) taken from UNESCO reports (UNESCO report on science: On the way to 2030, 2015).

Figure 2: Renewable energy installed capacity in the world, the EU and BRICS at the end of 2017



Source: http://www.ren21.net/wp-content/uploads/2017/10/17-8399_GSR_2017_KEY-FINDINGS_RU_low.pdf

Unlike the European countries, the funds allocated for R&D in Russia are small, therefore the scale of RES introduction is insignificant. One of the essential conditions necessary for implementing RES is legislative support for consumers and manufacturers of RES facilities and their protection against the actions of energy monopolies not interested in the development of RES. Despite some problems, domestic developments and technologies for implementing RES are being introduced in Europe, for example, for small hydropower plants; use of biomass, geothermal power plants. Figure 4 shows the development of the electric power industry in Russia, including RES.

The total capacity of Russia's power stations has been steadily growing since the 2000s and has reached 240 GW. Most of the power capacity (67.9%) falls on thermal power stations, 20.2% - hydroelectric power stations, and 11.7% - nuclear thermal power stations. RES in Russia are at an early development stage. Since 2013 the country has begun to develop this segment through the mechanism of the power delivery contract. In Russia, RES are mainly represented by solar and wind power plants. The total capacity of RES is more than 560 MW (0.2% of all capacities). At the end of the first half of 2017, the capacity of solar power plants was about 460 MW, the capacity of wind power plants was about 100 MW.

4. METHODS AND MODELS

Wind turbine and solar power generators convert the energy of the sun or wind into electrical energy. All processes associated with the use of the current value of wind speed, or the magnitude of solar radiation have a complex random character. The generator power output can be represented by a sequence of rectangular impulses of constant amplitude (A), random duration (L) arising at a random time (t). The capacity of RES (W) which is a periodic function of time (T) depends on a number of factors and indices necessary to determine the efficiency of the electric power generator.

When implementing the impulsive, random process I(t), the pulse shape is defined through a deterministic function that is zero

Figure 3: Projected values of the expected growth in installed capacity for the heat and electricity production

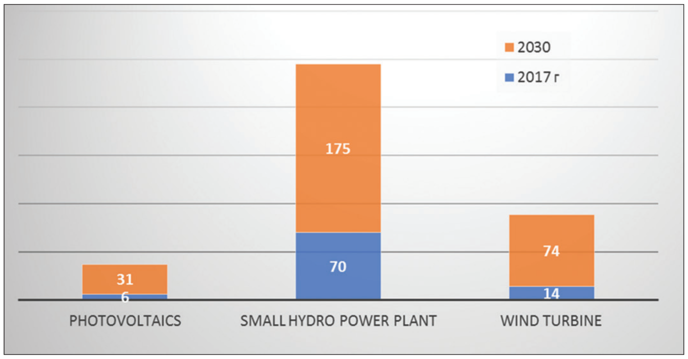
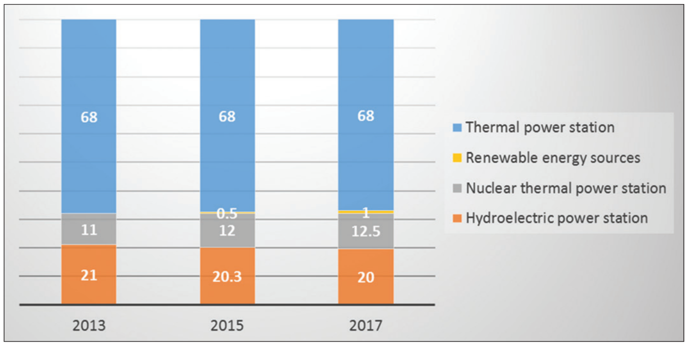


Figure 4: Development of the electric power industry in Russia (%)



Source: Review of the Russian electric power industry for 2017 (2018).

outside the interval $0 \leq t \leq 1$. The shift along the time axis by the value t_{2n} depends on the length of the interval L and the random variable μ_n with zero mean value.

$$t_{2n} = nL + \mu_n \tag{1}$$

The description of impulsive, random processes requires the use of the energy spectrum, which shows the averaged picture of the energy distribution in a random process over the frequencies of elementary components that do not take into account their phase structure. As is evident from physics, the energy spectrum of the impulsive, random process with deterministic clock intervals consists of a continuous part and a discrete part. The energy spectrum for an electric generator model with an output energy flux (a sequence of rectangular impulses with a deterministic clock interval) is represented by the formula (2).

$$F(\omega) = \frac{4a^2}{\omega^2 \mathrm{T}} \left[\begin{array}{l} 1 - \dfrac{\sin^2 \alpha\omega T}{\alpha^2\omega^2T^2} + \left(\dfrac{\sin^2 \alpha\omega T}{\alpha^2\omega^2T^2} - \dfrac{\sin^2 \alpha\omega T}{2\alpha\omega T} \right) \cos \omega\tau_0 \\ + \dfrac{4\pi}{T} \left(\dfrac{\sin \alpha\omega T sin \dfrac{\omega\tau_0}{2}}{\alpha\omega T} \right)^2 \sum_{\tau=-\infty}^{\infty} \delta\left(\omega - \dfrac{2\pi\tau}{T} \right) \end{array} \right] \tag{2}$$

Where τ is an averaged value of the impulse duration; α is a relative value of the time length of the pulse modulation.

The models described by aperiodic impulse random processes with energy accumulation differ from those without energy storage for which the difference between two consecutive pulses cannot exceed twice the duration of the clock interval $\alpha_n = t_{2n+2} - t_{2n}$ (3)

The energy spectrum of such a model can be expressed as follows:

$$F(\omega) = \frac{2a^2}{\mathrm{T}} \left\{ \begin{array}{l} \left[1 + \left(\dfrac{\sigma}{\alpha} \right)^2 \right] \mathrm{K}_0(\omega) + \\ 2\mathrm{Re}\left[\dfrac{\mathrm{n}(-\omega)\mathrm{n}_1(-\omega)\theta_{1\tau_\iota}(\omega)}{1 - \theta_{1\mu}(\omega)} \right] + \dfrac{\mathrm{n}^2(0)\tau_0^2}{T} \delta(\omega) \end{array} \right\} \tag{4}$$

Such mathematical models, describing electric energy generation processes, make it possible to optimize and create adaptive energy systems.

5. RESULTS AND DISCUSSIONS

Based on the trends in the energy market, it should be noted that the development of RES directions is associated with the use of a different spectrum of energy source technology shown in Figure 5.

Modern RES technologies make it possible to use microgenerating adaptive energy complexes containing several (two or more) RES for off-line electric and/or heat supply facilities. The use of technologies and composition of RES equipment must take into account the geographical and climatic features of the region, and be economically feasible.

Such adaptive energy complexes are a technology-integrated process system containing RES. Hybrid technologies of RES are known for wind-solar, wind-diesel and wind-solar-diesel installations using two and three RES, which can be recallable only under certain conditions (availability of appropriate energy sources).

For instance, Bogatyrev and Kreymer (2003) developed a simulation model that reflects the dependence of the propeller shaft capacity on the wind speed and propeller radius at a constant rotation frequency. The mechanical rotational energy of the wind wheel W_m is determined by the use of wind energy C_p. Doroshin et al. (2011) performed calculations that proved the possibility of using the complex of wind, heat pump, diesel installations, and hydrogen accumulation systems. However, the simulation model was not built to address the problems of its further testing. In his works, Russian scientist Popel (2007) was able to model the configuration of complex RES, a PV battery, a wind turbine, and their combination is chosen as the primary energy sources. An electrochemical battery and a hydrogen storage combination were used as an accumulation system and secondary energy sources.

Sidelnikov (2003) proposed a design method for an energy complex based on RES consisting of wind, solar and hydraulic power plants using a simulation and optimization model that can be used as part of CAD systems based on RES. However, it is only on paper.

As you can see, all the considered complex systems using renewable energy in Russia are those using two, three, maximum four RES. Taking into consideration the fact that the consumer of equipment does not have an idea about the capabilities of the RES cluster systems, and there is no mathematical apparatus for optimizing them for a consumer and linking them in place due to the objective conditions and consumer's capabilities, we attempted to design a simulation model taking into account area capabilities trio- (three), quatro (four), penta- (five), sextet- (six), sept- (seven), oct- (eight) clusters of RES. The consumer wants to have energy in all conditions, which is a fact of life. The most comfortable level of energy supply is the one in which the consumer does not think about the connected loads and has an unlimited possibility of the increased capacity of electrical equipment.

In this study, we propose an adaptive simulation model with simultaneous application of a wide range of energy sources with the same type of coupling, where the system parameters: $\Theta_1, \Theta_2 \ldots \Theta_m$ are the system characteristics which are constant over the entire interval T, where $T = [t_{0,} t_1]$ is the system simulation time interval. The effectiveness of the model depends on the environmental concerns: V_b - wind speed (wind turbine), £ - insolation; T - temperature, R - mode of methane generation, types of clusters used, depending on the kinds of RES in the system, as well as on the cost of production of 1 kWh by different types of RES and the cost of 1kWh of the RES installed capacity.

We introduce the object of the simulation model of the study in the form of a structural diagram shown in Figure 6, which has the following parameters:

Xi - Input parameters (cost of power generation, cost of the installed capacity, etc.)

Yi - State parameters (the cost of power generation by the CS of RES)

Zi - Parameters of perturbing impulse actions (wind speed, insolation, temperature, etc.).

Figure 5: Examples of technologies based on the use of renewable energy sources (%)

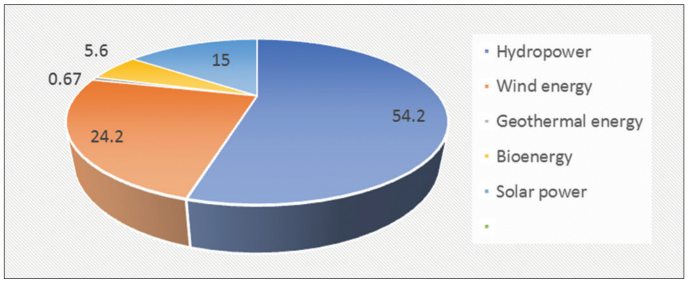
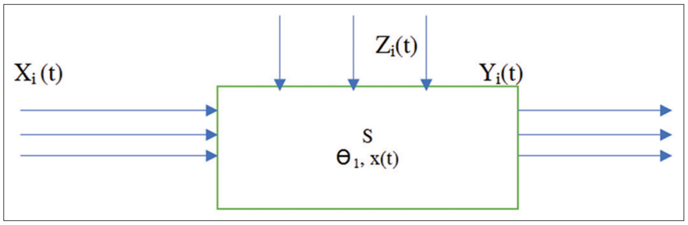


Figure 6: Structural diagram of the simulation model



$Z_i(t)$

X_i (t) $Y_i(t)$

The task is to determine the optimal composition of RES equipment of the installed capacity, which allows determining what type of renewable energy will be optimal, i.e., with a minimum cost of generating 1 kWh of electricity for the area under study.

The effectiveness of the mathematical simulation model of the used RES cluster is represented by the equation:

$$Э=f\,\{k\,(M_k, M_n, M_l M_s, M_f);\ k(d,h,k,p,s,sp);\ C_c\ U_i\} \tag{5}$$

Where Э - an indicator of the RES cluster efficiency

k - a set of environmental concerns

M - the type of cluster depending on the fraction of power being replaced (clusters: M_k -micro; M_n -mini; M_s-small; M_l -medium; M_f - full).

Types of clusters depending on the types of RES in the system: (d-double hybrid, h-trio cluster, k-quatro cluster, p-penta cluster, s-sextet cluster, sp-sept cluster) and the cost of production of 1 kWh by different types of RES and the cost of kWh of the RES installed capacity: C_c - the cost price of production 1кВт-ч various kinds of RES; U_i - cost of kW of the RES installed capacity.

It is assumed that the external perturbing parameters Z_i are random. Each factor Xi has a definition area, for example, the cost of generating kWh of energy, the unit cost of equipment per 1 kW of installed capacity, etc. All the parameter values are known to be imposed restrictions on by r_i. It should also be noted that the operation of RES is always subject to the influence of random perturbations Z_i.

We determine the dependence of environmental concerns as follows:

$y = f\,(x_{1,} x_{2,} \ldots x_n)$ and find the values

y_{max} and y_{min}), then we build the target response function:

$$y = y\,(x_{1\ opt,}\ x_{2\ opt,\ldots}\ x_{nopt}) \tag{6}$$

And find the values ($x_{1\ opt,}\ x_{2\ opt,} \ldots\ x_{nopt}$), which provide the extremum of function:

$$y = y\,(x_{1\ opt,}\ x_{2\ opt,} \ldots\ x_{nopt}) = y_{min}\,(y_{max}) \tag{7}$$

If we assume that W_n is the amount of energy produced by RES, and q_n is the operation cost of equipment (RES) for an hour, then we calculate it for each of the random parameters:

$$Q = q_n/W_n \tag{8}$$

Where Q - the cost of energy produced by RES, subject to the influence of random perturbations.

The choice of equipment for the RES cluster of in the system (d, h, k, p, s, sp) should be economically feasible. The search for the optimal equipment for the renewable energy cluster is necessary to reduce the initial costs of purchasing an efficient and independent energy supply system. We assume that the permissible level of the average cost is 1кВч $S \leq q_0$, and the restrictions are as follows:

$$\text{đ}_0+\text{đ}_1+\text{đ}_2+\ldots+\text{đ}_n=1; \tag{9}$$

$$\text{đ}_0 q_0+\text{đ}_1 s_1+\ldots+\text{đ}_n s_n=S \tag{10}$$

Where đ_0 - energy fraction generated by risk-free energy sources
đ_n - energy fraction generated by risky energy sources (RES)
q_0 – operation cost of a risk-free source per unit time
at which $\text{đ}_i \geq 0$, i=0, 1…n

The work of a risk-free energy source will be considered independent of random perturbations. The work of other sources of RES is subject to random perturbations (for example, the use of wind and solar energy WDPP (wind-driven powerplant) + PV (flexible PV device). These are risky sources, depending on random variables (wind, sun, etc.). The risk in this model will appear in the variation of the electricity cost generated by the RES cluster per unit time.

The cost variance for the energy generated by the RES cluster per unit time D(Y/a) is an objective quadratic function of $x_1, x_2, \ldots x_n$ n n

$$D(Y/n) = \sum\sum\sigma_{ij}\, x_{ij}\, y_{ij} \tag{11},$$

Where
x_i - the proportion of installed capacity of each of the RES included in the RES cluster;
σ_{ij} - the sample covariance calculated from the samples for Y_i, Y_j in the context of the following restrictions:

$$x_0+x_1+x_2+\ldots+x_n=1$$

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

$$x \geq 0,\ i=0,1,\ldots,\ n$$

$$A<r_0.$$

The construction of the vector (“Markowitz bullet”) will allow determining the optimal RES cluster. The proportions of the installed capacities of the RES cluster are defined by the vector of mathematical expectations b_k, and the covariance matrix with the components σ_{ij}, and are found from the samples for Z_i. Then, the values of the objective functions are determined, and the samples of the optimal RES cluster are grouped.

Thus, the use of the simulation adaptive model makes it possible to determine the optimum configuration of the RES cluster regarding composition and installed capacity of the equipment.

In view of the foregoing, it is necessary to note the importance of the development of work on experimental development and further improvement of simulation models of complex power plants using RES in Russia, taking into account the significantly different real climatic operating conditions and consumer characteristics. The need to introduce an integrated approach to the energy supply in Russia is conditioned by a whole range of unique peculiarities of our country: The length of the territories; remoteness of consumers from centralized networks; low population density in remote areas; preservation of the ethnos; low incomes of a significant part of the population.

6. CONCLUSION

In conclusion, it should be noted that unconventional and RES are the strategic future of humanity because of the inevitable rise in price and the exhaustion of natural resources, and in the long term, nuclear materials for the functioning of nuclear power engineering. Each research into the development of renewable energy is an approach to the more efficient use of RES. The cluster approach in the development of renewable energy allows consumers to choose the most appropriate RES cluster for remote areas, and optimize it regarding composition and installed capacity, which in its turn will lead to increased reliability of energy supply, lower total costs, and increased energy efficiency.

Many countries set themselves the tasks of an expanded cluster implementation of RES. Pride of place goes to Western European countries. According to the report of the European Commission, the EU’s goal in the field of renewable energy is coordinated actions ensuring that the share of renewables in power generation will reach 12% by 2020. Thus, in the coming years, RES will be able to change the fuel and energy balance of both individual countries and the world community as a whole.

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