Ways to improve the energy efficiency of renewable energy sources

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Abstract. The ways of increasing the energy efficiency of the use of renewable energy sources are considered. The descriptions of universal energy complexes that simultaneously use converters of various types: solar rays, wind flows into electrical energy, patented at SKGMI (GTU) are given. The prospect of using renewable energy sources for autonomous power supply of objects in mountainous regions has been substantiated.

1. Introduction
Currently, there is a widespread introduction of renewable energy sources (RES) in various areas of energy supply [1-2], in connection with which the increase in the energy efficiency of the use of RES becomes important. The use of RES is characterized by different types of efficiency: economic, social, environmental, energy. These types are inextricably linked, and a separate consideration of each type is of a methodological nature, designed to accentuate certain parameters of the single process of using RES.

Next, three types of RES will be considered: solar panels, wind farms and low-power hydroelectric power plants.

2. Materials and methods
The energy efficiency of the use of RES is determined by the following main parameters: the energy payback period; the price and quality of the generated energy; stability of output parameters; reliability of power supply, etc.

The main ways to increase the energy efficiency of renewable energy sources are shown in Figure 1. The most significant ways are: increasing the efficiency of primary converters of natural energy flows (sun rays, wind, water flow) into electrical energy; reduction of the energy payback period; prevention of anomalous impact of natural environmental factors on RES facilities - manifestations of various kinds of environmental risks. These methods are integral, generalizing in nature and determine the general state of the facility that generates renewable energy. In figure 1, in addition to those already listed, other methods that are important for practice are also indicated.

One of the main ways to increase the energy efficiency of renewable energy sources is to reduce the energy payback period of power plants based on renewable energy sources (photovoltaic, wind and micro HPPs). In this case, the full life cycle of the object is considered: production of the installation, including all auxiliary operations; installation with the necessary change in natural conditions; operation and disposal of used parts of the installation and further - the installation itself. For the
implementation of all components of the full life cycle of an object, a certain amount of energy is spent, which is sometimes called "connected" [3].

\[
T_{ok} = \sum_{k=1}^{N} \frac{W_k}{W_{av}} \cdot t_{ok}
\]

where \(W_k\) - energy consumption at the "k" stage of the life cycle of the object under consideration, kWh;
\(W_{av}\) - average annual energy production by the facility, kW·h/year;
\(t_{ok}\) - is the term of the object's energy recoupment, year.

In the formula (1), \(W_k\) and \(W_{av}\) are determined by calculation or experiment for the object under consideration; the energy payback period is defined as the ratio:

\[
T_{ok} = \sum_{k=1}^{N} \frac{W_k}{W_{av}}
\]

As already mentioned, to reduce the energy payback period, the energy intensity (energy consumption) should be reduced at all stages of the complete life cycle of RES use. In addition, it is necessary to increase the level of energy output by the facility for the development of renewable
energy sources, increasing its operational and technical characteristics and implementing various methods of increasing energy efficiency.

One of the ways to increase the energy efficiency of using renewable energy sources, as shown in figure 1, is the concentration of natural energy flows, an increase in their intensity. The sun's rays and wind are characterized by a low concentration of energy (the amount of energy per unit area of the working surface of the converter installation). This leads to the need to use various kinds of concentrators.

3. Results
In the installations developed at the North Caucasian Mining and Metallurgical Institute (State Technological University), Vladikavkaz [4-8] concentrators, respectively, of solar rays and air flow are used. To increase the intensity of solar irradiation in the wind turbine, reflectors are used that direct the sun's rays to the working surfaces (solar panels) of the installation; to increase the effect of the wind, a guiding device is used that changes the direction of air movement towards the working body - the blades of the wind generator drive. The use of concentrators can increase the productivity of the installation by approximately 1.2÷1.5 times.

One of the problems associated with the use of renewable energy sources is the inconstancy of the parameters of natural energy flows used in energy generation. The wind can change speed and direction; solar irradiation can change with changes in weather conditions (clouds), with a change in the time of day, etc. All this leads to significant fluctuations in the output power of the installation. However, the power supply to consumers should not depend on fluctuations in the output power, therefore, wind and solar generators must have appropriate devices that stabilize their output parameters.

One of the effective ways to stabilize the output parameters of generating sets using RES is the use of intermediate energy storage devices (figure 2).

![Figure 2. Scheme of using a storage device in a RES generation plant.](image)

In figure 2 SES - natural energy flows of renewable energy sources, which in the primary converter (generator) are converted into electrical energy, which can be transferred partially to the consumer and partially to the storage device. The energy balance equation in general form will be:

\[ S_G = S_P \pm S_N \]  \hspace{1cm} (3)

\( S_G \) - output power of the converter (solar panel, wind generator, etc.);
\( S_P \) - the power consumed by the load;
\( S_N \) - the power transmitted to the storage device.

With an excess of generated power, part of it is transferred to the storage device, and it operates in the consumer mode ("+" sign). If the generated power is insufficient (in comparison with the one required for normal operation of the consumer), it comes from the storage device and the power \( S_N \) has a "-" sign (goes with a plus to the first part of equation (3)).
In some cases, all the power from the generator goes to the storage device, the energy consumption of which must be significantly higher than the power consumption of the load in order to create a stability margin in the general energy system using RES.

More formally, a real electrical circuit with power supply from renewable energy sources can be represented as a circuit with an active four-pole, shown in figure 3.

![Figure 3. Equivalent electrical circuit of power supply from renewable energy sources.](image)

**E<sub>VN</sub>** - a source of EMF of an active four-terminal network.

An essential point when using an active four-port network is the condition that its power and energy capacity could compensate for both fluctuations in energy supply from RES and possible fluctuations in energy consumption by the load. To do this, its energy parameters in the calculation should be selected with a margin that takes into account the possibility of these fluctuations.

As you know, an active four-pole, i.e. containing the EMF **E<sub>VN</sub>** inside itself, can be replaced by a passive one, if you short-circuit all the EMF contained inside the four-pole, replacing them with internal resistances, and add additional EMF into the equations of the four-pole: EMF **E<sub>01</sub>** into the primary circuit, and **E<sub>02</sub>** into the secondary EMF, which are equal to the voltages at the ends open clamps of this active four-port network.

Using this technique, we write the equations of an active four-port network in symbolic form, for example, for a fairly common Z-form:

\[
\dot{U}_1 = Z_{11} \cdot I'_1 \cdot Z_{21} \cdot I'_2 + \dot{E}_{01} \tag{4}
\]

\[
\dot{U}_2 = Z_{21} \cdot I'_1 \cdot Z_{22} \cdot I'_2 + \dot{E}_{02} \tag{5}
\]

When deriving equations (4), (5), it was assumed that the EMF of the sources does not depend on the currents in them. Based on the above reasoning, you can write down the equation of the four-port network in other forms and use them in accordance with the specifics of the task. The introduction of an intermediate four-port network with an energy storage device between the generator and the consumer is an effective means of stabilizing the output parameters of a RES power plant.

For individual objects using energy supply from renewable energy sources, an important circumstance is the possibility of placing a generator set in close proximity to the consumer (for example, placing solar panels on the roof of a house to supply electricity to consumers inside it). At the same time, there are practically no energy losses for its transportation, which significantly increases the energy efficiency of the use of RES.

In general, you can write:

\[
P_{GEN\text{H}} = P_{PR} + P_{TR} + P_N \tag{6}
\]

- **P<sub>GEN</sub>** - full power of the generator set;
- **P<sub>PR</sub>** - power of converting devices;
- **P<sub>TR</sub>** - power of transmission (transmission) of energy to the consumer;
- **P<sub>N</sub>** - power consumed directly by the load.

To transport energy, appropriate converting devices and transmission lines or cables are required. Lack of transportation means direct consumption of the output power at the place of its production. At
the same time, there are no losses both in converting devices and in power transmission lines. In addition, the reliability of the system increases, the production of energy becomes cheaper; the accompanying environmental effects decrease in general - the energy efficiency of the use of renewable energy sources increases.

4. Discussion

As an example of the spatial combination of a generator and a consumer, a road dividing block with an illumination system [8], which is supplied with electricity from renewable energy sources - wind and photovoltaic generators located directly on the block (Patent No. 196315 published on February 25, 2020, authors Yu.S. Petrov, M.K. Khadikov, A.K. Muzaev).

On the upper part of the block there is a bladed wind wheel, using the effect of oppositely moving air flows (in accordance with the oncoming traffic of traffic flows on opposite sides of the block, which is part of a separation road barrier); solar panels are applied to the sides of the block; inside the block there are switching, storage and conversion devices, from which electricity is transmitted directly to the luminaire, fixed on the side surfaces of the block.

Self-sufficiency in the lighting system of the road separation barrier allows for a reliable and efficient lighting system on motorways.

The features of energy generation from renewable energy sources allow the development of hybrid plants that implement various generation principles in one device. An example is developed at the North Caucasian Mining and Metallurgical Institute (State Technological University), Vladikavkaz, wind turbine plant [7] (patent No. 188444 published on 12.04.2019, Yu.S. Petrov, M.K. Khadikov, A. A. Sokolov, A.K. Muzaev).

The principle of operation of a wind turbine consists in the simultaneous conversion of wind energy and solar energy into electricity. The benefits of this transformation are clear. Firstly, the power of the power plant increases with practically unchanged dimensions in comparison with the sizes of installations using only one type of conversion. Secondly, the reliability of generation increases, since in the absence of one source of energy, another can operate; termination of the action of two energy sources of different types at once is unlikely. Thirdly, the total density of energy taken from a unit volume of total space increases, i.e. there is a concentration of the used energy flows by superimposing them on each other in different parts of the general converter installation. Fourthly, the environmental damage from the operation of a hybrid plant is reduced in comparison with plants using only one type of RES (single-profile type).

And, finally, it should be noted an obvious decrease in the energy payback period for hybrid installations - due to a significant increase in power.

Theoretically, hybrid installations that combine renewable energy sources of any type (wind, solar, hydro and other converters) have the right to exist. The development of hybrid plants of a specific type depends on the availability of this type of renewable energy in one place, on the characteristics of the consumer, the environmental situation, etc. According to some scientists [9-11], hybrid installations for the simultaneous use of RES of various types have a great future.

An increase in the energy efficiency of a RES installation can also be achieved by implementing a coordinated regime between the energy source and the load. As you know, in the case of a linear active two-terminal network with a known internal resistance $R_{VN}$ - for direct current and for alternating current (in the general case $Z_{VN}= R_{VN} + jX_{VN}$, i.e. it consists of active $R_{VN}$ and reactive $X_{VN}$ components), the conditions for the release of maximum power in the load are as follows:

- For direct current:

$$R_{N} = R_{YN}$$

(7)

- For alternating current:

$$R_{N} = R_{YN}, \quad X_{N} = X_{YN}, \quad Z_{N} = Z_{YN}$$

(8)
That is, the complex resistance of the load must be equal to the conjugate complex internal resistance of the energy source.

In the event that the internal resistance of the energy source (active two-terminal network) is nonlinear, as, for example, for a solar battery, the relationship between the resistances of the source and the load becomes more complicated and for the analytical determination of the parameters of the matched mode one should have an analytical expression for the output current-voltage characteristic of the source.

To increase the reliability of power supply to consumers, it is possible to create a network of autonomous power plants that use renewable energy sources, and form a single energy system that autonomously supplies a certain number of consumers. In addition to generating sets and consumers, such a network will include general energy storage and distribution system, the energy intensity of which will depend both on the number and power of consumers and on fluctuations in the generated power in the system.

The use of various types of converters (wind, hydro, solar batteries) in the general generation network will significantly reduce the risks of critical fluctuations in the generated power in the general system (simultaneous failure of various installations is unlikely), and will increase its resistance to changes in external factors.

Figure 4 shows a diagram of the application of a network of installations containing wind, hydro generators, and solar batteries.

The network works as follows. The energy generated by the different installations is transmitted to the general switchgear together with the necessary information about the operation mode of the installations. From consumers to the switchgear, information is transmitted about the power required for the normal operation of consumers. The generated power is distributed among consumers; in case of its lack, the storage station is activated. With an excess of generated power, it replenishes the energy reserves of the storage station. The switchgear operation is organized in accordance with the information received from consumers, storage station and generator sets.

In some cases, to increase the overall reliability of the network of complex RES facilities, the system can be supplemented with a diesel generator. It will be turned on in abnormal situations of a sharp decrease in the capacity of generating renewable energy.

The operation of various generating sets using renewable energy sources on a common (autonomous) power grid with the corresponding consumers and a storage station will significantly increase the operational parameters of the system; improve its energy performance, and, consequently, the energy efficiency of using renewable energy sources.

Mountain areas have wide opportunities for using renewable energy sources. However, in mountainous conditions there is a real danger of manifestation of environmental risks of various natures. The most typical of them are: river floods, mudflows in summer, snowfalls and avalanches in winter; showers, strong winds, rockfalls, etc. up to environmental disasters (for example, the gas-
dynamic discharge of the Kolka glacier into the Genaldon river gorge in 2002 (North Ossetia - Alania)).

In a number of cases, and not only in mountainous areas, natural factors can cause accidents both in the centralized electric power system and in autonomous power supply systems using renewable energy sources. Energy efficiency, the stability of the operation of electrical installations in this case will significantly depend on the possible hazardous impact on them of environmental risks, in particular, mountainous areas, especially since the bulk of installations on renewable energy sources are located, usually, in mountain conditions due to the presence in them a large number of renewable energy sources of various types.

For renewable energy installations, abnormal natural impacts will have the most destructive consequences, because these installations directly use natural energy flows (wind, water flow in a mountain river) in their own designs. Therefore, the prevention of the impact of natural hazards on generating sets using RES is of utmost importance.

Environmental safety, and, consequently, the energy efficiency of installations using renewable energy sources, can be ensured by implementing appropriate measures both at the design stage and at the stage of plant operation. When designing, it is necessary to take into account the degree of environmental risks in the place of the future location of the installation, the dynamics of changes in the environmental situation in the relevant area. During operation, it is necessary to observe measures to prevent the impact of environmental risks on the generating sets.

The algorithm of actions to prevent the dangerous impact of environmental risks on generating sets using RES is shown in figure 5. To ensure environmental safety in the area under consideration, first of all, information about the ecological state of the natural environment (OPS) is needed, which can be obtained, in particular, using a GIS (geographic information system) for the relevant area, as well as information on the parameters of natural energy flows (CES) - wind, river flows, sun rays, which are involved in the corresponding generator sets.

The assessment of the degree of hazard of environmental risks is made by comparing information on the environmental parameters \( P_i \) of the environment with their normalized \( P_{iN} \) values:

\[
\frac{P_i - P_{iN}}{P_{iN}} = \delta_i \leq \delta_{iD}
\]

where \( \delta_i \) and \( \delta_{iD} \) - real and permissible, respectively, relative deviations of the "i" -th ecological parameter \( P_i \) of the environment from the normalized \( P_{iN} \) value.

Cases of excess of \( P_i \) values over \( P_{iN} \) are considered, that is \( P_i \geq P_{iN} \). Cases \( P_i < P_{iN} \) certainly satisfy the safety conditions and therefore are not involved in further analysis.

If all real deviations \( \delta_i \) satisfy condition (9), then the ecological situation is recognized as normal, not dangerous for the operation of generating sets with renewable energy sources. If any one parameter \( \delta_k \) (or several parameters) does not satisfy condition (9), then the situation is recognized as dangerous (according to one or several parameters) and the implementation of measures is required to reduce the influence of relevant natural factors on autonomous generating sets.

After the implementation of the required measures, the monitoring of the ecological state of the environment and the parameters of natural energy flows is carried out again. If necessary, the described cycle is repeated. Prevention of the hazardous effects of abnormal manifestations of natural factors is a guarantee of stable operation of generating sets based on renewable energy sources, a significant way to increase the energy efficiency of renewable energy sources.

5. Conclusion

The use of renewable energy sources takes an increasing part in the general energy of almost any industrialized country and is increasing every year. To increase the energy efficiency of the use of renewable energy sources, it is necessary to: increase the efficiency of conversion plants for energy generation based on renewable energy sources; take measures to reduce the energy payback period of
installations, focusing on their entire life cycle (production, operation, disposal); using concentrators of various kinds to increase the concentration of natural energy flows, converted into electrical energy; stabilize the output parameters of generating sets, in particular through intermediate energy storage. A promising direction in the development of renewable energy generators is the creation of hybrid plants that combine converters of various types. The practical advantage of autonomous conversion plants based on renewable energy sources is the possibility of their spatial location in the immediate vicinity of the consumer and the possibility of implementing a coordinated mode of the generator and load. However, it should also be noted that the reliability of the operation of autonomous generating sets powered by renewable energy sources depends on external conditions - on the ecological situation in the natural environment, in connection with which it is necessary to take timely measures to prevent the dangerous impact of environmental risks on the power supply system of autonomous generating sets using renewable energy sources.

**Figure 5.** Algorithm of actions to prevent the dangerous impact of environmental risks on generating sets using RES.

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