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Development of a methodology for calculating the consumption of a combined renewable energy source for a mini–workshop

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Abstract. A methodology for calculating the consumption of combined alternative energy sources is proposed. The provision of electrical energy to the mini–workshop area for 7 hours a day with equipment that constantly consumes 5.5 kW of electricity was considered. The amount of electrical power needed to meet daily needs has been calculated. It is Rd = 38.5 kWh. Solar stations' daily solar energy output is determined by considering the required backup power. It is Rst = Rd ·2 = 77.0 kWh. The total power of the solar panels is found. It is Rsp = 9.7 kW. The number of solar panels for the proposed Solar LR5-54HTH-435M example is calculated as several panels Nnp = 23.3 pieces. An inverter with more than 5.5 kW was selected in the given example. Anern EVO-6200 has a power of 6.2 kW and an input for connecting a 48 V battery. Its technical characteristics are presented. A scheme for connecting 24 solar panels was proposed, connecting 12 in series into one electrical circuit. There should be two such chains that are connected in parallel. The calculation is made for a Jarrett 120Ah 12V battery. Its capacity is Rb = 1440 Wh. The battery has the technical ability to store 1440 Wh of electrical energy. The batteries should be Nb = 17.4 pieces ≈ 20 to provide a mini–workshop. The choice of a storage station with 20 pieces of Jarrett 120Ah 12V batteries was justified.

1. Introduction

Today, humanity's energy consumption is limited by the insufficiency of existing capacities for its production [1]. New energy technologies must be utilized worldwide, and their development faces many challenges. Modern methods of energy transmission prevent its uniform distribution. In addition to high equipment costs [2,3], electricity transmission over long distances leads to significant energy losses. Traditional energy threatens the stability of the global climate. This is evidenced by a critical analysis of the disadvantages of using nuclear energy, which consists of the following aspects. Nuclear and thermal power plants run on fossil fuels. Uranium mining results in the destruction of renewable lands, emissions into the environment, hazardous waste, and high concentrations of radioactive radon gas, which can irradiate miners and cause serious illnesses when inhaled. For nuclear reactors, uranium is mined and needs further processing to make it usable. For every ton of atomic fuel, 2-3,000 tons of radioactive uranium ore must be processed. The rest becomes waste and requires special processing. Reactors cannot simply be turned off at the end of their life and turned into art spaces or open-air sites. Since most components are radioactive, they must be dismantled, isolated, and buried. For more than 100 years, humanity has yet to find a way to store such waste safely. The most problematic issue is the handling of spent nuclear fuel. It remains radioactive and dangerous, with a half-life of tens of thousands of years. Currently, only interim storage facilities are in operation. Since the establishment of the industry, 11 major accidents have occurred (the melting of nuclear fuel or the failure of the reactor). Five such accidents happened during the production of nuclear fuel at the facilities. This is far more than the industry expected. Nuclear plants are designed in the most protected version against accidents, terrorist attacks, natural disasters, and fatal errors. However, experience shows that nuclear engineers must also worry about minor problems like birds and marine animals. Attacks from marine animals such as jellyfish recently challenged the “reliability and stability” of the nuclear industry. Nuclear energy is often promoted as "green" and presented as a solution to the climate crisis. However, during its operation, pollution occurs at all stages. Greenhouse gas emissions from the entire nuclear energy cycle (including all necessary stages) are 24 times higher than solar energy and only four times higher than coal [4].

Thus, using nuclear energy leads to the main dangers - increased atmospheric temperature and environmental pollution [5].

An increase in the scale of electricity production from alternative energy systems is a general trend [6,7]. Wind turbines are the most common type of these systems [8,9].

Since wind energy is free, there is much potential to use it to generate electricity. However, getting the right wind speed to convert this energy into electricity is sometimes possible. This is because they are installed in places with restrictions on climatic conditions and wind currents. Such limits include building envelopes, vegetation, etc. [10-12].

Therefore, scientific research is needed to find the best power plant design for low wind speeds and to combine this design with an alternative solar energy source [13].

It should also be noted that specific climatic features characterize certain regions. Wind speeds are low or moderate in many areas. This affects the production of large amounts of energy from wind turbines [14].

Developing systems capable of operating at low wind speeds [15,16] is one of the challenges for many manufacturers of alternative energy systems, not only in individual countries but also worldwide [17-19].

For both owners of private homes and developers of power plants, the cheapest option almost anywhere in the world is solar energy. Government incentives have made solar energy even more attractive for investment. Once installed, solar power plants have nearly zero operating and maintenance costs and can replace fossil fuels such as gas and coal. This energy is renewable and thus reduces emissions of harmful gases that contribute to air pollution and climate change. Despite the relatively low intensity of radiant energy, solar power has developed progressively in recent years [20,21].

Solar energy is currently the cheapest form of electricity in almost all countries. Between 2015 and 2022, its cost has fallen by 90%, making building new solar plants more affordable than maintaining existing coal-fired plants. As demand increases and production expands, the cost of solar PV panels is expected to decline according to Swanson's Law, which states that solar

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panels decrease by 20% for every doubling of production. Most of the cost of solar photovoltaic plants is spent on installing equipment. Still, since solar energy is free, it is possible to generate electricity with zero or negative marginal costs [22,23].

Once photovoltaic plants are installed, maintenance is minimal, which is one of the reasons why the marginal cost of solar energy is so low. Most solar panels can be easily cleaned by rain. Snow covers the solar panels and prevents energy conversion. Still, it melts relatively quickly and flows off through the sloping glass panels, increasing the amount of solar radiation absorbed by the panels due to the albedo (reflected light) from the snow-covered roof. Solar inverters convert the direct electricity generated by the panels into alternating current, fed into the home and grid, and have a lifespan of 10 to 15 years. The panels have no moving parts and an average lifespan of 25 years. The efficiency of solar panels is declining at a rate of about 0.5 percent per year. If the rate of degradation is doubled, then in 30 years, the efficiency of the solar panel will still be 74% [24,25].

1.1 Literature Review

According to the U.S. Department of ENRE Lab, a rooftop solar system that provides all of the average home's electricity needs produces 200 tons less carbon dioxide over its lifetime than a fossil fuel-powered system [26].

Although some environmental costs are associated with producing and disposing of solar panels, solar energy does not lead to ecological disasters that cause enormous human suffering and the cost of cleaning up the polluted environment. There are no solar spills, solar panel explosions, oil well fires, solar cell meltdowns, mine collapses, pipeline explosions, tanker accidents, train derailments, or refinery spills. Solar energy has helped reduce reliance on coal and has led to more than a 50 percent reduction in carbon emissions from burning coal [27].

It is already known that a third of the world's electricity is generated from renewable sources. Still, by 2050, with the growth of the world's population and increasing energy needs, the share of renewable energy may increase to maintain climate stability [28]. Therefore, the researchers believe that fossil fuels should be abandoned entirely. Thus, renewable energy is a global priority for the energy sector. Currently, the global market offers ample opportunities for the design of wind and solar power plants. But both of them, of course, are justified under certain climatic conditions. Both wind and solar energy have a significant disadvantage: hourly instability at different times of the day and at other times of the year. Solar and wind power plants peak at various times and on different days of the week [29].

In addition, factors such as regional latitude, time of year, and solar radiation also play an essential role in the amount of solar energy produced [30,31].

The usefulness of solar panels should be analyzed in this case, depending on the latitude of the installation mini-workshop, the range of the angle of incidence of the directional radiation flow, the presence of air pollution, and other climatic conditions. The maximum efficiency of converted solar energy is at most 25% [32,33].

Today, many countries are successfully developing an alternative source of energy - wind energy. It is known that the power of wind power plants depends on the use of wind energy, wind speed, operating power, availability of the wind turbine, and air density. The axial cross-sectional area of the installation is rotated by the blades of the wind farm [34].

Directly using wind energy is challenging, as wind speed is unstable, and its magnitude and direction change stochastically over time. Therefore, the temporal instability issues of both solar and wind power need to be addressed to reduce fluctuations in energy output [35].

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One possible approach is to simultaneously develop combined solar–wind power plants using wind and solar energy. Such combined installations can be used in industry to power process equipment [36] or to supply energy to ensure the maintenance of indoor climatic conditions [37]. Solar and wind farms can be better stand-alone energy sources, especially for small private buildings, cottages, small farms, mini-food processing plants, etc. [38].

This article aims to develop a methodology for calculating the consumption of combined use of solar and wind energy (vertical wind farms of medium speed) and to analyze the features of their further operation in a mini-workshop for electricity use for the manufacturer's needs.

2. Material and methods

The use of solar energy in food and processing enterprises makes it possible to reduce the cost of manufactured products and improve the implementation of the technological process by uninterrupted electrical power consumption. The general scheme of obtaining electrical energy from solar energy is shown in Figure 1.

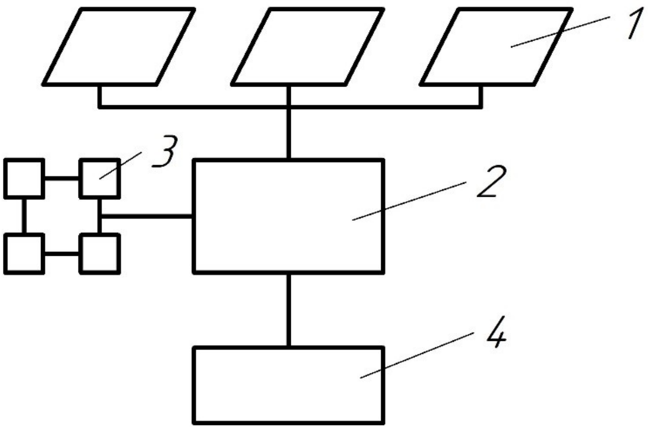

Figure 1. Scheme of using solar energy, which is converted into electrical energy:
1- panel, 2 - inverters, 3 - devices, 4 – source of electrical energy.

The mini-workshop method for calculating solar energy consumption involves calculating each element of the presented scheme. Let's consider all the aspects of the scheme separately.

1. Solar panels. These are devices that convert the energy of solar radiation into DC electrical energy. Each solar panel has two wires at the output. One wire is a positive voltage, the other - negative. The primary technical indicator of a solar panel is its electrical power. Solar panels with up to 500-600 watts are produced. Each solar panel is capable of producing electric current and voltage. The specifications indicate these indicators. For example, the Longi Solar LR5-54HTH-435M solar panel has an electrical power of 435 W. It can provide a maximum current of Imp = 13.17 A at a maximum voltage of Vmp = 33.04 V. Such a panel has the following overall dimensions: height of 1722 mm, width - of 1134 mm, and depth of 30 mm - the weight of such a panel - 22.3 kg. Thus, solar panels can be connected in parallel or series, like conventional power batteries, thereby increasing the total capacity of the solar station.

To provide specific equipment with electrical energy obtained from solar panels, it is necessary to calculate the number of panels to be installed.

Calculating the capacity of the solar station and selecting solar panels are necessary. The calculation will be carried out according to the following sequence.

1) During the day, the equipment of the mini–workshop will consume a certain amount of electrical energy Rd, which is determined by the following equation:

$$Rd = Ro \cdot Ts, \tag{1}$$

where Ro is the total power of the equipment that will work at the same time, kWh;
Ts - an indicator that shows how many hours per day the equipment works, such as hours.

When calculating, it is essential to consider the power reserve that compensates for possible low solar activity, which is affected by a sunny day or cloudy weather. Such a margin should be 2-3 times. If we take into account the last caveats, then for the example under consideration, the volume of electrical solar energy Rst should be determined by the following equation:

$$Rst = 2Rd. \tag{2}$$

2) Each solar station operates all year round, and the amount of electrical energy it produces per day varies significantly depending on the time of year. This is due to the length of the daylight during the day. The shortest length of the world day is in December; the largest is June. Figure 2 presents a diagram of the change in daylight length for 50° north latitude depending on the months of the year. On the segment of the diagram, 1 is the month of January with a daylight length of 9.3 hours, and 2 is February with a daylight length of 10.6 hours. And so until the 12th month - December, with a daylight length of 8.02 hours.

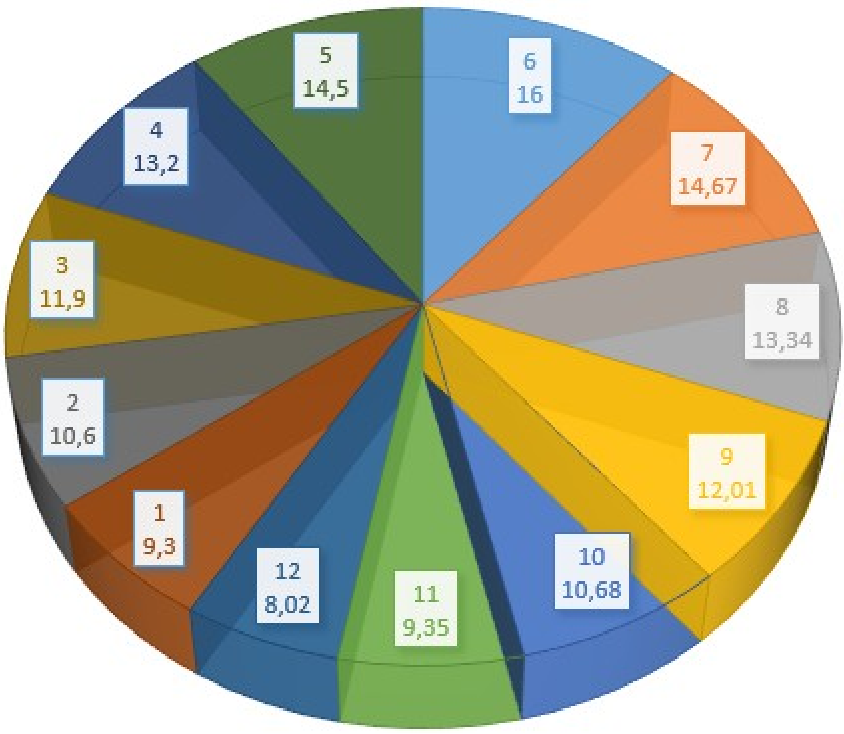

Figure 2. Diagram of changes in daylight length depending on the months of the year.

Therefore, the calculation must be carried out according to the most minor indicator. In December, the daylight for the European part of the earth at the latitude of the city Kyiv (50°north latitude) is Td = 8 hours, and in June, Td = 16 hours. The following equation determines the total capacity of solar panels R_{SP}:

$$R_{SP} = Rst/Td. \quad (3)$$

3) Calculating the number of panels Nnp is done by considering which panels will be used to install the solar station by the following equation:

$$Nnp = Rsp/Rp, \quad (4)$$

where Rp is the panel power, kW.

2. Solar inverter. The device converts the DC electrical energy of the solar panels into 220 V 50 Hz AC voltage. The leading indicator that influences the choice of inverter - is the power of the payload that can be connected to it. In this case, it must be borne in mind that some electrical appliances have high inrush currents. Such equipment includes electric motors (refrigerators, conveyors, etc.) and switching power supplies (computers, laser printers, etc.). Therefore, it is necessary to increase the power of the inverter twice if such a load is planned.

3. Accumulating devices. They allow electrical energy to be stored when there is more electrical energy than is consumed by the equipment and fed into the electricity grid when the solar panels do not provide enough energy. Electric batteries are used in systems to provide electric energy produced from sunlight. Since the batteries will be operated in charge-discharge mode, there will be at least one such cycle daily. This is because there will be at least 365 such cycles per year. Several battery types are on the market, including acid-alkali type AGM, gel, $LiFePO_4$, and lithium-ion. Acid-alkaline batteries of the AGM type can withstand at least 800 charge-discharge cycles, gel batteries - at least 2,000 cycles, $LiFePO_4$ - at least 4,000 cycles, and Li-ion - at least 10,000 cycles. The difference in these types of batteries is the cost. The main technical parameters of the battery are capacity, nominal voltage, maximum charge current and voltage, and maximum discharge current. Capacity is a technical indicator of the battery that indicates the possible amount of stored electrical energy. It is measured in A-hours (ampere-hours). The higher this indicator, the more electrical energy the battery can store. Nominal voltage is the voltage at the battery terminals. As a rule, it is 12 V. The battery charge current is measured in amperes. The higher this indicator is, the less time the battery needs to charge. For calculations, it is necessary to consider that the battery should be discharged within 25-30 % of its capacity. Li-ion batteries can be fully discharged. Calculating the storage device involves installing several batteries, capacity, and type. The use of accumulative equipment is mandatory for autonomous solar stations, the production of electrical energy, which is not constant during the day, if necessary, to ensure a continuous estimated level of consumption. This is due to different solar activity during daylight hours. In the morning and evening, the sun is low above the earth's horizon, and the sun's rays have a low electrical potential. During the day, clouds are possible, which interfere with the sun's rays, thereby reducing their electrical potential. Based on the experience of using such systems, the total operating time from the inverter batteries should be calculated as 50% of the total operating time of the station equipment. For the above example, the equipment uses 38.5 kWh per day. Therefore, for such a system, a storage station with a capacity of Rss is necessary, which is calculated according to the following equation:

$$Rss = (Rd / K_1) \cdot K_2, \quad (5)$$

where Rd - electricity consumed daily by mini-workshop, kWh;
K_1 is a coefficient that takes into account the total daily operating hours of the equipment; K_1 = 2 for 50% of the supply;
K_2 - is the coefficient considering the need to discharge the battery at no more than 70%. For Li-ion batteries, K_2 = 1; for other types of batteries, K_2 = 1.3.

A storage station must calculate and select a certain number of batteries. The batteries' total capacity must not exceed the station's estimated capacity. The calculation of the number of Nb batteries is carried out according to the following equation:

$$Nb = Rss/ Rb, \tag{6}$$

where Rb - is the capacity of one battery, kWh.

The capacity of a battery can be determined by its specifications. For example, we use the Jarrett 120Ah 12V gel battery. Such a battery has a rated voltage of Un = 12V and can withstand an output current of In = 120A for 1 hour. The following equation should determine the capacity of this battery Rb:

$$Rb = Un\cdot In. \tag{7}$$

The decisive characteristic of a solar–wind power plant is the sum of the capacities of two energy sources, which ensures better stability of its supply to the consumer. In general, the amount of energy obtained in a given period can be determined by the following equation [13]:

$$P = C_{sc}\int_{t_1}^{t_2} I\,dt + C_p \eta F \frac{\rho}{2}\int_{t_1}^{t_2} U_\infty\,dt, \tag{8}$$

where Csc is the efficiency coefficient of a solar panel;
I is the intensity of solar radiation per unit of time (the t function);
dt is the differential time;
Cp is the utilization coefficient of wind power;
η is the coefficient of efficiency of mechanical components of wind power installations;
F is the wind wheel area, m^2;
ρ is the air density, kg/m^3;
U∞ is the wind velocity (the function).

The technical characteristics of the developed medium-speed vertical wind farm were given in our previous article [13].

The equation can find the utilization coefficient of wind power Cp:

left part of capacity characteristic - $C_p = 20{,}14\,\theta^2(3-1{,}66\,\theta)$;

the right part of capacity characteristic -$C_p = 29\left[1-\frac{(\theta-1{,}2)^2}{0{,}4225}\right]$.

The annual amount of energy R_{year} can be determined using the equation [13]:

$$R_{\text{year}} = C_{sc} \sum G_{tcp} \tau_Y + \frac{\rho}{2} F \sum U_\infty^3 \tau_n C_p \eta, \tag{9}$$

where G_{tcp} is the average insolation value per hour;
τ_Y annual working hours;
τ_n is the total time (number of hours) that each wind speed is repeated.

3. Theory/calculation

We will consider the proposed method of calculation based on the example of providing the enterprise mini–workshop with electrical energy for 7 hours a day with equipment that constantly consumes 5.5 kW of electrical power. The calculation is carried out in the following sequence:

1) We calculate the volume of electrical energy necessary to meet daily needs according to equation (1).

Rd = 5.5 ·7 = 38.5 kWh.

2) We calculate the daily amount of solar energy for a solar station, taking into account the required power reserve according to the equation:

Rst = 2 Rd = 38.5 · 2 = 77.0 kWh.

3) We calculate the total power of solar panels according to the equation (3).

Rsp = 77/8 = 9.7 kW.

4) We calculate the number of solar panels for the proposed Solar LR5-54HTH-435M example using equation (4). If we use the above Solar LR5-54HTH-435M panel, with a power of each Rp = 435 W, then the number of panels is calculated using the equation:

Nnp = 9.7·103 / 435 = 23.3 pieces.

We take Nnp = 24 solar panels.

5) We decide on an inverter. There are no caveats in the above example, so we chose an inverter with a power of more than 5.5 kW. It can be an Anern EVO-6200 inverter with a power of 6.2 kW and an input for connecting a 48 V battery. Get 48 V. Also, the inverter can connect solar panels with a total voltage of up to 500 V. For the above example, it is necessary to connect 24 solar panels by connecting 12 in series in one electrical circuit. There will be two such chains, and they will be connected in parallel.

6) Thus, the total current of the solar station will be equal to 13.16·2 = 26.34 A, and the total voltage of the solar station will be 33.03·12 = 396.48 Wh.

7) We calculate the capacity of the storage station according to the equation (5).

Rss = (38.5/2) · 1.3 = 25.025 kWh.

8) Determination of the number of batteries according to the following equation (6).

For example, the calculation was made for a Jarrett 120Ah 12V battery. Such a battery has Rb = 120 · 12 = 1440 Wh. Thus, the battery is capable of storing 1440 Wh of electrical energy. To provide the mini-workshop, the above example, the number of accumulators Nb = 25.025 · 103 / 1440 = 17.4 pieces. We accept the number of batteries depending on the technical characteristics of the inverter, which was determined earlier. The Anern EVO-6200 inverter has an input for connecting 48V batteries, i.e., four 12V batteries each, connected in series. Thus, the number of batteries must be a multiple of 4. The closest number to 17.4, a multiple of 4, is 20. Therefore, it is assumed that 20 Jarrett 120Ah 12V batteries are needed to meet the enterprise mini–workshop's needs.

4. Results

MS Excel is used to automate calculations. The input information is the following indicators: the power of the equipment that needs to be supplied with electrical energy and the number of hours per day of equipment operation.

Thus, the calculations of a solar station to provide the mini-workshop of the enterprise with electrical energy for 7 hours a day with equipment that constantly consumes 5.5 kW of power are shown in Table 1.

Table 1. Fundamental indicators for the calculation of a renewable energy source.

Element for calculation	Indicators that are calculated	Quantitative indicators for the considered example
Solar panel	1. Produced volume of electrical energy per day: Rst =2 · Ro·Ts; 2. Total power: R_{SP} = Rst/Td; 3. Number of panels Nnp = Rsp/Rp.	1. Rst = 77.0 kWh; 2. R_{SP} = 9.7 kW; 3. Nnp = 24 solar panels. Longi Solar LR5-54HTH-435M
Inverter	1. Inverter power ≥ Ro; 2. The total voltage of the solar panels does not exceed the permissible voltage of the inverter.	1. $P_{Inverter}$ = 6.2 kW; 2. $U_{Inverter}$ = 500 V. Anern EVO-6200
Accumulator device	1. Capacity Rss = (Rd / K1)·K_2; 2. Number of accumulators Nb = Rss/ Rb.	Rss = 25.025 kWh; Nb = 20 pieces. Jarrett 120Ah 12V

5. Discussion and conclusions

The instability of the energy supply negatively affects the fulfillment of the requirements for the continuity of technological production processes. Intermittent centralized electricity supply, caused by wars, natural disasters, etc., with 12 hours or more outages, prompts local businesses and small farms to switch to decentralized electricity consumption. The use of an alternative source of energy will ensure uninterrupted technological processes, reduce the cost of manufactured products, and increase the stability of the energy system as a whole. The proposed method allows you to make simple calculations and choose a set of the necessary equipment. With the help of the developed methodology, it is possible to ensure the combined use of solar and wind energy for the consumer's needs. This technique uses the method of expert evaluation of equipment available on the market. Equipment and equipment are selected according to specific criteria. Such criteria are cost, country of manufacture, technical characteristics, etc. The customer's financial ability to purchase existing energy equipment is also considered. The selected equipment was calculated based on existing prices for the considered example. The cost of the inverter is 440 euros, the cost of solar panels is 2120 euros, and the cost of storage devices is 4000 euros. To meet the company's needs, it is necessary to spend an additional 6,560 euros on solar station equipment. The specific cost of 1 kW of power for constructing new fossil fuel power plants is 1090-1635 euros, cogeneration plants - 545-872 euros, and solar storage power plants - 650-850 euros. The cost of equipment for cogeneration plants and solar plants is about the same, but the maintenance costs of a solar plant will be lower. 60% of the cost of solar accumulative stations are accumulative devices. The organization of electricity consumption during the daytime will reduce the volume of the storage device, reducing the equipment cost. Also, a smaller area of land is required for installing a solar station, and there are practically no polluting factors that arise during operation, which is essential for the city.

The scientific research may continue in the future. The issue of the realization of excess electrical energy can be directly considered. In this scientific study, calculations were made for the minimum intensity of solar radiation. This corresponds to the supply of electrical energy to the consumer in December. In December, daylight hours are minimal. The amount of electrical energy produced will increase as the daylight hours increase. The excess electrical energy can be additionally used or implemented in the general energy network. Additional electrical energy will provide further financial profit. The solar power plant in the example can generate 21,078 kWh of electrical energy per year. If we compare the production of 1kWh of electricity produced from fossil fuels, then 0.68 kg of CO2 is produced. Considering the amount mentioned above of electrical energy per year, 14,333 kg of CO2 will not be released into the earth's atmosphere. Such a volume of CO2 can absorb a forest with an area of 4 hectares per year. Therefore, in addition to solving financial problems, there is an opportunity to influence the ecological component of the region positively.

The need to convert the consumer's existing equipment from grid to green electricity has many difficulties. One of the issues that needs to be resolved is finding the location of a low-power combined solar-wind electric station. It is advisable to place it directly near the consumer of electrical energy. Solar panels must be placed in a place with constant contact with the sun. A place with a suitable wind speed is required to place a wind turbine. Such factors significantly affect the use of green energy facilities. The proposed technique expands the possibility of introducing green energy in places with such restrictions.

Thus, the method proposed in the article for calculating the combined use of solar and wind energy for consumer needs has universal practical use. This method makes it possible to make calculations and select the necessary equipment. The calculated and equipment chosen, in its entirety, will be able to ensure an uninterrupted power supply for the consumer in the required volumes.

Author Contributions

M.S., O.R., V. G., and A Ch. contributed to writing the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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