USEFULNESS OF SMALL-SCALE STAND-ALONE HYBRID SOLAR-WIND POWER PLANTS IN RURAL AREAS

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Abstract. Reliability of electric energy supply and its cost-efficiency are the main indicators, which are highly important for electric energy customers. In rural areas, especially those not far from the sea, strong winds blow quite often, and they are causing a lot of damage – electricity supply failure, damage to electricity networks. As a result, villages, small settlements, farmsteads, and farms near them remain without electricity for a long time – up to a week and sometimes more. As a result, farmers and other villagers suffer significant material and financial losses. Nowadays, the cheapest power-producing RES-based power plants dominate the electricity production sector, allowing for the installation of autonomous hybrid solar-wind power plants in rural areas with sufficient wind energy resources. Solar energy resources in countries up to 60º parallel (and a bit more) are sufficient for electricity production. They do not vary much by location and are sufficient for power users in homesteads, farms, or small companies. Such a hybrid solar-wind power plant could be a continuous power supplier for local needs. Only in rare cases, when solar and wind energy resources are insufficient, could a hybrid power plant charge its batteries at night. The hybrid power plant could use the cheapest nighttime energy from the electricity system grid as a backup source to charge its battery. It can also be useful for the energy system itself, which wants to increase electricity consumption at night. In areas with abundant solar and wind resources, stand-alone hybrid solar-wind plants can produce electricity at a lower cost compared to purchasing it from the power system. The installation and operation of the experimental power plant can provide a definitive answer to this question. The article presents and describes a block diagram of connections in a stand-alone hybrid solar and wind power plant (HSWPP) and explains its benefits to its owners. The conclusions of this study and the list of literature for useful information are submitted.

Keywords: solar power plants, wind power plants, hybrid power plants, batteries, efficiency.

Introduction

Most the world's energy producers are currently making great efforts to replace old fossil fuel-based energy technologies with new technologies based on free renewable energy sources such as solar, wind, and hydropower. The phenomenon of climate warming is forcing such actions and solutions. A large number of the Earth's pollution and climate worsening indicators have been increasing in a dangerous direction for many years. The rate of deterioration of these indicators accelerated significantly at the end of the 20th century and especially in the first decades of the 21st century [1; 2]. Significant weather anomalies continued in 2023, in accordance with ongoing themes. Three summer months, three autumn months, and December saw record-breaking high average air temperatures that surpassed previous temperature records. The temperature measurement data for all months of 2023 also showed that the average annual air temperature above the Earth's surface in that year significantly exceeded previous records and was the highest in the entire history of perennial measurements [3]. The absolute majority of the world's ecologists and climatologists, after examining all the recorded long-term indicators of environmental pollution and climate change on our planet, came to the unanimous conclusion that in order to avoid catastrophic consequences on the Earth, it is necessary to abandon the use of fossil fuels and other environmentally polluting technologies as soon as possible [4-6]. International organisations and the world's most advanced countries are working hard to prevent very large catastrophic consequences or at least minimise their damage as much as possible [7].

In 2022, the International Renewable Energy Agency (IRENA) elaborated the energy development strategy for the near future and prepared the publication "World Energy Transitions: Outlook 2022. 1.5 ºC Pathway". Data are presented on the world's renewable energy development rates and planned investments, energy efficiency improvement plans, electrification, green hydrogen production and CO_2 equivalent emission removal volumes in the period from 2021 to 2050 [7]. The International Renewable Energy Agency world energy development plans for 2050 anticipate wind and solar power plants to play a leading role in electricity generation. Both of these green technologies are already firmly at the forefront of the electricity generation sector in terms of their economic, ecological, operational and health protection indicators. Additionally, judging by the number of new innovation improvements, WT (as well as PVPP) has a lot of room to improve and further reduce the cost of electricity produced. It is

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predicted that WT and PVPP will be in first place in Lithuania in the electricity generation sector after a few years. Lithuania has set itself the goal of producing 60% of its electricity from renewable energy sources by 2030. In February of this year, Lithuania achieved a significant milestone when its cumulative capacity of operating PVPPs surpassed 1 GW. March 3, 2024, will also be recorded in the history of Lithuanian electric power production, when the entire country for a short time, had enough energy produced only by wind and solar power plants. A huge step in increasing RES-based power production was made in Germany, when this country undertook to set the goal of increasing green energy production in its country to 80% by 2030.

Apart from utility-scale RES-based power plants, microgrids and small-scale power plants running on renewables will have significantly greater importance in future power production. Consumers in private homes, small businesses, and institutions will use the electric power these small autonomous power plants and microgrids produce. Large power plants, which produce power based on fossil fuels and supply it to consumers through long transmission lines and distribution networks, typically charge high prices for all services, including energy losses in a complex energy supply system. This is understandable because that system needs to be maintained, repaired, and periodically modernized. Meanwhile, the production and supply of electricity in a RES-based stand-alone small-scale power plant or microgrid for a small number of users is a much easier problem to solve. In addition, almost every year, storms in windy areas uproot trees, topple overhead power lines, and cut wires, and after this the repair work takes a long time. Microgrids and autonomous power plants can prevent such failures in advance. Local specialists can usually fix a fault much faster if it occurs.

A review of articles on small-scale stand-alone hybrid power plants (SAHPP) of various types revealed that this type of power plant has been widely used to meet small electricity needs in remote areas since the first decades of this century [8-10]. Initially, the development of SAHPP in the world did not gain a large scale because favourable conditions did not develop for it – the necessary equipment was still expensive, and the operational efficiency was quite low. The number of SAHPPs in EU countries' remote areas and islands alone now exceeds 300,000 [8]. At present, the price of solar modules has decreased very significantly: the price of PERC (Passivated Emitter and Rear Cell) has fallen to an undreamed level 0.110 USD·Wp^{-1} since January 16, 2024, and the price of TOPCon (Tunnel Oxide Passivated Contact) – to 0.119 USD·Wp^{-1} and is constant until now [11]. The warranty of solar modules was also improved and significantly extended. For example, AEG (Allgemeine Elektricitäts-Gesellschaft AG) solar modules with 23.3% efficiency are already guaranteed for 30-40 years [12]. The maximum rated power of a single solar module has also increased significantly and will continue to increase in the future. It currently stands at 675-700 Wp for bifacial solar modules. The power production of these modules will not decrease much after 30 years of operation – only by 9.25% (the module will produce 635.25 Wp instead 700 Wp) [13]. Batteries used in stand-alone HSWPPs, electric cars and elsewhere have also made great progress [14; 15]. Previously, the energy efficiency of one charge-discharge cycle of widely used lead-acid batteries was only 75-80%. Much more efficient are the Li-ion batteries, which are now in use, and the vanadium-ion batteries, which are being developed. The process of LI-ion-batteries breaking of energy density records is shown in Fig. 1 [14]. The gravimetric charge density of Li-ion batteries has increased from 80 Wh·kg^{-1} (1992) to 711.3 Wh·kg^{-1} (2023). The volumetric charge density has also increased – up to 1654 Wh·ltr^{-1} and the price of these batteries has decreased. Researchers are gradually approaching the gravimetric electricity charge density of 1 kWh·kg^{-1}, which was unimaginable just 30 years ago. The article [15] contains interesting information about vanadium-ion batteries. Asian countries such as South Korea, China, and Japan have large reserves of vanadium. The degradation of these batteries is only 1% after 20,000 charge-discharge cycles. The efficiency of this type of battery in one charge-discharge cycle is the same as that of Li-ion batteries – 96%. For comparison, it can be mentioned that lead-acid batteries usually work only about 500-1000 charge-discharge cycles in a period of 3-5 years. There is no doubt that in the near future, vanadium-ion batteries will join the group of the best batteries and will be used for various purposes, including HSWPP. A gigafactory to produce these batteries is already under construction in South Korea [15].

Two more innovations have recently emerged that can be successfully applied in stand-alone HSWPPs. Recently, this type of power plant used two separate battery charge controllers, one charging the battery from PVPP and the other from WPP. This is a useful innovation because the hybrid battery charge controller (HBCC) reduces the number of HSWPP blocks and simplifies its installation [16-19]. Another useful innovation is the battery protection unit (BPU). A low-cost BPU extends the life of the HSWPP battery B and protects it from harmful operating modes. The HSWPP can also utilize a second BPU to disconnect loads during power plant shortages [20]. BPU allows for remote control of HSWPP work. DC/AC inverters for stand-alone RES-based power plants were also significantly improved during the first decades of this century. They became cheaper and their warranties were extended up to 10 years.

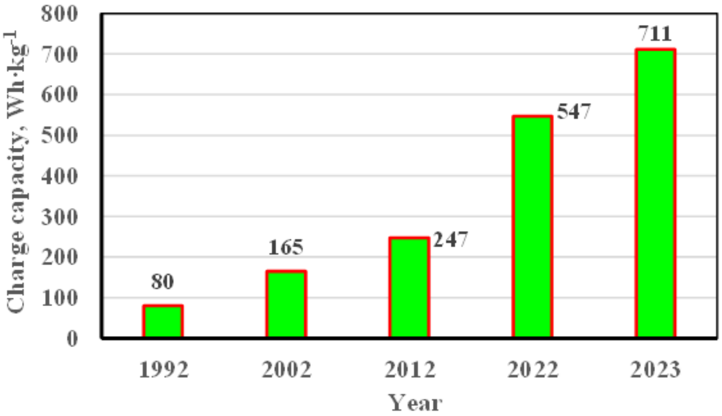

Fig. 1. **Grow of gravimetric density of Li-ion battery power charge 1992-2023, Wh·kg^{-1}**

The latest scientific articles on stand-alone HWSPP solve various problems: minimization of power storage battery capacity [21], optimisation of power generation in solar, wind, and fuel cell hybrid power plants for the islands of Thailand [22], optimal design problems for stand-alone HSWPP for hydrogen refuelling stations in Oman [23]. The article [24] examines the possibilities of supplying electricity to two cities with large solar and wind energy resources in the south-east of Iran until the year 2030. The article estimates that both cities would economically justify investments in stand-alone solar and wind power plants. One of the main conclusions presented in the article [25] is that one of the most important tasks in the design of hybrid solar and wind power plants is to optimise the sizes of all elements of the system and the ratio of these sizes. Only in this way is it possible to reduce the costs of installing a power plant and the price of the power it produces.

A review of publications that appeared in the first decades of this century on the subject of stand-alone HSWPP showed that the development of these systems has not yet reached the level we would like to have today. Despite the fact that the quality and efficiency indicators of solar modules, batteries, chargers, inverters, other equipment have improved significantly, their prices have also dropped, especially for solar modules. However, we hope that the great progress made in improving the necessary equipment will lay a solid foundation for the further and faster development of RES-based power plants in the near future. Also, we hope this article will be useful for those who are interested in self-sustaining solar and wind farms and would like to be less dependent on the power grid, rising power prices, the vagaries of nature, and belligerent neighbouring countries. It may be users who would like to compete with the main electricity system in the area of electricity prices and supply reliability.

Summarising the information presented, we can confidently conclude that it is high time for old polluting power plants to go to museums or to scrap metal, and for RES power plants, together with energy-saving measures, to strengthen, grow and establish themselves in the new pages of the history of the world's electricity production and its economical consumption.

Materials and methods

An analysis of the recent available sources of information on the topic of small-scale stand-alone HSWPP renewable energy power plant structures was carried out. Possibilities for reliable and efficient power production at a low price for electric energy were analysed. An analysis of the main indicators of small-scale solar and wind hybrid power plants, battery chargers, battery protection units, and autonomous inverters has been performed. The reviewed information was summarised, and a block diagram of connections for a stand-alone HSWPP is proposed in Fig. 2. This type of power plant is mostly recommended for coastal areas, which are characterised by the largest wind energy and solar irradiation resources in Lithuania. A second power charger BC is included in this block diagram for the case where analogous stand-alone HSWPPs are intended to be used in areas with low wind energy resources since the sun is always "on vacation" during the winter.

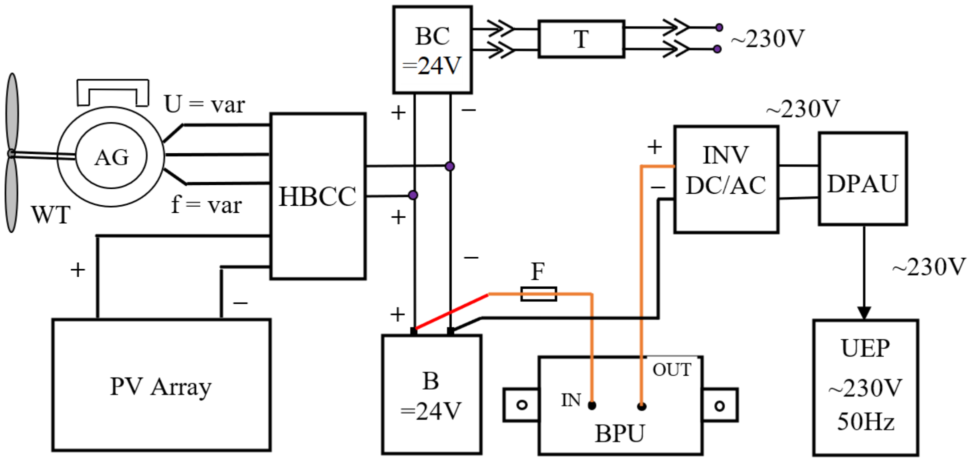

Fig. 2. **Block diagram of connections in a stand-alone hybrid solar and wind power plant:** WT – wind turbine; AG – AC generator with permanent magnets; HBCC – hybrid battery charge controller; BC – battery charger from the electric grid of the power system; T – timer for the battery charger BC; PV Array – photovoltaic array; B – battery; BPU – battery protection unit; F – fuse; INV DC/AC – inverter from direct current to alternating current; DPAU – electric energy distribution, protection and accounting unit; UEP – users of electric power

This HSWPP has two battery chargers. The main of them is the charge controller HBCC, which receives power from WT and PV array. HBCC supplies power to the battery B. Another battery charger BC and the timer T are provided for those cases where HSWPP would be installed in areas with low wind energy resources. Solar energy resources are minimal in Lithuania during the winter months (irradiance is about a few $W \cdot m^{-2}$) because the sky is almost constantly covered by clouds. Sunny days are extremely rare and short in winter. Wind speeds are also low in areas farther from the sea (mostly 1-5 $m \cdot s^{-1}$). Therefore, the second BC and the timer T can be useful in this case because the battery B could be charged at night. Timer T allows the charging time of HSWPP battery B only between 22:00 and 06:00 hours when electric power is not expensive. Those who wish to install a stand-alone HSWPP should prepare and connect the control scheme for this power plant. The control scheme must be based on the relevant BPU [20]. BPUs are currently produced for several types of batteries with rated currents of 65 A, 100 A and 220 A and voltages of 12/24 V. This BPU series enables the installation of a stand-alone HSWPP ranging from 1.5 to 5 kW. Rural homesteads and small businesses require this power quantity the most.

Results and discussion

This article offers advice and explanations to farmers and other rural residents on how to produce electricity on their own more cheaply due to the rising cost of electricity in recent years. It is explained how to install a stand-alone HSWPP with an electric energy battery B and its charging capacity that meets the needs of a small farm. A block diagram of connections in a stand-alone hybrid solar and wind power plant was created to explain the purpose of its blocks and their necessary connections. The battery B can be recharged from solar and wind power plants at any time. A common hybrid battery B charge controller, HBCC, is used for this purpose. The battery B protection unit (BPU) is used to control its loads. This guarantees a longer working period for the battery B. In areas with low wind energy resources during the winter, when solar energy resources are also greatly reduced, the battery B can also be charged from the mains grid at night when the price of electricity is the cheapest. Stand-alone HSWPP uses a timer T and another electrical energy charger BC for this purpose.

It is possible that in the coastal area, where strong winds often blow, natural experiments will show that nighttime battery charging from the distribution network is not really necessary. In addition, powerful storms often occur on the coast, which destroy the electricity transmission lines of the distribution network for several days. Therefore, we believe that additional nighttime charging of the stand-alone HSWPP battery from the mains would be most needed during the winter months in areas where wind energy resources are scarce.

Presently, a hybrid solar array and power distribution network connected to the battery are already used for supplying DC power to the DC/AC inverter [26; 27]. Annual solar energy resources in the Baltic States are good (about 1000 $kWh \cdot m^{-2}$, as in the Netherlands). This system is operating on a similar principle as the one described in this paper, stand-alone HWSPP. These hybrids are already used in areas where the batteries of solar power plants are charged from the distribution network when the network has excess energy and when the solar irradiance is low, as we have in late autumn, winter and early spring.

Conclusions

1. When the cost of power increases and other factors influence it, electricity users and researchers are seeking ways to reduce the costs in this area. Self-consuming solar power plants with microprocessors, semi-autonomous hybrid PVPP-distribution network plants that recharge their batteries from the network when it is worth it, and hybrid stand-alone solar and wind power plants are becoming increasingly popular. Price of PVPP with microinverters – around 5-7 EUR ct per kWh.
2. This article presents the results of a review of literature sources in the field of hybrid autonomous solar and wind power plants, examines the progress made in the field of equipment used in them, and further develops the possibilities of these power plants in the near future.
3. A block diagram of connections in a stand-alone hybrid solar and wind power plant is presented and briefly described. In our opinion, such experimental stand-alone HSWPPs could be easily installed in coastal areas that have sufficiently large solar and wind energy resources when the average annual wind speed exceeds 4-5 $m \cdot s^{-1}$. This would allow for a much more accurate assessment of the efficiency, viability and real price of electricity produced by these power plants.
4. If the experiments with the stand-alone HWSPP prove successful and confirm the predicted indicators of its functioning, RES-based power plants will have a chance to compete with the main power system in the field of electricity production and supply. It will be very useful in coastal areas where hurricanes disrupt power supply from the distribution network for a long time, which greatly complicates the work of farmers and other coastal residents. Selecting and installing WEs and PVPPs to withstand hurricanes, which occur mostly in coastal zones, is not difficult.
5. Faster development of solar and wind power plants, energy conservation would greatly contribute to the reduction of environmental pollution and slowing down of the global climate warming process, which has accelerated significantly recently. In 2023, the average annual temperature above the Earth's surface for all summer, autumn, and all year (16.77 °C) was the highest in the entire history of this temperature measurement (in 2014 was 16.2 °C).

Author contributions

Conceptualization, formulation of the idea of the article, search for information sources and their analysis, evaluation of the significance of information sources (V.A., G.Š., and A.D.), figures and calculations (A.D.), preparation of the article draft (V.A), editing of the article (G.Š., A.D.), preparation of the final version (V.A), acquisition of financing, preparation of slides, presentation of the report at the conference (G.Š). All three authors read and agreed with the final published version of the manuscript.

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