SMALL-SCALE SOLAR-WIND POWER PLANTS FOR RURAL AREAS

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Abstract. The article describes stand-alone small-scale hybrid solar-wind power plants (HSWPP) and solar power plants (PVPP) of various types for use in rural areas with sufficient or very good wind energy resources. Currently, there are many solar and wind power plants operating as hybrid systems that can produce electricity in stand-alone mode, feed the generated electricity into the power grid, or support rural residential and farm buildings using a self-sufficient exploitation mode. Stand-alone hybrid solar-wind power plants can be useful in areas that are characterized by frequent power supply disruptions due to hurricane winds and long power supply restoration times. Restoration of electricity in Lithuania takes up to 10 days at serious blackouts, when hundreds of thousands of consumers do not receive electricity. Large financial losses can be incurred in farms and rural homesteads during a period without electricity. A complete disconnection from the power system grid is also possible, when the owner of a farm or homestead installs HSWPP and uses it all the time in stand-alone operation mode. Such an option would not be expensive, generate electricity reliably and the aforementioned financial losses would be avoided in this case. The cost of electricity would be low, and the maintenance of the power plant would be simple. It is possible that the electricity produced by a self-installed HSWPP will cost even cheaper than that supplied from the electricity grid. This article includes a review of new scientific articles, describing many different low-power solar power plants, HSWPP, their schemes and advantages, discussions and advantages of the distributed method of electricity production. It also provides conclusions and a list of the latest reviewed literature.

Keywords: solar, wind power plants, hybrid systems, distributed generation, losses, efficiency, resilience.

Introduction

Rural areas have their own specifics for power generation. Stronger winds blow there, solar radiation is several percent higher on the sea coast, and large areas of arable land create favourable conditions for more efficient use of renewable solar and wind energy. The conditions there are good for producing electricity also because the same land plots can be used for electricity production in combination with agricultural needs. Such systems have been tested many times and have proven themselves. The land equivalent ratio (LER) on the experimental plot was 3.54. This shows that the land was used much more efficiently compared to the case when the same plot of land was used solely for agricultural needs [1].

This is one of the best LER indicators that can be achieved in PV systems. This indicator is calculated by evaluating the one-year yield obtained on the PV system area and the electricity produced per the same year by the solar modules installed in the system. Over the course of about 150 years of electricity generation history, each country has developed a centralized, nationwide electricity generation method that is not optimal in many respects. First of all, the electricity system is complex, expensive to install and maintain. In addition, the electricity system suffers from very high energy transmission losses. For example, the estimated energy transmission losses in the Lithuanian energy system in 2024 amounted to almost a third of all energy consumed [2] – 29.33%. Other countries with very large territories have even higher electricity transmission losses. Moreover, such energy systems with centralized electricity generation and distribution are easy very vulnerable to wars, hurricanes and various sabotage acts. The current senseless war in Ukraine has made even the naivest people convinced of this once again.

The number of this type of power plants is gradually increasing, but not at the same pace in all countries. Most of the information published worldwide is about PVPP, which are also part of HWSPP. However, PVPP alone would not be enough in the energy system, because in winter the solar radiation is very low. Therefore, in the RES-based power system, other power plants running on RES must also be used. Solar and wind power plants (WPP) are well combined with each other in HSWPP, because WPP produces more electricity in winter. States, their cities and villages will be resilient to the destruction of their energy systems for various reasons in the event that they already have decentralized energy production and distribution. Different factories produce PVPP and WPP. Currently, the fastest development is taking place in the PVPP field. The following countries are leading the world in terms of installed total PVPP and WPP capacity per capita: Sweden, Australia, Netherlands, Germany and

Denmark. Besides, global PVPP capacity has been doubling every 3 years, and WPP – every 6 years. Capacities of fossil and nuclear power generation remained almost static in recent years [3].

Distributed electricity generation for rural homesteads in small-capacity power plants based on renewable energy sources (RES-based) is the best choice for the following reasons.

1. The share of energy losses in the local microgrid would be very small, because the electricity transmission losses for one homestead or a small number of homesteads would be many times smaller compared to the losses incurred in the electric power system.
2. If a centralized power system can be quickly and easily destroyed in the event of war, in the case of a widely distributed electricity generation system only a small number of stand-alone power plants could be destroyed (but it would hardly be worth it since the damage to the system would be minor).
3. If in the events of a powerful hurricane when electricity transmission lines in Lithuania are destroyed and hundreds of thousands of electricity consumers are cut off from power supply for a long time (up to 10 days), well-installed HSWPP have much more chances to withstand hurricane winds.
4. Self-produced electric power in stand-alone PVPP or hybrid SWPP is cheaper than bought from an electric power system, because all the equipment of these RES-based power plants rarely breaks down and it requires very little maintenance and repair.
5. If all fossil fuel-powered power plants require quite large areas of land to build, then solar power plants can do without land dedicated solely to them. WPP do not need much land – only to build towers. PVPP can be installed on the roofs of buildings. The electricity generation potential on rooftops around the world has been calculated. They have about 67% of the necessary global potential. Upper reservoirs of hydroelectric power plants (HEPP) and other water bodies greatly exceed the whole necessary potential. Agrivoltaic systems also have a huge potential for power production. Additionally, sound attenuation and bird deterrent barriers near highways, car parking lots are giving considerable space for PVPP too.
6. Solar modules are also placed on electric cars, electric buses, trains, trucks, and elsewhere. The energy conversion efficiency of solar modules has been increasing over time and is now around 24–27%. A new type of module with a perovskite layer is being developed. Predicted energy conversion efficiency of these modules can reach 40-43% according to predictions of scientists. Then the efficiency of PVPP will be improved and it will be cheaper to drive electric vehicles. Car battery will have significant support because of the solar modules attached to the car.
7. Ability to generate electricity on your homestead saves a lot of time, as you no longer have to worry about high electricity prices, their fluctuations, electricity meter readings, declaring them on time, and making periodic payments for electricity consumed over a very long period of time, or in short – fewer worries related to electricity suppliers.

There are many more reasons why it is necessary to restructure the power production technologies, the power supply system, electrify transport, and modernize other technologies in order to reduce greenhouse gas emissions into the atmosphere. First of all, this is required because of the increasing frequency and intensity of disasters related to environmental pollution and the increase in greenhouse gas concentrations in the Earth's atmosphere, which cause more and more significant damage to people and nature.

Materials and methods

The main method used to prepare a review article on the best ways for self-production of electric power in rural areas by means of PVPP and stand-alone HSWPP is a search for the latest scientific and technical sources of literature. This is followed by an analysis of the relevant literature sources and an evaluation of the ideas presented in them. The latest and most advanced information found in the literature sources is used to find the most valuable innovations and "know how", to describe them in the article and offer them to readers so that they can use the information either for their own personal needs or for further development of the described ideas in order to achieve even greater progress in the area of renewable energy systems. The information provided in this article is only a brief summary of the most important ideas presented in the list of references. Much more complete information with photos, pictures, formulas and graphs can be found by reading all the articles given in the list of references.

Results and discussion

Research has been conducted on the topic of small-scale solar-wind power plants capable for the reliably operating in stand-alone mode. The latest available information sources have been used for creating a power plant for the needs of a small farm or homestead. HWSPP are recommended primarily for those homesteads that are located in areas with sufficiently high average annual wind speeds at a height of 10-20 m – at least 3 $m \cdot s^{-1}$ and more. Solar energy resources are distributed much more evenly, so less attention can be paid to them. However, it is important to ensure that the solar radiation power ($W \cdot m^{-2}$) falling on the PV array of the power plant is as high as possible. All natural and artificial means can be used for this purpose. For example, choosing the optimal angle of inclination of the solar modules relative to the horizontal plane, placing white-painted reflectors on the ground under the solar modules when the PV array is composed of bifacial modules, surface of the modules can be sprayed with water when it does not rain for a sufficiently long time and the surface of the modules becomes dusty, natural white-colored reflectors can be used when it is possible.

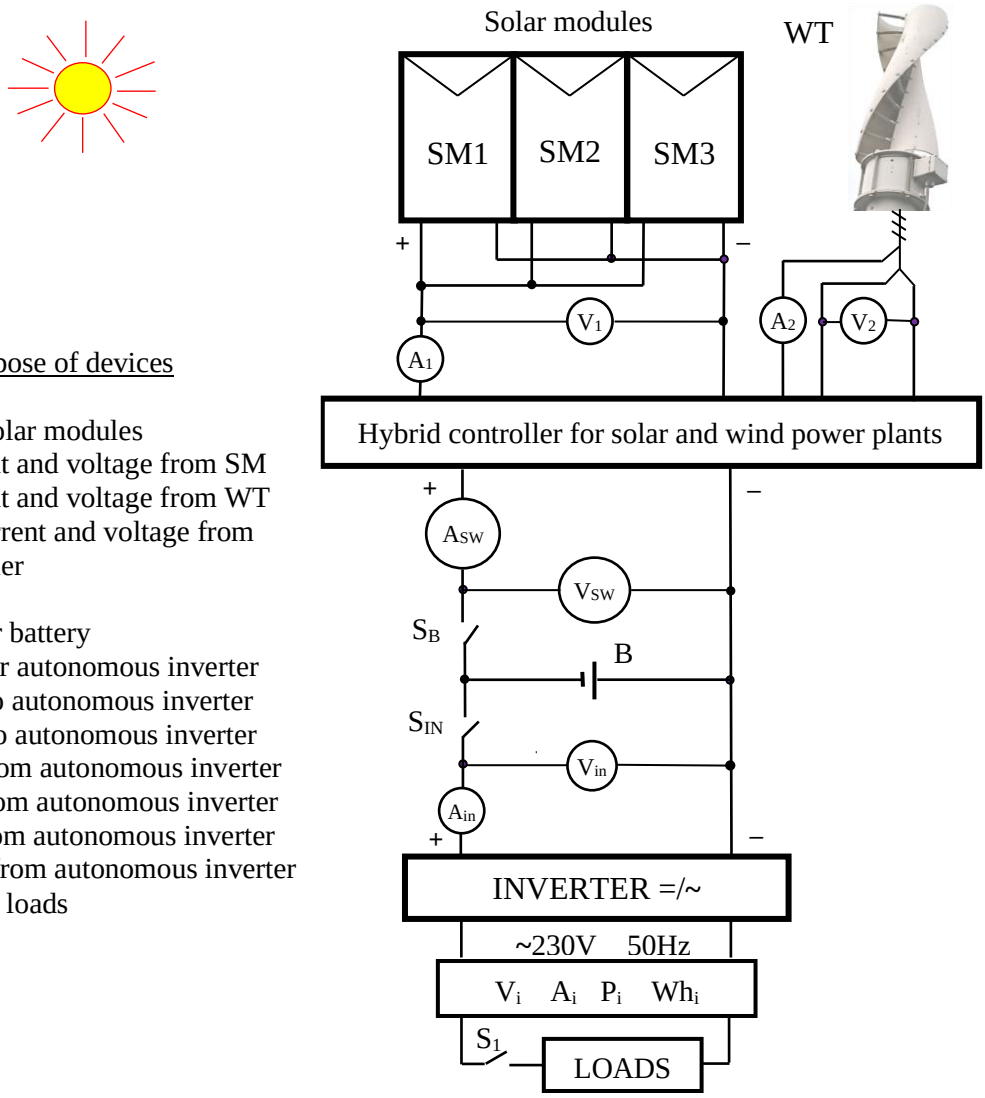
However, the greatest benefit comes from the continuous improvement of solar cells. The average efficiency of solar modules was below 20% just 10-15 years ago. The efficiency of solar modules which are currently being produced is usually around 24-26%. The US research laboratory Tandem PV is working on modules with a perovskite layer and plans to increase the operating efficiency limit of this module to over 30% by the end of 2025 [4]. Another article provides information that Indian scientists have already exceeded the 30% efficiency limit of solar modules with a perovskite layer [5]. Their result obtained last year is 31.16%. Another article provides information that by 2030, the operating efficiency limit of solar modules with perovskite layers can be increased even further and achieve significantly better results [6]. Longi, the developer of solar cells for the production of solar modules, announced that they have already produced a solar cell with a perovskite layer. The energy conversion efficiency of a tandem solar cell measured in their laboratory reached 33.9%. According to their opinion, the efficiency of tandem solar cells could increase to 45% in the near future [6].

The capacity of WPP must be increased in areas where wind speeds are lower. The ratio of PVPP and WPP capacities must be chosen after assessing the ratio of solar and wind energy resources. The power consumer does not have to feel a shortage of electricity. It is also necessary to select a battery with sufficient charge capacity, so that there is no shortage of energy during those winter periods when solar radiation is very low and the wind may not blow for several days in a row, or its speed is low. It is necessary to constantly monitor the battery charge level and, if necessary, save energy by refraining from energy-intensive tasks. Our grandparents used the same tactic when they milled grain with windmills.

All information and conclusions in our paper are based on the results of the overviewed scientific articles. The article was prepared in order to show possibilities of creation the power grid of a new type. The new power systems must be much more resilient for destruction of various types in near future. Power losses in the system will be significantly reduced due to the distributed power generation in many stand-alone RES-based power plants and short distances of the produced power supply. This is why many small-scale power plants in the system must be stand-alone HSWPP and have batteries, especially in rural areas. In addition, large scale solar and wind power plants, which already account for the largest share of the cheapest electricity produced in Lithuania, will produce much more competitive electricity (Ignitis group) for export to Germany, whose energy needs are very high. This article is not about numerical analysis and comparison of the economic differences, which are small and unnecessary for our article. Actually, our paper is a review prepared by us on basis of relevant global articles for letting interested people know about the best ideas useful for creating modern, green, cost-effective, and resilient state power grids.

A simplified diagram of a small-scale HSWPP is submitted in Fig. 1. The measurement devices in the diagram can be omitted. However, for some people it may be interesting to observe the operation of this hybrid power plant. But if this is not of interest, you can use only the most necessary devices (their cost is not high). An experimental low-power stand-alone HSWPP was installed according to this scheme in the Laboratory of Renewable Energy Systems and Power Storage of the Kaunas University of Technology. Three solar modules and a vertical axis small-scale wind turbine (WT), type Windside-0.30C, are installed on the roof of the faculty. Capacity of the WT at the rated wind speed and voltage 12 V is 94 W. Power at the maximum WT's rotation speed 1500 $rev \cdot min^{-1}$ is higher –166 W, but in our

locality (Kaunas city) is not available. Total capacity of PVPP modules is 365.70 W. All system was installed in 2019.



Purpose of devices

SM1-SM3 – solar modules
A_1-V_1 – current and voltage from SM
A_2-V_2 – current and voltage from WT
A_{SW}-V_{SW} – current and voltage from hybrid controller

S_B – switch for battery
S_{IN} – switch for autonomous inverter
A_{in} – current to autonomous inverter
V_{in} – voltage to autonomous inverter
V_i – voltage from autonomous inverter
A_i – current from autonomous inverter
W_i – power from autonomous inverter
Wh_i – energy from autonomous inverter
S_1 – switch for loads

Fig. 1. **Simplified diagram of a small-scale hybrid stand-alone solar power plant**

Since then, this power plant has been constantly producing electricity in two ways. It operates in stand-alone mode very shortly – only during laboratory work. The rest of the time during all days it operates in self-consumption mode and transfers all the produced electricity to the faculty's internal network for free. Electricity is consumed for the faculty needs during the day and in small amounts at night. As shown by the electricity meters of this HSWPP, now it is producing the third megawathour of free electricity for the faculty during its entire operating time.

Fig. 1 shows a simplified scheme of a small-scale HSWPP, intended to explain the principles of operation of such power plants. However, the residents of each rural homestead need RES-based power plants of sufficient capacity, the installation of which requires more information about local solar and wind energy resources and about the power plants themselves. Additional information on the design of stand-alone HSWPPs and the calculation of the required capacity of electrical energy storage can be found in articles [7-9]. Stand-alone HSWPPs now have only a very small share in many countries around the world, as powerful power plants prevail almost everywhere, the energy produced by which is distributed with significant losses through long and multi-level electricity system networks.

Aggressors easily bombard powerful power plants of the power and heat systems when they want to subjugate a country. If there were no wars, the centralized power system would still have major shortcomings due to large losses in it (a large part of the electricity must be produced and then wasted in the distribution system), have expensive and complicated maintenance. Therefore, we propose to

install stand-alone microgrids wherever it is possible with hybrid RES-based power plants with sufficient capacity power storage. Microgrids are intended for remote single-family homes, homesteads or their groups, apartment buildings, small villages and other remote objects. Modern heat pumps can also significantly complicate the destruction of urban infrastructure during war when the electricity generation system is distributed and less vulnerable [10; 11]. A very powerful heat pump Vilter VQ95 was created in Denmark in 2024. It is intended for heating urban areas and industrial processes. The parameters of the heat pump are very good: power 1-5 MW, heated water temperature – up to 95 °C, coefficient of performance (COP) – up to 6.77 [11]. Other countries have also made significant progress in this area. Heat pumps using RES energy will also contribute significantly to reducing environmental pollution and saving energy.

It is recommended that users install only PVPP for self-consumption with a deep-discharge battery of sufficient capacity in areas with low wind energy resources. In this case, it is not worth disconnecting from the power grid, so that at least in spring, summer and autumn it would be possible to use cheap self-generated electricity. Small-scale wind, hydropower and bioenergy have been used for self-consumption since ancient times. At the beginning of this century, low-power PVPP also joined them. Detailed information on the use of all four types of renewable energy resources for self-consumption is provided in references [12; 14]. More information about solar power plants for self-consumption can be found in the scientific literature [15-19]. There are already several variants of this type of solar power plants. There is an “all-in-one” variant, in which solar modules are installed outdoors and a box with all other solar power plant equipment is mounted on the wall of the building or in another convenient place in the building. The cable from the solar modules comes to the box, and from it the cable goes to any electrical outlet inside the building. In addition, there are also small-power balcony solar power plants, the modules of which are mounted on a south-facing balcony, and the rest of the equipment is in the building. The output cable is also connected via a plug to any outlet in the house.

PV modules and panels can be used in all areas that receive a lot of solar irradiation during the day and are not covered (or only slightly covered) by shadows. Agricultural farms are very suitable places for solar power plants, and windy rural fields are also suitable for wind power plants. State support for the installation of solar power plants is no longer necessary these days, but the countries that want to provide themselves with cheap electricity as soon as possible and pollute the environment less for the benefit of future generations, financially support solar, wind and other types of green energy. Lithuania also financially supports the installation of solar power plants. Lithuania is currently leading among the Baltic States [20]. This country added 870 MW of solar power in 2024. It is predicted that the total capacity of solar power plants in Lithuania will continue to grow rapidly: 2.7 GW by the end of 2025, 3.2 GW by the end of 2026, and 4 GW by the end of 2028. Estonia is not far behind. Only Latvia is still lagging behind. The achievements of the world scientists in the field of electrical energy are often gratifying. It was recently announced that the new SI-30 battery in the USA is given a 30-year warranty [21]. This is a truly great achievement, since all solar module manufacturing companies give a 25+ year warranty on their products.

Conclusions

1. The authors of this article set themselves the goal of reviewing the scientific literature on the modernization of power systems that is already underway around the world. A little more attention was paid to small-scale stand-alone HSWPPs, their functions and the benefits they provide to the entire power system.
2. The world’s energy systems are now reorienting towards increasing the efficiency of energy production, reducing losses in the power system, increasing resilience to natural disasters and destruction in the event of an attack by aggressive states.
3. Many inexpensive, easy-to-manage microgrids and other small self-consumption power plants have already been installed in the leading countries, and their number is constantly increasing with a rapidly increasing pace.
4. The state of each country’s electricity system and its efficiency depend greatly on the level of energy science in that country, and therefore their achievements are uneven. Countries with a high level of energy science achieve significantly better results.

5. Further widespread implementation of stand-alone hybrid solar and wind micropower plants with power storage and other types of self-consumption plants in each country will help reduce electricity distribution losses, simplify maintenance, reduce operating costs and price of electricity, and the number of failures due to various disasters.

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., A.D.), writing and draft first version preparation (V.A.), reading of the draft version and discussion (G.Š., A.D., V.A.), editing of the article (G.Š.), discussion of the article (V.A., G.Š., A.D.), preparation of the final version (G.Š.), preparation of report slides (A.D.), acquisition of financing (G.Š), presentation of the report at the conference (A. D.). All authors have read and agreed with the final published version of the manuscript.

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