Analysis of the Efficiency of the Experimental Design of an OFF-GRID Photovoltaic System for Local Purposes of Electricity Generation

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Abstract

Research background: Increasingly the implementation of vehicles with alternative propulsion such as battery or hydrogen vehicles there are higher demands on electricity production. The main factor affecting the environment such vehicles is mainly a source of electricity, which recharges the batteries of vehicles or hydrogen produced as fuel for fuel cells.

Purpose of the article: Presented analysis examines the effectiveness of the experimental design of a local OFF-GRID photovoltaic system intended to support of alternative automotive drives.

Methods: As a basis for determining the efficiency of the proposed device is the analysis of a run-in photovoltaic system is used installed in the same geographical conditions with data validation with database PV-GiS.

Findings and added value: From the analysis of the investigated design of the photovoltaic system shows that electricity production during the year it is directly dependent on the intensity of global radiation. The proposed solution makes it possible to partially cover the energy requirements in transport with active use RES.

Keywords: photovoltaic system; global radiation; solar energy; electricity

1. Introduction

With the constant progress in the field of transport and increasing emission requirements the boundaries of internal combustion engines are increasingly shifting up to the efficiency limit. A possible solution is implementation of vehicles with alternative propulsion. The most promising method of transportation is currently applied electric transport in the form of battery vehicles. The main current competitor of this technology is implementation of fuel cells in electric cars which are powered by hydrogen [1].

Battery vehicles are a strong competitor to internal combustion engines. The technology used to drive it is considered an emission-free mode of transport. The main advantage of these vehicles is the increasingly strong infrastructure of charging stations [5, 10].
However, from an ecological point of view, the whole cycle of energy from production up to the wheel must be taken into account, it is a so-called well-to-wheel cycle. From this point of view, it can be concluded that the degree of ecology of electric cars also depends on the method of electricity production. In the case of the use of conventional methods of energy production, such as a coal-fired power plant where the energy source is fossil fuels in the form of coal, the cleanliness of battery cars is debatable. With the ever-increasing number of battery cars, the need for energy supply is also increasing, which significantly increases the carbon footprint. However, the introduction of electric vehicles will not achieve significant reductions in CO₂ emissions, especially in countries with a high emission factor for electricity generation [11, 13].

In the case of hydrogen vehicles with fuel cell technology, hydrogen is the primary energy source. Despite the fact that these vehicles emit no local emissions and the energy carrier is hydrogen, which is one of the cleanest and best energy carriers, an important factor influencing the environmental friendliness of this technology is the origin of hydrogen fuel. At present, steam reforming of natural gas is the most widespread hydrogen production technology in Europe. The problem is that natural gas is a fossil fuel which affects the efficiency of hydrogen vehicles. One of the best and purest ways to produce hydrogen is water electrolysis. This method of hydrogen production, despite its environmental friendliness, requires high energy requirements, which limits its wider application for the needs of the transport sector. To expand the use of water electrolysis, it is necessary to reduce the energy consumption, cost and maintenance of current electrolyzers and, in turn, increase their efficiency, durability and safety [3, 7, 14].

Battery and hydrogen vehicles are currently the most promising path to emission-free transport, but it is necessary to take into account not only their real-time operation but also their way of obtaining energy for propulsion. With the ever-increasing number of such vehicles, the need for electricity production is also growing, which significantly affects the stability of the electricity grid. A suitable solution to this discrepancy between the production and the need for electricity is, in particular, the ever-increasing implementation of renewable sources. Renewable energy technologies hold the promise of clean, abundant energy from self-renewing sources such as hydro, wind and solar power [6, 12, 15].

From the point of view of efficiency and low geographical intensity, the most promising way of generating electricity is solar energy. Such a source in terms of system efficiency can be placed directly in places of electricity consumption such as: on the roof of gas stations, where it can serve as a source of battery charging or a source of power to electrolysis to produce hydrogen. With the correct dimensioning of RES in the transport sector, it is possible to effectively and safely cover the growing need for energy resources. [2, 8, 9, 10].

2 Design of an experimental OFF-GRID photovoltaic system

Photovoltaic panels are the basic element for converting solar energy into electricity. It is this element that provides the greatest possible degree of optimization as technology advances. For the purpose of designing this system, we have therefore considered panels that have the highest possible performance and are commonly available on the market. The panel system consists of 120 monocrystalline panels with a power output of 550 Wp for a total system output of 66 kWp.
For the design of our system, we have chosen a series-parallel circuit. Each string consists of 10 panels and they are connected in series in groups of 5 and these 2 groups are interconnected in parallel. In total, the whole system consists of 12 strings, which are connected in parallel into a single unit by means of separate regulators. The calculation of voltage, current and power of a single string is as follows:

\[
Umpp = 5 \times 41.6 \text{ V} = 208 \text{ V} \tag{1}
\]

\[
Impp = 2 \times 13.23 \text{ A} = 26.46 \text{ A} \tag{2}
\]

\[
P_{\text{max, string}} = 208 \text{ V} \times 26.46 \text{ A} = 5503.68 \text{ W} = 5.5 \text{ kWp} \tag{3}
\]

\[
P_{\text{max, celk}} = 5.5 \text{ kWp} \times 12 = 66 \text{ kWp} \tag{4}
\]

One of the main elements of the photovoltaic system, which ensures the correct operation of the entire system and adjusts the voltage from the panels, is the voltage regulator or their system. The main task of the charge/voltage regulator is to adjust the voltage, which is then routed to the batteries or directly to the inverters and then to the grid. For larger applications, a 48 V system is best suited, which is what we have used in this design, so the regulators must also be dimensioned for a 48 V system.

In the case of our system, we have chosen the regulator with the designation Victron MPPT 250V/100A-Tr VE.Can. The basic condition in the dimensioning of the panel array is mainly the compliance with the limits of the regulator and for this reason the PV strings are dimensioned in terms of voltage, current and power levels.
Because each PV string requires its own solar regulator, so 12 regulators were also used in the design. Figure 2 shows the principle of connecting the string to the corresponding regulator as well as their parallel interconnection.

The principle of functionality or operation of the regulators is based on the intensity of solar radiation. The battery charging process starts when the panel voltage exceeds the battery voltage (48 V) by 5 V, otherwise the charging process stops when the panel voltage drops to 1 V higher than the battery voltage.

Each of the regulators provides a charging current of 26.46 A, which means that when twelve units are connected in parallel, the total charging current of the batteries is 317.52 A. The parallel connection of the regulators is ensured by a double CYA battery cable with a cross section of 6 mm² and AGU 30 A fusing, flowing into a double connection rail with a conductor diameter of 100 mm².

For the purposes of our design, BYD LVS 16.0 batteries with LiFePO4 technology were used. The main advantage of these batteries is that they are lithium-iron-phosphate batteries of the latest generation with the possibility of ON-GRID but also OFF-GRID connection, the possibility of up to 100% discharge but also the possibility of assembling larger units according to the required capacity.

Depending on the calculation of the required capacity, a total of 8 BYD LVS 16.0 batteries with a total capacity of 128 kWh were used for the design of the photovoltaic system. Each battery consists of four battery packs with a capacity of 4 kWh. In total, the capacity can be increased up to 256 kWh if required, which represents 16 of these batteries or 64 battery packs.
Figure 3 shows the schematic connection of the regulators to the batteries and also to the so-called battery tracker. The batteries are connected in parallel and the fusing between the charge regulators as well as the voltage converters is provided by two knife fuses with a rated breaking current of 400 A on both the positive and negative conductors.

The final component of the whole photovoltaic system is the voltage converter. The inverter covers the mismatch between the current required for the appliance system and the current coming from the solar panels. As the general whole PV assembly operates with direct current, it is necessary to invert the direct current to alternating current for common grid sized appliances or devices [4]. In this particular case, it is a change from a DC system with a nominal voltage of 48 V to a single-phase AC system with a voltage of 230 V. For the purpose of our photovoltaic system design, considering the output power, a combined inverter with purely sinusoidal output voltage was chosen as the most suitable, with the designation Victron Quattro 48V 15000 VA/200 A - 100 A/100 A. Figure 4 shows a schematic representation of the wiring of a group of three inverters in relation to the batteries and regulators and also to the power distribution board.

![Solar battery wiring diagram](image1)

**Fig. 3** Solar battery wiring diagram

Figure 4 shows a schematic representation of the wiring of a group of three inverters in relation to the batteries and regulators and also to the power distribution board.

![Voltage converters wiring diagram](image2)

**Fig. 4** Voltage converters wiring diagram
All three inverters shown in Figure 4 are connected in parallel at the input from the regulator and battery pack using a cable designed for a CYA type inverter with a cross-sectional area of 35 mm². In addition to the three-phase output, this circuit also provides the possibility, in the case of an alternative reverse power source (grid, generator,...), to charge the batteries with a current of up to 600 A for a specific type of inverter [4].

The output of the inverters is a three-phase alternating current with a voltage of 400 V and a frequency of 50 Hz, which flows through a conductor marked CYKY 4 × 16 into the photovoltaic switchboard to the main switching point (HRM) with a fusing of 80 A.

3 Measuring the efficiency of the proposed experimental photovoltaic system

Considering the measurements made on existing PV systems with the same geographical conditions and validations of the data with the PV-GIS database, we can determine with high accuracy what amount of electricity we can produce. The main difference of the measured PV systems is first of all the dimensionality of the assembly but also the way of handling the surplus energy. Since the proposed PV system is characterized as an OFF-GRID circuit, it is not possible to distribute the excess energy to the utility grid. Therefore, this energy can be characterised as untapped. In terms of the technologies used in the design, the loss of performance of the panels in terms of their age can be excluded, and the total loss of the components used with losses on the conductors is roughly 10%.

![Average monthly sum of global radiation (kWh/m²)](image)

**Fig. 5** Rate of global radiation incident on PV panels

Due to the correct calculation of the efficiency of the PV system, it is necessary to know the solar energy intensity. Since the measured system includes a global radiation sensor that collects real-time data using an AHLBORN transducer called ALMEMO 2490, we can determine the rate of incident radiation on the PV panels. Although the average irradiation rate for the city of Prešov is about 1100 kWh/m² per year, we can see from the measured data that when the panels are angled at 35°, the incident energy rate is 1410 kWh/m² per year. Figure 5 shows the sum of the global radiation rates of the panels for each month during the year. The graph shows that the highest radiation exposure with a value of 178.5 kWh/m² is in the month of August and the lowest exposure is in the month of December when the sum of global radiation reaches the level of 36.5 kWh/m².

Based on measured data in real operation and global radiation data compared with PV-GIS, the expected system production can be determined. Figure 6 shows the potential...
energy production on an average day and also the fraction of energy that we are unable to capture. One of the reasons is e.g. to reach the maximum consumption of the powered appliances and energy surpluses during the production peak, when the PV system has to go into a slight decay. The graph shows that the highest average value of usable energy can be achieved in the month of June at 197 kWh, while the lowest value with 50 kWh on average per day is expected for the month of December. Although June is the most efficient month in terms of energy production, the system has the highest average losses in August, averaging 63 kWh per day. Due to the low efficiency of energy production in the winter months, it can be concluded that the energy loss is negligible. This is mainly due to the persistent condition where the full capacity of the batteries cannot be reached.

**Fig. 6** Average daily production of the proposed system

When calculating the total production potential of the proposed system, it is necessary to take into account the energy that we can recover but also the energy that we cannot capture due to the surplus. It is apparent that the highest level of potential production is in the months of June to August where the value exceeded 250 kWh per day.

**Fig. 7** Percentage of days with a fully charged battery
In Figure 7 it can be seen to what extent it is realistic to achieve a full battery charge within a year. The chart shows that the highest rate of full battery capacity is in the summer months (June-August), with the standard rate of full charge over 50% of the days in a month being between April and September. In the case of winter operation, reaching full capacity is minimal. This is mainly due to the short days of low global radiation. The system supplies power to the load as a priority, which greatly affects the battery charging process.

![Monthly energy output rate of the proposed system (kWh)](chart)

**Fig. 8** Total monthly energy production

Based on the previous analysis, it is possible to determine the total share of energy produced per calendar year. The graph in Figure 8 shows that the highest level of electricity generated is in the month of July with a value of 6045 kWh. Throughout the year, 51,047 MWh of energy can be generated using the proposed system.

4 Conclusion

The design of the photovoltaic system resulted in an independent device capable of operating without additional support from the grid. The presented analysis shows that it is currently not possible to ensure constant electricity production during the whole year, however, the presented proposal has significant benefits for the application of RES in transport infrastructure. Considering the large scale of the entire PV system, it can be stated that the installation requirements are minimal. Devices of this type can be installed on the roofs of petrol stations, thus eliminating the degradation of farmland and increasing the economic use of buildings. Despite the variations in electricity production from month to month throughout the year, this proposal is a good basis for further development of zero-emission transport.

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References


