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Design and Analysis of a Stand-Alone Photovoltaic System for Footbridge Lighting

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A B S T R A C T

The rapid industrialization and growth of the world's human population have resulted in an unprecedented increase in the demand for energy, in particular, electricity. Depletion of fossil fuels and the impacts of global warming have caused widespread attention using Renewable Energy Resources (RESs), especially solar energy. This paper provides a practical method for the technical feasibility study for the construction of a Stand-Alone Photovoltaic (SAPV) system with a capacity of 863 Wp. Solar module, battery, DC/AC pure sine wave power inverter, and the charge controller are the main components of this PV system design. Choosing optimal capacity and arrangement increase the plant's efficiency and reduces the overall system costs. In this method, according to the geographical location and type of site construction, e.g., on the ceiling of the footbridge, shadow analysis, and the calculations regards to the number of solar modules and their optimal angles are performed. This off-grid PV system is designed for the AC loads. PVSyst software is used for the system analysis, and the simulation results show the performance of the designed system.

1. ntroduction

Applications of PV systems have increased significantly over the past decade. This is mainly due to the rapid depletion of conventional energy sources and the broad availability of solar radiation. PV energy is considered as a prime candidate of energy in many countries with high power density. The PV system technologies are rapidly expanding with an increasing role in electric power technologies, providing pollution free and secure power sources. These applications include water pumping, refrigeration, air conditioning, light sources, Electric Vehicles (EV), PV power plants, hybrid systems, military and space applications. PV systems are highly dependent on the nonlinear current-voltage (I-V) characteristics under differen environmental (insolation, temperature, etc conditions. Moreover, for the PV systems, the fabrication cost is high, and the energy conversion efficiency is low. But if the PV systems become used in public places, e.g., footbridges, they can reduce electricity consumption, which will be economical for the government in the long run.

Design and simulation of the PV systems can be beneficial in many scientific studies. It can be helpful in monitoring the physical system to describe the observation, predicting the behavior of the system, and finally testing the validity of the model [1-3]. During the last few years, there has been an increasing demand in both states and private sections to have more precise analysis models for efficient operations of the PV systems. Indeed, researchers have presented different models, such as control of DC/DC converters, to get the maximum power [4-7].

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In some cases, researchers have proposed methodologies for either control of the battery voltage [8-9] or power-sharing between batteries and supercapacitors for increasing the batteries' lifespan [10].

On the other hand, optimizing the configurations of the PV system is notable among the researchers. Because of that, standard sizing of Stand-Alone Photovoltaic (SAPV) systems, as well as an assessment of different types of photovoltaic cells and their compatibilities are considerable [11-15]. In some areas, due to the seasonally-dependent production in PV systems, it is necessary to connect different systems to the PV systems. Using wind turbines is a suitable option which needs exact meteorological data of the region [16-18]. There are a lot of applications for PV systems in various fields, such as residential, public services, commercial, industrial, agriculture, etc. [19-20]. In spite of technical issues, economic viability is so essential. An economic comparison between SAPV system and the diesel-powered system is done in [21]. One of the most crucial points that can help to increase system performance and enhance its life span are the operation, inspection, troubleshooting, repair, and maintenance which investors should regard after installing photovoltaic systems [22].

The purpose of this paper is to identify the performance of SAPV system in different months of a year in a specific region and also give an overview of Research and Development (R&D) in the field of simulation of SAPV systems. One of the essential tasks in designing such a SAPV system is to match the prospective energy consumption with the local average solar irradiation, which results in energy production and helps calculate the required storage capacity. In this study, first, the data for one year and the information of the solar radiation based on the latitude and longitudinal information of the site are generated by the PVsyst software. Then, the software gives different values regarding the generation of solar energy for the specified load. The second section includes the PV system design. Technical specifications of the components in the PVSA system are demonstrated in the third section. After that, the simulation results of the system are performed. Lastly, the final section is the conclusions of the paper.

1. General Data

The first step in designing a PVSA system is to have general data from the area and consumers is required. In this paper, the load model and metrological data are extracted from the selected site, and then, the SAPV system is suggested.

A. *Load Model*

The load for the footbridge system is regular lighting. In this model, 6 W Surface Mount Incandescent (SMD) light are considered. The total number of SMD lights is 51. Table 1 shows the parameters of the footbridge. The total time that all the SMD lights should be on is 12 hours. Also, the system backup is calculated for two days.

Table 1. Footbridge Parameters

Parameters	Values
Length	50 m
Width	3 m
Height	10 m

B. *Meteorological Data of the Selected Site*

The geographic coordinates of the location of the proposed SAPV system are 29.659°, and 52.490° as latitude and longitude, respectively, with 5.475 kWh/m^2/day average global solar radiation per year [23]. It has been assumed that the PV modules will be placed on the ceiling of the footbridge. Figures 1 and 2 show the radiation and temperature and the rain and moisture curves of the selected area, respectively. As shown in figures 1 and 2, the maximum temperature and radiation are in June and July, and also the minimum rain and moisture are in these two months.

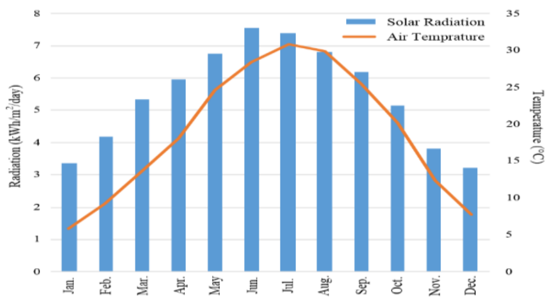

Figure1. Radiation and temperature curves of the location of the proposed SAPV system

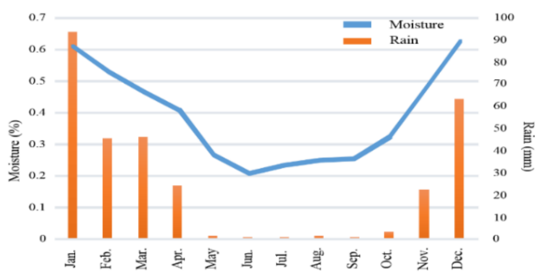

Figure2. Moisture and Rain-months curves of the location of the proposed SAPV system

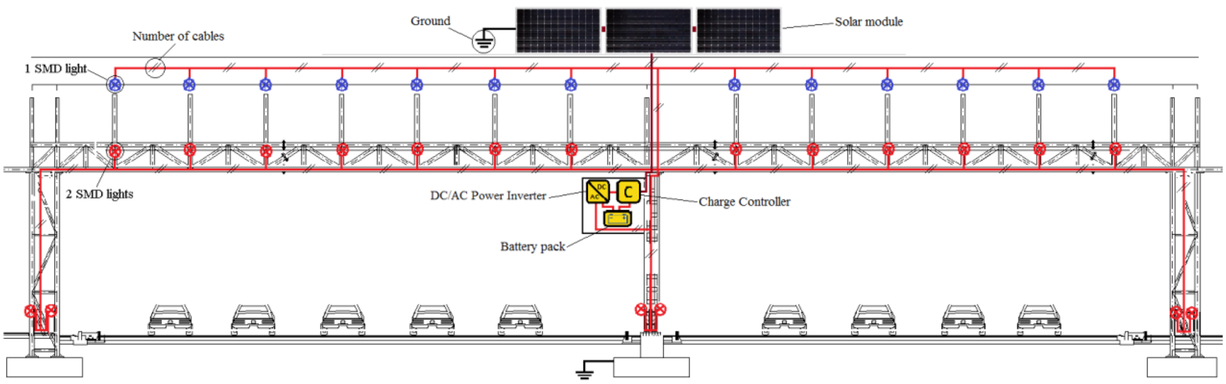

Figure 4. Diagram of the proposed SAPV system on the footbridge

C. Stand-Alone PV System Modeling

The combination of all components, as shown in figure 3, satisfy the system configuration. According to figure 3, the generated power by the PV modules is controlled by the charge controller so that prevent both overcharging of the battery pack on the day, as well as over-discharging of the battery back during the night when the AC loads are supplied by the battery pack. From the PVSyst software simulation, the total number of batteries is seven to fully satisfy the energy requirements. Each battery is a 12 V/100 Ah lead-acid battery. The coulombic efficiency of the battery is 97%. Furthermore, the battery with the considered capacity expects to support the electrical load for two days. Figure 4 shows the diagram of the system on the footbridge.

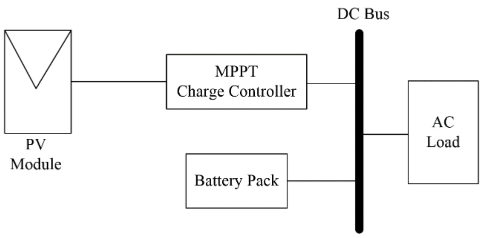

Figure 3. Configuration of a SAPV system

2. System Design

A. PV Module Model

According to figure 5, the energy received to the user in the mono-crystalline solar module is more than a multi-crystalline one in the location of the studied SAPV system. Indeed, three units of mono-crystalline PV modules selected to satisfy ener consumption at night. The PV modules must have adequate energy supply to the load and charging the battery pack. About 863 Wp of the nominal power from the PV modules is expected to be generated. The deviations in the output of a single PV module depends on the solar radiation, the temperature of the PV module, and the total load demand. Figure 6 shows the incremental level of radiation at a constant temperature (ambient temperature = 25 ºC), which has increased the output power of the solar module. The cell temperature is also increased due to the increase of solar irradiance.

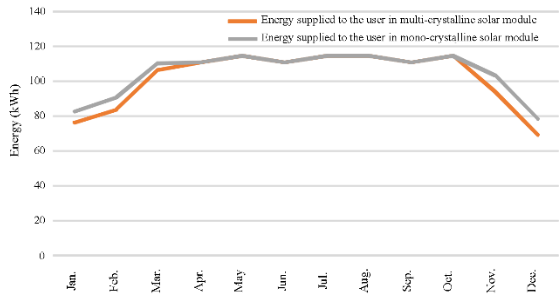

Figure 5. The energy supplied to the user in multi-crystalline and mono-crystalline solar modules

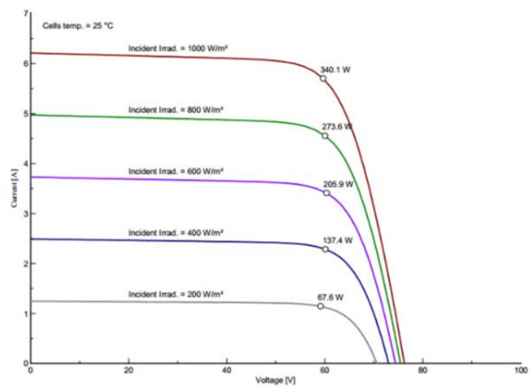

Figure 6. Current-Voltage (I-V) curves of a 340 W mono-crystalline solar module

B. Battery Model

The battery pack is an important component in any SAPV system but can be optional depending upon the design. Batteries are used to store the produced energy during the day for the night or in case of emergency need during the day [24-32]. The voltage of the battery packs is based on the configuration of the solar modules, between the range of 12 to 48 V, and many hundreds of amperes in total. In the proposed SAPV system, the recommended voltage and capacity of the battery pack are 12V and 700 Ah, respectively. The State-of-Charge (SoC) is the essential parameter of the batteries [29-30]. In general, the SoC of a battery is explained as the ratio of the current capacity, $Q(t)$, to the nominal capacity, Q_n. The nominal capacity is given by the manufacturer and represents the maximum amount of charge that can be stored in the battery. The SoC can be defined as follows:

$$SoC(t) = \frac{Q(t)}{Q_n} \quad (1)$$

Figure 7 shows the battery voltage versus SoC curve. As shown in figure 7, the charge and discharge current of the battery is regarded as 16.8 A, and 12.7 A, respectively.

C. Controller Model

The primary function of a charge controller in a SAPV system is to protect the battery from overcharge and over-discharge. Any system that has unpredictable loads and/or user intervention requires a charge controller to control the charge and discharge ratio. Otherwise, the result will be a shortened battery life and decreased load availability. PVSyst introduces general purpose “generic” universal controllers, for the three different strategies name Direct coupling, MPPT converter, and DC/DC converter. In this paper, an MPPT converter is selected to reduce the complexity of system design, while the output of the system is high efficiency. For the design consideration of the battery pack and PV modules, the MPPT converter will adapt their parameters to the system to always stay compatible with a normal behavior without control losses during the hourly simulation. Figure 8 demonstrates the efficiency of the input and output power in a controller with MPPT converter. As shown in figure 8, by increasing the power, the efficiency of the input power, P_{in}, changes, while the efficiency of the input power, P_{out}, continues its routine trend.

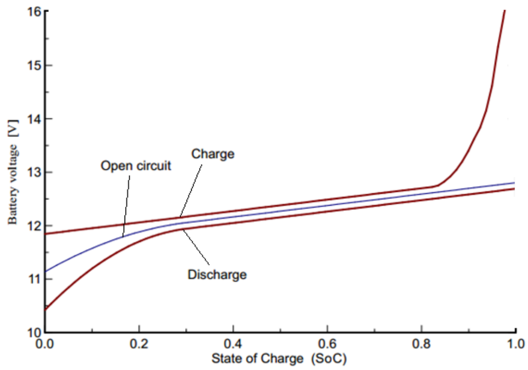

Figure 7. Battery voltage versus SoC curve

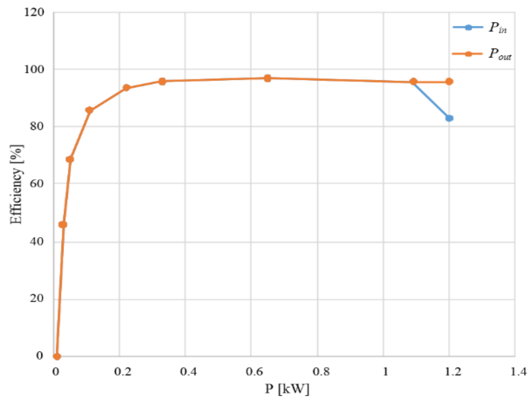

Figure 8. The efficiency of the input and output power in a controller with MPPT converter

D. DC/AC Power Inverter Model

DC/AC power inverter is a fundamental part of the PV power generation. The DC/AC power inverter is required to convert the DC voltage from the PV modules into the AC voltage, which can be used both in off-grid or on-grid modes. The quality of output waveform of the DC/AC power inverter is characterized by harmonic contents present. DC/AC semi-sine wave power inverter often produces low-quality output [33]. Among DC/AC semi-sine wave inverter and DC/AC pure sine wave inverter, the latter is better because of high efficiency and power quality. In this study, a DC/AC pure sine wave power inverter is used for simulation. Figure 9 illustrates that although input power change, the efficiency of the DC/AC pure sine wave power inverter remains constant.

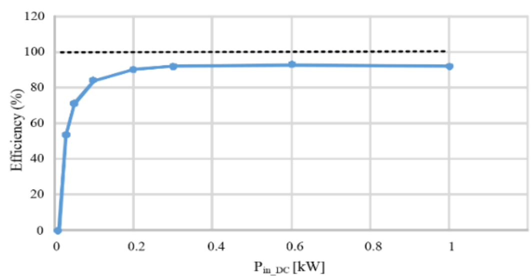

Figure 9. The efficiency of the input power in a DC/AC pure sine wave power inverter

3. Simulation results

PVSyst software updates its weather database based on the location of the proposed SAPV system, as shown in table 1, which helps to calculate all the output parameters. The degree of irradiation and the average temperature of the surveyed sites are the two key factors to study the PV systems. Table 2 demonstrates the monthly values of irradiance, diffuse, temperature, and wind speed of the location of the proposed SAPV system.

Table 2. Monthly Values of Irradiance, Diffuse, Temperature, and Wind Speed of the Location of the Proposed SAPV System

Month	Global Irradiance [kWh/m^2]	Diffuse [kWh/m^2]	Temp. [°C]	Wind Speed [m/s]
Jan.	99.10	44.0	5.80	1.60
Feb.	115.3	41.8	9.20	1.90
Mar.	154.6	61.6	13.5	2.39
Apr.	182.5	69.6	18.0	2.49
May	235.7	64.0	24.6	2.69
Jun.	242.5	57.1	28.4	2.41
Jul.	229.3	67.6	30.8	2.30
Aug.	240.7	43.8	29.8	2.10
Sep.	187.4	47.8	25.4	1.89
Oct.	168.4	39.0	20.1	1.60
Nov.	117.7	31.8	12.4	1.40
Dec.	99.40	33.3	7.70	1.30
Year	2072.6	601.4	18.80	2.005

Based on the data in table 2, PVSyst software determines a trajectory of the sun in the sky, which provides information on losses that occur during the entire year due to the fact that the solar modules cannot generate continuous electricity, as shown in figure 10.

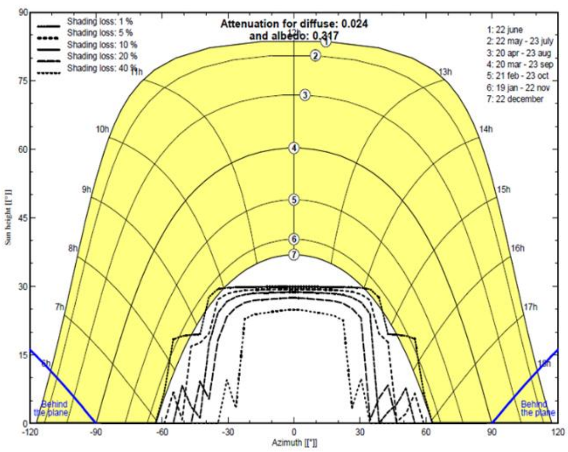

Figure 10. Sun trajectory depending on the parameters set for Shiraz location

In figure 11, the normalized energy production, which is distributed over the whole year, is demonstrated. The highest generated energy production is less than 4 kWh/kWp/day and would occur from April to October. On the contrary, the lowest production would occur in winter from November to January with a value of above 2 kWh/kWp/day. As shown in figure 11, the most losses of PV modules occur in October, November, and December. Furthermore, the highest unused energy is in August.

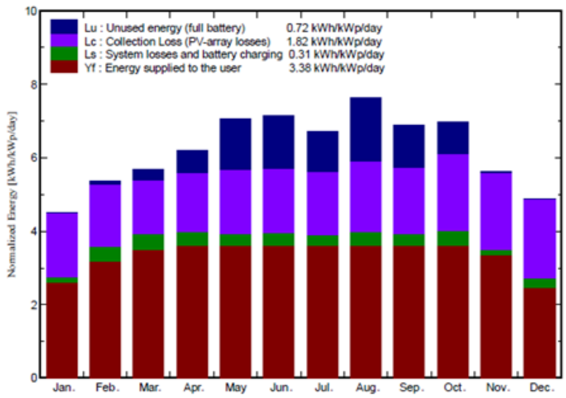

Figure 11. Monthly energy production with losses

Figure 12 reports the Performance Ratio (PR) during the year. PR is the system efficiency during the year and gives information about the impact of overall system losses on the rated output. The losses include PV module, tilt angle, dust, shade, module temperature losses. Results using monocrystalline silicon PV module indicate that during a year, there is fluctuation in the performance of the system, while solar fraction has experienced an increasing trend in the first three months of the year. Then, it has remained constant for seven months, and finally, a decreasing trend has occurred in the last two months of the year. Table 3 shows the annual balances and main results of SAPV system. The energy that can be delivered to the user is about 1256.9 kWh.

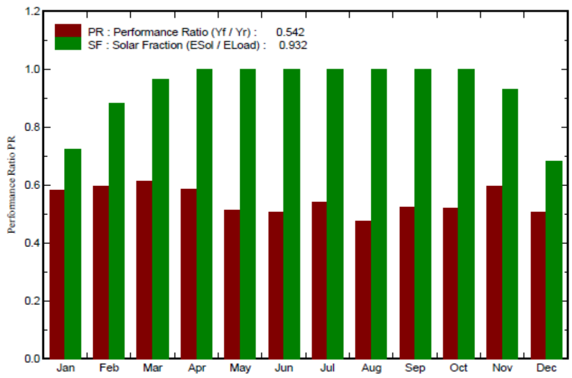

Figure 12. Performance ratio and solar fraction using PVSyst

Table 3. Results of Simulation in PVSyst software

Month	Horizontal Global Irradiation [W/m^2]	Effective Global Irradiation [kWh/m^2]	Produced Solar Energy [kWh]	Unused Energy Losses [kWh]	Missing Energy[1] [kWh]	User Energy[2] [kWh]	Load Energy[3] [kWh]	Solar Fraction
Jan.	99.1	86.1	88.8	0	31.55	83	114.6	0.725
Feb.	115.3	105.8	98	1.91	12.34	91.1	103.5	0.881
Mar.	154.6	137.9	127.7	9.86	4.18	110.4	114.6	0.964
Apr.	182.5	145.2	134	18.10	0	110.9	110.9	1
May	235.7	179.3	163	44.23	0	114.6	114.6	1
Jun.	242.5	177.4	158.8	43.68	0	110.9	110.9	1
Jul.	229.3	169.7	151.5	33.72	0	114.6	114.6	1
Aug.	240.7	198.3	175.5	54.74	0	114.6	114.6	1
Sep.	187.4	167.8	148.8	35	0	110.9	110.9	1
Oct.	168.4	165	147.5	26.95	0	114.6	114.6	1
Nov.	117.7	112.4	102	0.87	7.81	103.1	110.9	0.930
Dec.	99.4	86.5	80.9	0	36.29	78.3	114.6	0.683
Year	2072.5	1731.4	1569.4	269.05	92.17	1256.9	1349	0.932

[1] The missing energy in order for the system to function.
[2] The energy supplied to the user.
[3] The energy needed of the user.

4. Conclusions

Sizing and simulation of a photovoltaic system before installation is a crucial step. Critical information could result in finding unknown errors in the system, and consequently, it can enhance the overall performance of the system. This paper aims to propose a SAPV system which can be used as a power supply for the lightings of a footbridge. Therefore, the footbridge can provide its required electricity by installing SAPV on top of its ceiling instead of supplying electricity from the power grid. Hence, design the system configuration, as well as predicting solar energy production, are essential factors. The sizing of the system considerably depends on the geographical site location. Also, a series of factors, such as the emplacement, solar resources availability, type of application, operating period, etc., can change the results of simulation and surely can differ from other PV applications in various regions. For the analyzed system, the simulation results show that monocrystalline solar cell technology offers better results in terms of overall performance.

References

1. L. Dorobantu, M. O. Popescu, C. Popescu, and A. Craciunescu, “Simulating Shadow Effect on PV Panels,” *International Conference on Renewable Energies and Power Quality*, Mar. 2012.
2. Y. M. Irwana, A. R. Ameliaa, M. Irwantoa, M. Fareq, W. Z. Leowa, N. Gomesha, and I. Safwatib, “Stand-Alone Photovoltaic (SAPV) System Assessment Using PVsyst Software,” *Energy Procedia*, Vol. 79, Nov. 2015.
3. N. M. Kumar, M. R. Kumar, P. R. Rejoice, and M. Mathew, “Performance Analysis of 100 kWp Grid Connected Si-poly Photovoltaic System Using PVsyst Simulation Tool,” *Energy Procedia*, Vol. 117, Jun. 2017.
4. V. Salas, E. Olías, A. Barrado, and A. Lázaro, “Review of the Maximum Power Point Tracking Algorithms for Stand-Alone Photovoltaic Systems,” *Solar Energy Materials and Solar Cells*, Vol. 90(11), Jul. 2006.
5. R. J. Wai, W. H. Wang, and C. Y. Lin, “High-Performance Stand-Alone Photovoltaic Generation System,” *IEEE Transactions on Industrial Electronics*, Vol. 55(1), Jan. 2008.
6. E. Ozdemir, S. Ozdemir, and L. M. Tolbert, “Fundamental Frequency Modulated Six-Level Diode-Clamped Multilevel Inverter for Three Phase Stand-Alone Photovoltaic System,” *IEEE Transactions on Industrial Electronics*, Vol. 56(11), Nov. 2009.
7. M. S. Ngan, and C. W. Tan, “A Study of Maximum Power Point Tracking Algorithms for Photovoltaic Systems,” *IEEE Applied Power Electronics Colloquium (IAPEC)*, Apr. 2011.
8. K. S. Ng, C. S. Moo, Y. P. Chen, and Y. C. Hsieh, “State-of-Charge Estimation for Lead-Acid Batteries Based on Dynamic Open-Circuit Voltage,” *IEEE 2nd International Power and Energy Conference*, Dec. 2008.
9. N. Watrin, B. Blunier, and A. Miraoui, “Review of Adaptive Systems for Lithium Batteries State-of-Charge and State-of-Health Estimation,” *IEEE Transportation Electrification Conference and Expo (ITEC)*, Jun. 2012.
10. V. M. Miñambres-Marcos, M. Á. Guerrero-Martínez, F. Barrero-González, and M. I. Milanés-Montero, “A Grid Connected Photovoltaic Inverter with Battery-Supercapacitor Hybrid Energy Storage,” *Sensors*, Aug. 2017.

11. A. Balouktsis, T. D. Karapantsios, A. Antoniadis, D. Paschaloudis, A. Bezergiannidou, and N. Bilalis, "Sizing Stand-Alone Photovoltaic Systems," *International Journal of Photoenergy*, Vol. 2006, Feb. 2006.
12. A. Diaconu, L. Fara, P. Sterian, D. Craciunescu, and S. Fara, "Results in Sizing and Simulation of PV Applications Based on Different Solar Cell Technologies," *Journal of Power and Energy Engineering*, Vol. 5(1), Jan. 2017.
13. L. Zaghba, M. Khennane, I. Hadj Mahamed, H. S. Oudjana, A. Fezzani, A. Bouchakour, and N. Terki, "A Combined Simulation and Experimental Analysis the Dynamic Performance of a 2 kW Photovoltaic Plant Installed in the Desert Environment," *International Journal of Energy and Environmental Engineering*, Vol. 7(3), Sep. 2016.
14. J. Abdulateef, "Simulation of Solar Off- Grid Photovoltaic System for Residential Unit," *International Journal of Sustainable and Green Energy*, Vol. 4(3-1), May 2015.
15. S. Ahsan, K. Javed, A. S. Rana, and M. Zeeshan, "Design and Cost Analysis of 1 kW Photovoltaic System Based on Actual Performance in Indian Scenario," *Perspectives in Science*, Vol. 8, Sep. 2016.
16. C. Wang, and M. H. Nehrir, "Power Management of a Stand-Alone Wind/Photovoltaic/Fuel Cell Energy System," *IEEE Transactions on Energy Conversion*, Vol. 23(3), Sep. 2008.
17. R. Chedid, H. Akiki, and S. Rahman, "A Decision Support Technique for the Design of Hybrid Solar-Wind Power Systems," *IEEE Transactions on Energy Conversion*, Vol. 13(1), Mar. 1998.
18. N. Bigdeli, "Optimal Management of Hybrid PV/Fuel Cell/Battery Power System: A Comparison of Optimal Hybrid Approaches," *Renewable and Sustainable Energy Reviews*, Vol. 42, Feb. 2015.
19. M. M. Shebani, and T. Iqbal, "Dynamic Modeling, Control, and Analysis of a Solar Water Pumping System for Libya," *Journal of Renewable Energy*, Vol. 2017, Apr. 2017.
20. Sandia National Laboratories, "Stand-Alone Photovoltaic Systems," *National Technical Information Service (NTIS)*, 1995.
21. M. Kolhe, S. Kolhe, and J. C. Joshi, "Economic Viability of Stand-Alone Solar Photovoltaic System in Comparison with Diesel-Powered System for India," *Energy Economics*, Vol. 24(2), Mar. 2002.
22. Sandia National Laboratories, "Maintenance and Operation of Stand-Alone Photovoltaic Systems," *Photovoltaic Design Assistance Center*, 1991.
23. https://www.suncalc.org/#/29.6581,52.4907,17/2017.09.26/09:21/1/0
24. F. Mohammadi, "Electric Vehicle Battery Market Analysis: Lead Acid," *9th Iranian Conference on Electrical and Electronics Engineering (ICEEE)*, Aug. 2018.
25. F. Mohammadi, "Electric Vehicle Battery Market Analysis: Nickel Metal Hydride," *9th Iranian Conference on Electrical and Electronics Engineering (ICEEE)*, Aug. 2018.
26. F. Mohammadi, "Electric Vehicle Battery Market Analysis: Lithium-ion," *1st International Conference on Modern Approaches in Engineering Science (ICMAES)*, Nov. 2018.
27. F. Mohammadi, "Lithium-ion Battery Market Analysis for Hybrid, Plug-in and Solar-Powered Electric Vehicles," *Journal of Solar Energy Research (JSER)*, Vol. 4(1), May. 2019.
28. F. Mohammadi, "Analysis and Electrification of the Solar-Powered Electric Vehicle," *5th Iranian Conference and Exhibition on Solar Energy (ICESE)*, Aug. 2018.
29. F. Mohammadi, "Design and Electrification of an Electric Vehicle Using Lithium-ion Batteries," *3rd International Conference on Electrical Engineering*, Sep. 2018.
30. F. Mohammadi, "Hybridization of an Electric Vehicle Using Lithium-ion Batteries," *1st International Conference on Modern Approaches in Engineering Science (ICMAES)*, Nov. 2018.
31. F. Mohammadi, "Research in the Past, Present, and Future Solar Electric Aircraft," *Journal of Solar Energy Research (JSER)*, Vol. 3(3), Dec. 2018.
32. F. Mohammadi, "Design, Analysis, and Electrification of a Solar-Powered Electric Vehicle," *Journal of Solar Energy Research (JSER)*, Vol. 3(4), Dec. 2018.
33. F. Mohammadi, "Power Management Strategy in Multi-Terminal VSC-HVDC System," *4th National Conference on Applied Research in Electrical, Mechanical Computer and IT Engineering*, Oct. 2018.

Appendix A:

The parameters of the proposed SAPV system for the simulation in PVSyst software are as follows:

Table 3. Monocrystalline PV Module Parameters

Parameters	Values
Length	1900 mm
Width	1235 mm
Weight	33.30 kg
Cells in Series	110
Cells in Parallel	3
I_{mmp}	5.655 A
V_{mmp}	60.13 V
V_{oc}	76.22 V
I_{sc}	6.212 A
Power	340 W

Table 4. Control Mode and the Specifications of the Charge Controller

Parameters	Values
Charge controller	
Charging Current	17 A
Discharging Current	12.8 A
Input side (MPPT converter)	
Minimum MPP Voltage	43 V
Maximum MPP Voltage	65 V
Output side (Battery and load)	
Nominal Output Voltage	12 V
Nominal Output Current	68 A
Nominal Output Power	816 W

Table 5. Battery Pack Parameters

Parameters	Values
Nominal Voltage	12 V
Nominal Capacity	100 Ah
Total Number of Batteries	7
Width	272 mm
Depth	203 mm
Height	385 mm
Weight	44.5 kg

Table 6. DC/AC Pure Sine Wave Power Inverter Parameters

Parameters	Values
Power	1000 W
Frequency	50/60 Hz
Nominal Output Voltage (AC)	200 V
Nominal Input Voltage (DC)	12 V