Optimal Design of Solar Photovoltaic Power System with Battery Storage for Sustainable Campus Buildings

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Abstract. The increasing energy demand and the development of renewable energy technology has been the catalyst for utilization of energy from renewable resources. Harvesting solar energy especially through photovoltaic technology is the most attractive and favoured in Malaysia. The aim of this study is to optimally design a solar PV system with battery storage for university building and evaluate the technical performance of the proposed system by using PVsyst simulation. Three buildings from Faculty of Electronic Engineering Technology, University Malaysia Perlis have been chosen as case study. The methodologies include data gathering for load profile and meteorological data such as solar irradiation and temperature, sizing of system’s components and lastly using PVsyst simulation to evaluate technical performance of the proposed system. The result shows the system could produce 168,989 kWh of energy to the load which is technically suitable for the site due to the high specific yield production and the performance ratio in addition to high solar fraction. In addition, the system could save RM 61,801 annually from electricity bill while from sustainability aspect, 117 tons of CO₂ could be avoided by using renewable energy annually.

1. Introduction
Electricity is a fundamental element in a country's financial progress and socio-economic growth. Fossil fuels like petroleum, gas, and coal are generally used in large-scale energy generation which have cause environmental pollution, depletion of the ozone layer, and global warming. In the latest years, environmental awareness of worldwide warming has concentrated on renewable resources such as solar, wind, biomass and tidal. As a result, small distributed generation (DG) plants using renewable energy resources (RE) are being developed. In particular, DG systems are designed to supply energy to remote regions where there is no grid. For off-grid applications, hybrid energy systems using renewable power resources together with diesel generators are common. The transport of fuel, however, is a major problem for distant regions. Depending on the site place, ability, and resources available, the setup of the hybrid system differs. To assess the size, cost, and effectiveness, assessment of technical and economic viability is necessary [1]. At the same time, global escalation of the fuel cost has encouraged countries to discover other power supply resources. Politics, environmental, and scientists around the globe are now looking to substitute standard fossil fuels with prospective renewable energy sources and simultaneously decrease emissions. Malaysia’s government
has implemented numerous sustainable energy development policies, for example, tax exemptions and additional allowances. During the 8th Plan of Malaysia from 2001 until 2005, and the Five Fuel Policy of Malaysia emphasize the utilization of energy from renewable resources for energy production. The government has also emphasized promoting incentives from Feed in Tariff (FiT) in accordance with the Ninth Malaysia plan (2006-2010). This enables major energy distributors, as the electricity is produced from renewable resources at fixed rate over a period between 16 to 21 years, to purchase from the authorized feed-in tariff holders (FiAH) [2]. Previous papers describe many different systems and methods to analyze in photovoltaic. For example, analyses of the sizing and simulation of a grid-tied photovoltaic system has been carried out for a project in Bucaramanga, Colombia with the virtual tool PVsyst. which found the solar irradiation is equal to 1882 kWh/m² and the system performance is 72.7% [3]. Another study on stand-alone photovoltaic (SAPV) system assessment using PVsyst software, which has been conducted in Perlis, Malaysia has shown the average daily radiation is 4.90 kWh/m² while the energy produced from the PV array is 841.3 kWh per annum [4]. A study in Southern Iraq, has used HOMER software to estimate the system size and its lifecycle cost. In comparison with the DG-alone system, the solar PV system designed is more cost-effective, the PV system reduces the CO₂ and other harmful gas emissions by 14,927 kg/yr. The COE and NPC of the diesel-alone system equal to $1.332/kWh and $352,303 respectively and for the solar-PV systemic equal to $0.238/kWh and $60,375, respectively [5]. Another work in Tunisia has to analyze the feasibility of PV power generation for such a remote area where 207174 gallons of fuel could be saved over 30 years with the PV system and the total cost and COE over the 30 years period for the stand-alone PV system is equal to $542,618 and $0.240/kWh respectively, and the DG-alone system equal to $651,822 and $0.289/kWh respectively [6]. For this paper, the objective is to optimally design a solar PV system with battery storage for university buildings and evaluation of the proposed system by using PVsyst simulation for its technical performance.

2. Methodology

In this section, methodology of the study is presented where the activities include data gathering for load profile and meteorological data such as solar irradiation and temperature, sizing of system’s components and lastly using PVsyst simulation to evaluate technical performance of the proposed system.

2.1. Load Profile

Three buildings from Faculty of Electronic Engineering Technology, University Malaysia Perlis (UniMAP) have been chosen as case study. The buildings, which geographical coordinates are 6°27’34’’ N, 100°21’01’’ E, are been divided into three main block: Block 1, Block 2 and Block 3. Generally, the electrical energy will be distributed to different area including lab utilities, electrical equipment, lighting systems, ventilation, and air-conditioning system. Fluke 1735 Three Phase Power Logger device has been used to measure actual load profile of the buildings for one week. It has been installed at switch board room within the building as shown in Figure 1.

Result is shown in Figure 2 for the daily profile that has been recorded for a week. From the result, total energy usage for a week is measured to be 3249.78 kWh where high demand time is from 8.00 a.m. to 5.00 p.m. in the weekday due to the routine teaching and learning activities. The highest power demand recorded is 60kW which occurs on Tuesday. The average daily electricity consumption during weekday is 559.88 kWh while during weekend is 225.19 kWh per day. Therefore, the weekly average consumption is 470 kWh per day. With these data, the expected yearly energy consumption is 168,988 kWh.
Figure 1. Measurement of daily load profile by using Fluke 1735 meter.

Figure 2. Daily load demand

2.2. Solar Irradiation and Meteorological Data
The solar irradiation data for Kampung Ulu Pauh in Malaysia is obtained from the National Aeronautics and Space Administrative, NASA-SSE, and METEONORM 7.2 software. In general, the nature of the weather in Malaysia is tropical year-round but the climate is often highly humid due to its nearness to water. In the monsoon season where the weather is much likely to be raining. The weather is never too hot, however, and temperatures range between 22° C to 34° C average throughout the year.

Figure 3 shows data for solar irradiation and temperature for the location of the case study. The monthly irradiance average ranges between 126.9 kWh/m² to 180.1 kWh/m² while the annual average is 151.05 kWh/m² per month. The total annual irradiation is 1812.6 kWh/m² where March has the highest irradiation while November is the lowest. The temperature averages range from 25.2 C° to 26.8 C° and the yearly average is 26.2 C°.
2.3. Design Calculation of The System
The design calculation of the system is based on the energy required for the site thus in this part is all about the PV sizing, battery sizing, and inverter/charger sizing.

(a) PV Sizing
The solar photovoltaic module used for this study is JINKO 370M-72V monocrystalline solar PV module where the selected parameters form manufacturer’s datasheet is listed in Table 1 below.

| Parameter                      | STC Value |
|--------------------------------|-----------|
| Maximum Power ($P_{mp}$)       | 370Wp     |
| Maximum Power Voltage ($V_{mp}$)| 39.9V     |
| Maximum Power Current ($I_{mp}$)| 9.28A    |
| Open-circuit Voltage ($V_{oc}$) | 48.5V     |
| Short-circuit Current ($I_{sc}$) | 10.15A    |
| Module Efficiency STC (%)      | 19.07%    |

Calculation of the total array power and number of modules is done by using the below equation.

\[ P_{array} = \frac{E_{sys}}{P_{SH_{period}} \times f_{temp} \times f_{d} \times f_{mm} \times \eta_{inv}} \quad (1) \]

\[ N_{module} = \frac{P_{array}}{P_{module}} \quad (2) \]
(b) Battery Sizing
The battery chosen for this study is Rolls 12-CS-11P lead-acid batteries which has 12V terminal voltage and 296 Ah capacity. Roundtrip efficiency is 80%. In order to cover the energy stored required, batteries are connected in 10 parallel string each string consists of 32 batteries with a total of 320 unit.

Calculation of battery system capacity and required battery in parallel and series is done by using the below equation.

\[
\text{Capacity} = \frac{\text{Avg daily energy} \times \text{Autonomy days}}{\text{DoD} \times \text{System Voltage}}
\]  

(3)

\[
\text{Battery in parallel} = \frac{\text{System Capacity}}{\text{Battery Capacity}}
\]  

(4)

\[
\text{Battery in series} = \frac{\text{System Voltage}}{\text{Nominal Voltage}}
\]  

(5)

(c) Inverter/Charger
Hybrid inverter MASTER POWER with 30 kW rated power is selected for this study. The design configuration will divide into 4 arrays which means there are 4 inverter required. The maximum PV array input power is 45 kW with maximum DC input voltage 950 V and MPP input voltage range is between 460 VDC to 900 VDC. The maximum input current is 72 A while the charger system voltage is 384 V with a maximum charging current of 80 A.

To estimate the total energy generated, the following equation is used.

\[
E_{sys} = P_{array, stc} \times PSH_{period} \times f_{temp, avg} \times f_{dirt} \times f_{nn} \times \eta_{inv}
\]  

(6)

To estimated specific yield and performance ratio of the system after one-year, the following equations are used.

\[
Y_f = \frac{E_{sys}}{P_{array, stc}}
\]  

(7)

\[
PR = \frac{E_{sys}}{E_{ideal}} = \frac{E_{sys}}{P_{array, stc} \times PSH_{period}}
\]  

(8)

2.4. PVsyst Simulation
PVsyst software is a professional tool for sizing, performance analysis and studying the photovoltaic system, which regular been utilized for grid-connected, stand alone, and water pumping application, is developed by the University of Geneva. [8], [9]. Various studies and research such as on-grid or off-grid system have utilized PVsyst for designing and simulating processes. For instance, a work from [10] has analyse the solar PV system performance for residential house that using fully DC system while a comparative study by [11] on solar PV system for university buildings for different PV array capacity of also by using PVsyst. Figure 4 shows typical layout of solar PV off-grid system in the simulation.
3. Result
Evaluation of the proposed designed system for its technical performance has been carried out by utilizing PVsyst simulation. Result summary is shown in Figure 5.

![Figure 5. Basic block diagram of the system.](image)

The PV array will consist of 17 modules in a series string and 20 in a parallel with total 340 units of PV module in order to meet the energy demand energy to the load and also to charge the battery. It is estimated 126 kWp could be generated by PV array at STC but only could be produced 114 kWp at the operating condition. Moreover, the overall battery required are 320 units to cover the energy requirement and the minimum discharging SOC is 20%. The system voltage is 384 V and the nominal capacity is 2960 Ah. In addition, the stored energy is 909.3 kWh, which will be able to support the electrical loads up to 2 days.

Table 2 shows the summary of the system performance. The total yearly energy required by the user (Eload) is 168,989 kWh while the available solar energy (Eavail) is 179,567 kWh annually. The amount of energy that could be supplied to the user is 164,125 kWh from the PV array (Euser). This is because of losses such as the mismatch module, wiring loss and the availability of solar irradiation. Nevertheless, the energy generated by the PV array is adequate to meet the annual load demand. The missing energy is higher in June, July, August, November, and December with a total of missing 4,863 kWh/year and the unused energy with a total of 12,021 kWh/year due to the batteries are full.
Table 2. Summary of the system performance

|                | GlobHor kWh/m² | GlobEff kWh/m² | E_Avail kWh | EUnused kWh | E_Miss kWh | E_User kWh | E_Load kWh | SolFrac |
|----------------|----------------|----------------|-------------|-------------|------------|------------|------------|---------|
| January        | 151.0          | 160.5          | 16579       | 3433        | 0          | 14353      | 14353      | 1.00    |
| February       | 155.3          | 160.0          | 16341       | 2122        | 0          | 12963      | 12963      | 1.00    |
| March          | 175.8          | 171.3          | 17537       | 2692        | 0          | 14353      | 14353      | 1.00    |
| April          | 176.7          | 164.5          | 16896       | 2725        | 0          | 13889      | 13889      | 1.00    |
| May            | 162.2          | 143.9          | 14883       | 912         | 0          | 14353      | 14353      | 1.00    |
| June           | 149.0          | 129.5          | 13478       | 0           | 675        | 13214      | 13889      | 0.951   |
| July           | 157.0          | 137.2          | 14173       | 1           | 699        | 13433      | 14353      | 0.951   |
| August         | 150.2          | 137.3          | 14175       | 709         | 1394       | 12759      | 14353      | 0.889   |
| September      | 140.2          | 133.6          | 13861       | 0           | 0          | 13889      | 13889      | 1.00    |
| October        | 142.7          | 142.7          | 14680       | 428         | 0          | 14353      | 14353      | 1.00    |
| November       | 130.7          | 135.0          | 14040       | 0           | 674        | 13215      | 13889      | 0.951   |
| December       | 119.2          | 125.4          | 12912       | 0           | 1221       | 13132      | 14353      | 0.915   |
| Year           | 1810.0         | 1740.8         | 179567      | 4863        | 164125     | 168989     | 0.971      |

Legends: GlobHor Horizontal global irradiation, GlobEff Effective Global, corr. for IAM and shadings, E_Avail Available Solar Energy, EUnused Unused energy (battery full), E_Miss Missing energy, E_User Energy supplied to the user, E_Load Energy need of the user (Load), SolFrac Solar fraction (EUnused / ELoad)

Figure 6 shows analysis from the aspect of system performance, the energy production per installed capacity that has been normalized. Daily losses for PV array is 0.78 kWh per kWp while the daily losses for the system is 0.31 kWh per kWp and the unused energy is 0.26 kWh/kWp per day as a result of battery is full. In addition, user has been supplied with 3.57 kWh per kWp amount of energy daily and the specific yield production (Yf) is 1427 kWh/kWp/yr. As shown in Figure 7, the yearly solar fraction of the system is 97.12% which is considered suitable while the performance ratio is 72.5% annually.

![Figure 6. Normalized system production.](image-url)
Figure 7. Performance ratio and solar fraction.

Annual system energy loss is shown in Figure 8. The energy generation from the PV array at STC is 220,112 kWh, however at the output of the inverter, the amount of energy reduced to 164,125 kWh. The effective energy at the output of the array is only 178,485 kWh and reduced to 167,546 kWh and 164,125 kWh because of converter and battery losses. Factors that contribute to energy produced from the PV array are such as temperature, irradiation availability, mismatch module, wiring losses and inverter conversion efficiency.

Figure 8. Loss diagram.

In terms of economic aspect of the system, the load consumption throughout the year is 168,988 kWh and from Tenaga Nasional (TNB) tariff pricing of medium voltage commercial tariff (Tariff C1) is RM 0.365 per kWh. Therefore, the total cost saving from buying energy from the grid system is RM 61,801 per year. In terms of environmental sustainability, 168,988 kWh of solar energy produced
annually is equivalent to more than 117 tons of CO$_2$ avoidance to the environment at rate 0.694 tCO$_2$/MWh.

4. Conclusion
As conclusion, this paper presents the optimal design of solar photovoltaic power system with battery storage for university buildings. To attain the power demand, 340 units of PV modules at rated power of 370 Wp were required, together with 320 units of 296 Ah batteries. Overall, the system could produce 168,989 kWh of energy to the load which is considered suitable for the site technically due to the high specific yield production and the performance ratio in addition to the high solar fraction. From the economic aspect, the system could save RM 61,801 annually from buying energy from grid system while from sustainability aspect, 117 tons of CO$_2$ could be avoided by using energy from the sun annually.

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References
[1] H. S. Das, C. W. Tan, A. H. M. Yatim, and K. Y. Lau, “Feasibility analysis of hybrid photovoltaic/battery/fuel cell energy system for an indigenous residence in East Malaysia,” *Renew. Sustain. Energy Rev.*, vol. 76, no. April, pp. 1332–1347, 2017.
[2] N. M. Isa, H. S. Das, C. W. Tan, A. H. M. Yatim, and K. Y. Lau, “A techno-economic assessment of a combined heat and power photovoltaic/fuel cell/battery energy system in Malaysia hospital,” *Energy*, vol. 112, pp. 75–90, 2016.
[3] Y. Muñoz, V. Orlando, P. Gustavo, and V. Jairo, “Sizing and Study of the Energy Production of a Grid-Tied Photovoltaic System Using PV syst Software,” *Tecchiencia*, vol. 12, no. 22, pp. 27–32, 2016.
[4] Y. M. Irwan et al., “Stand-Alone Photovoltaic (SAPV) System Assessment using PVSYST Software,” in *Energy Procedia*, 2015, vol. 79, pp. 596–603.
[5] A. Al-Karaghouli and L. L. Kazmerski, “Optimization and life-cycle cost of health clinic PV system for a rural area in southern Iraq using HOMER software,” *Sol. Energy*, vol. 84, no. 4, pp. 710–714, 2010.
[6] M. El Mnassri and A. S. Leger, “Stand alone photovoltaic solar power generation system: A case study for a remote location in Tunisia,” *IEEE PES Gen. Meet. PES 2010*, pp. 1–4, 2010.
[7] Jinko Solar, “Datasheet: Eagle PERC 72 350-370 Watt,” pp. 2–3, 2018.
[8] M. Bouguenda, A. Al Omair, A. Al Naeem, M. Al-Muthaffar, and O. B. Wazir, “Design of an Off-Grid 2 kW Solar PV System,” in *2014 9th International Conference on Ecological Vehicles and Renewable Energies, EVER 2014*, 2014, pp. 1–6.
[9] V. Sharma and S. S. Chandel, “Performance analysis of a 190kWp grid interactive solar photovoltaic power plant in India,” *Energy*, vol. 55, pp. 476–485, 2013.
[10] T. M. N. T. Mansur, N. H. Baharudin, and R. Ali, “Performance Analysis of Self-Consumed Solar PV System for A Fully DC Residential House,” *Indones. J. Electr. Eng. Comput. Sci.*, vol. 8, no. 2, pp. 391–398, 2017.
[11] T. M. N. T. Mansur, N. H. Baharudin, and R. Ali, “A comparative study for different sizing of solar PV system under net energy metering scheme at university buildings,” *Bull. Electr. Eng. Informatics*, vol. 7, no. 3, pp. 450–457, 2018.