Sizing Off-Grid PV Configurations on Electrical Performance and Electrical Energy Storage in Air Conditioning System Applications

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Abstract. The number of households using air conditioning (AC) systems in tropical climates has significantly increased in a few decades. The off-grid AC-powered solar PV becomes a new option for AC users to reduce electricity costs from existing grid sources. Therefore, optimization is required to size the supporting equipment in off-grid PV installations. This study simulates various equipment configurations such as nominal power (400 Wp, 550 Wp, 500 Wp, and 660 Wp), number of PV units (adjusted to the total load accordingly), and battery arrangement to obtain the performance ratio, losses, and battery performance for AC-powered solar PV applications. We use university classrooms equipped with two units of 1-hp split AC and other supporting typical class-electronic equipment at about 2,168 watts and 18,232 Wh of load and energy consumed per day respectively. The simulation results indicate that a configuration consisting of eight 550 Wp PV panels coupled with a 17.05 Ah Li-Ion battery yields the highest performance ratio, minimizes energy losses, and achieves the most balanced battery performance.

INTRODUCTION

The number of air conditioners used in households has significantly increased due to rising environmental temperatures and air pollution issues, making AC necessary for comfort and health. Urban areas in tropical climates are the most affected by climate change and the urban heat island effect, leading to increased indoor cooling loads and potentially impairing work productivity [1]. Currently, global air conditioner usage consumes around 1 trillion kWh of electricity annually, which is expected to increase tenfold by 2050 [2]. Another factor driving the increased use of AC is the rising demand for occupant comfort, as people in both residential and commercial settings prefer to maintain an optimal indoor temperature [4]. Uncomfortable indoor temperatures and working environments can lead to health issues and are crucial for keeping occupants' productivity.

The increased use of air conditioning leads to higher electricity consumption and, if the energy source is non-renewable, contributes to climate change. This also exacerbates the urban heat island effect and increases exposure to ambient heat. This means that the AC significantly impacts energy consumption and the environment, prompting research into developing more efficient systems that use less energy and have a lower environmental impact. Using solar energy for mechanical cooling becomes an option for this issue. Rebelo [3] has compared the solar thermal cooling system with the solar PV system and found that the Efficiency of PV cooling system demonstrated higher efficiency and better performance compared to the thermal cooling system under varying conditions. Besides that, the PV cooling system with energy storage proved to be more cost-effective in the long run due to lower operational costs and higher energy efficiency. A study of solar PV-driven air conditioners has been conducted by [4], exploring various configurations to match the PV power generation with the air conditioner's power consumption. The study of PV configuration has been explored by focusing on maintaining high efficiency even under partial shading conditions. The paper presents a design for a stand-alone photovoltaic (PV) system intended to supply electricity to a rural household in Jordan. The design process includes assessing site radiation data and household electricity consumption. System reliability is evaluated using loss of load probability. A computer program is developed to simulate PV system performance and optimize the configuration of PV arrays and battery banks based on reliability and cost considerations. Simulation results demonstrate that various PV array and battery combinations can achieve the required reliability levels, with significant cost differences among configurations [5]

This study aimed to evaluate the PV configuration for PV-driven AC which are differentiated based on voltage, current, and the number of inverters and batteries in order to determine the best in the performance ratio, loses, and battery performance for AC-powered solar PV applications.

METHODOLOGY

Load Profile

A university classroom is used to depict the hourly energy usage as a load profile for the input simulation process. We use two ACs with a 1-hp rate capacity as the major load and other supporting equipment in the classroom as shown in detail in Table 1. The total power consumption of the equipment is 2,168 Watt and energy consumed per day assumed to have 18,232 Wh.

TABLE 1. Energy consumption in test-chamber

Load component	Power per unit (W)	Quantity	Number of hours/day	Energy consumed per day (Wh/day)
Lamps	36	8	11	3,168
AC	840	2	8	13,440
Projector	200	1	8	1,600
	Total daily energy			18,232

The hourly load profile in a day from Table 1 can be conceived in Fig. 1. We assume the AC operated from 8 a.m. to 4 p.m. and other electronic equipment is adjusted accordingly.

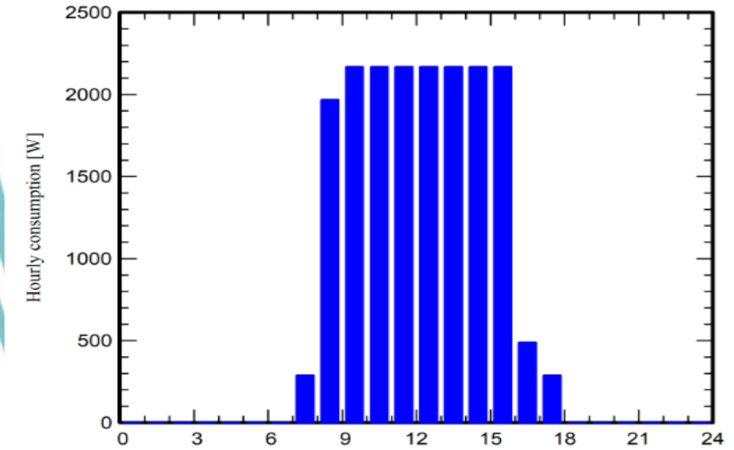

FIGURE 1. Hourly Distribution Load

In this study, we employed several parameters as measuring media to evaluate solar energy performance, including solar irradiation (kWh/m²), potential energy production (kWh), energy availability from solar photons (kWh), energy stored but not used (kWh), and energy absorbed in batteries (kWh). Additionally, we determined the solar fraction, defined as the ratio of energy consumed from solar power to the total energy consumption of the user. This comprehensive analysis aimed to provide insights into the efficiency and effectiveness of solar energy utilization [6].

$$PV\ Power[\mathrm{W}] = PV\ Modules\ area\ [\mathrm{m}^2] \times Irradiance[\mathrm{W/m}^2]$$

System Configuration

We use the PVsyst version 7.4 to simulate with a stand-alone mode system. The system configuration is divided into four schemes as shown in Table 2 and Table 3 for PV and Battery configuration respectively. We adjust the PV rate capacity per panel according to the manufacturer which has various total capacities.

TABLE 2. PV Configuration

PV Module	Configuration			
	A	B	C	D
Manufacturer	Trinasolar	Trinasolar	Longisolar	Trinasolar
Model	TSM-DE18M-500	TSM-DEG21C-20-650Wp Vertex	LR5-54HPH-400M	TSM-DEG21C-20-660Wp Vertex
Unit nom. power (Wp)	550	500	400	660
Number of PV module	8	12	16	9
Total PV capacity (Wp)	4.4	6	6.4	5.94

TABLE 3. Battery Configuration

Battery	Configuration			
	A	B	C	D
Manufacturer	Pylontech	Pylontech	Concorde	Pylontech
Technology	Lithium-ion	Lithium-ion	Lead acid	Lithium-ion
Model	Rack PhantomX_50Ah	Rack PhantomX_50Ah	PVX-560T	Rack PhantomX_50Ah
Unit nom. power (kWh)	17.05	17.5	17.05	17.05
Number of Battery	1	1	1	3
Total capacity (kWh)	17.05	17.05	17.05	17.05

We use coordinates location at -6.37, 106.82 and set the temperature of 25ºC for outdoor environment. We set stand-alone PV in the system and designed to operate in several modes to ensure optimal performance, including charging mode, discharging mode, and night mode. During charging mode, as illustrated in Fig. 2, the PV panels generate energy during the day, which is stored in the batteries. At night, when the PV panels are not operational, the stored energy in the batteries supplies power to the system. The system is designed with an autonomous day lighting ratio of 1:2, meaning that the energy stored during one day can supply energy for up to two nights. This configuration ensures a reliable energy supply for the intended load, even in the absence of sunlight.

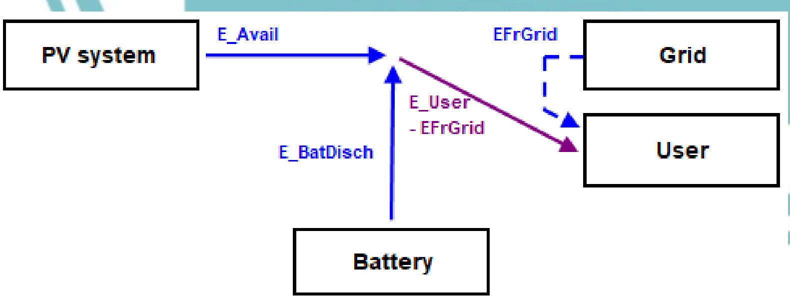

FIGURE 2. Charging mode scheme (no supply from PV)

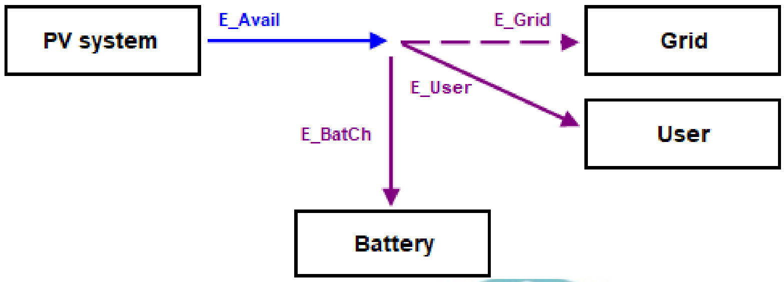

FIGURE 3. Discharging mode scheme (when in full direct sunlight)

Figure 3 illustrates the discharging mode, where the batteries are in a fully charged condition and cannot accept additional charge from the PV panels because they have exceeded their depth of charge capacity. At this mode, if the load can be supplied directly, the excess energy generated by the PV panels becomes unused, resulting in energy losses. This highlights the importance of optimizing the storage system to minimize energy wastage and enhance the overall efficiency of the stand-alone PV system [8]

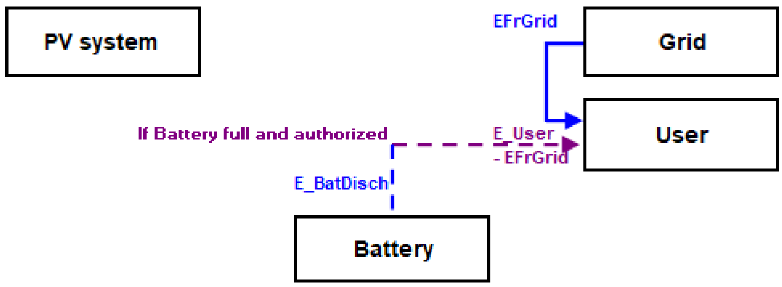

FIGURE 4. Night mode when battery full

At night, as shown in Fig. 4, there is no solar irradiation, and the system relies entirely on the batteries to power the load. The battery capacity (Wh) is calculate using following equation:

$$Battery\ Capacity = \frac{DEC\ -\ (ADL\ \times\ t)}{\eta\ \times DoD},$$

where *DEC* is daily energy consumption (Wh), *ADL* is the average day load (W) and t is the number of hour of effective charging, η and *DoD* is the battery efficiency from manufacturer and depth of charge in %.

RESULT AND DISCUSSION

The simulation results indicate that Configuration A is the most effective among the four configurations evaluated. Nearly all the energy generated by the system is directly distributed to the load, resulting in a system efficiency rating above 1, which is considered optimal for a solar power plant. Meanwhile in Configuration B, the voltage and current output are lower than those in the comparison system. Increased battery temperatures negatively impact the chemical reactions within the battery, leading to a rapid depletion of power.

Configuration A produces the least amount of unused energy due to its smaller capacity relative to the other configurations. The balanced energy supply between the PV panels and the battery prevents the battery from being in a continuous charging state throughout the day, thereby minimizing power losses due to a full battery.

Configuration C achieves the highest solar fraction, as all the energy produced by the PV panels is successfully stored in the battery. This is attributed to the use of the greatest number of panels among the configurations.

TABLE 5. Parameters defined from each configurations

Parameters	Configuration			
	A	**B**	**C**	**D**
Balance and main results				
Unused energy (kWh/day)	427.58	506.90	593.38	619.60
Solar fraction ratio	0.97	0.96	0.99	0.99

Meteo and Incident energy				
Wind velocity (m/s)/monthly	1.075	1.073	1.075	1.075
Global horizontal irradiation(kWh/m^2)/monthly	147.3	147.3	147.3	147.3
Ambient temperature (°C)	25.49	25.48	24.49	25.45
Sky diffuse incident in collector (kWh/m^2)/monthly	47.34	47.32	47.3	47.31
Balances of Currents in System Operating				
Array current (Ah)	6746.40	5874.23	5587.47	9429.50
Battery charging current (Ah)	477.24	416.36	434.06	484.15
Battery discharging current (Ah)	452.29	391.95	404.07	456.41
Ohmic losses (%)	3.12	4.58	4.20	6.89

Simulations conducted for four configurations show that the results are fairly consistent, particularly in determining the solar fraction. The solar fraction is defined as the amount of energy provided by the solar technology divided by the total energy required. This fraction ranges from zero, indicating no solar energy utilization, to 1.0, indicating all energy is provided by solar technology. The solar fraction savings of a system depend on various factors, including load, collection and storage sizes, operation, and climate[10].

Every simulation exhibits losses due to battery charging, as indicated in the table showing unused energy in the simulation results. These losses in PV plants are primarily caused by overcharging, which occurs when too many storage batteries are used, leading to inefficiencies in the power plant or wiring system.

Figure 5 shows the wiring diagram system from PV Array, system and user. A wiring diagram is a simple visual representation of the physical connections and physical layout of an electrical system or circuit. It shows how the electrical wires are interconnected and can also show where fixtures and components may be connected to the system.

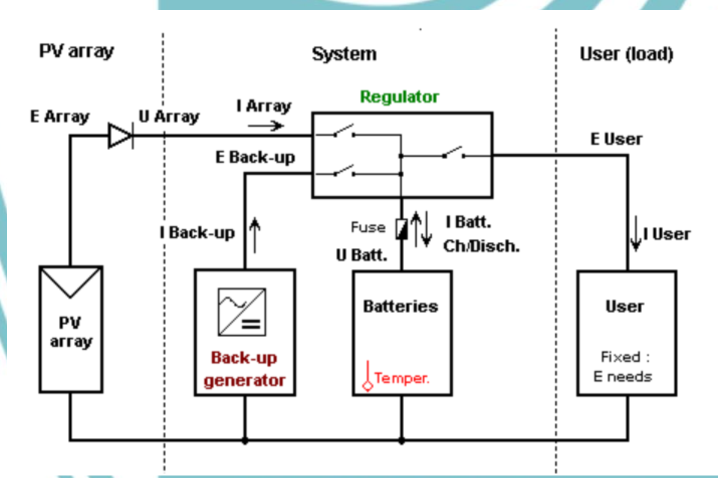

FIGURE 5. Wiring Diagram System

Figure 6 below illustrates the optimal configuration and layout for the classroom's load. This configuration is achieved by arranging 4 PV modules in 2 strings on the right and left sides of the roof, with a recommended installation slope of 10 to 15 degrees, oriented north and south. Using a battery rack with a capacity of 17.5 kW, this system can supply energy for two days without sunlight.

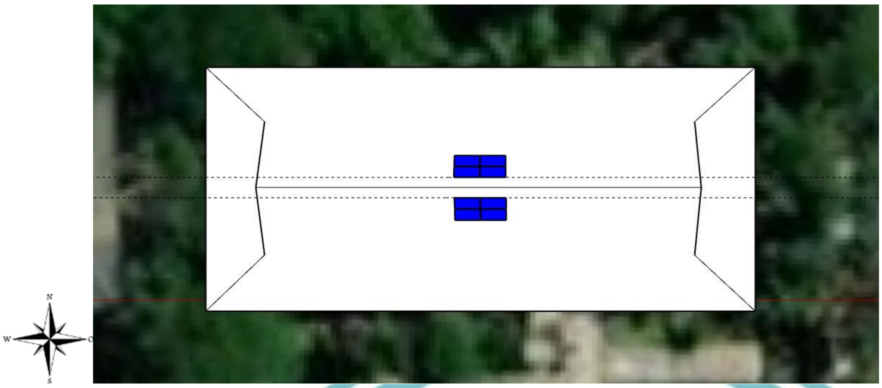

FIGURE 6. Layout PV Panel

CONCLUSIONS

One primary goal of this study is to explore the substitution of existing fossil energy with clean energy directly from the sun using a stand-alone system. In this context, photovoltaic (PV) panels are combined with pack bundle batteries to serve as the primary energy source for cooling systems (air conditioning) in primary-class buildings within government areas, specifically university buildings.

To conduct a thorough technical analysis and assess the feasibility of PV-battery systems, we examined each configuration considering real-time weather conditions, load demands, and the materials used in the system scheme. The most suitable system for this preliminary system are 550 Wp panels, arranged in 4 series and 2 parallel with 1 pack rack battery this system can reach 0.974 fraction solar ratio.

For future work, we aim to build on the results obtained in this paper by investigating strategies to minimize both the energy losses and the storage system, focusing on these aspects as the main optimization criteria.

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