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Development and Evaluation of Solar Energy Educational Kit for DC and AC Load Applications

Norliana Yusof[1,*], Siti Nurul Akmal Yusof[1], Nor Ziratul Aqma Norzaman[1], Siti Maryam Sharun[1], Noor Hidayah Mohd Yunus[2]

[1] Faculty of Innovative Design and Technology, Universiti Sultan Zainal Abidin, 21300 Kampus Gong Badak, Terengganu, Malaysia
[2] Advanced Telecommunication Technology, Communication Technology Section, Universiti Kuala Lumpur British Malaysian Institute, Jalan Sungai Pusu, 53100, Batu 8 Gombak, Selangor, Malaysia

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ABSTRACT

Education in renewable energy plays an important role in meeting global sustainability goals, including the proliferation of solar power technologies. Nevertheless, insufficient laboratory facilities and practical teaching aids prevent students from mastering the solar energy system. In this work, we develop and evaluate a low-cost solar power educational kit for secondary school and higher education. The kit facilitates hands-on understanding of the principles of solar photovoltaics (PV), series and parallel PV circuits, charge control systems and battery storage systems for an introduction to basic DC-to-AC inverter operation. Under simulated solar illumination from halogen lamps, we measured current–voltage (I–V) characteristics, power output behaviour and system response to changing illumination. Results indicated that towards theoretical prediction, the series PV arrangements have greater voltage and power outputs than single or even parallel configurations. The developed learning tool is shown to be successful in delivering basic solar knowledge with an affordable, safe and user-friendly format for STEM education. This method reinforces the students' practical exposure to renewables systems and will assist in sustainable energy-type teaching schemes.

1. Introduction

The advancement of science and technology, particularly in the field of renewable energy, depends heavily on education. The usage of renewable energy is one of the 2030 Sustainable Development Goals, which are currently being reiterated. Two promising and sustainable renewable energy sources are solar and wind power [1]. There is, therefore, a dire need for engaging and user-friendly educational materials in teaching students about solar energy and its applications. The solar power education kit represents the fulfilment of this need through practical learning provision to all categories of students. Traditionally, concepts in solar energy education are theoretical and visual concepts. Whereas practical learning is the core of learning for sustainable energy, where students

* *Corresponding author.*
E-mail address: norliana@unisza.edu.my

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need to be exposed to the skills to identify appropriate equipment, measure, troubleshoot, and connect circuits to create a solar system that can function well. However, the lack of laboratory equipment and learning facilities is one of the challenges to hands-on learning power generation courses, including solar systems [2,3]. Many existing solar power kits are complex to assemble and operate, requiring specialized knowledge and skills. This complexity can be a deterrent for non-experts, including students and hobbyists, who may find it challenging to work with such systems. An instructional kit for solar system education was described in this study. This simple and easy training set makes it possible to demonstrate the series-parallel integration of PV panels, integrating PV powering for DC and AC loads, focusing on off-grid applications. The training equipment is inexpensive and appropriate for both high school and higher education students. It is due to challenges faced by STEM educators, such as a lack of educational resources to support educators, which leads to educators having a lack of confidence to work with renewable energy resources [4-6]. Outdated teaching materials due to the fast progress of solar technology, teaching materials are frequently rendered obsolete, limiting students' capacity to connect with the most recent breakthroughs [7-11]. A solar power education kit is a great solution to raise an awareness of and interest in solar technology. Comprehensive discussion of such elements as inverters, load management and AC loads complete with overview of methods from utility direct installation to curtailment of solar output. Figure 1 shows a block diagram of the solar system components, including solar panels, charge controller, battery DC loads, inverter and AC loads. Before purchasing any of the related components, it is required to thoroughly understand the role each component plays and know their respective specifications and circuit connection between components. Solar panels are the devices that change light into direct current electricity when sunlight is shining directly on them while charge controller controls the voltage and current from solar panels to the battery. Its primary function is to stop battery overcharging, which leads to destruction. It also aids in the charging process, maximizing the system efficiency. Energy from solar panels is stored in a battery during the day and this energy can later be utilised when no sunlight is available. Batteries are typically stored energy in DC form. This energy can be used to power up DC loads devices include DC lighting, small electronics, or any other equipment designed to run on DC power. The inverter is a device that converts DC power from the battery into AC (alternating current) power [12-14]. AC is the standard form of electricity used in most household appliances such as fan, air-conditioning, computers, lights, and any other equipment designed to run on AC power [15]. Figure 1 shows the typical block diagram of solar systems for powering an AC dan DC load. Figure 2 shows the current-voltage (IV) curve for a solar cell. The shape of the curved graph shows the performance of the solar panel under certain sunlight, where open circuit voltage (Voc) is the voltage when no load is connected to the solar cells and short circuit current (Isc) is the current when the panel terminal is shorted. The point in the middle of the curve where the panel produces the maximum power, $P_{max}=I_{mp} \times V_{mp}$.

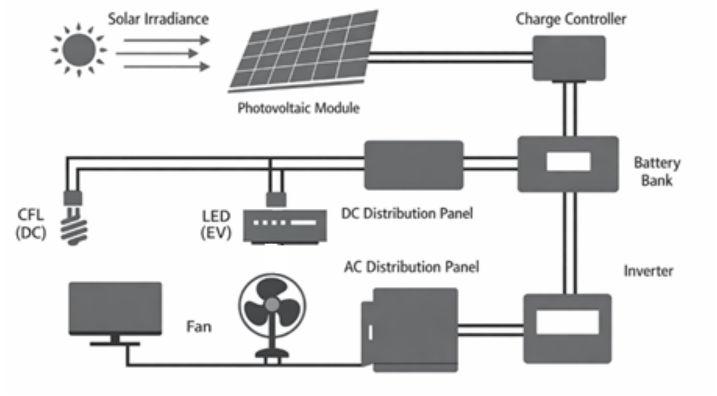

Fig. 1. Typical Block Diagram for Solar Systems

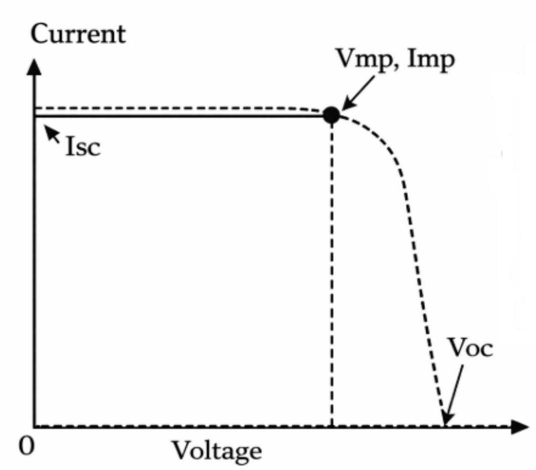

Fig. 2. Current-Voltage (IV) curve for solar cell

2. Methodology

2.1 Solar kit design for PV configurations study

To make sure solar energy can be delivered to the load in maximum power, the solar panel configuration must be comprehended. Hence, solar kit for PV configuration analysis was developed to understand the effect of the current-voltage curve for single cell, series, and parallel configurations. Figure 3 shows a solar-charging system with a single solar panel, a battery, and a solar charge controller with a DC load. This DC electricity is stored by the charged battery for subsequent use on low sun days. Basically, the solar charge controller protects the battery from damage due to overcharge and strong drainage, both factors that can drastically shorten the life of the battery. It will also optimize the charge process to top off the battery fully and quickly [16-18].

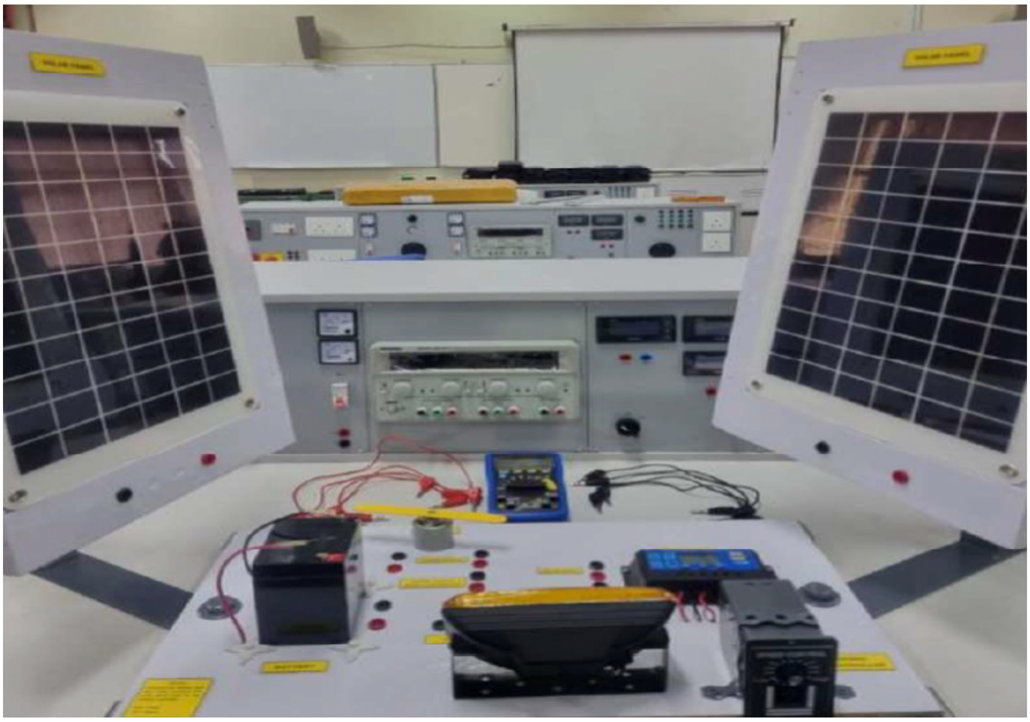

Fig. 3. Solar Kit Design for PV configurations study

Figure 4 shows the solar panel configuration in a) parallel b) series and c) single connection simulated by using TinkerCAD software. The simulation of these configurations was done to study the effect of output voltage and power for each configuration. Before getting to the battery for storage, the solar panel's current must pass via the solar charge controller for voltage and current control. Connecting the batteries in series may bypass the controller and potentially damage the battery. However, it is possible to consider a situation where a series connection exists within the system solely to power a specific load. Connecting the battery directly to the light bulb in a series setup would cause current to flow from the battery, through the bulb, and back to the battery, so completing the circuit. Nevertheless, this system would not allow simultaneous charging since the light would drain the accumulated energy. Usually use a parallel connection to the battery and the loads, a solar system charges and runs appliances. This allows an independent current flow at once power electronic devices and charge the battery. First it raises the total current output while preserving the voltage. Faster battery charging or handling greater power loads follow from this. Second, every element functions separately. The controller can control charging independent of the load condition, and the solar panels can create electricity even in cases with a load consuming power. At last, a parallel system claims higher scalability and unlike a series configuration, adding extra solar panels in parallel makes expansion system's capacity. Basically, the parallel connection in this solar charging system offers a more efficient and versatile approach to exploiting solar energy [19-20].

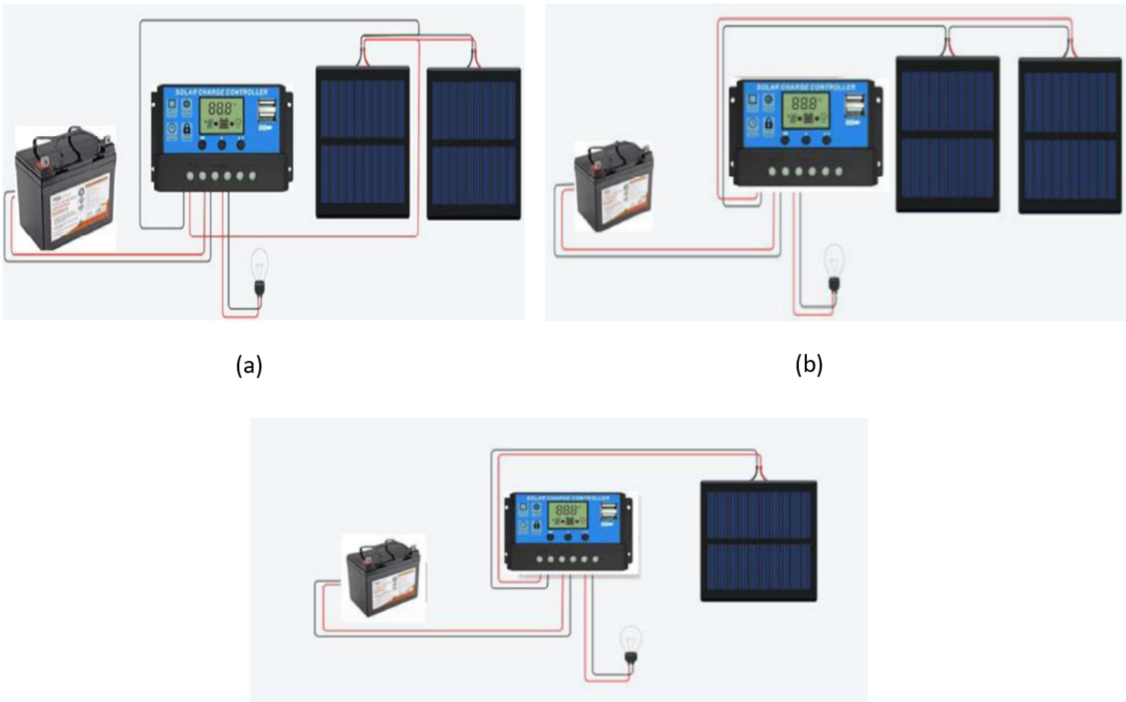

Fig. 4. Solar panel configuration for (a) parallel (b) series and (c) single connection

2.2 Solar Kit Design for DC and AC Loads

Apart from the configuration of solar panels, an important should be stressed in order to develop a solar system is how to connect energy from solar panels to AC/DC loads. The design should begin with the selection of the right components, including a charge controller (CC), battery, inverter and also AC/DC loads. Figure 5 shows the solar kit design for power up the AC/DC loads. In this solar kit design, both AC/DC loads were used to give understanding how both loads should be connected to the energy source, charge controller (CC) and AC/DC converter. The CC is chosen for its ability to optimize energy conversion; this guarantees effective charging of the battery storage and maximization of the solar panels' power output. Meantime, high-quality wiring and connectors are used so that inefficient energy transfer is deemed acceptable. The CC is integrated into the system, with wires connected from the solar panels, battery storage, and AC/DC loads. The different DC loads are connected to the system, and their performance is tested in order to guarantee compatibility and efficiency. Instead, it is a carefully organized multi-step process in which every stage (design, choice of components, material procurement), exactingly executed with the utmost calculation for each power requirements. This sort of painstaking attention to detail makes it possible for us at final assembly and inspection to verify that everything is both reliable and as efficient as possible. The solar power kit is composed of monocrystalline solar panels that have been assembled and systematically incorporated into a high-performance system.

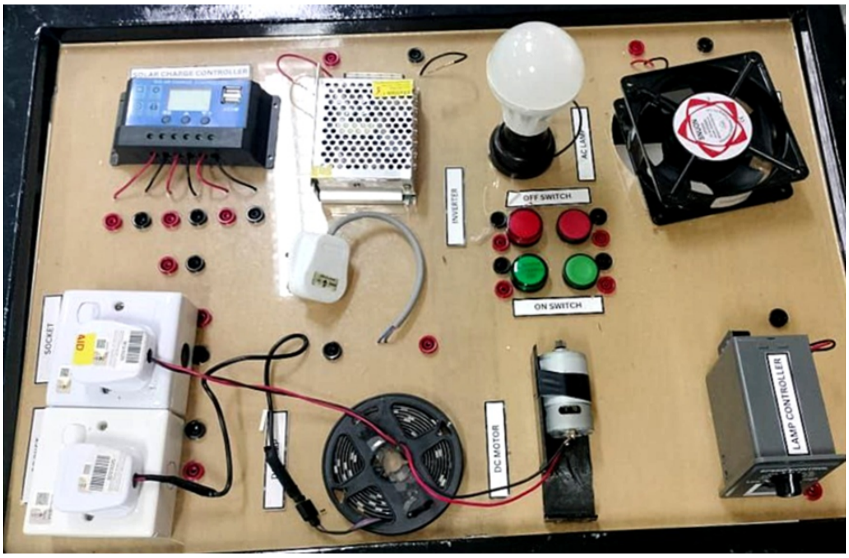

Fig. 5. Solar Kit Design for AC dan DC loads

4. Results and Discussion

Both of the solar kits design was tested in term of their performance and effectiveness. First, testing of the solar configuration was done under indoor and outdoor conditions. The current and voltage were measured for series, parallel and single configuration and power output were calculated based on the measurement. Second, the testing of solar kit for AC/DC loads was done and both performance of AC and DC loads were analysed. A halogen bulb was utilized to simulate a solar source in order to test this solar kit and give steady energy source.

4.1 Testing of solar configuration Design

Figure 6 shows the comparison of photovoltaic output voltage under indoor and outdoor conditions. From the figure, it shows that the open-circuit voltage is always higher outdoors than indoors, and it is higher in series than in parallel. That is because the open circuit voltage depends on the number of cells connected in series, as it is proportional to the number of cells. The voltage of each cell adds together, producing a greater total voltage in series. In a parallel setup, the currents from the cells add up while the voltage remains the same. The maximum voltage amongst three circuits is 36.3V, while the minimum is 16V. Figure 7 shows that the power (W) output of the solar panel is higher at outside than indoors, and that it can be higher in a series configuration than in a parallel layout. In a series system, the voltage of each cell adds up, just the current remains constant, as if the panel were one. This can be useful if the application demands a greater voltage. However, if one panel in a series configuration is shaded, it affects the whole circuit as current cannot pass through it. In a parallel configuration, though, the current from each cell adds up while the voltage stays constant, as in a single panel. This may be of use if an application requires more current. However, in case one panel in a parallel setup fails, the other panels will still be working. The output power from three circuits maximum is 0.1565 W, and the minimum is 0.0304 W following of P-V theory, power is equal to voltage multiplied to current.

The voltage results demonstrate that under indoor conditions, the single panel and parallel configuration produced approximately 16 V, while the series configuration doubled the output to 32 V. Under outdoor irradiance, the values increased to 18.5 V for both the single and parallel configurations, and 36.3 V for the series configuration. These outcomes align with P-V theory, where a series connection approximately doubles the voltage while a parallel connection maintains the same voltage as a single module. The higher outdoor voltages are attributed to increased irradiance and reduced internal resistance at higher photocurrents. Although temperature rise can reduce the open-circuit voltage, this effect was outweighed by the irradiance gain. For power output, the single and parallel configurations were nearly identical, yielding 0.0304 W indoors and 0.04064 W outdoors, whereas the series connection delivered significantly higher values of 0.1216 W indoors and 0.1565 W outdoors, nearly four times that of a single panel. This result can be explained by the relation of P-V theory under a fixed high-resistance load, where doubling the voltage results in approximately four times the power. The lack of power gain in the parallel case suggests that the load was voltage-determining and operated the modules close to open-circuit conditions, preventing the utilization of additional current capacity.

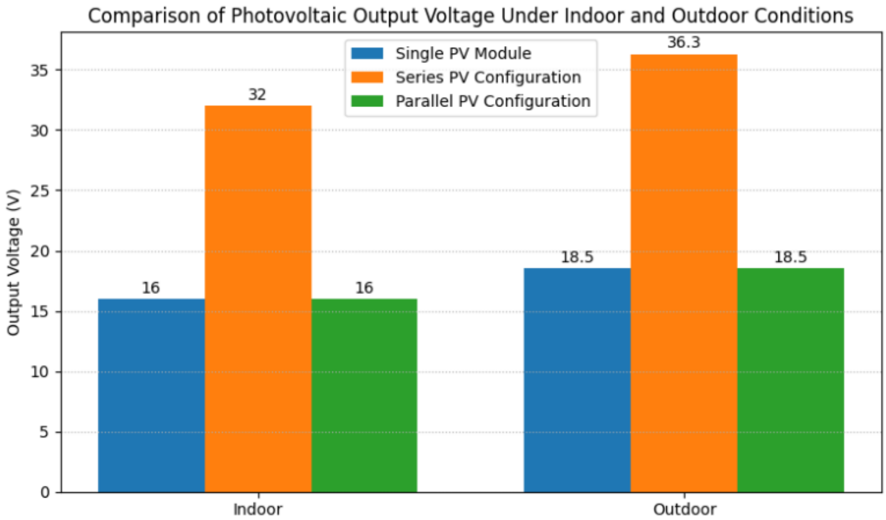

Fig. 6. Comparison of PV output voltage under indoor and outdoor conditions

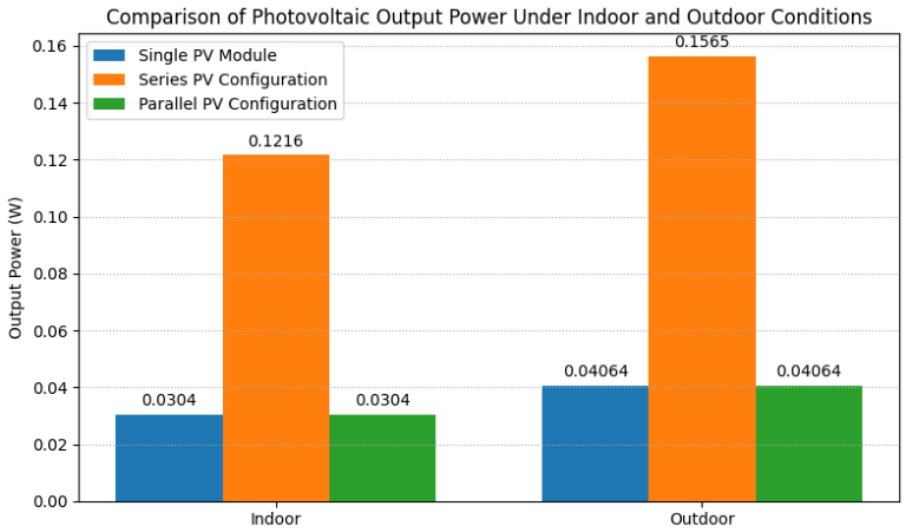

Fig. 7. Comparison of PV output power under indoor and outdoor conditions

4.2 Analysis of a Solar Power for DC and AC Loads

Figure 8 illustrates how different voltages from a halogen lamp affect the performance of a photovoltaic (PV) power system. This figure plots on a single graph the voltage of the solar panel, the output from the charge controller (battery voltage as measured by the ammeter), the battery voltage, the current from the solar panel and the power used by an AC load. The data offers insight into a system's electrical response as simulated irradiance (in this case lamp voltage) increases. Solar panel voltage decreases linearly from ~18 V at 2 V lamp voltage to ~15.5 V at 12 V lamp voltage. This negative correlation shows that the need for power—in this case, a higher current draw—increases as the lighting level does. The charge controller output voltage starts out around 14 V at low lamp voltages and drops steadily to ~11 V at 12 V lamp voltage. This decline implies that the system responds to increasing load demand by reducing its output. Also, possibly depending on battery charging status, the voltage remains fairly constant but shows a slight trend downwards from ~12.5 V with a 2 V lamp voltage to ~11.5 V when the lamp voltage is increased to 12V. In comparison to other components of the power supply that are coming to life in order to meet current demand, this behaviour indicates that the battery will, in fact, discharge slightly under higher load conditions, but only by a few volts. AC load power rises steeply with lamp voltage, from about 30 W at 2V to nearly 125 W at 12V. This strong positive correlation means that as the lamp voltage goes up, so does energy out from the system carrying load with it. Thus, system power output is amplified in direct response to higher environmental illumination levels. While panel and controller voltages decline with lamp voltage, AC load power increases significantly, suggesting that available energy is being directed more toward load demand rather than maintaining higher DC voltages.

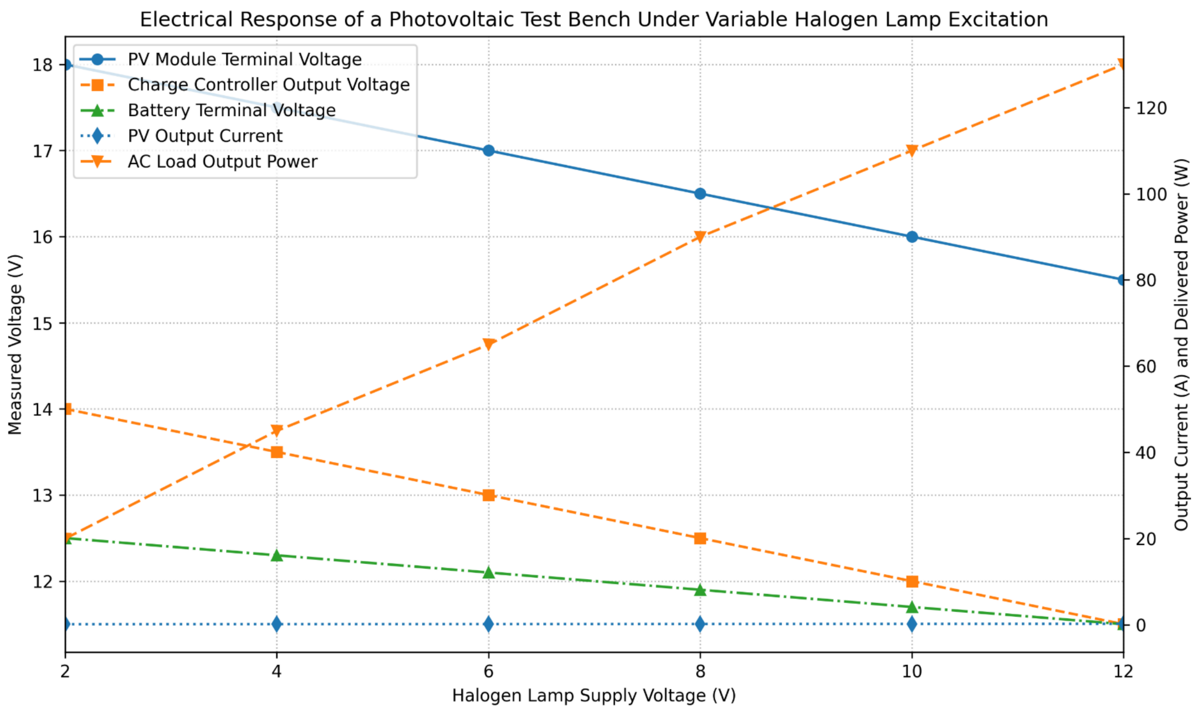

Fig. 8. Testing measurement on solar kit desigokn for A/DC loads

The battery voltage is declining only slightly, so that it is relatively constant in terms of capacity during this experiment. Experiments indicate system operation to be voltage-regulated and that power output is not severely limited by experiments and thus constrained. Solar panel output is near zero current; with the system, it means there may be some restrictions on maximum PV current output. The increase in AC power despite declining DC voltage suggests that the charge controller and inverter are efficiently converting electricity at high irradiance levels. Table 1 shows the DC electrical response of the solar components, with halogen input voltages ranging from 2 V to 12 V. These data offer an indication of how PV module, controller and all the components interact when exposed to simulated under sunlight conditions.

Table 1
DC Electrical Response of the Solar Educational Kit

Halogen Lamp Voltage (V)	Solar Panel Voltage (V)	Solar Panel Current (A)	Charge Controller Output Voltage (V)	Battery Bank Voltage (V)	Battery Bank Current (A)
2	18	1.2	14	12.5	3
4	17.5	1.3	13.5	12.3	3.5
6	17	1.4	13	12.1	4
8	16.5	1.5	12.5	11.9	4.5
10	16	1.6	12	11.7	5
12	15.5	1.7	11.5	11.5	5.5

The solar panel voltage decreases from 18 V at 2 V halogen input to 15.5 V when it had 12 V output, showing a negative correlation with irradiation. Conversely panel current increases from 1.2 A to 1.7 A over the same range, this inversely proportional relationship is in line with I-V curve characteristics of photovoltaic modules. More sunlight naturally leads to more current, but this causes a slight drop in operating voltage. This shows that the panel responds rapidly to light conditions, producing larger currents under stronger illumination. At low light levels the charge controller's output voltage is 14V, but this falls to 11.5 V as irradiance increases. This trend indicates active regulation by the controller, changes its output depending voltage stored in battery bank. As irradiance increases, the dropping controller voltage also means that more current is being directed to the battery. Therefore, charging becomes the priority over maintaining a high DC voltage. The battery bank voltage trends downward from 12.5 V to 11.5 V. This small reduction reflects the increased load and charging demand at higher irradiance. The increase in charging current gives proof that the additional energy captured by the PV module is correctly transmitted into storage.

5. Conclusion

This study has succeeded in developing and validating a low-cost, portable solar energy educational kit intended for hands-on studies in solar performance analysis. By employing this solar kit, students can improve their comprehension in understanding the behaviour of solar panel configuration and its performance to the output voltage and power. Through the solar kit for AC/DC loads, students may study the components involved, and how the connection between them to power AC/DC loads from solar panels. The solar kit design may reduce the existing barriers in renewable energy education in terms of complexity, price, and lack of solar education kit. It has been surmounted with the development of this comprehensive user-friendly platform which would be suitable for college and universities students. Future work will focus on evaluating the effectiveness of the designed solar energy kit in a space where energy is integrated into STEM education as well as its application in all new curricula reforms.

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