



HARNESSING THE SUN'S POTENTIAL: AN ARDUINO-BASED SYSTEM FOR OPTIMIZED ENERGY MANAGEMENT IN PV SYSTEMS

S.AKHINBOHUN*, F. K. ALLI, and M. OMOSIGHO

Department of Computer Engineering, Faculty of Engineering, University of Benin, Benin City, Edo State. Nigeria.

*Corresponding author's email address: sylvester.akhinbohun@uniben.edu.ng

ARTICLE INFORMATION

Submitted: 7th May 2024
Revised: 4th December 2024
Accepted: 7th December 2025

Keywords:

Photovoltaic systems
Arduino
Energy management
Renewable energy
Sustainability

ABSTRACT

The global shift towards renewable energy sources has placed photovoltaic (PV) systems at the forefront of sustainable energy solutions. Traditional PV systems often suffer from inefficiencies due to fixed load thresholds that do not adapt to changing environmental conditions, leading to energy waste. It proposes an innovative Arduino-based system for optimizing energy management in PV systems. The Arduino platform was selected for its ease of programming, affordability, and compatibility with various sensors. By continuously monitoring real-time data such as solar irradiance, battery status, and local energy consumption, the proposed system dynamically adjusts load thresholds to prevent energy waste and grid overload. The system architecture includes high-efficiency PV panels, a solar charge controller, deep-cycle batteries, and various sensors to monitor voltage, current, and temperature. The system employs deep-cycle batteries with capacities based on the energy requirements and expected usage patterns, and voltage regulators such as the LM7805 to ensure safe operation of the Arduino microcontroller at 5V, converted from the standard 12V input. This setup shows the comprehensive integration of components to ensure optimal performance. Simulation results demonstrate the system's ability to manage power effectively, preventing overload and promoting energy efficiency. By maintaining precise control over energy distribution and utilizing a user-friendly interface for real-time monitoring, this research highlights the potential of an intelligent, cost-effective solution for enhanced energy management in PV systems, paving the way for more sustainable energy consumption.

© 2025 Faculty of Engineering, University of Maiduguri, Nigeria. All rights reserved.

1.0 Introduction

The global transition towards renewable energy sources has propelled photovoltaic (PV) systems to the forefront of clean and sustainable energy solutions (Farid, Rahman, and Uddin, 2011). These systems capture solar energy and convert it into electricity for residential and commercial applications (Etawil, Massoud, and Finney, 2010). However, traditional PV inverters often have fixed load thresholds that fail to adapt to fluctuating environmental conditions and energy demands, leading to potential energy waste (Farid, Rahman, and Uddin, 2011; Zheng *et al.*, 2017). This inefficiency, coupled with the additional costs associated with inverter installation and rewiring, necessitates the development of more intelligent systems. This study proposes an innovative approach to optimize energy management in PV systems using an Arduino microcontroller. Arduino's user-friendly programming, affordability, and diverse sensor compatibility make it an ideal platform for integrating advanced energy management systems (Zhao, Gao, and Zhai, 2011). By continuously monitoring real-time data like solar irradiance, battery status, and local energy consumption, the Arduino-based system architecture can dynamically adjust load thresholds, preventing energy waste and grid overload (Zhao, Gao, & Zhai, 2011). The research aims to develop a system that is not only user-friendly and cost-effective but also relieves users of the burden of manual appliance operation and eliminates the need for expensive rewiring (Frauenfelder, 2011). Through simulations, this study investigates the feasibility and effectiveness of the proposed system architecture. The methodology involves simulating power supplies, incorporating sensors to monitor electrical parameters, and utilizing an Arduino Uno microcontroller as the central processing unit (Frauenfelder, 2011). A user-friendly interface allows for manual

threshold setting and real-time system monitoring. Ultimately, it seeks to address the need for efficient power control in PV systems, to promote sustainable energy solutions and a seamless integration of renewable energy sources.

McGowen *et al.* (2005) developed a system called Foxton Technology, which uses a 90-nm Itanium family processor to regulate power distribution in integrated circuits. The system uses on-chip technology and an embedded system to detect power usage by specific devices and compare it with a predefined power-temperature envelope. The system aims to achieve optimal performance without exceeding the specified threshold limit, using both voltage and frequency adjustments. Palamar *et al.* (2011) designed and implemented a digital control and monitoring module for an AC/DC Uninterruptible Power Supply (UPS). The system includes an LCD for the user interface and a real-time clock powered by a lithium battery for time tracking during power outages. The ADuC831 microcontroller is used for real-time control, and the system's initialization process involves setting interrupts, initializing LCDs and DACs, and assigning initial values to variables. Al-Hassan *et al.* (2018) presented research on implementing the ZigBee communication protocol for smart sockets and central control systems. They demonstrated effective bidirectional communication and reliable wireless connectivity over distances exceeding 18 meters. Edeoghon *et al.* (2022) designed and implemented an IoT-Based Solar-Powered inverter control system using the NodeMcu microcontroller unit connected to the internet via Wi-Fi. This system allows remote monitoring and management of solar outlets, providing data such as current values, outlet loads, and battery levels via a mobile application interface. Elkholy *et al.* (2022) introduced HAMS, a Home Automation Management System that optimizes renewable energy consumption. The system uses Raspberry Pi 4 as the main controller and collects data from sensors deployed throughout the house, monitoring parameters like temperature, humidity, smoke levels, and lighting. The system uses Passive Infrared (PIR) sensors for human presence detection and updates data to an IoT server for remote access and control via the Cayenne IoT platform.

2. Materials and Methods

The Arduino microcontroller board is the core of the system, chosen for its versatility, ease of programming, and compatibility with various sensors and peripherals (Álvarez, Mozo, & Durán, 2021). High-efficiency photovoltaic (PV) solar panels are used to capture solar energy, and a solar charge controller regulates voltage and current to efficiently charge the battery bank. Deep-cycle batteries are used to store excess solar energy during low sunlight or high-demand periods.

Voltage and current sensors measure voltage and current at various points within the system, providing real-time data for monitoring system performance and optimizing energy management algorithms. A temperature sensor is integrated to monitor ambient temperature conditions, which can affect the efficiency and performance of solar panels and batteries. A user-friendly LCD provides a user-friendly interface for monitoring system status, including energy generation, battery charge level, and load consumption. Relays and switching circuitry control the flow of energy within the system, directing power from the solar panels to the battery bank or load, and disconnecting loads during low battery conditions to prevent over-discharge. The Arduino microcontroller is programmed using the Arduino Integrated Development Environment (IDE) with custom-written code to implement energy management algorithms, including MPPT for maximizing solar energy harvesting, battery charging and discharging control, load prioritization, and system protection mechanisms. A data logging and communication module is integrated to record system performance data and enable remote monitoring and control capabilities. An enclosure and mounting hardware protect the system components from environmental factors and securely install them in their intended location. Before deployment, the system undergoes rigorous testing and calibration procedures to ensure proper functionality and performance. By integrating these materials and methods, our Arduino-based system for optimized energy management in PV systems offers an efficient, reliable, and user-friendly solution for harnessing the sun's potential to meet energy needs sustainably.

2.1 System architecture design for the system

In the course of carrying out this research work, several components that make the system architecture function were simulated in proteus. These parts are essential pieces that make the functionality of the system. The designed system architecture was simulated to select the load threshold for PV inverters including the connected components. The process flowchart operation of the modeled system is shown in Figure 1.

The simulation setup relies on a robust power supply system, consisting of a main source and an inverter source, which ensures voltage availability for system functionality and command execution. The system configuration includes dual power supply mechanisms, providing redundancy and reliability for uninterrupted operation (Kumar et al., 2018).

When AC, represented by the sinusoidal wave, is sourced from the main supply, it undergoes initial transformation via a step-down transformer which helps to convert a higher voltage input into a lower voltage output, and a voltage rating of 220V was adopted. To lower the voltage from 220 volts to 12 volts, a transformer with an appropriate turn ratio was employed.

$$\text{Turns Ratio } (N) = \frac{V_2}{V_1} \tag{1}$$

Where; V_1 is the input voltage (220 volts), V_2 is the desired output voltage (12 volts).

$$N = 12V / 220V \approx 0.0545 \tag{2}$$

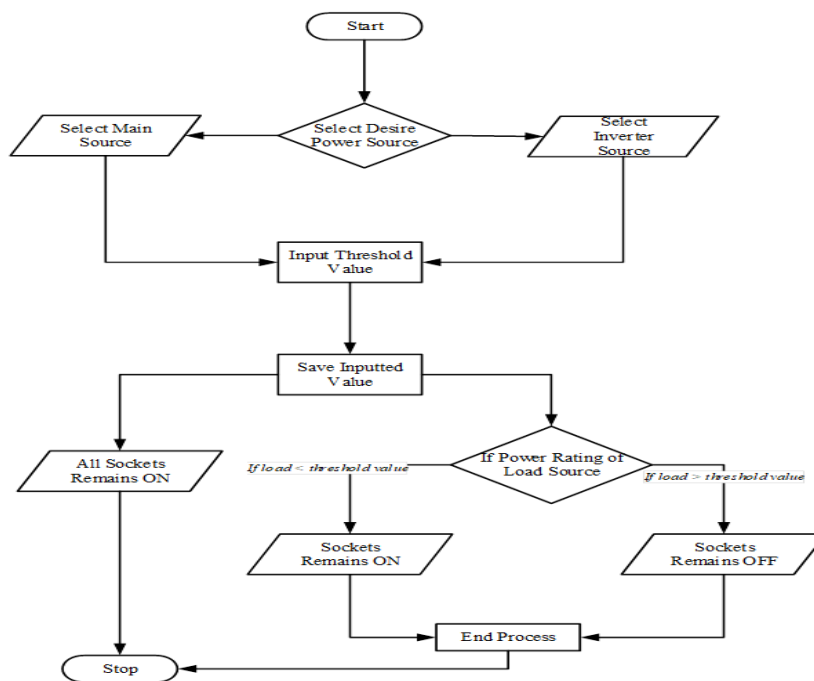


Figure 1: Flowchart of System Architecture

Transformer operation involves a step-down transformer with a primary coil having a higher number of turns than the secondary coil, maintaining a specific ratio of 1:N. This ratio is approximately 0.0545, resulting in a transformer with a 20:1 turn ratio. The voltage is then converted to direct current (DC) to ensure compatibility with the Arduino Uno Microcontroller, which operates with DC input. The stepped-down voltage from the secondary coil is converted through a rectifier, which transforms AC into DC, ensuring seamless integration with the Arduino Uno Microcontroller. The voltage is then passed through a 100uF capacitor C1 to remove noise, and a voltage regulator reduces 12V to the desired voltage. This process ensures seamless integration with the Arduino Uno Microcontroller. The Arduino Uno Microcontroller has a maximum voltage rating of 5V, any higher would destroy it. The voltage regulator used for this simulation is the LM7805 and it drops the 12V to 5V by considering the following parameters: Input Voltage (V_{in}): 12V, Output Voltage (V_{out}): 5V

Load Current (I_{out}): The maximum current your circuit or device connected to the regulator will draw. A load current of 1A is used. The following formula is used to calculate the necessary values. Differential Voltage (V_d) parameter represents the voltage drop across the regulator and is calculated as the difference between V_{in} and V_{out} . It is mathematically, expressed as $V_d = V_{in} - V_{out}$. That is, if V_{in} is 12V and V_{out} is 5V, then V_d would be 7V. This relationship can be denoted as follows:

$$V_d = 12V - 5V = 7V \tag{3}$$

Power Dissipation (P_d): This refers to the power dissipated by the regulator and is determined by the product of the voltage drop (V_d) and the load current (I_{out}). Expressed in mathematical terms, P_d can be represented as $P_d = V_d \times I_{out}$. For instance, if V_d is 7V and the load current (I_{out}) is 1A, then the power dissipation would be 7W. This calculation is demonstrated as follows:

$$P_d = 7V \times 1A = 7W \quad 4$$

The LM7805 voltage regulator ensures stability and minimizes output voltage ripple by incorporating an output capacitor, C2. The capacitor, with a 10nF capacitance rating, stabilizes the voltage output. Once regulated to 5V, it is directed to the Arduino Uno microcontroller through Pin 9, MAINS. The 5V supply enters the microcontroller through this Pin 9. This pivotal connection establishes the foundation for the microcontroller's operation and subsequent functionalities. The Inverter supply follows the same procedure as the Main supply, filtering output voltage through capacitor C3 and voltage regulator through capacitor C5, with a stabilized 5V output which is directed into the Arduino Uno microcontroller through Pin 10. The system consists of push buttons, a central processing unit, digital pins, analog pins, and a display unit (20x4 LCD). The Arduino Uno microcontroller serves as the core component, interconnecting all necessary elements for the simulation. Digital pins include Pin 0 (RXD) for receiving serial data, Pin 1 (TXD) for transmitting serial data, and Pins 2 & 3 (RS & EN) for controlling the LCD. Data pins 4 - 7 (D4 - D7) are directly connected to the LCD, facilitating data transmission from the Arduino to the LCD.

Pin 8 receives 5V power from the inverter source to power the microcontroller, ensuring its functionality. Pin 9 receives 5V power from the main source to power the microcontroller, ensuring consistent operation. Analog pins A3, A4, and A5 (MENU, INC, and DEC) are linked to switch buttons for menu navigation and selection operations. Meanwhile, the display unit connects to the Arduino Microcontroller using specific data pins 4, 5, 6, and 7. The switching unit facilitates the seamless transition between different power sources. Outlets, consisting of a transistor and a relay switch, play a pivotal role in assessing the system's output. The BC547 transistor is used for its signal amplification capabilities, with three terminals: the emitter, collector, and base. In the other hand, the relay uses five pins, including two coil pins and three additional pins designated as common, normally open, and normally closed. The common pin maintains a continuous connection to the output, while the normally open connection establishes a connection solely upon the relay's activation. The relay's operational functionality is facilitated by the two coil pins powering the electromagnet and one coil pin connecting to a positive voltage source and the other to a ground or negative voltage source.

2.2 Applied Procedure

Figure 2 shows the complete system diagram; the Arduino Uno serves as the central processing unit (CPU) in this setup. Built around the Atmel ATmega328p microcontroller, it boasts 14 digital input/output pins, with 6 of these configurable for pulse-width modulation (PWM) applications (Hossain *et al.*, 2022). Programmed through the Arduino Integrated Development Environment (IDE), the Uno supports a range of programming languages and libraries, making it an optimal choice for its user-friendly interface, ease of programming, and cost-effectiveness (Silva *et al.*, 2020). Code for the microcontroller is composed in C++, compiled, and converted into a .hex file format via the Arduino IDE. In tandem with the Uno, a 20x4 LCD is employed for its superior display capabilities compared to the standard 16x2 LCD.

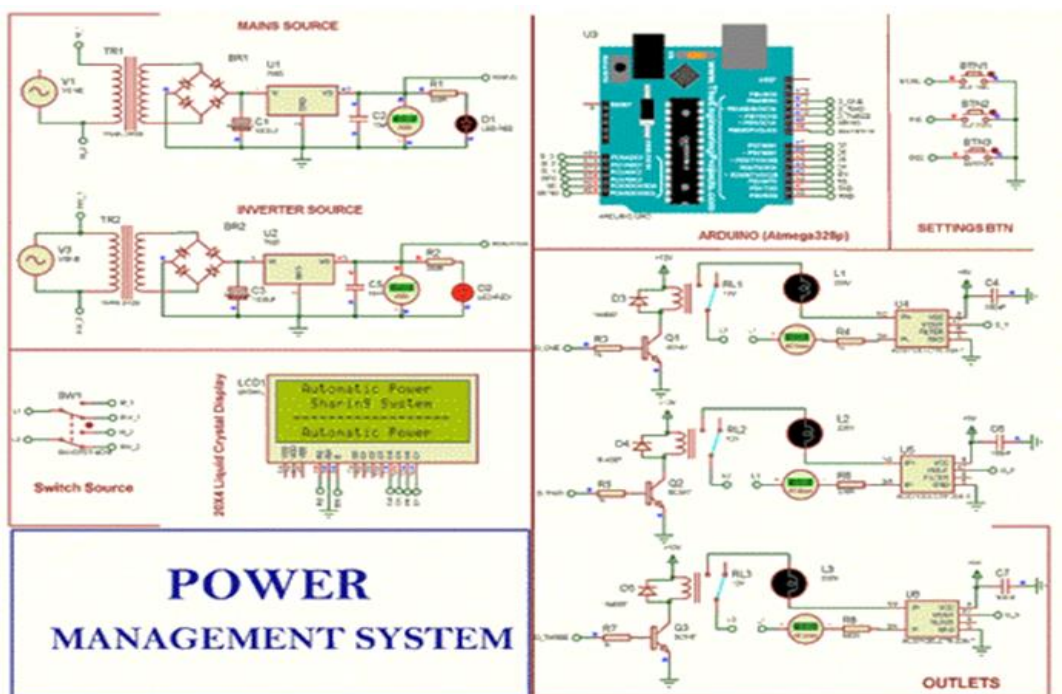


Figure 2: Circuit diagram of the system

The Arduino Uno uses a step-down transformer to reduce incoming alternating current (AC) from 240V to 12V. This AC is rectified to DC to align with the microcontroller's requirements. The DC voltage is then filtered using a capacitor to eliminate noise. A voltage regulator is used to reduce the voltage from 12V to 5V, which is then further filtered through another capacitor before reaching the microcontroller. The inverter source is integrated similarly, with the 5V output fed into the microcontroller through Pin 8. Users can input and store the threshold limit, and the power source can be chosen between the main source or the inverter power sources. However, the Switch Source component facilitates seamless transitioning between the main and inverter power sources. Push buttons (BTN1, BTN2, BTN3) allow manual adjustment of the threshold power limit. Press and hold BTN1 to access the menu interface, where the threshold value can be modified and saved. BTN2 and BTN3 increment and decrement the threshold value, respectively.

3. Results and Discussion

In this section, the results obtained from testing the system architecture are presented. The system architecture was thoroughly evaluated by adjusting the threshold value three times.

3.1 Results

At 25W, 20W, and 10W. This iterative process aimed to validate the seamless operation of the designed system. The power allocated to each outlet was manually adjusted by editing the resistance values of the resistors connected to each outlet. This adjustment simulated the allocation of power to the outlets in the absence of actual loads being connected. Specifically, for this phase, R4 (connected to D_1) was set to 1.7K Ω , R6 (connected to D_2) was set to 2K Ω , and R8 (connected to D_3) was set to 1.2K Ω .

3.1.1 Threshold AT 25W

Main Source Behavior: Figure 3(a) shows what happened when the system drew power from the main source, it was verified that no socket was turned off. Figure 3(b) demonstrates that every socket received power from the Microcontroller.

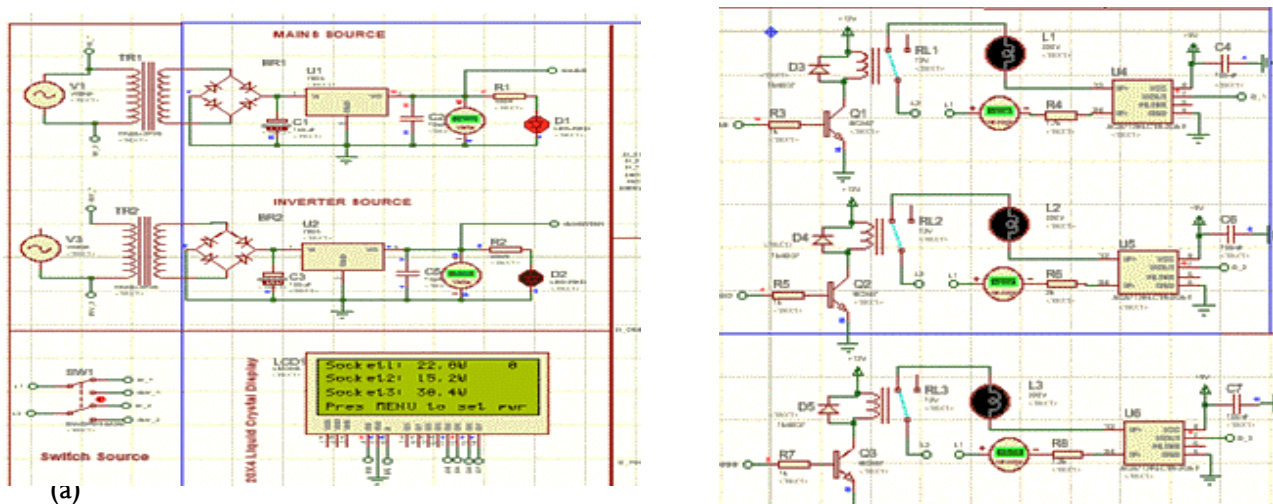


Figure 3: (a). Socket shown power drawn from the main (b) power distribution to each outlet

Inverter Source displayed that the load entering socket 3 exceeded the set threshold of 25W. Consequently, power to socket 3 was cut off.

3.1.2 Threshold at 20W

With the threshold at 20W, the main behaviour when drawing power from the source indicated that sockets remained powered and that no changes in power distribution. Thus, power is supplied to every socket from the Microcontroller. However, when the load connected to outlets 1 and 3 exceeded the set threshold of 20W. Consequently, power to outlets 1 and 3 was cut off to control the inverter drained.

3.1.3 Threshold at 10W

When the threshold is adjusted to 10W, and drawing power from the main source, no sockets are cut off, and every socket receives power from the Microcontroller. The load-drawn power from all three outlets exceeded the set threshold of 10W, consequently power to all three outlets was cut off.

3.1.4 Implication of Findings

Thus, the results obtained from testing the system architecture indicate several significant implications for the design and implementation of photovoltaic (PV) systems. The system's precise power distribution, based on user-defined threshold values, ensures stability and prevents overloading, promoting efficient use of solar energy resources in smart grids. This aligns with the findings by Al-Hassan *et al.* (2018). The manual adjustment of threshold power ratings via push buttons enhances user interaction with the system, allowing for customized energy distribution. This approach is supported by the work of Edeoghon *et al.* (2022), which highlights the importance of user-friendly interfaces in enhancing the functionality and acceptance of solar-powered systems. Moreso, the system improves the reliability and safety of PV inverter systems by incorporating real-time monitoring sensors and relay switches for power supply control. This aligns with Zheng *et al.* (2017) findings on the importance of real-time data collection and automated control. The Arduino Uno Microcontroller simplifies system architecture, making it an economical solution for implementing complex control algorithms in renewable energy systems, this also agreed with Silva *et al.* (2020).

3.2 Further Discussions

The system was evaluated by adjusting the threshold value at three different levels: 25W, 20W, and 10W, under both main and inverter power sources. The results showed that the system could effectively manage power distribution, cutting off outlets that exceeded the set threshold.

3.2.1 Threshold at 25W

The main source and inverter sources remained powered, demonstrating their ability to handle the load without issues, while socket 3, which exceeded the 25W threshold, was cut off. These findings are consistent with previous

studies that emphasize the importance of load management in preventing system failures (Etawil, Massoud, & Finney, 2010).

3.2.2 Threshold at 20W

The main source showed stable power distribution, while the inverter source effectively managed dynamic load by cutting off outlets 1 and 3 when their load exceeded 20W.

This supports the research by Farid, Rahman, and Uddin (2011), who demonstrated that adaptive load management systems can significantly enhance the efficiency and reliability of PV systems.

3.2.3 Threshold at 10W

The main source ensures consistent power distribution without cut-offs, while the inverter source maintains load limits by cutting off all three outlets exceeding the 10W threshold.

These results are in agreement with Al-Hassan et al. (2018), who found that precise control mechanisms are vital for the optimal performance of renewable energy systems.

4. Conclusion

This research work focused on designing an architecture for selecting load thresholds in photovoltaic inverters simulated using Proteus version 8 software. The system's performance was rigorously tested under various conditions, demonstrating adherence to design objectives. Key components such as the power supply, manual adjustment buttons, sensors, and the Arduino Uno Microcontroller significantly enhanced system functionality and safety. Effective power management observed in the simulation prevents overloading, promoting energy optimization and system reliability. These findings hold practical significance, facilitating more efficient and cost-effective PV systems. Moreover, the potential for implementing more complex system architectures to respond to evolving energy demands presents promising avenues for future research. This research highlights the potential of an intelligent, cost-effective solution for enhanced energy management in PV systems, paving the way for more sustainable energy consumption.

References

Al-Hassan E., Shareef H., Islam M. M., Wahyudie A. and Abdrabou A. A., 2018. Improved Smart Power Socket for Monitoring and Controlling Electrical Home Appliances," in IEEE Access, 6:49292-49305, doi: 10.1109/ACCESS.2018.2868788.

Álvarez, J. L., Mozo, J. D., and Durán, E. 2021. Analysis of single board architectures integrating sensor technologies. *Sensors*, 21(18):6303.

Edeoghon, A. I., J. Chibuzor Okocha, J. S. Ebu, R. E. Ohiocheoya, O. V. Chukwunweike, G. Ebikade, M. Efemena, E. O. Akinlade, Ekwunife O., and Odey N. 2022. Design and Implementation of an IoT-Based Solar-Powered Inverter Control System. 10(8).

Elkholy, M. H., Senjyu, T., Lotfy, M. E., Elgarhy, A., Ali, N. S., & Gaafar, T. S. 2022. Design and implementation of a real-time smart home management system considering energy saving. *Sustainability*, 14(21): 13840.

Etawil, A. M., Massoud, A. M., and Finney, S. J. 2010. Grid-connected photovoltaic generation system: An overview. *Renewable and Sustainable Energy Reviews*, 14(1): 54-73.

Farid, A. M., Rahman, M. A., and Uddin, M. N. 2011. Design and development of a novel solar tracking system. *International Journal of Renewable Energy Research*, 1(4): 213-218.

Frauenfelder, M. (Ed.). 2011. *Make Technology on Your Time Vol. 25*. O'Reilly Media, Inc.

Hossain, M.R., Kamruzzaman, M., Rashid, M.M., Alam, M.S. and Robbani, M. G. 2022. Microcontroller-based Environment Monitoring and Load Control System (Doctoral dissertation, Sonargaon University (SU)).

Kumar, M., Memon, Z. A., Uqaili, M. A., and Baloch, M. H. 2018. An overview of uninterruptible power supply system with total harmonic analysis & mitigation: an experimental investigation for renewable energy applications. *IJCSNS International Journal of Computer Science and Network Security*, 18(6): 25-36.

McGowen, R., Poirier, C. A., Bostak, C., Ignowski, J., Millican, M., Parks, W. H., and Naffziger, S. 2005. Power and temperature control on a 90-nm Itanium family processor. *IEEE Journal of Solid-State Circuits*, 41(1): 229-237.

Palamar, A., Karpinsky, M., and Vodovozov, V. 2011. Design and implementation of a digital control and monitoring system for an AC/DC UPS. In 2011 7th International Conference-Workshop Compatibility and Power Electronics (CPE) (pp. 173-177). IEEE.

Zhao, L., Gao, Y., and Zhai, J. 2011. A novel transformerless photovoltaic grid-connected power inverter. *IEEE Transactions on Power Electronics*, 26(1): 362-370.

Zheng, S., Quevedo, D. E., Guerrero, J. M., Vasquez, J. C., and Savaghebi, M. 2017. High-efficiency and high-power-density DC-DC converters for renewable energy systems: A review. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 5(1): 365-379.