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Simulation-Based Arduino Basic Electrical Monitoring System for Educational Applications

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Abstract

This paper presents a fully simulation-based and low-cost electrical monitoring system for educational applications in embedded systems laboratories, developed entirely in Tinkercad using Arduino Uno simulation. The methodology employs Arduino Uno simulation in Tinkercad with a voltage divider circuit for input voltage measurement, potentiometer (connected to A0) for variable load conditions and LED brightness control, 16x2 LCD (D4-D11) for real-time display of input voltage, load voltage, power consumption and three LEDs (red, yellow, green) for load indication based on voltage thresholds, validated using Tinkercad's built-in multimeter. Results show accurate voltage and power monitoring with close agreement between LCD values and built-in multimeter readings, plus correct LED status responses (green for low load <3V, yellow for medium 3-5V, red for high >5V). This project offers a fully virtual, accessible, and hands-on learning experience, helping students build foundational knowledge in electrical monitoring, circuit interfacing, and embedded programming using simulation-based tools.

1. Introduction

Electrical energy plays a vital role in modern households, powering essential appliances and supporting daily activities. However, excessive and unmonitored usage can lead to significant consequences, including increased electricity bills and even fire hazards due to overloading or overheating of circuits [1]. These issues are especially prevalent in rural areas, where infrastructure and awareness may be limited. Moreover, at a macro level, unchecked energy consumption also contributes to environmental degradation and pollution, reinforcing sustainability concerns [2].

Many users, particularly in under-resourced or remote communities, are unaware of their actual energy consumption and have limited access to tools that could help them monitor or manage their usage effectively. This lack of awareness can contribute to energy waste, equipment damage, and unnecessary financial strain [1]. Traditional energy monitoring systems are often complex, expensive, or require dedicated hardware and sensor integration. For students or beginners learning embedded systems, such setups may pose logistical and financial challenges. Moreover, manual measurement methods are prone to human error and do not provide continuous or real-time feedback [3].

Physical hardware requirements in traditional electrical monitoring systems impose substantial barriers for embedded systems students in resource-constrained institutions, including high costs, procurement difficulties, laboratory safety hazards, and configurations too advanced for novices. Students require proficiency in voltage measurement, power computation, real-time visualization, and safety threshold identification for professional roles in embedded engineering, HVAC systems, IoT, and industrial automation [3].

Simulation platforms like Tinkercad address these limitations by providing cost-free virtual environments for circuit design and testing, ideal for embedded systems curricula emphasizing measurement, control, and real-time feedback principles [4]. This study introduces a simulation-based, low-cost electrical monitoring system implemented in Tinkercad using Arduino Uno. The platform enables students to track input voltage, load voltage, power consumption, and LED status through real-time LCD displays, serving as an essential educational tool for embedded programming and circuit design in fully virtual settings that remove hardware constraints while fostering practical competency.

2. Related Work

Recent developments in power monitoring systems have centered on Internet of Things (IoT)-enabled platforms, artificial intelligence (AI), and fuzzy logic frameworks, aimed at achieving real-time monitoring, predictive analytics, and automated energy optimization. IoT-based energy management systems increasingly employ energy disaggregation to determine appliance-level consumption patterns and support sustainable decision-making [5]. Real-time acquisition, visualization, and fuzzy logic have been integrated into decision-making frameworks to improve energy efficiency [6]. Hybrid approaches, such as neuro-fuzzy IoT-assisted power monitoring models, combine wireless sensor networks with adaptive algorithms for smart grid applications [7].

Several studies emphasize IoT-based smart energy management for grids and homes. For instance, IoT-integrated smart grid management systems have been developed using ZigBee-based communication for peak load restriction, price optimization, and predictive analytics [8]. Adaptive Neuro-Fuzzy Inference Systems (ANFIS) combined with IoT and wireless sensor networks have been shown to improve renewable-integrated smart grid performance, achieving a 20.50% improvement during solar–wind hybrid startup [9]. IoT-based smart energy meters designed with Arduino, ESP8266, and GSM modules enable real-time billing and appliance monitoring, facilitating effective consumer–utility data exchange [10]. In addition, fuzzy logic has been applied to microgrid energy management, incorporating IoT dashboards for renewable energy optimization [11].

Beyond residential and small-scale systems, industrial and building-level applications have also emerged. Industrial IoT-based condition monitoring for wind energy conversion systems has been demonstrated [15], while real-time monitoring of distributed energy resources in microgrids has been piloted in Oman [16]. Smart-meter frameworks for monitoring load energy and power quality have been implemented in laboratory microgrid environments [17]. Similarly, IoT-based transformer monitoring systems have been designed to track voltage, current, temperature, methane, and hydrogen [18]. IoT-enabled platforms have also been deployed in office buildings to balance energy conservation with user comfort [19], and energy-smart management has been applied to nearly zero-energy buildings (NZEB) to enhance performance monitoring [20]. Cloud-based communication frameworks, such as MQTT, have additionally been proposed for socket-level power monitoring and control [21].

Despite their capabilities, these IoT–AI–fuzzy systems typically require dedicated hardware, stable internet access, and significant computational resources. IoT-based photovoltaic station monitoring has been demonstrated using ESP32 and cloud platforms [12], while Wi-Fi–enabled ESP32-Blynk systems have been proposed for home energy monitoring [13]. Transformer-level monitoring of voltage, current, and temperature has also been extended through IoT-enabled systems [14]. Although effective, these hardware-dependent approaches pose challenges in low-resource or offline environments, and their complexity may hinder adoption by beginners.

In educational and prototyping contexts, low-cost microcontrollers such as Arduino remain widely used for introducing embedded system and energy monitoring concepts. However, these approaches—including Arduino-based photovoltaic monitoring and load control—still rely on physical components and laboratory setups, which may not always be accessible to all learners. Arduino has also been highlighted as a valuable educational tool in higher education, where its role in enhancing teaching and learning practices has been systematically reviewed [4].

To address these limitations, the present study proposes a fully virtual, simulation-based monitoring system using Tinkercad, a cloud-based electronics simulation platform. The system replicates a basic Arduino-powered monitoring circuit entirely in simulation, enabling students to practice electrical measurement, control, and embedded programming without requiring physical hardware or constant internet access. By eliminating the hardware barrier while preserving interactivity, this approach bridges the gap between advanced, high-resource IoT/AI systems and accessible, beginner-friendly educational tools, making it particularly suitable for offline or resource-constrained environments. The contributions and limitations of the related studies discussed above are summarized in Table 1.

Table 1 *Comparative analysis of related studies*

Author(s)	Contribution	Limitation
Huang et al. [5]	Reviewed IoT-based smart energy management systems, highlighting the role of energy disaggregation for appliance-level monitoring.	Requires IoT infrastructure and high computational resources.
Stecyk and Miciuła [6]	Applied fuzzy logic in energy efficiency decision-making frameworks with visualization and real-time acquisition.	Limited scalability and depends on fuzzy rule accuracy.
Ghosh [7]	Proposed a neuro-fuzzy IoT-assisted monitoring model for smart grids, combining adaptive algorithms with wireless sensor networks.	Complex implementation; requires robust communication links.
Madhuri et al. [8]	Developed an IoT-enabled smart grid management system using ZigBee for peak load control and predictive analytics.	Requires specialized hardware and network setup.
Tabassum et al. [9]	Introduced ANFIS integrated with IoT and WSN for renewable-based grids, showing 20.50% performance improvement at hybrid startup.	High complexity and dependent on AI models
Sulthana et al. [10]	Designed an Arduino–ESP8266 smart energy meter for real-time billing and appliance monitoring.	Hardware dependent; limited accessibility in low-resource settings.
Sumarmad et al. [11]	Implemented fuzzy logic for microgrid energy management with IoT dashboard integration.	Limited to simulated microgrid scenarios.
Cheddadi et al. [12]	Proposed ESP32-based IoT photovoltaic monitoring system with cloud integration.	Requires stable internet and external cloud services.
El-Khozondar et al. [13]	Designed a Wi-Fi–based ESP32-Blynk home energy monitoring system.	Relies on Wi-Fi connectivity and Blynk cloud service.
Mina et al. [14]	Extended IoT monitoring to transformer-level voltage, current, and temperature.	Limited to transformer use case; not easily adaptable to households.
Hossain et al. [15]	Developed an Industrial IoT-based condition monitoring framework for wind energy conversion systems.	Domain-specific; focused mainly on wind energy applications.
Hosseinzadeh et al. [16]	Designed a real-time monitoring platform for distributed energy resources in microgrids, validated in Oman.	Pilot-scale study; requires robust communication infrastructure.
Isanbaev et al. [17]	Applied smart meters for energy and power quality monitoring in microgrid laboratories.	Restricted to lab environments; scalability to larger grids untested.
Kartika [18]	Proposed an IoT-based transformer monitoring system for voltage, current, temperature, methane, and hydrogen.	Hardware intensive; limited to transformer-level monitoring.
Li [19]	Analysed IoT-based monitoring systems in office buildings to balance energy conservation with comfort.	Focused only on building environments; lacks generalizability.
Magrini et al. [20]	Studied energy smart management and performance monitoring in a Nearly Zero Energy Building (NZEB).	Limited to NZEB application; not easily transferable to other contexts.
Sundaramoorthi & Albert [21]	Introduced a cloud-based MQTT protocol for socket-level power monitoring and control.	Dependent on cloud services; requires continuous internet access.

3. System Design and Implementation

The proposed monitoring system is developed and evaluated entirely within the Tinkercad simulation environment, which offers a virtual platform for designing, wiring, and programming electronic circuits. This environment supports realistic and interactive testing of embedded systems without the need for physical hardware. The system architecture is centered on an Arduino Uno microcontroller and incorporates several simulated components, including a 16×2 Liquid Crystal Display (LCD) for displaying real-time measurements of voltage, power, and LED brightness; a potentiometer to simulate user-adjustable load conditions and enable variations in voltage levels or LED brightness; Light Emitting Diodes (LEDs) in red, yellow, and green to represent load states based on voltage thresholds; and, optionally, a Light Dependent Resistor (LDR) to introduce environment-based variations or dynamic voltage influence.

Tinkercad is a cost-free, accessible platform that supports serial communication, analogue/digital interfacing, and real-time component adjustments, making it particularly suitable for educational applications where safe experimentation is essential. Furthermore, the selection of the Arduino Uno as the core controller is supported by comparative analyses of microcontroller development boards, which highlight its balance of simplicity, versatility, and widespread educational adoption [4],[22].

3.1 Circuit Design and Functionality

The proposed system operates on a basic voltage monitoring and control loop, as illustrated in Fig. 1. The input voltage is generated through a voltage divider composed of resistors, and the Arduino measures this signal using its built-in Analog-to-Digital Converter (ADC) pins. The resulting load voltage, V_o is defined by the resistance ratio or the position of the potentiometer. Visual feedback is provided through a three-color LED indicator system, where the green LED signifies a normal load, the yellow LED indicates a medium load, and the red LED warns of a high load or potential overcurrent. The potentiometer acts as a dynamic input device, allowing users to vary load conditions; any adjustments immediately alter the voltage detected by the Arduino, which then processes the change to update both the LCD readings and LED indicators according to predefined threshold logic.

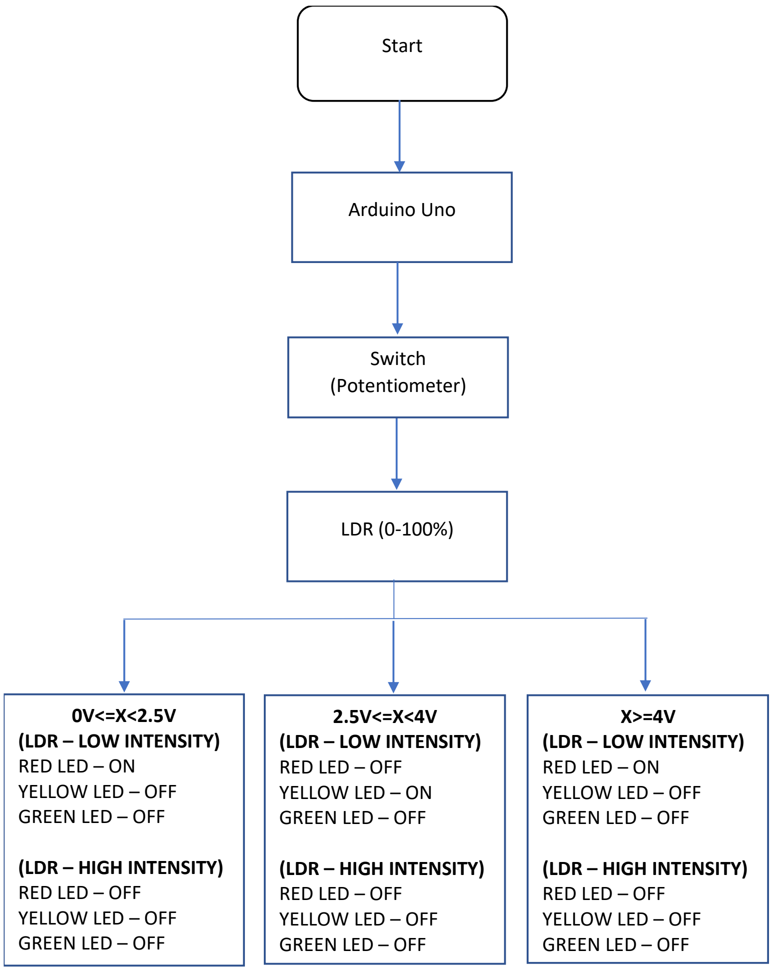


Fig. 1 *Block diagram of the proposed Arduino-based monitoring system*

The real-time simulation in Tinkercad enables rapid iteration, adjustment of circuit parameters, and immediate observation of results. This not only reduces experimentation risks and eliminates component wear but also facilitates repeated testing, making it highly effective for instructional purposes in embedded systems and electrical measurement concepts.

The complete circuit schematic for the Arduino-based monitoring system is shown in Fig. 2. The Arduino Uno microcontroller (U1) serves as the central processing unit, interfacing with the following components: a potentiometer (RPOT2) connected to analogue pin A0 for adjustable input; a Light Dependent Resistor (R1) configured in a voltage divider with a fixed resistor (R3, 10 kΩ) to measure light intensity on pin A1; three LED indicators (red, yellow, green) with series resistors connected to digital pins for status indication; and a 16×2 LCD display connected in 8-bit mode to digital pins D4–D11 for real-time parameter display.

The system operates at 5 V DC supplied through the Arduino Uno board, with all components sharing a common ground. The design ensures that voltage inputs, load status indicators, and display outputs are processed in real time while maintaining electrical isolation between input and output components.

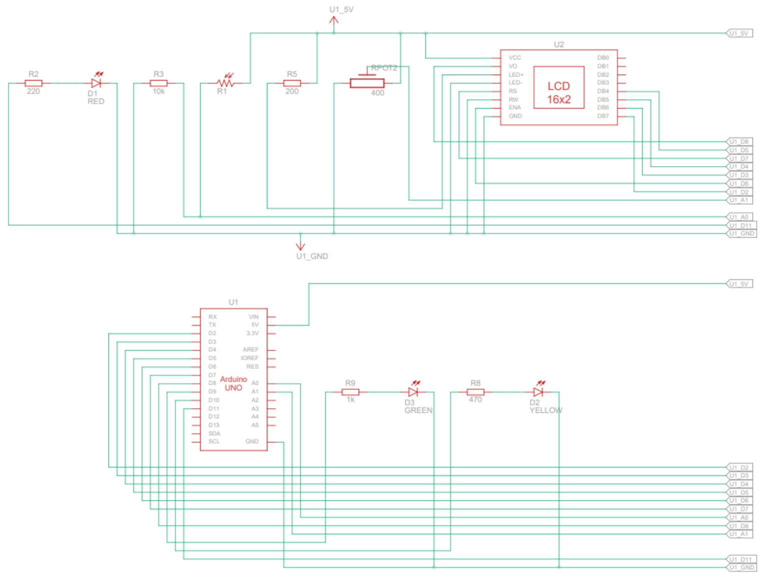


Fig. 2 *Circuit schematic of the proposed system in Tinkercad*

The circuit in Fig. 2 enables power monitoring through four fundamental electrical engineering equations (1) until (4), each derived from basic circuit theory [23].

$$V_o = \left(\frac{R_{ref}}{R_{ref} + R1}\right) V_i \quad (1)$$

$$V_i = \left(\frac{R_{ref} + R1}{R_{ref}}\right) V_o \quad (2)$$

$$R_{ref} = \frac{1}{\frac{1}{R2} + \frac{1}{R3} + \frac{1}{R4} + \frac{1}{R5}} \quad (3)$$

$$P_o = \frac{(V_o)^2}{R_{load}} \quad (4)$$

These relationships allow the Arduino to compute both the input and output voltages, as well as the corresponding power, based on resistor configurations and potentiometer adjustments. The inclusion of parallel LED loads in the circuit further demonstrates how variations in voltage affect current distribution and system behaviour.

3.2 Software Logics

The Arduino sketch governs data acquisition, computation, and display operations. The analogue pins (A0–A2) are connected to the voltage divider and potentiometer, while the digital pins (D2–D13) are assigned to the LCD and LED outputs. The Serial Monitor is enabled to provide debugging and output verification during development and testing.

The LCD display is organized so that the first line shows the input and output voltages, while the second line displays the calculated power output and the corresponding load state. The display updates occur every 4000 milliseconds, implemented using delay-based timing method to ensure smooth transitions without unnecessarily blocking processor activity.

As summarized in the software data flow in Fig. 3, the Arduino first reads voltage values from the potentiometer and voltage divider. These readings are then converted into voltage and power measurements using calibrated formulas. The results are output to the LCD, while the LED indicators change state in response to the measured load condition. Concurrently, the Serial Monitor provides a secondary verification channel for debugging and cross-checking results.

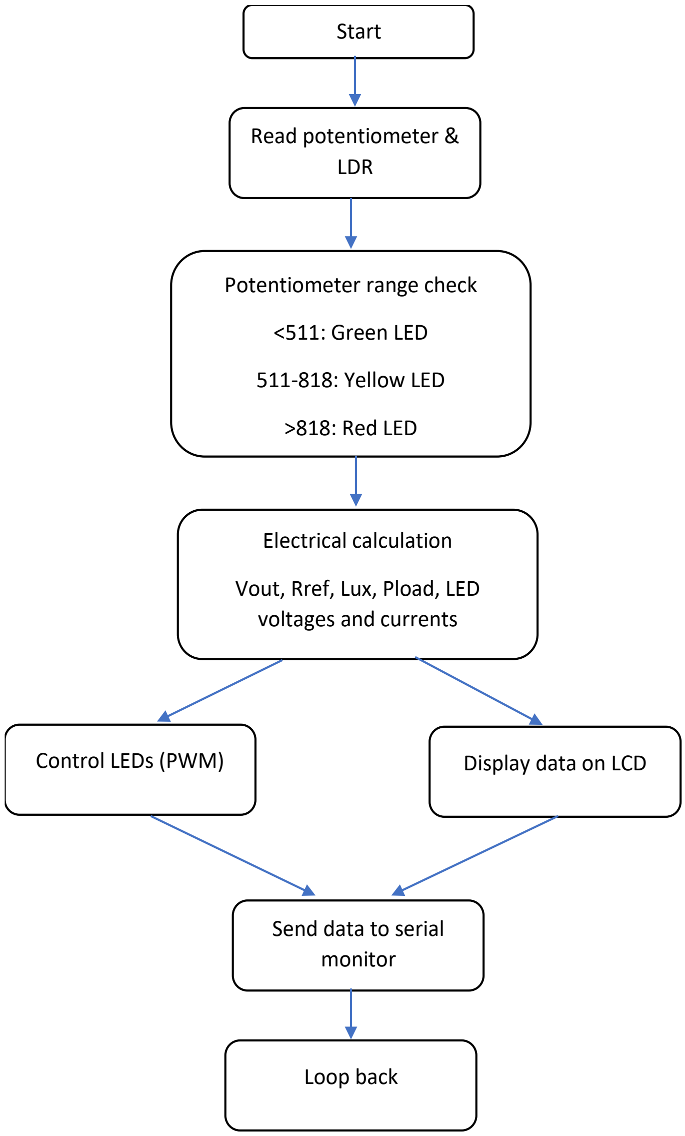


Fig. 3 *Software data flow of the Arduino-based monitoring system*

Through this architecture, the system successfully simulates the essential functions of real-world embedded monitoring devices, delivering both numerical data and visual feedback in real time. This combination offers learners an engaging, risk-free environment to understand the principles of circuit monitoring, control logic, and electrical safety.

4. Results and Validation

A set of simulation scenarios was conducted in Tinkercad to examine how the proposed monitoring system responds to variations in load resistance, controlled through the potentiometer, and ambient light intensity, represented by the LDR. The potentiometer simulated different load conditions, while the LDR introduced environmental light variations that influenced circuit behaviour. Together, these factors directly impacted the measured voltage, calculated power, and LED status indicators.

At a high resistance setting, the load voltage increased significantly. Under bright light (LDR high), this remained within safe limits. However, under dim light (LDR low), the same configuration pushed the voltage beyond the programmed threshold, activating the red LED to signal overcurrent. At medium resistance, the circuit generated moderate voltage levels. While bright light kept values well below the critical threshold, reduced light intensity slightly raised the voltage, activating the yellow LED as a precautionary warning. At a low resistance setting, the load voltage stayed low regardless of light intensity, and the green LED consistently indicated safe operation.

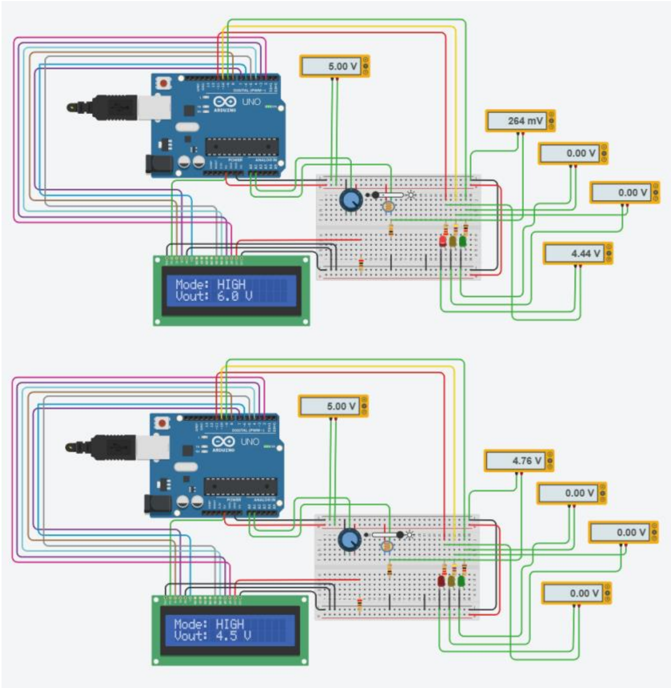
The consolidated outcomes of these cases are presented in Fig. 4 and Table 2, which summarizes the effects of each potentiometer setting under both high and low light conditions. These results demonstrate that the Tinkercad-based monitoring system reliably reproduces expected electrical behaviour across varying operating scenarios. Moreover, validation was achieved by comparing LCD-displayed values of voltage and power with readings obtained from Tinkercad's built-in multimeter, which showed close agreement as presented in Table 3. This confirms the accuracy of the simulation and strengthens its value as an educational tool for illustrating voltage monitoring, current thresholds, and system safety without the need for physical hardware.

Table 2 *Simulation results of the Arduino-based monitoring system under different potentiometer and light conditions*

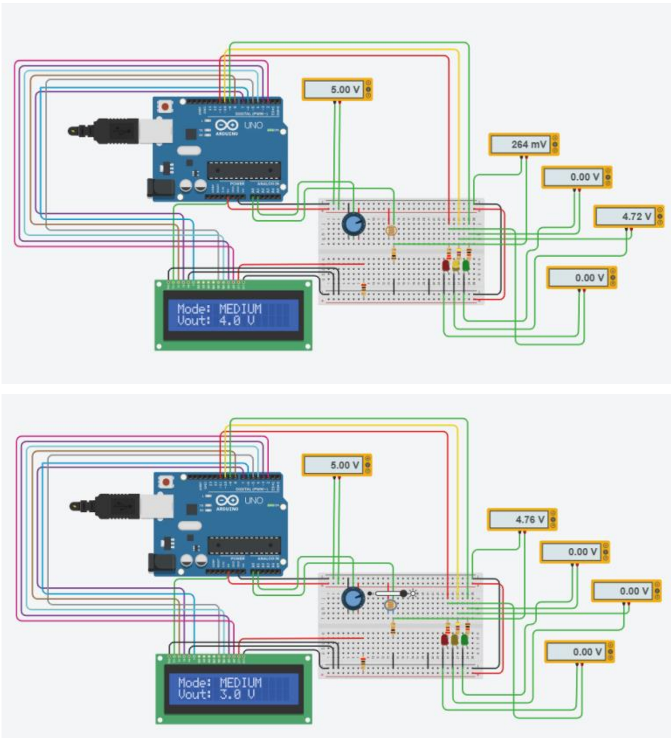
Potentiometer ADC Range	LDR Value	Brightness (Mapped 0–255)	Voltage Across Load (V)	LED Indicator
< 511 (Low)	54	255	~1.5	Green
	500	131	~1.2	Green
	974	0	~1.0	Green
511 – 818 (Medium)	54	255	~4.0	Yellow
	500	131	~3.5	Yellow
	974	0	~3.0	Yellow
> 818 (High)	54	255	~6.0	Red
	500	131	~5.0	Red
	974	0	~4.5	Red

Table 3 *Validation between simulation and built-in multimeter*

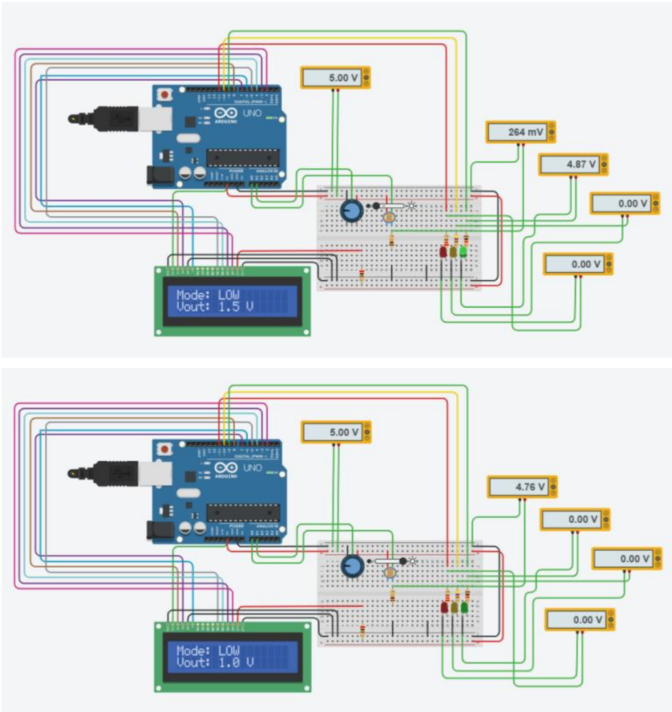
Potentiometer Setting	Parameters	LCD		Built in multimeter	
		LDR High	LDR Low	LDR High	LDR Low
High (High Resistance)	Voltage input	5 V	5 V	5 V	5 V
	Voltage output (LDR)	4.76 V	0.26 V	4.76 V	264 mV
	Brightness LED	0%	100%	-	-
	Power output	92 mW	163.6 mW	-	-
Medium (Moderate Resistance)	Voltage input	5 V	5 V	5 V	5 V
	Voltage output (LDR)	4.76 V	0.26 V	4.76 V	264 mV
	Brightness LED	0%	100%	-	-
	Power output	19.1 mW	34 mW	-	-
Low (Low Resistance)	Voltage input	5 V	5 V	5 V	5 V
	Voltage output (LDR)	4.76 V	0.26 V	4.76 V	264 mV
	Brightness LED	0%	100%	-	-
	Power output	1 mW	2.2 mW	-	-


5.00 V
264 mV
0.00 V
0.00 V
4.44 V
Mode: HIGH
Vout: 6.0 V
5.00 V
4.76 V
0.00 V
0.00 V
0.00 V
Mode: HIGH
Vout: 4.5 V

(a)


5.00 V
264 mV
0.00 V
4.72 V
0.00 V
Mode: MEDIUM
Vout: 4.0 V
5.00 V
4.76 V
0.00 V
0.00 V
0.00 V
Mode: MEDIUM
Vout: 3.0 V

(b)



(c)

Fig. 4 *Simulation results of the Arduino-based monitoring system in Tinkercad, showing different potentiometer settings tested under both bright light (LDR high) and low light (LDR low) conditions (a) High potentiometer setting; (b) Medium potentiometer setting; (c) Low potentiometer setting*

Fig. 5 illustrates the relationship between power output and potentiometer settings under both high and low light conditions, with LED indicators marking each operating mode (Red = High, Yellow = Medium, Green = Low). As shown in Figure 5, the graph confirms that as the potentiometer setting shifts from High to Low (corresponding to decreasing resistance), the available power decreases significantly. Furthermore, LDR Low consistently produces higher power transfer compared to LDR High, highlighting the influence of light intensity on system performance.

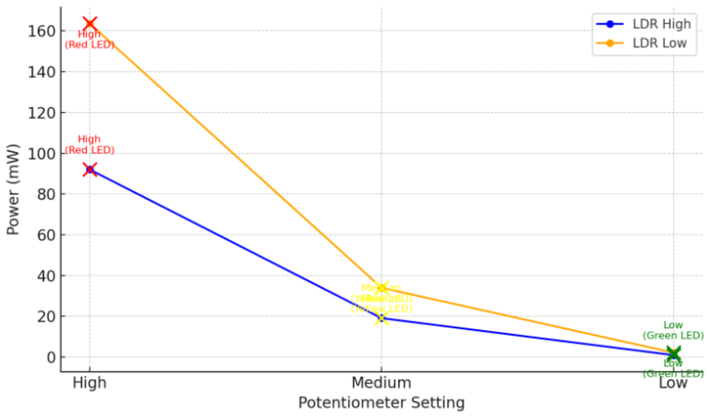


Fig. 5 *Power output versus potentiometer setting*

The LED indicators provide a clear visual mapping of these behaviours: the Red LED corresponds to high resistance and higher power in brighter conditions, the Yellow LED marks the transition at moderate resistance, and the Green LED represents low resistance where power transfer is minimal. This visualization reinforces the role of both load resistance and light intensity in governing voltage regulation, LED brightness, and overall energy delivery. The results confirm that the monitoring system not only reproduces expected electrical behaviour but also reliably demonstrates the interplay between resistance, illumination, and system efficiency in a low-cost educational setup.

5. Conclusion

This study successfully demonstrated a simple and low-cost electrical monitoring system using only the Arduino Uno and Tinkercad simulation platform, designed specifically for educational use in embedded systems laboratories. The system is capable of monitoring key electrical parameters such as input voltage, load voltage, power output, and LED brightness, while providing real-time feedback through an LCD interface and simulated multimeter validation.

The results confirm that even without physical components, students can effectively observe and understand how voltage variations affect load behaviour, power consumption, and safety indicators. The simulation also responds dynamically to changes in potentiometer settings and light intensity, reinforcing concepts such as analogue input processing, condition-based output control, and basic power calculations.

This approach holds strong potential for rural and underfunded educational institutions, where access to physical lab equipment is limited. It offers an accessible, scalable, and risk-free learning environment that strengthens embedded systems and electronics fundamentals.

Future work may include adapting this system for real-world implementation using actual sensors and expanding it to include wireless data monitoring or IoT integration, enabling students to bridge the gap between virtual simulation and hands-on experimentation.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Siti Syafinah Ahmad Hassan, Nuril Azmi Muslimin, Fabian Halley Pata, Nadia Austin, and Hushairi Zen****; data collection:*** *Siti Syafinah Ahmad Hassan, Nuril Azmi Muslimin, Fabian Halley Pata, Nadia Austin, and Hushairi Zen* ***interpretation of results:*** *Siti Syafinah Ahmad Hassan, Nuril Azmi Muslimin, Fabian Halley Pata, Nadia Austin , and Hushairi Zen****; draft manuscript preparation: :*** *Siti Syafinah Ahmad Hassan, Nuril Azmi Muslimin, Fabian Halley Pata, Nadia Austin , and Hushairi Zen. All authors reviewed the results and approved the final version of the manuscript.*

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