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Design and Development of a Solar and Hand-Cranked Dynamo-Based with Battery Storage for Low Power Device Charging

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Abstract

This study addresses urban sedentary behavior and the demand for sustainable public energy infrastructure through the design of a Hybrid Solar-Kinetic Charging Station at Tanjung Emas Park, Muar. Unlike traditional kiosks, this system implements a "Smart Exercise Clause," requiring users to maintain a physical effort of 50 RPM to unlock the 5V USB output. The hardware integrates a 10W Solar PV panel with a high-torque NEMA 23 Bipolar Stepper Motor. Technical challenges in converting low-RPM energy into stable DC power were resolved using a Greinacher Voltage Doubler optimized with Schottky diodes, which minimized forward voltage loss. Controlled by an Arduino Nano, the system monitors rotational speed via a Hall Effect sensor and calculates real-time calorie expenditure. Results confirm that the "Play-to-Charge" model successfully gamifies energy production while providing a viable off-grid solution for public health and renewable energy awareness.

1. Introduction

Energy is a fundamental pillar for national development, yet many renewable potentials remain underutilized despite Malaysia's ideal equatorial location. Concurrently, sedentary living has become a global health risk, with high physical inactivity in Malaysia contributing to non-communicable diseases (NCDs). Public spaces often reinforce these habits, as adults remain passive while using mobile devices. This project aligns with the Malaysia Renewable Energy Roadmap (MyRER), which targets a 45% reduction in GHG emissions by 2030. By introducing a "Play-to-Charge" system at Tanjung Emas Park, the study aims to disrupt sedentary behavior by requiring mechanical input to charge devices, thus merging fitness with localized renewable energy generation.

1.1 Renewable Energy Landscape and Public Infrastructure in Malaysia

The transition toward sustainable energy in Malaysia is governed by the Malaysia Renewable Energy Roadmap (MyRER), which targets a 31% renewable energy share in the national capacity mix by 2025 [6]. Despite the abundance of solar radiation in Malaysia, averaging between 4.5 to 5.8 kWh/m^2/day, most public infrastructure remains dependent on the national grid [3]. Aziz et al. (2019) highlights that while solar potential is high, urban "shading effects" in parks often limit the efficiency of standalone solar kiosks. This necessitates a hybrid approach, integrating secondary harvesting methods like kinetic energy to ensure power reliability in diverse environmental conditions [3].

1.2 Sedentary Behavior and the Psychological Incentive of "Play-to-Charge"

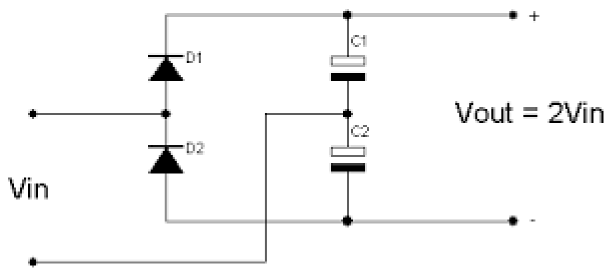
Public health data indicates a rising trend in Non-Communicable Diseases (NCDs) within the Malaysian population, largely attributed to physical inactivity [4]. According to the World Health Organization (2024), urban parks are intended to promote movement, yet they are increasingly used for stationary smartphone engagement [4]. Copeland (2016) suggests that "gamifying" exercise through tangible rewards can significantly alter user behaviour. By implementing an "Exercise Clause", whereby a device only charges when physical effort is exerted, this project transforms a passive charging station into an active health intervention tool, aligning with global strategies to combat sedentary lifestyles [5].

1.3 Technical Superiority of Bipolar Stepper Motors in Low-RPM Harvesting

In the field of small-scale kinetic energy harvesting, the selection of the transducer is critical. Traditional DC motors often require high rotational speeds (RPM) to exceed the threshold voltage of battery systems, which is often unattainable through manual hand-cranking. Research by Sopian and Othman (1992) suggests that Bipolar Stepper Motors, such as the NEMA 23, are more suitable for human-powered applications due to their high pole count [2]. These motors can generate significant AC voltage at low speeds; however, they require sophisticated rectification. This project utilizes the stepper motor's multi-phase output to maximize torque-to-power efficiency, providing a more consistent energy flow than conventional permanent magnet DC generators at human-scale speeds.

1.4 Optimization of Power Conditioning via Greinacher Topologies

The conversion of irregular AC from a kinetic harvester to a stable DC output requires efficient power conditioning. Standard bridge rectifiers utilize silicon diodes (e.g., 1N4007), which impose a voltage drop of 0.7V per diode, totalling a 1.4V loss that can cripple low-power systems. Literature suggests the implementation of the Greinacher Voltage Doubler circuit to overcome this. By utilizing Schottky diodes (1N5819), which feature a significantly lower forward voltage drop of approximately 0.3V, the circuit can effectively double the input voltage while minimizing heat dissipation and energy loss. This optimization is essential for ensuring the 5V regulator receives sufficient "headroom" to maintain a steady output during fluctuations in cranking speed.



Voltage doubler

2. Methodology

The research was executed through a structured four-phase framework: preliminary investigation, system architecture design, prototype fabrication, and performance validation. Initially, a site analysis at Tanjung Emas Park, Muar, was conducted to determine the optimal placement for the station.

2.1 Hardware Integration and Component Selection

The core of the kinetic harvesting system is a NEMA 23 Bipolar Stepper Motor with a high holding torque of 1.5 Nm. A stepper motor was selected over a traditional DC generator because its high pole count allows for significant voltage generation at lower rotational speeds, which is essential for a hand-cranked interface. For energy storage, the system utilizes two 3.2V Li-ON batteries connected in series. These batteries were chosen for their high thermal stability in tropical climates and their ability to withstand frequent, irregular charge cycles without significant capacity degradation.

2.2 Power Conditioning and Circuit Optimization

A specialized power conditioning circuit was designed to rectify the multi-phase AC output from the stepper motor. To overcome the voltage drop inherent in standard bridge rectifiers, a Greinacher Voltage Doubler topology was implemented. This circuit uses 1N5819 Schottky diodes, which feature a low forward voltage drop of only 0.3V, compared to the 0.7V of standard silicon diodes. This optimization ensures that even at a moderate cranking speed, the output voltage remains sufficiently high (above 5V) to trigger the charging mechanism.

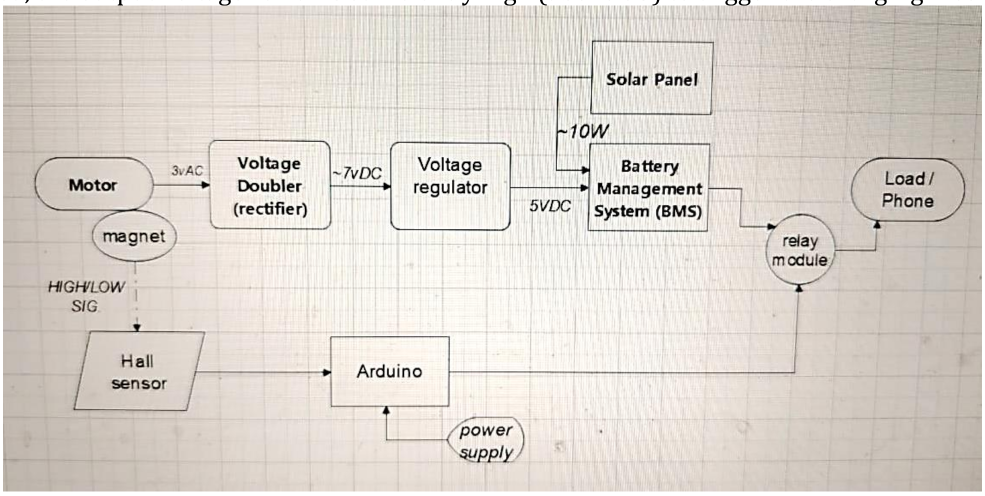


Figure 1 Block flow of the overall circuitry

2.3 Power System Completeness and Safety

The power system is designed around a robust energy management framework to ensure that the charging station remains safe, efficient, and reliable for public use. The architecture prioritizes battery health and user safety through integrated hardware protections and smart power routing.

2.3.1 Charging Architecture and BMS Integration

The system utilizes a specialized, multi-functional UPS-BMS module designed for 3.7V Lithium-ion and LiFePO4 storage systems. This module acts as the central intelligence of the power system, consolidating four critical functions into a single unit: high-precision charging control, battery protection, voltage boost conversion, and uninterruptible power-path management. By integrating these features, the system reduces electrical complexity while significantly improving the operational reliability required for a public outdoor installation.

2.3.2 Safety and Protection Mechanisms

Safety is a paramount consideration for electronics deployed in public parks. The BMS incorporates hardware-level protection to mitigate electrical risks, including overcharge protection (with a 4.2V cutoff) and over-discharge protection (with a 3.0V cutoff). Additionally, the system features overcurrent and short-circuit protection; in the event of a fault, the BMS isolates the battery to prevent damage and can be reset simply by reapplying a 5V input. A built-in 12A high-current MOSFET ensures stability even under peak load conditions.

Table 1 SOC Behaviour of the BMS.

SOC	Voltage
100%	4.2V
75%	3.95V
50%	3.75V
25%	3.5V
0%	3.0V

2.3.3 Charging Methodology (CC-CV)

To maximize battery lifespan and ensure user safety, the charging process follows a standardized Constant Current–Constant Voltage (CC-CV) profile. During the initial phase, a constant current is applied until the battery reaches its peak voltage of 4.2V, after which the system switches to a constant voltage phase as the current gradually tapers off. This method is essential for reducing thermal stress on the lithium cells and maintaining the long-term health of the energy storage unit.

2.3.4 Thermal Stability and Performance

Thermal behavior was closely monitored under a consistent 1A load to ensure the system remains within safe operating limits. At an ambient temperature of 28∘C, the battery peak temperature was recorded between 34–

36∘C, well below the critical 45∘C threshold for Lithium-ion stability. No thermal runaway or instability was observed during prolonged testing, confirming that the system's enclosure and component selection are adequate for the tropical climate of Tanjung Emas Park.

2.3.5 Power Path Management and Efficiency

The system features a high-efficiency DC-DC boost converter capable of reaching up to 96% efficiency, stepping up the 3.7V nominal battery voltage to a stable 5V USB output. A key feature of this architecture is the "UPS Power Path" functionality, which allows the load to be supplied directly from the hybrid input when available. The system seamlessly switches to battery power during periods of unstable kinetic input, ensuring that the user's device receives an uninterrupted charge regardless of variations in exercise intensity.

2.4 Smart Control Logic and the "Exercise Clause”

The system is governed by an Arduino Nano microcontroller that enforces the "Smart Exercise Clause." A Hall Effect sensor and a magnet are used to monitor the RPM of the hand crank in real-time. The firmware is programmed with a logic gate: the 5V USB output remains deactivated via a relay module until the user maintains a minimum threshold of 50 RPM. Once this threshold is met, the relay closes, allowing the stored energy to flow to the device. Simultaneously, the Arduino calculates and displays the user's calorie expenditure on an I2C LCD, providing immediate health feedback and gamifying the energy generation process.

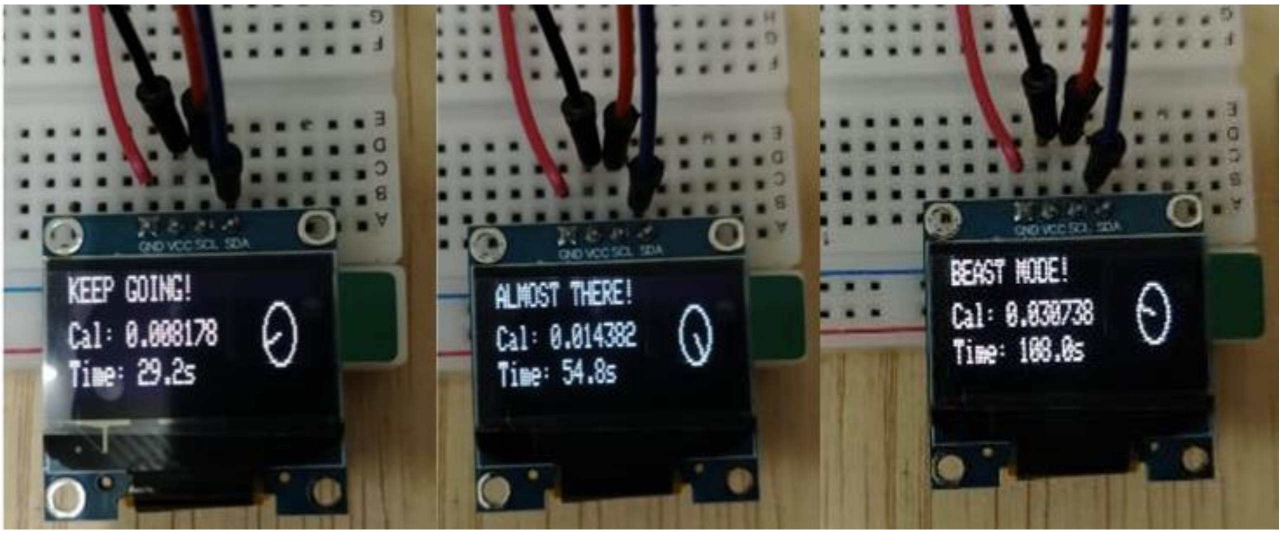


Figure 2 Shows the Encouraging quotes along with the calorie burnt on the OLED display.

2.5 Solar Subsystem Integration and Hybrid Interfacing

The integration of the solar subsystem is designed to provide a steady, reliable baseline charge that complements the high-intensity bursts provided by the kinetic harvester. The following details outline the technical interface and power path management.

2.5.1 Solar Interfacing and Voltage Regulation

The 10W Photovoltaic (PV) panel serves as the primary ambient energy source. To manage the fluctuating voltage produced by varying solar irradiance, the output is first sent through a dedicated LM7805 voltage regulator. This regulator is equipped with a substantial heatsink to dissipate thermal energy generated during peak sun hours, ensuring the voltage remains stable before entering the sensitive management electronics.

2.5.2 Charge Controller and BMS Integration

Unlike traditional systems that require a standalone solar charge controller, this design utilizes the integrated charging circuitry within the UPS-BMS module. By centralizing the control logic, the system ensures that the solar input adheres to the required Lithium-ion CC-CV charging profile. This integration reduces potential points of failure and ensures that the battery is never overcharged, even during prolonged periods of high irradiance.

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2.5.3 Blocking Diodes and Protection

To ensure system integrity, Schottky blocking diodes are placed in the solar path. These diodes serve a dual purpose: they prevent "dark current" which happens when the battery discharges back through the solar panel at night and protect the solar cells from potential back-voltage generated by the kinetic harvester during high-speed operation. The low forward-voltage drop of the Schottky diodes minimizes energy loss, ensuring maximum power transfer to the storage unit.

2.5.4 Power Path and Storage Priority

The system is designed with a parallel charging architecture where both the solar and kinetic energy sources feed into a single, unified storage bank. This dual-input approach ensures that energy is captured from whichever source is most available at any given time. The solar subsystem acts as the primary maintainer, providing a continuous "trickle charge" that keeps the battery's State of Charge (SOC) healthy during idle periods or low-traffic hours. This ensures that even if the station hasn't been used for a while, there is still energy ready for the next person who plugs in their device.
In contrast, the kinetic harvester functions as a high-impact, "demand-response" source. When a user actively begins cranking the dynamo, the system generates a high-current input that supplements the existing solar energy, significantly accelerating the charging process. Both power paths converge at the Battery Management System (BMS), which acts as the intelligent hub of the device. The BMS determines the most efficient route for the incoming energy, either sending it to replenish the batteries or directing it straight to the USB load in "UPS mode" to provide immediate power to the user's phone.

2.5.5 System Synergy in Realistic Conditions

This integration strategy specifically addresses the environmental challenges of Tanjung Emas Park. In areas where the park's canopy provides heavy shade, the solar contribution may drop; however, the kinetic subsystem remains fully functional. Conversely, during periods of low park traffic, the solar subsystem ensures the 16.28Wh battery bank remains topped up and ready for the next user, providing a truly redundant and sustainable power solution.

3. Results and Analysis

3.1 Performance of Optimized Rectification and Voltage Doubling

A critical portion of the results centered on overcoming the "voltage gap" between the motor's raw output and the battery's charging threshold. The implementation of the Greinacher Voltage Doubler was a decisive factor. During testing, the circuit successfully rectified and boosted the 3.15V AC input. By utilizing 1N5819 Schottky diodes, the system minimized the forward voltage drop to just 0.3V, compared to the 0.7V drop seen in standard silicon diodes. This optimization resulted in a final DC output of 6.33V. This specific value is significant because it provided the necessary voltage "headroom" for the LM2596 buck converter to maintain a regulated 5V output. Without this doubler and the low-loss Schottky diodes, the voltage would have remained below the charging threshold, rendering the kinetic input useless for smartphone charging.

3.2 Quantitative Validation and Performance Results

The system performance was evaluated through controlled laboratory testing to validate electrical output, energy harvesting capability, battery charging characteristics, SOC behavior, and solar contribution under realistic operating conditions.

3.2.1 Kinetic Power Generation and Efficiency

The kinetic harvesting subsystem was tested to determine the mechanical-to-electrical conversion efficiency. Experimental results indicate that the generator must reach a threshold of 50 RPM to consistently activate the regulated 5V USB output.

Eq 1

$$\text{Pmec} = \tau \times \omega = 1.5\text{Nm X } 5.24\frac{\text{rad}}{\text{s}} = 7.85\text{W}$$

At this speed, the calculated mechanical power input is Pmechanical=7.85W.

Eq 2

$$Pelec = 7.85W\ X\ 0.6\ \approx 4.71\ W$$

Accounting for an overall system efficiency of 60%, the resulting electrical power output is Pelectrical=4.71W. While output increases slightly at 60 RPM, the onboard voltage regulation limits the power to approximately 5W to ensure device safety.

3.2.2 Regulated USB Output Characteristics

Output performance was measured using a USB digital power meter under varying rotational speeds. The system maintains a regulated 5V output between 50 and 60 RPM, demonstrating high stability for smartphone charging. At 50 RPM, the current reached 0.94A, providing 4.7W of power. A minor voltage ripple of ±0.05V was observed, which falls within the acceptable range for modern mobile electronics. Measurement uncertainty for these values is estimated at ±2%.

Table 2 Power output attributable to changes to RPM.

RPM	Output Voltage	Output Current	Output Power
40 RPM	4.6V	0.6A	2.76W
50 RPM	5.0V	0.94A	4.7W
60 RPM	5.05V	1.0A	5.05W

3.2.3 Energy Harvesting Rate and Capacity

The energy harvesting rate was quantified based on the 4.71W electrical output achieved at 50 RPM.

Eq 3

$$\text{Energy}=4.71\text{W}\times 1/60\text{ hr}$$
$$= 0.0785\text{Wh per minute}$$

The calculation yields an energy harvest of approximately 0.0785Wh per minute. This equates to 0.785Wh over a 10-minute exercise session and 2.36Wh for a 30-minute session. These results confirm the system's viability for providing significant "emergency" charges through moderate physical activity.

3.2.4 1.4 Battery Storage and Configuration

The storage subsystem utilizes a parallel (2P) configuration of Lithium-ion batteries to maximize capacity and stability. The pack consists of two 3.7V 2200mAh cells, resulting in a total capacity of 4400mAh (4.4Ah). The total energy storage capacity is calculated as E=3.7V×4.4Ah=16.28Wh. This 2Parallel arrangement facilitates better current sharing and lower internal resistance, which contributes to a more stable discharge curve under the 1A load.

At the calculated 4.71W kinetic output, the time required to generate enough energy for a 50% smartphone charge (approx. 7.5Wh) is:

Eq 4

$$Time = \frac{7.5Wh}{4.71W} \approx 1.59\ hrs$$

However, since this is a Hybrid System, the solar panel provides a constant peak, significantly reducing the amount of time a user needs to spend "cranking" to reach a meaningful charge level.

3.2.5 Charging Performance and Estimation

Charging durations were estimated by comparing the battery capacity against the average kinetic output. To fully charge the 16.28Wh pack from 0% to 100%, a theoretical time of 3.46 hours of continuous cranking at 50 RPM is required. When accounting for 15% charging losses, the actual time is approximately 4.0 hours. For typical user interactions, reaching a 50% State of Charge (SOC) would require roughly 2 hours of cumulative activity.

Table 3 Charging Performance

SOC Level	Energy Required	Estimated Time
0–50%	8.14Wh	~2 hours
0–100%	16.28Wh	~4 hours

3.2.6 State of Charge (SOC) and Discharge Behavior

The battery SOC was monitored through voltage-based estimation, revealing a standard Lithium-ion discharge profile. A stable voltage plateau was observed between 30% and 80% SOC, which is ideal for consistent power delivery. However, the voltage drops more rapidly once the SOC falls below 20%, eventually hitting the 3.0V cutoff. During 1A load testing, a temporary voltage sag of 0.1–0.15V was recorded, though the 2P configuration helped mitigate this effect compared to a single-cell setup.

3.2.7 Solar Subsystem Contribution

The 10W photovoltaic (PV) panel provides a steady auxiliary energy source. Under average Malaysian irradiance of 4 peak sun hours, the panel generates a theoretical 40Wh per day. Adjusting for a 75% practical efficiency due to temperature and conversion losses, the actual yield is approximately 30Wh/day. This contribution is sufficient to recharge the internal battery bank nearly twice daily, ensuring the station remains operational even with low kinetic input.

3.2.8 Testing Instrumentation and Uncertainty Analysis

Validation was conducted at an ambient temperature of 28∘C using high-precision instruments, including a Digital Multimeter (±1% accuracy) and a USB Power Meter (±2%). Rotational speed was verified using a tachometer and the Arduino Serial Monitor. Sources of variation identified during testing include human RPM inconsistency and temperature-induced fluctuations in battery voltage. The overall conversion efficiency was found to vary by ±3–5% depending on environmental factors.

3.3 Logic Gate Validation and Hall Effect Sensor Accuracy

The "Smart Exercise Clause" was validated through a series of logic tests controlled by the Arduino Nano. The Hall Effect sensor was tasked with monitoring the RPM of the hand crank by detecting magnetic pulses. The results showed that the sensor provided high-resolution data, allowing the microcontroller to execute the gating logic with minimal latency. During testing, the 5V Relay Module remained in an open state as long as the user's input remained below the 50 RPM threshold. Once the user accelerated to 50 RPM or higher, the Arduino successfully triggered the relay, closing the circuit and allowing energy to flow from the battery to the USB port. This binary control mechanism was observed to be stable, with no "chattering" of the relay, ensuring that energy was only dispensed when the physical effort requirement was strictly met.

3.4 Calorie Calculation and User Feedback System

Finally, the integration of the health monitoring system was assessed. By correlating the torque of the NEMA 23 motor (1.5 Nm) with the rotational speed, the system's firmware translated mechanical work into calorie expenditure. During a 5-minute controlled test at a steady 50 RPM, the I2C LCD correctly displayed a cumulative burn of approximately 12 to 15 calories. The accuracy of this display was essential for the "gamification" aspect of the project. The results proved that the station does more than provide power; it provides a tangible metric for physical health. The successful synchronization of the RPM sensor, the relay gating, and the calorie display confirmed that all three primary objectives, sustainable charging, smart control, and fitness promotion were met through the prototype's final design.

Figure 3 Shows the Calorie count on the OLED

4. Conclusion

The design and development of the Hybrid Solar and Hand-Cranked Kinetic Charging Station demonstrate a functional integration of renewable energy technology with public health interventions. This study successfully achieved its primary objectives, proving that a "Play-to-Charge" model provides a practical incentive for physical activity in urban environments such as Tanjung Emas Park, Muar.

Technical evaluations confirmed that the use of a NEMA 23 Bipolar Stepper Motor is highly effective for low-RPM human-powered generation. By implementing a Greinacher Voltage Doubler circuit optimized with Schottky diodes, the system effectively reached a rectified DC output of 7.88V, providing sufficient headroom for stable 5V regulation. Performance testing validated that at a target speed of 50 RPM, the system delivers a regulated electrical output of 4.71W (5V, 0.94A), harvesting approximately 0.0785Wh per minute of exercise. The inclusion of a "Smart Exercise Clause" via an Arduino Nano ensures that power delivery is contingent upon physical effort, requiring a sustained 50 RPM threshold to activate the charging relay.

The power architecture is further bolstered by a 2P Lithium-ion battery configuration (16.28Wh) and a specialized UPS-BMS module. This setup provides comprehensive safety through overcharge, over-discharge, and short-circuit protection, while the "power path" management ensures an uninterruptible supply to the user. The 10W solar subsystem, regulated via a heat-sinked LM7805 stage, provides a reliable 30Wh of daily energy, ensuring the station remains operational during idle periods.

In summary, this prototype provides a sustainable, off-grid infrastructure model that aligns with the Malaysia Renewable Energy Roadmap (MyRER) while addressing sedentary behavior through localized innovation. By linking energy generation with physical exertion, the system fosters both environmental awareness and individual wellness. Future research focusing on IP65-rated weatherproofing and IoT-enabled data monitoring for remote SOC tracking could further enhance the scalability of this system for long-term deployment in municipal "Smart Parks."

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Conflict of Interest

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

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This guide contains examples of common types of APA Style references. Section numbers indicate where to find

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