

Digital Innovation in Smart Waste Sorting Using Renewable Energy for Sustainable Startups

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ABSTRACT

The accumulation of inorganic waste in urban environments requires innovative technological solutions that support the Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production). Smart waste management systems integrating Artificial Intelligence (AI) and the Internet of Things (IoT) have emerged as promising digital innovations to improve waste sorting efficiency. **This study presents** the development of a smart waste sorting system called Orange Box, designed to support sustainable startup initiatives in environmental technology. **A major challenge** in deploying IoT-based devices in outdoor public areas is the limited availability of conventional electrical infrastructure, where reliance on extension cables is inefficient and potentially unsafe. Therefore, this research aims to design and evaluate an independent off-grid electrical system based on renewable energy to ensure continuous operation of the device. **The proposed system** utilizes solar panels as the primary energy source, with energy conversion and distribution managed through a 500W inverter and a 20A Power Supply Unit (PSU) that supplies power to a Raspberry Pi 5–based control system. Experimental measurements indicate that the system operates with an average power consumption of approximately 10–12W and reaches a peak load of 17.17W during active waste sorting operations. The estimated daily energy consumption ranges from 288Wh to 338Wh when considering inverter efficiency. **These findings** demonstrate that integrating renewable energy infrastructure with IoT-based smart waste sorting technology represents a viable digital innovation to support sustainable startups while contributing to SDG 7 (Affordable and Clean Energy).

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1. INTRODUCTION

Waste management, particularly inorganic waste, remains a major environmental challenge that requires immediate and systematic solutions. Rapid population growth and urbanization have significantly increased the volume of municipal waste, creating serious environmental and public health concerns. Recent data

from the National Waste Management Information System (SIPSN) in 2023 indicates a continuous increase in waste generation in Indonesia, highlighting the urgent need for more effective and technology-driven waste management strategies. In this context, waste sorting at the source has become a critical step in reducing land-fill pressure and improving recycling efficiency. Data from the Ministry of Environment and Forestry (KLHK) also emphasizes the importance of integrating digital technologies into domestic waste management systems in order to enhance operational efficiency and promote environmental sustainability [1].

In response to these challenges, a technological innovation known as the Orange Box, an automatic waste sorting device, was developed. This system integrates Artificial Intelligence (AI) and computer vision technologies to automatically detect, classify, and separate different types of waste without requiring direct human intervention [2]. Through image recognition and intelligent classification algorithms, the system can identify waste categories and trigger automated sorting mechanisms. The implementation of this technology is expected not only to improve waste management efficiency but also to function as an educational tool that increases community awareness regarding proper waste disposal practices [3]. By combining automation with environmental education, the device contributes to the development of smarter and more sustainable urban waste management systems [4].

Despite the advanced technological capabilities of the Orange Box, several infrastructure challenges were identified during field deployment, particularly related to the availability of electrical power sources [5]. Smart waste sorting devices are ideally installed in open public spaces such as parks, community centers, or the yards of public facilities to ensure easy accessibility for residents [6, 7]. However, these strategic locations are often located far from conventional electrical outlets or the main power infrastructure of nearby buildings, including community facilities such as Posyandu [8]. Extending conventional power cables from nearby buildings to outdoor devices is considered inefficient due to installation costs, maintenance requirements, and potential safety risks in public environments [9]. These limitations highlight the importance of developing an independent and reliable power infrastructure that can support continuous device operation [10].

To address these limitations, an independent power supply system that operates without relying on the national electricity grid (off-grid) is required [5, 11]. Renewable energy, particularly solar energy, represents one of the most feasible and environmentally sustainable solutions due to its abundant availability in tropical regions such as Indonesia [12]. Solar-based power systems have the potential to provide a stable and autonomous energy source for IoT devices deployed in outdoor environments. Previous studies have explored the application of Artificial Intelligence (AI) and Internet of Things (IoT) technologies in smart waste management systems [13, 14]. However, most of these studies primarily focus on improving waste detection accuracy, sensor integration, and automation mechanisms [15]. Limited attention has been given to the sustainability and reliability of the supporting energy infrastructure required to maintain continuous system operation, particularly in outdoor environments where access to grid electricity is limited [4]. Therefore, integrating AI-based waste sorting technology with renewable energy-based off-grid power systems remains an important research gap in the development of sustainable smart waste management solutions [16]. Addressing this gap is essential to ensure reliable, energy-independent, and environmentally sustainable deployment of intelligent waste sorting devices [8].

2. LITERATURE REVIEW

2.1. Waste Management and Internet of Things (IoT)

Waste management has become a critical global issue due to the rapid growth of urban populations and consumption patterns. Technological innovation is increasingly used to support efficient waste management systems, particularly through the integration of the Internet of Things (IoT). IoT refers to a network of interconnected physical devices embedded with sensors, software, and communication technologies that enable real-time data exchange through internet connectivity [17]. In smart waste management, IoT enables devices to monitor, detect, and classify waste automatically [18].

The Orange Box system represents a practical implementation of IoT combined with Artificial Intelligence (AI) and Computer Vision to automatically detect and separate waste categories without human intervention [19]. Such automation improves waste sorting accuracy and promotes environmental awareness in communities. However, IoT-based systems require continuous and stable electrical power to maintain device connectivity, processing capability, and operational reliability [19]. Power instability may lead to system interruptions, data loss, or device resets, which reduce the effectiveness of smart waste solutions.

2.2. Off-Grid Solar Power System

Renewable energy plays an essential role in supporting the development of sustainable digital infrastructure, particularly for systems that operate continuously in outdoor environments. Among various renewable energy sources, solar energy has become one of the most widely adopted solutions due to its abundance, scalability, and environmentally friendly characteristics [12]. Solar photovoltaic (PV) technology enables the direct conversion of sunlight into electrical energy through semiconductor materials, allowing electronic devices and smart systems to operate without relying entirely on conventional fossil-fuel-based electricity. In the context of sustainable technology deployment, solar energy provides a practical approach to reducing carbon emissions while ensuring long-term energy availability for digital devices.

For locations where access to the national electricity grid is limited or unavailable, Off-Grid solar power systems provide an independent and reliable energy solution [20]. In this configuration, solar panels capture solar radiation during the daytime and convert it into electrical energy, which is then stored in battery systems for later use. The stored energy allows devices to continue operating during nighttime or periods of low solar irradiation, such as cloudy weather conditions [15]. This energy storage mechanism ensures system stability and supports uninterrupted operation of connected devices.

Off-grid solar power systems have been widely implemented in various applications, including remote environmental monitoring, agricultural sensing systems, and smart infrastructure deployed in public outdoor environments. These systems are particularly suitable for Internet of Things (IoT) devices that require continuous operation but are often installed in locations far from conventional electrical infrastructure. By integrating renewable energy with IoT-based systems, it becomes possible to develop energy-independent technological solutions that support sustainable urban development while minimizing operational costs and environmental impact.

2.3. Power Conversion Mechanism

In renewable energy systems, electrical energy typically undergoes several conversion stages before reaching the load device. Since most solar panels and batteries produce direct current (DC), power conversion is required to match the voltage specifications of electronic devices. A DC-to-AC inverter is commonly used to convert 12V DC battery power into 220V AC electricity [21]. In this study, a Modified Sine Wave (MSW) inverter was used due to its affordability and suitability for small-scale off-grid applications [22]. Although MSW inverters generally have lower efficiency and higher harmonic distortion compared to Pure Sine Wave (PSW) inverters [6], they remain adequate for low-power IoT devices such as microcontrollers and embedded systems.

Following the inverter stage, a Power Supply Unit (PSU) converts the 220V AC voltage into a stable 5V DC output required by the Raspberry Pi microcontroller and peripheral components [23]. Maintaining voltage stability is essential to ensure system reliability and prevent damage to sensitive electronic components [17]. The efficiency of these conversion stages significantly influences the overall energy consumption and sustainability of IoT-based systems [24, 25].

2.4. Related Works

Several previous studies have investigated the integration of renewable energy into smart waste management systems, developed a solar-powered automatic waste sorting system and concluded that renewable energy is highly suitable for outdoor applications, although accurate battery capacity planning is required [26]. Similarly, implemented solar energy in smart waste bins and highlighted the importance of stable power supply to maintain system performance [27].

In addition, analyzed Off-Grid power systems and emphasized that accurate load estimation is crucial to prevent system failure and ensure stable operation. Similarly, [28] demonstrated that a 100 Wp solar panel can adequately support low-power electronic devices, although excessive power conversion stages may reduce overall system efficiency. Despite these contributions, most existing studies primarily focus on device functionality or waste detection accuracy. Limited attention has been given to the sustainability of the supporting energy infrastructure required for continuous system operation. Therefore, integrating AI-based smart waste sorting technology with renewable energy systems remains an important area for further research to ensure reliable and sustainable deployment.

3. METHOD

3.1. Research Flow

This research was conducted systematically to ensure that the electrical system of the Orange Box operates efficiently and reliably. The study began with a comprehensive literature review to identify relevant theories, previous studies, and technological approaches related to off-grid power systems and energy management for electronic devices. The insights obtained from this stage served as the foundation for designing the electrical architecture using an Off-Grid topology, which allows the system to operate independently from the conventional power grid. After the design phase, the research continued with the integration and assembly of all electrical components, including solar panels, charge controllers, batteries, inverters, and supporting power supply units to ensure stable power distribution. Finally, a series of performance tests were conducted to evaluate voltage stability, energy efficiency, and the overall reliability of the system in supporting the operational needs of the Orange Box. The complete sequence of the research stages is visually illustrated in Figure 1.

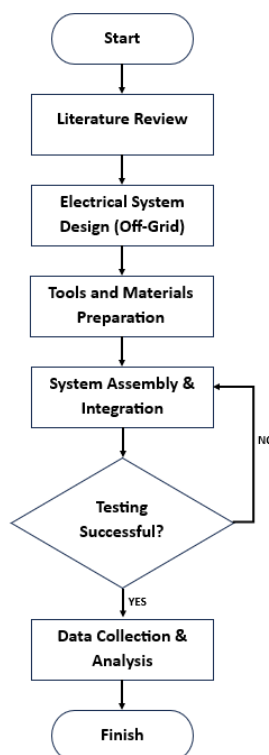


Figure 1. Research Flowchart

The applied research flow is illustrated in Figure 1. The stages begin with a literature review to gather references related to IoT and renewable energy, followed by the design of the off-grid electrical system. Following the preparation of tools and materials, the process proceeds to assembly and system integration [29]. Performance testing is conducted iteratively to ensure the device's reliability. If the test results do not meet established standards, the process reverts to the assembly stage for refinement. The study concludes with performance data collection and an analysis of the implementation results.

3.2. Research Tools and Materials

To realize the electrical infrastructure for the Orange Box, a set of tools and materials with the following technical specifications were utilized:

3.2.1. Power Generation and Energy Storage Components

A 100 Wp solar panel is utilized as the primary component for converting solar energy into electrical power. The panel used in this system is a polycrystalline type manufactured by ICA Solar or an equivalent brand

with similar specifications. Polycrystalline solar panels are widely adopted in small-scale renewable energy systems due to their reliability, durability, and relatively stable energy conversion efficiency under varying environmental conditions.



Figure 2. 100 Wp Solar Panel

The physical implementation and configuration of the solar panel used in this study are presented in Figure 2, which illustrates the solar module installed as part of the renewable energy infrastructure supporting the automatic waste sorting system [30].

A 10A Solar Charge Controller (SCC) is used to regulate the electrical energy generated by the solar panel before it is stored in the battery system. The controller employed in this study is a PWM (Pulse Width Modulation) type, commonly recognized by its blue model design, and is equipped with a digital LCD display that enables real-time monitoring of voltage and charging status [31].



Figure 3. Solar Charge Controller (SCC)

In addition, the integrated LCD indicator provides important operational information, allowing users to monitor system performance and battery condition more easily during deployment. The Solar Charge Controller utilized in this system is illustrated in Figure 3, which shows the physical device used to manage energy flow within the off-grid solar power system.

A 12V 100Ah VRLA (Valve Regulated Lead-Acid) battery manufactured by Yuasa is used as the primary energy storage component in the off-grid power system. This type of battery is widely utilized in renewable energy applications due to its reliability, low maintenance requirements, and stable performance in continuous charging and discharging cycles. With a nominal capacity of 100Ah at 12V, the battery is capable of storing approximately 1200Wh of backup electrical energy.



Figure 4. 12V 100Ah VRLA Battery

This stored energy ensures a stable power supply for the IoT-based device, including the Raspberry Pi microcontroller and supporting hardware components. The physical implementation of the battery used in this

system is shown in Figure 4, illustrating the VRLA battery that serves as the main energy storage unit within the renewable energy infrastructure [32].

3.2.2. Distribution and Power Conversion Components

A 500W inverter is utilized in the system to convert direct current (DC) electricity stored in the battery into alternating current (AC) required by several electronic components. The inverter used in this study is a Modified Sine Wave type, with an input voltage of 12V DC and an output voltage of 220V AC, making it suitable for standard electrical devices operating on household voltage levels. Modified sine wave inverters are commonly employed in small-scale renewable energy systems due to their relatively high efficiency, compact design, and cost-effectiveness compared to pure sine wave alternatives [33].



Figure 5. Power Inverster 500W

In this system, the inverter ensures that electrical energy stored in the VRLA battery can be safely and effectively utilized to power supporting devices that require AC input. The inverter unit features a distinctive orange or gold aluminum casing, which functions not only as a protective enclosure but also as a heat dissipation structure to maintain stable operation during continuous power conversion. The physical appearance and implementation of the inverter used in this renewable energy system are illustrated in Figure 5.

A Power Supply Unit (PSU) is used to regulate and convert electrical power into a stable voltage required by the system's electronic components. The PSU employed in this study is a mesh-type switching power supply, designed with an open metal casing that facilitates heat dissipation and improves airflow during continuous operation. The unit supports an input voltage of 110/220V AC and provides a stable output of 5V DC with a maximum current capacity of 20A, making it suitable for powering microcontroller-based systems and other low-voltage electronic devices [17].



Figure 6. Power Supply Unit (PSU)

The stable voltage regulation provided by the PSU ensures reliable system performance and protects sensitive electronic components from voltage fluctuations or electrical instability. The physical form and configuration of the Power Supply Unit utilized in this study are presented in Figure 6, illustrating the mesh-type PSU integrated within the off-grid renewable energy system arch

A Miniature Circuit Breaker (MCB) is installed in the electrical system as a protective component to prevent damage caused by electrical overloads and short circuits. In this study, two types of MCBs are utilized, namely C16 and C6, which function as automatic protection switches within the low-voltage electrical distribution system. These breakers operate by automatically disconnecting the electrical circuit when the current exceeds the predefined safety threshold, thereby protecting critical components such as the inverter, power supply unit, and other electronic devices from potential electrical faults [31].



Figure 7. MCB (Miniature Circuit Breaker)

The use of different current ratings allows the system to provide layered protection for various electrical loads operating at different power levels. The selection and installation of these protective components follow the low-voltage protection standards outlined in the component safety manual, ensuring safe and reliable system operation during continuous use. The MCB device implemented in the renewable energy system is illustrated in Figure 7, which shows the protective switch integrated into the overall off-grid electrical infrastructure



Figure 8. Terminal Block

A Terminal Block is utilized as a connection interface for organizing and distributing electrical wiring within the system. This component functions as a secure and structured point for connecting multiple distribution cables, enabling efficient electrical routing between different hardware components such as the power supply unit, inverter, MCB, and other electrical modules. Based on Figure 8 use of terminal blocks helps improve wiring management by reducing cable clutter and ensuring stable electrical connections, which is essential for maintaining system reliability and safety [34].

3.2.3. Load Components (Orange Box Device) :

A Miniature Circuit Breaker (MCB) is installed in the electrical system as a protective component to prevent damage caused by electrical overloads and short circuits. In this study, two types of MCBs are utilized, namely C16 and C6, which function as automatic protection switches within the low-voltage electrical distribution system. These breakers operate by automatically disconnecting the electrical circuit when the current exceeds the predefined safety threshold, thereby protecting critical components such as the inverter, power supply unit, and other electronic devices from potential electrical faults [35].

The Raspberry Pi 5 is utilized as the main processing unit responsible for handling digital data processing and executing Artificial Intelligence (AI) algorithms within the system. As a single-board computer, the Raspberry Pi 5 provides sufficient computational capability to manage multiple tasks, including sensor data acquisition, image or signal processing, and communication between hardware components in the IoT-based waste sorting device. Its compact design, energy-efficient operation, and flexible connectivity options make it well suited for embedded system applications and smart environmental technologies.



Figure 9. Raspberry Pi 5

The Raspberry Pi 5 serves as the central controller, processing input signals, executing AI-based classification, and coordinating the automated waste sorting mechanism. It also integrates with the renewable energy power system to enable continuous off-grid operation. The device used in this study is shown in Figure 9.

The MG995R servo motor functions as the mechanical actuator that drives the waste sorting mechanism. In this system, five servo motors are installed to control different components of the automated sorting process. Each motor receives control signals from the Raspberry Pi 5 to adjust the rotation angle and direct waste into the appropriate sorting compartment.



Figure 10. Motor Servo MG995R

Through pulse-width modulation (PWM) signals, the servo motors achieve precise positioning, allowing controlled and repeatable movements during operation. This actuator translates AI-based classification decisions into physical sorting actions. The servo motor used in this study is shown in Figure 10.

The Camera Module V2 serves as the primary visual sensor for capturing image data used in the waste classification process. Integrated with the Raspberry Pi 5, it enables real-time image acquisition for the AI-based sorting system. The captured images are analyzed to classify waste based on visual features such as shape, color, and texture, enabling automated and contactless waste identification.



Figure 11. Camera Module V2

Additionally, the compact design and compatibility of the Camera Module V2 with Raspberry Pi make it suitable for embedded IoT applications requiring visual data processing. The camera module implemented

in this study is presented in Figure 11, illustrating the visual sensing device used to capture image inputs for the intelligent waste sorting system.

3.2.4. Measurement and Testing Instruments :

A Digital AC Wattmeter is utilized as a real-time electrical measurement device to monitor the performance of the power system. The wattmeter is installed at the output terminal of the inverter, enabling continuous observation of the electrical parameters supplied to the system. This device is capable of measuring several key indicators, including Voltage (V), Current (A), Power (W), and Power Factor (PF), which are essential for evaluating the efficiency and stability of the electrical supply. By providing real-time monitoring, the wattmeter allows researchers to analyze the power consumption characteristics of the system and verify whether the electrical load operates within the designed power capacity.



Figure 12. Digital AC Wattmeter

The collected measurements also support the evaluation of energy usage patterns and help identify potential electrical inefficiencies or irregularities during system operation. The Digital AC Wattmeter used in this study is shown in Figure 12, illustrating the monitoring device installed to measure and record the electrical parameters of the off-grid renewable energy system.

A Digital Multimeter is employed as a diagnostic and measurement instrument to obtain accurate electrical readings within the system. In this study, the digital multimeter is primarily used to measure direct current (DC) voltage at critical points of the electrical circuit, particularly at the battery terminals and the output of the Power Supply Unit (PSU). These measurements are essential for verifying the stability of the electrical supply and ensuring that the voltage levels remain within the required operating range for the connected electronic components.



Figure 13. Digital Multimeter

The use of a digital multimeter also supports system validation and troubleshooting by allowing precise monitoring of electrical parameters during system installation and testing. Accurate voltage measurements help confirm that the energy storage and power regulation components function properly within the off-grid renewable energy configuration. The Digital Multimeter utilized in this study is presented in Figure 13, illustrating the measurement device used to monitor and verify DC voltage levels in the electrical system.

3.3. Data Collection Method

The data collection procedure was conducted through several systematic stages: ensuring the battery was fully charged (voltage > 12.5 Volts), recording idle power consumption via the Wattmeter, triggering the

waste sensor to actuate the servos for peak power recording, and measuring the stability of the PSU output voltage using a digital multimeter to ensure the safety of the power supply to the microcontroller [36].

4. RESULT AND DISCUSSION

4.1. Implementation of Power Generation System Circuit

The implementation of the electrical system was carried out on-site in accordance with the established Off-Grid topology design. All control and power distribution components are centrally housed within a custom panel enclosure to ensure installation safety and facilitate maintenance.

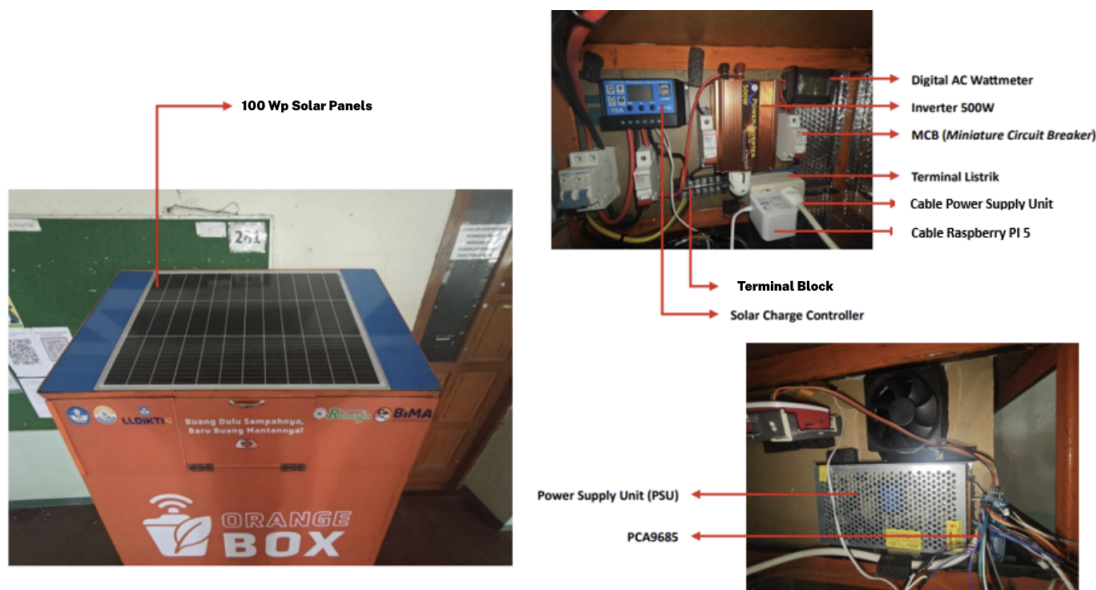


Figure 14. Physical Layout and Component Interconnection within the Panel Box

The physical realization of the system assembly is shown in Figure 14. As depicted in the panel, the Solar Charge Controller (SCC) functions as the central regulator, receiving input from the Solar Panel and managing the battery charging process [37]. From the battery terminals, power is distributed through a safety MCB to the Inverter for conversion into 220V AC. The inverter output is subsequently directed to the Power Supply Unit (PSU), which converts it back into stable DC current to power the Raspberry Pi microcontroller and servo motors [38].

4.2. Distribution Voltage Measurement Results

Voltage stability is a critical parameter that determines the reliability and performance of IoT-based systems [39]. Stable voltage ensures that all electronic components, including sensors, controllers, and actuators, operate within their required electrical limits. Based on direct measurements conducted using a digital multimeter, the following voltage data were obtained from the system components:

- Charging Voltage (PV to SCC): Measured stable at 12.58V at the SCC terminal.
- Battery Voltage: Read between 12.7V and 12.8V. This figure indicates the battery is in a full (100%) and healthy condition.
- Load Voltage (PSU Output): Measured constant at 5.0V . This is crucial because the Raspberry Pi 5 is sensitive to *undervoltage*.



Figure 15. SCC display indicating a fully charged battery (12.7V)

Figure 15 shows the Solar Charge Controller (SCC) display indicating the battery voltage status during system operation. The LCD screen displays a voltage reading of 12.7V, which represents a fully charged condition for the 12V VRLA battery used in the off-grid power system. This voltage level confirms that the charging process from the solar panel through the SCC has successfully reached the optimal charging stage, ensuring that sufficient electrical energy is stored in the battery. Monitoring the voltage value through the SCC display is essential for evaluating the charging performance and overall stability of the renewable energy system. The displayed voltage also provides a quick visual indication that the battery is operating within a safe and efficient range, which is important for maintaining the reliability and longevity of the energy storage component.

4.3. Real-Time Power Analysis

Power consumption measurements were conducted using a Digital AC Wattmeter at the Inverter output side. The detailed data is presented in Table 1.

Table 1. Power Consumption Measurement Data of the Orange Box Device

No	Condition	Volt (V)	Amp (A)	Power (W)	PF	Analysis
1	Idle / Standby	230	0.09	7.26 - 7.32	0.36	System on, Raspberry Pi active.
2	Processing (AI)	230	0.10	10.50 - 11.10	0.48 - 0.51	Camera active detecting objects.
3	Active (Servo)	230	0.11	13.79 - 17.17	0.58 - 0.65	Servo motors moving.

Based on the data presented in the table above, the visualization and analysis of the device's operational conditions are as follows:



Figure 16. Wattmeter reading during normal system operation

As shown in Figure 16, when the device is in an idle or standby state, the power consumption is recorded to be very low, specifically in the range of 7.32W. The display also indicates a Power Factor (PF) value of approximately 0.48. This low PF value is attributed to the non-linear load characteristics of the Power Supply Unit (PSU). However, given that the total active power (Watt) is minimal, this inefficiency remains within safe limits. In addition to voltage stability, power quality is an important aspect in renewable energy based IoT systems [40]. The current implementation utilizes a standard switching Power Supply Unit (PSU) without active Power Factor Correction (PFC), which contributes to a relatively low power factor due to its non-linear load characteristics. Although this condition does not significantly affect system performance given the low total power demand, future system optimization may consider the use of a PSU equipped with active PFC or the integration of additional filtering components, such as LC filters. These improvements would enhance power quality by reducing harmonic distortion, improving power factor, and minimizing stress on the inverter, thereby supporting higher efficiency and long-term system reliability.

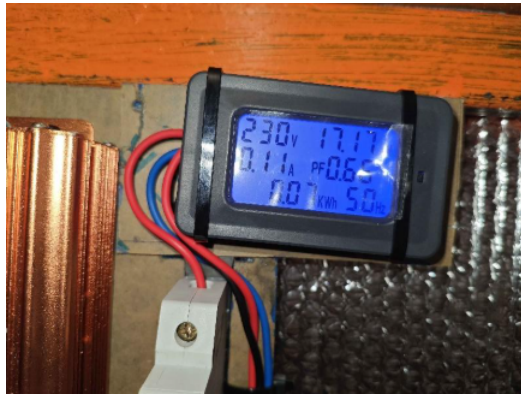


Figure 17. Wattmeter display showing a peak load of 17.17W

Furthermore, Figure 17 captures the instance where the peak load reached 17.17W. This surge occurred when the sensors detected waste, triggering the servo motors to actuate the door mechanism. Despite this increase, the peak load of 17.17W remains significantly below the 500W maximum capacity of the Inverter. Consequently, the system is ensured to be safe from overload risks and capable of continuous 24-hour operation.

4.4. Energy Autonomy Calculation

To verify the sustainability of the proposed system, a mathematical calculation was conducted to evaluate the balance between the energy generated by the renewable energy source and the total power consumption of the system components. This calculation provides a quantitative basis for assessing whether the system can operate continuously under the available energy supply. To verify system sustainability, a mathematical calculation was performed as follows:

- **Total Daily Energy:** The total daily energy consumption is calculated assuming an average load of 12W running continuously for 24 hours:

$$E_{load} = 12 \text{ W} \times 24 \text{ h} = 288 \text{ Wh}$$

Considering an inverter efficiency of 85%, the actual energy required from the battery is:

$$E_{battery_req} = \frac{288}{0.85} \approx 338.8 \text{ Wh/day}$$

- **Effective Storage Capacity:** The battery specification is 12V 100Ah, providing a total capacity of 1200 Wh. With a safe usage limit of 80% (Depth of Discharge/DoD):

$$E_{usable} = 1200 \text{ Wh} \times 80\% = 960 \text{ Wh}$$

- Days of Autonomy: The system autonomy is determined by dividing the usable energy by the daily energy requirement:

$$Days = \frac{960 \text{ Wh}}{338.8 \text{ Wh}} \approx 2.83 \text{ Days}$$

For maximum theoretical depletion:

$$Days_{max} = \frac{1200}{338.8} \approx 3.5 \text{ Days}$$

The system demonstrates an autonomy of 2.8 to 3.5 days without sunlight. This duration complies with the recommendations for reliable Off-Grid systems [41]. To further enhance energy efficiency and extend battery autonomy during periods of limited solar irradiation, power management strategies can be incorporated at the device level [42]. One effective approach is the implementation of a sleep or low-power mode for the Raspberry Pi during idle or standby periods, where no waste detection or actuation is required. By reducing CPU frequency, disabling non-essential peripherals, or scheduling periodic wake-up intervals, the system's average power consumption can be significantly lowered. Such power management strategies are particularly beneficial during consecutive days without sunlight, as they help preserve battery capacity and ensure continuous system availability in off-grid operating conditions.

5. MANAGERIAL IMPLICATIONS

The findings of this research offer practical insights for community leaders, local administrators, and waste bank operators regarding the adoption of smart waste infrastructure in residential areas. First, cost efficiency for community-funded operations. Since the Orange Box operates independently using solar energy, it eliminates the burden of monthly electricity bills typically charged to community funds. For local administrators, this implies that the system can be installed in public spaces, community parks, or waste collection points without requiring complex electrical wiring or increasing the neighborhood's operational budget. Second, enhancement of local waste collection efficiency. The integration of IoT monitoring assists local waste collectors in managing their pickup schedules more effectively. Instead of daily checking every bin, collectors can monitor the fill-levels via smartphone, prioritizing areas that are already full. This improves the workflow of community waste services and prevents waste overflow in residential neighborhoods. Third, fostering an educational and sustainable environment. The implementation of automated sorting technology serves as an educational tool for residents and children. It encourages the community to participate in waste segregation practices directly. For community organizers, adopting this technology demonstrates a proactive step towards creating a "Smart Village" aligning local practices with national environmental standards.

6. CONCLUSION

This study demonstrates that the implementation of a renewable energy-based off-grid power system successfully supports the continuous operation of the IoT-based Orange Box in public areas with limited access to conventional electricity. The experimental results indicate that the device operates with a relatively low average power consumption of 10–12 W and a peak load of 17.17W. Supported by a 12V 100Ah battery, the system provides energy autonomy ranging from 2.8 to 3.5 days without solar input. Moreover, the stable 5.0 Volt output ensures the safe and reliable operation of the Raspberry Pi 5 as the main control unit. These findings confirm that integrating solar energy infrastructure with IoT-based waste management systems is both technically feasible and operationally efficient for sustainable urban and community applications. For future research, further improvements may focus on enhancing energy efficiency by replacing the inverter-PSU configuration with a direct DC-DC buck converter. This approach would maintain a direct DC power flow from the battery to the load, eliminating unnecessary DC-AC-DC conversion stages that introduce additional power losses. As a result, overall system efficiency could be significantly improved, and battery autonomy could be extended, particularly for low-power IoT-based applications such as the Orange Box system. The novelty of this research lies in its integrative approach that combines an AI-based automatic waste sorting system with a quantitatively evaluated off-grid renewable power infrastructure under real field conditions. Unlike previous studies that primarily focus on IoT functionality or solar energy utilization in isolation, this work provides a comprehensive

analysis of actual power consumption, energy conversion efficiency, and system autonomy. This contribution positions the proposed system as a practical reference model for developing smart waste solutions that are not only digitally intelligent but also energy-independent and environmentally sustainable.


For future research, further improvements may focus on enhancing energy efficiency by replacing the inverter–PSU configuration with a direct DC–DC buck converter, thereby minimizing power losses caused by multiple conversion stages. In addition, the integration of IoT-based monitoring sensors for both the battery and solar panel would enable real-time and remote supervision of system health. By incorporating voltage, current, and temperature sensors, key parameters such as battery state of charge, charging efficiency, and solar panel performance can be continuously monitored to support preventive maintenance and long-term system reliability in off-grid environments.

Future studies may also investigate system scalability by deploying multiple units or accommodating higher loads across diverse locations to strengthen the role of this technology within Smart City and Smart Village initiatives aligned with sustainable development goals. However, large-scale deployment introduces several technical and economic challenges. From a technical perspective, scalability raises issues related to system standardization, interoperability with existing urban IoT platforms, and the reliability of renewable energy components under varying environmental conditions. Differences in solar irradiation, battery lifespan, and local maintenance capabilities may affect overall system performance. From an economic standpoint, the initial investment required for solar panels, batteries, and control hardware can be substantial when implemented at scale. Moreover, long-term operational costs associated with battery replacement, system monitoring, and maintenance must be carefully considered. Addressing these challenges requires integrated planning that balances technical robustness, cost efficiency, and institutional support to ensure sustainable and scalable implementation.

7. DECLARATIONS

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7.2. Author Contributions

Conceptualization: UR; Methodology: NS; Software: FO; Validation: MM and MS; Formal Analysis: NS and MM; Investigation: MM and MS; Resources: FO; Data Curation: MS; Writing Original Draft Preparation: NS and MM; Writing Review and Editing: MS and FO; Visualization: FO and MM; All authors, UR, NS, FO, MM, MS, have read and agreed to the published version of the manuscript.

7.3. Data Availability Statement

The data presented in this study are available on request from the corresponding author

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7.5. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

- [1] Ministry of Environment and Forestry, “National waste management information system (sipsn): Waste composition data 2023,” 2023, accessed: 2024-01-20. [Online]. Available: <https://sipsn.menlhk.go.id/>

- [2] R. Indrawan, E. D. Very, D. Tribuana, and E. A. Nabila, "Aiot driven smart solar system for real time predictive sustainable energy management," *International Transactions on Artificial Intelligence*, vol. 4, no. 1, pp. 105–114, 2025.
- [3] Sutanta and H. Al Hasbi, "Appropriate technology service journal for household waste management (in indonesian)," *Jurnal Pengabdian Masyarakat*, vol. 2, no. 1, 2021.
- [4] D. Denis, J. Windarta, V. Prasetya, G. D. Nathania, R. J. Hariara, and A. A. Razaqi, "Grand design and economic analysis of solar-wind hybrid renewable energy systems in mstp jepara," *Infotekmesin*, vol. 15, no. 1, pp. 91–98, 2024.
- [5] Y. I. Yusuf, "Assessing the potential of off-grid solar energy systems to improve electricity access in the rural areas of nigeria," Ph.D. dissertation, , 2025.
- [6] O. O. Babayomi, B. Olubayo, I. H. Denwigwe, T. E. Somefun, O. S. Adedoja, C. T. Somefun, K. Olukayode, and A. Attah, "A review of renewable off-grid mini-grids in sub-saharan africa," *Frontiers in energy research*, vol. 10, p. 1089025, 2023.
- [7] J. Nikpouri and A. Safari, "Industrial and commercial gaps of hydrogen fuel cell electric vehicles for startup opportunities," in *Hydrogen Fuel Cell Electric Vehicles*. Elsevier, 2026, pp. 227–242.
- [8] K. Diantoro, D. Supriyanti, Y. P. A. Sanjaya, S. Watini *et al.*, "Implications of distributed energy development in blockchain-based institutional environment," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 5, no. 2sp, pp. 209–220, 2023.
- [9] Ministry of Energy and Mineral Resources, "Regulation of the minister of energy and mineral resources number 26 of 2021 concerning rooftop solar power plants and electrical safety," Jakarta, 2021.
- [10] S. Lyeonov, S. Podosynnikov, and W. Strielkowski, "Does a reliable electricity grid connection matter for the development of european renewable energy startups?" *Energy Policy*, vol. 206, p. 114749, 2025.
- [11] M.-M. Brezuleanu, M. Pîslaru, and A. Mămăligă, "Technological entrepreneurship in renewable energy: Challenges and opportunities in eastern europe," in *2025 International Conference on Electromechanical and Energy Systems (SIELMEN)*. IEEE, 2025, pp. 330–334.
- [12] L. O. M. Firman, *Theory and Application of New and Renewable Energy: Waste to Energy, Solar Energy, and Hydro Energy (in Indonesian)*. Ponorogo: Uwais Inspirasi Indonesia, 2024.
- [13] A. Aripriharta, A. P. Wibawa, and G. J. Horng, "Design and construction of off-grid solar panels for rat repellent power supply (in indonesian)," *Jurnal Energi Baru dan Terbarukan*, vol. 4, no. 3, pp. 224–245, 2023.
- [14] R. Sao, S. Chandak, P. Bhadade, and K. Wadhvani, "Sustainable entrepreneurship in urban planning and management: Ai as an enabler for green startups," in *Machine Learning and Robotics in Urban Planning and Management*. IGI Global Scientific Publishing, 2025, pp. 205–226.
- [15] E. Susanto and R. Aditya, "Analysis of off-grid solar power plant planning mechanism for residential power (in indonesian)," *Jurnal Teknik Elektro dan Informatika (E-Link)*, vol. 18, no. 2, 2023.
- [16] U. Tolipova, "Sustainable futures through innovation: Lessons from global models and uzbekistan's green transition." *Journal of Economics and Tourism Research*, vol. 1, no. 1, pp. 9–21, 2026.
- [17] Mean Well, *LRS-100-5 Series 5V 20A Switching Power Supply Datasheet*, Mean Well Enterprises Co., Ltd, 2022.
- [18] D. Kundu and N. Chatterjee, "Startups, skill development, and inclusiveness: The new model of sustainable development in india," 2026.
- [19] D. Cahyadi and A. Zulfikar, "Design and implementation of iot-based smart waste bins (in indonesian)," *Jambura Journal of Electrical and Electronics Engineering*, vol. 3, no. 1, pp. 7–12, 2021.
- [20] A. B. More and A. Shrivastava, "Scaling frugal innovation-based startups to accelerate sustainable development," in *Business and Management in Asia: Opportunities and Entrepreneurship*. Springer, 2026, pp. 71–93.
- [21] M. R. Abidin and B. Sudiarto, "Implementation of hybrid inverter in solar power plants to optimize power conversion efficiency (in indonesian)," *Jurnal Teknik Elektro Universitas Mataram*, vol. 6, no. 1, pp. 45–52, 2024.
- [22] A. A. Hassan and D. M. Atia, "Optimizing microgrid integration of renewable energy for sustainable solutions in off/on-grid communities," *Journal of Electrical Systems and Information Technology*, vol. 11, no. 1, p. 61, 2024.
- [23] S. BINDHU, "Sustainability-driven startups: Crafting a better world through innovation—an overview," *BUILDING SUSTAINABLE STARTUPS: STRATEGIES FOR LONG-TERM GROWTH*, p. 191, 2026.

- [24] N. Lestari and P. Utomo, "Efficiency comparison of pure sine wave and modified sine wave inverters for electronic loads (in Indonesian)," *Jurnal Arus Kuat*, vol. 5, no. 2, 2021.
- [25] A. Mohanty, A. K. Dash, A. K. Verma, and A. P. Das, "Smart and innovative technologies for waste disposal: Tools for sustainable environmental management," in *Sustainable Municipal Waste Management with a Zero Waste Approach*. Springer, 2026, pp. 195–215.
- [26] R. Pardede, H. Satria, A. Ridwan, and S. M. Putri, "Socialization of clean living culture using solar-based automatic waste sorting technology (in Indonesian)," *Jurnal Masyarakat Mandiri*, vol. 5, no. 6, pp. 3258–3268, 2021.
- [27] M. Rahman and I. Lammada, "Application of solar power generation as energy for IoT-based automatic waste bins (in Indonesian)," *Jurnal Ilmiah Wahana Pendidikan*, vol. 8, no. 13, pp. 257–267, 2022.
- [28] A. Hidayat, "Design of Internet of Things (IoT)-based smart waste bin (in Indonesian)," *Jurnal Teknologi Elektro*, vol. 12, no. 1, 2021.
- [29] N. D. Noviati, S. D. Maulina, and S. Smith, "Smart grids: Integrating AI for efficient renewable energy utilization," *International Transactions on Artificial Intelligence*, vol. 3, no. 1, pp. 1–10, 2024.
- [30] ICA Solar, *Polycrystalline Solar Panel 100Wp Specification Sheet*, ICA Solar Technology, 2021.
- [31] Schneider Electric, *Low Voltage Protection and Control: MCB Product Catalog*, Schneider Electric Indonesia, Jakarta, 2023.
- [32] Yuasa Battery, *NP Series VRLA Battery Specification: 12V 100Ah*, Yuasa Corporation, 2022.
- [33] Souer Electronics, *User Manual: Modified Sine Wave Inverter 500W*, Souer Digital Technology, 2021.
- [34] Tower Pro, *MG995R High Torque Metal Gear Servo Datasheet*, Tower Pro Official Documentation, 2021.
- [35] Raspberry Pi Ltd, *Raspberry Pi 5 Product Brief: Specifications and User Manual*, Raspberry Pi Ltd, Cambridge, 2023.
- [36] A. D. Garcia, A. M. Rosyid, M. Yusup, and M. Khasanah, "Product innovation of foodpreneurs towards customer loyalty," *Startupreneur Business Digital (SABDA Journal)*, vol. 4, no. 2, pp. 104–113, 2025.
- [37] I. P. Gustiah and H. Newell, "Enhancing human resource management efficiency through scalable blockchain networks with an adaptive AI approach," *Startupreneur Business Digital (SABDA Journal)*, vol. 4, no. 2, pp. 114–123, 2025.
- [38] R. E. Indrajit, M. V. A. Sin, E. A. Nabila, W. N. Wahid, and N. Septiani, "Optimizing business process efficiency through artificial intelligence integration in industry 4.0," *Sundara Advanced Research on Artificial Intelligence*, vol. 1, no. 2, pp. 47–55, 2025.
- [39] Musrianto and N. Fithri, "Power consumption analysis of Raspberry Pi in mini photovoltaic monitoring systems (in Indonesian)," *Jurnal Ampere*, vol. 6, no. 2, pp. 76–85, 2021.
- [40] Z. Zaharuddin, S. Wahyuningsih, A. Sutarman, and I. N. Hikam, "Understanding purposeful leadership in entrepreneurial contexts: A bibliometric analysis," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 6, no. 2, pp. 213–230, 2024.
- [41] G. Santoso and B. H. Purwoto, "Utilization of solar power plants as backup electrical energy sources (in Indonesian)," *Jurnal Elektrikal*, vol. 8, no. 2, pp. 45–52, 2021.
- [42] V. Melinda, T. Williams, J. Anderson, J. G. Davies, and C. Davis, "Enhancing waste-to-energy conversion efficiency and sustainability through advanced artificial intelligence integration," *International Transactions on Education Technology (ITEE)*, vol. 2, no. 2, pp. 183–192, 2024.
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