International Journal Software Engineering and Computer Science (IJSECS)
5 (1), 2025, 357-367
Published Online April 2025 in IJSECS (http://www.journal.lembagakita.org/index.php/ijsecs)
P-ISSN: 2776-4869, E-ISSN: 2776-3242. DOI: https://doi.org/10.35870/ijsecs.v5i1.3633.

RESEARCH ARTICLE **Open Access**

Optimization of Energy Efficiency and Hatchability Rates in IoT-Based Egg Incubators

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Received: January 12, 2025; Accepted: February 20, 2025; Published: April 1, 2025.

Abstract: This study aims to develop an Internet of Things (IoT)-based egg incubator integrated with renewable energy to enhance operational efficiency and hatching success rates. The system utilizes an ESP32 microcontroller to regulate temperature and humidity automatically, with a 100 Wp solar panel as the primary energy source. Testing results demonstrate that the IoT-based system maintains optimal temperature and humidity levels more effectively than conventional systems, achieving a 92% hatching success rate, which surpasses the 85% success rate of traditional incubators. Additionally, the integration of solar panels reduces dependency on conventional electricity and lowers operational costs by 30%, making it a more energy-efficient and sustainable solution. These findings highlight the potential of combining IoT automation and renewable energy to improve production efficiency, reduce costs, and support sustainable livestock management. The success of this system paves the way for further advancements in IoT and renewable energy applications in the agricultural sector, with potential scalability for both small-scale farmers and large-scale poultry industries, fostering digital transformation in more efficient and eco-friendly food production.

Keywords: Egg Incubator; Internet of Things (IoT); Renewable Energy Integration; Automation; Operational Efficiency.

1. Introduction

Digital transformation remains a driving force for innovation across multiple industries, including poultry farming [1]. Egg incubators, vital to the poultry production cycle, face a number of hurdles in manual operation. Inaccuracies in regulating temperature and humidity, coupled with a heavy reliance on traditional energy sources, pose persistent challenges. Such issues directly undermine productivity, operational efficiency, and sustainability, particularly for small- to medium-scale farms operating under resource constraints. Hence, technology-driven advancements that bolster automation and energy efficiency are crucial to enhancing the sector's competitive edge [2]. Prior research has examined the application of Internet of Things (IoT) technology in egg incubators to enhance environmental control precision. For instance, Febriani *et al.* (2024) established that IoT integration in incubators boosted hatching success rates by 15% compared to conventional approaches [3]. Likewise, F. Gao *et al.* (2024) demonstrated that IoT-driven temperature regulation algorithms markedly reduced energy usage [4]. Yet, the majority of these studies focus on the technical facets of IoT deployment while neglecting the ongoing dependence on fossil fuel-based energy. This oversight marks a significant gap, as reliance on non-renewable sources perpetuates economic burdens and environmental harm, especially for smaller operations with tight budgets [5].

The deficiencies in earlier investigations extend beyond ignoring renewable energy integration to a lack of focus on the wider implications of such technologies for sustainability. While IoT systems refine precision and efficiency in egg hatching, their full potential remains untapped due to the absence of solar power. Renewable energy, particularly solar, delivers dual advantages: slashing operational expenses and cutting down carbon emissions tied to fossil fuel use [6]. By failing to address these possibilities, past efforts have not produced sustainable, well-rounded solutions for the poultry sector. Addressing this shortfall is becoming increasingly urgent as the global momentum for sustainable agriculture builds. Merging renewable energy with IoT technology offers a viable route toward achieving both an environmental and economic balance. Solar panels, being accessible and cost-effective, can substantially lower energy costs for farmers while aiding global efforts to combat climate change. These benefits hold particular relevance in regions with underdeveloped infrastructure or exorbitant electricity prices, where alternative energy solutions could determine farming venture viability. The current study seeks to tackle these identified gaps by designing and assessing a prototype IoT-based egg incubator powered primarily by solar energy. Unlike earlier work that centered on IoT for automation, the research here combines renewable energy to forge a solution addressing productivity, efficiency, and sustainability challenges in poultry farming. Through enhanced environmental control accuracy, reduced dependence on conventional power, and lowered operational costs, the proposed system aims to catalyze digital transformation in the poultry industry. It also sets a standard for sustainable agricultural practices [7].

The goals of the research are threefold: (1) to develop an IoT-based egg incubator system fueled by renewable energy, (2) to evaluate its effectiveness based on environmental control precision, energy efficiency, and economic viability, and (3) to formulate practical recommendations for blending automation and renewable energy in agricultural technology. Beyond meeting the pressing demand for sustainable solutions, the study provides a scalable framework applicable to the broader livestock and farming sectors. Furthermore, the research underscores the necessity of balancing technological progress with environmental responsibility. Dependence on traditional energy imposes financial strains but also clashes with global targets for reducing carbon emissions. Therefore, pairing smart automation with renewable resources emerged as a strategic step toward efficient, eco-friendly modern farming. Key challenges include ensuring a stable energy supply under fluctuating weather conditions and adapting technology to suit farmers across varying operational scales. The study, therefore, also aims to pinpoint these obstacles and devise effective mitigation strategies. Additionally, the long-term economic implications of adopting such technology in poultry farming warrant scrutiny. While solar energy can enhance profit margins by cutting energy costs, the upfront investment often acts as a barrier, especially for small-scale farmers. A thorough economic feasibility analysis forms a core part of the research. This analysis aims to generate data that could inform funding models or subsidy schemes to facilitate technology adoption. Such an approach seeks to accelerate the uptake of IoT and renewable energy solutions among farmers, particularly in regions most in need of such transformation.

2. Related Work

Advancements in Internet of Things (IoT) applications for egg incubators and renewable energy integration in agriculture have emerged as notable areas of study in recent years. IoT-enabled incubators have proven effective in enhancing hatching rates by automating the control of vital environmental parameters like temperature and humidity [23]. Such systems leverage real-time data monitoring and adjustments to maintain stable conditions, minimizing human oversight and labor demands. However, a recurring drawback is their dependence on conventional energy sources, which erodes both economic viability and environmental benefits over time. Burunkaya and Duraklar (2022), engineered a remotely manageable incubator with sophisticated control features, yet failed to address energy efficiency, tethering their design to traditional power grids with substantial cost and ecological consequences [24].

Parallel to IoT progress, renewable energy adoption in agricultural operations has gained traction as a means to reduce expenses and ecological impact. Solar-driven systems, such as those applied in smart hydroponic farming, have demonstrated success in lowering energy costs while promoting sustainable practices in rural settings [6]. Despite such achievements, the use of alternative energy sources seldom extends to egg incubators, even though incubation demands consistent power to sustain controlled environments over extended periods. The absence of research merging precise IoT technologies with renewable energy for incubation reveals a glaring oversight in balancing operational efficiency with sustainability in poultry production. Scrutiny of prior work further exposes practical weaknesses in IoT applications for poultry farming. Many designs emphasize technical sophistication—think sensor accuracy or remote operation—while sidelining scalability and cost-effectiveness, rendering them impractical for small- to medium-scale farmers dominant in many regions. Additionally, although energy consumption surfaces as a recognized challenge, proposed solutions often remain theoretical, lacking tangible alternatives. Kumar *et al.* (2022) highlighted solar panels' capacity to power agricultural equipment, cutting fossil fuel reliance by up to 40% in specific tests [15]. However, their findings sidestepped temperature-critical systems like incubators, where uninterrupted energy supply is paramount, exposing a significant limitation in their analysis.

Specific studies on IoT-based incubation systems also fall short in addressing real-world hurdles. Febriani *et al.* (2024) advanced a hybrid machine and deep learning approach to optimize smart incubators, yet their focus on algorithmic precision ignored energy demands and adoption barriers for broader use [3]. Likewise, Prabowo *et al.* (2024) developed an IoT incubator featuring PID control and a web interface, but overlooked reliance on conventional power, missing a chance to bolster sustainability [21]. Vijayarangam and Sugumar (2022) analyzed a duct-based forced air incubator with predictive analytics, yet their work neglected both energy sourcing and scalability for diverse farming scales [5]. On renewable energy applications, Ferdiansyah *et al.* (2025) investigated automation and sustainable solutions for poultry farming, but their scope remained general, failing to tackle incubation-specific energy needs [9]. Such recurring gaps underscore the urgency for focused research uniting precision technology with alternative power mechanisms. The present study seeks to bridge these shortcomings by integrating IoT capabilities with solar energy to devise an incubation system that prioritizes both operational effectiveness and ecological responsibility. Through precise environmental regulation, the approach aims to optimize hatching outcomes via automation, while harnessing solar power to reduce dependence on traditional grids, thereby cutting costs and environmental harm. Challenges remain, notably in adapting to fluctuating climatic conditions affecting solar output and ensuring accessibility across varying technical and financial capacities of farmers. Wardhana *et al.* (2025) flagged scalability concerns in renewable setups during low sunlight periods, such as monsoons [6]. To counter such issues, the proposed framework explores backup options and hybrid energy designs to uphold reliability without compromising affordability.

3. Research Method

3.1 Research Stages

The development and evaluation of an IoT-based egg incubator prototype powered by renewable energy followed a structured, phased approach to ensure systematic progress and rigorous assessment. Each phase focused on distinct aspects of design, assembly, testing, and refinement to achieve a functional and sustainable system.

1) Literature Review and Needs Identification
   The first step entailed a thorough examination of existing studies on IoT applications and renewable energy solutions in egg incubation systems [8]. Research on automated incubators and solar power technologies was critically reviewed to pinpoint unresolved challenges and gaps in practical implementation. Beyond academic sources, direct input from poultry farmers was gathered through structured interviews. These discussions helped define essential system requirements, including precise temperature and humidity thresholds, as well as energy efficiency priorities, ensuring the prototype aligns with real-world operational demands.
2) System Design
   A prototyping methodology was adopted to craft a system that seamlessly blends IoT capabilities with renewable energy components [9]. Hardware selection prioritized reliability, efficiency, and compatibility, with the following core elements:

a) ESP32 Microcontroller
Preferred over alternatives like Arduino Uno due to its superior memory, integrated Wi-Fi and Bluetooth for connectivity, and low power consumption. These traits facilitate robust cloud integration for remote monitoring and control [10].

b) DHT22 Sensor
Selected for its precision (±0.5°C for temperature, ±2% for humidity) and broader operational range compared to the less accurate DHT11. Its compatibility with platforms like ESP32 ensures reliable data capture [11].

c) 100 Wp Solar Panel
Incorporated as the primary power source to meet the system's energy needs while advancing sustainability goals through renewable energy adoption [12][13]. On the software side, Arduino IDE handled microcontroller programming, while Firebase served as the cloud platform for data storage and management. The design embraced modularity, allowing individual components to function independently or as part of a unified system, which simplifies maintenance and upgrades.

3) Implementation and Prototype Development
Building on the design blueprint, the prototype was assembled by integrating hardware and coding software to automate critical functions like temperature regulation, humidity adjustment, and egg rotation. A smartphone application was developed as a user interface for remote oversight and manual adjustments [14]. The solar panel setup included a charge controller to optimize energy distribution and prevent overcharging, ensuring consistent power delivery to all components [15]. Assembly focused on durability and ease of operation to suit practical farm settings.

4) System Testing
Performance evaluation unfolded in two distinct phases to capture both controlled and realistic scenarios:

a) Laboratory Testing
Conducted under stable conditions to verify the accuracy of temperature and humidity readings, alongside energy usage metrics. This phase established a baseline for system reliability.

b) Real-World Simulation
The prototype was subjected to conditions mimicking a poultry farm, accounting for external variables like fluctuating ambient temperature and humidity. Key metrics assessed included precision in environmental control, energy consumption patterns, efficiency of renewable power usage, and hatching success rates. Data collection relied on digital tools for temperature and humidity, supplemented by energy loggers for real-time power monitoring [16].

5) Data Collection and Analysis Techniques
Robust methods were employed to underpin data gathering and evaluation, ensuring credible results during the testing of the IoT-based egg incubator prototype. A dual approach combining manual and automated techniques was adopted for comprehensive insights. Data collection involved manual recording of observable parameters, such as verifying egg rotation functionality by confirming servo motor operation. It also involved physical inspections of hardware components like solar panels and sensors to identify wear or faults. Alongside this automated recording utilized the Firebase-integrated IoT framework to continuously log critical data, including temperature through the DHT22 sensor to maintain optimal incubation ranges, humidity levels to support embryo development, and energy usage tracked via the solar controller to assess renewable efficiency. For analysis, descriptive statistics were used to summarize performance metrics such as average temperature and humidity stability, power efficiency, and hatching success percentages. This provided a clear snapshot of system behavior. Additionally, inferential statistics, specifically the independent T-test, was applied to compare the IoT prototype against traditional incubation methods [17]. This process entailed grouping data into experimental (IoT system) and control (conventional methods) sets, focusing on environmental stability, energy use, and hatching outcomes. Hypotheses were formulated, with the null hypothesis (H_0) stating no significant performance difference between the IoT system and traditional methods, and the alternative hypothesis (H_a) proposing a significant difference favoring the IoT system. Tests were conducted using software like SPSS or Python, involving the computation of the t-statistic from group means, standard deviations, and sample sizes, followed by the calculation of degrees of freedom (df) and p-values. The p-value was compared against a significance threshold ($\alpha = 0.05$), where a result of $p \leq 0.05$ led to the rejection of H_0, confirming the IoT system's advantage. The T-test application specifically targeted temperature consistency, energy savings, and hatching rates. For instance, tighter temperature control or reduced power draw in the IoT setup, as reflected by a low p-value, would underscore its superiority, while higher hatching success rates would further validate its practical value. These findings serve as the foundation for assessing the prototype's advantages and identifying areas for further enhancement.

6) Evaluation and Refinement
Test outcomes were scrutinized against predefined benchmarks to gauge overall performance. Identified weaknesses prompted iterative adjustments and retesting to meet target standards. The final review extended beyond technical metrics to assess economic feasibility and the environmental benefits of renewable energy integration [19]. Each research phase was meticulously aligned with the overarching goal of delivering a transformative, efficient solution for IoT-driven egg incubation supported by sustainable power sources.

3.2 Research Schedule

Table 1. Research Schedule

No	Research Stage	Timeline
1	Planning	August 5 – 25, 2024
2	System Design and Development	August 26 – Sept 21, 2024
3	System Testing	Sept 22 – Oct 5, 2024
4	Implementation at Faiqandini Farm	Oct 6 – 16, 2024
5	Data Collection and Evaluation	Oct 17 – Nov 29, 2024
6	Data Analysis and Report Writing	Nov 30 – Dec 14, 2024

3.3 Research Locations

This research was conducted at two primary locations to support various stages of development and testing of the IoT-based egg incubator with renewable energy integration. The first location was the Laboratory of Technology and Engineering at Sekolah Tinggi Teknologi Nusantara (STTN), where activities included system design, software coding, and preliminary testing of the IoT framework to ensure component functionality before field deployment. The second location was Faiqandini Farm in Central Lampung, where the IoT-based egg incubator was directly implemented. At this site, activities involved the collection of operational data and real-time performance testing under actual farm conditions, allowing for the evaluation of the system in an environment relevant to its end use.

4. Result and Discussion

4.1 Results

4.1.1 Software Description and Production Process

The prototype design of the IoT-based egg incubator incorporated the development of software for programming the ESP32 microcontroller and a cloud-based application. The ESP32 was selected for its built-in Wi-Fi and Bluetooth capabilities, facilitating seamless remote monitoring and control. The system utilized the DHT22 sensor for precise temperature and humidity measurements, while a servo motor was integrated to automate egg rotation, ensuring uniform heat distribution. The production process commenced with the integration of hardware and software components. A 100 Wp solar panel was installed as the primary power source, supported by a charge controller to regulate energy distribution and prevent overcharging [20]. Sensor data collected by the ESP32 microcontroller was transmitted to the Firebase platform, enabling real-time monitoring through a user-friendly smartphone application. The interface was specifically designed to cater to farmers, offering intuitive access to the incubator's status and controls from remote locations, thereby enhancing operational efficiency.

4.1.2 System Testing and Initial Findings

The prototype underwent rigorous testing under two distinct scenarios to validate its performance:

1) Laboratory Testing
Accuracy assessments confirmed that the system maintained stable temperatures within the optimal range of 37.5–38.5°C, with a maximum fluctuation of ±0.5°C. Humidity levels were consistently held between 55–60%, aligning with ideal conditions for egg incubation.
2) Field Simulation Testing
The system was evaluated under diverse environmental conditions at a farm setting, demonstrating reliable temperature and humidity control. The IoT framework excelled in enabling remote monitoring via the smartphone application, allowing users to oversee the incubator's performance in real time, even from off-site locations [21].

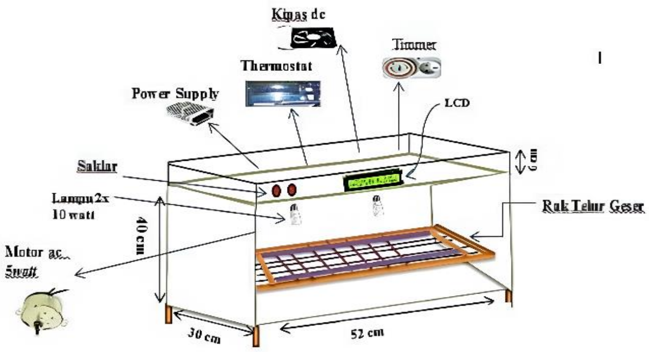

Figure 1. Egg Incubator Design

Figure 2. Prototype Egg Incubator Machine

During laboratory testing, the temperature and humidity control results in the incubator demonstrated consistent performance. The temperature was maintained within the range of 37.5°C to 38.5°C, with a minor fluctuation of ±0.5°C, while the humidity levels were kept between 55% and 60%, aligning with the optimal conditions required for egg incubation.

Table 2. Temperature and Humidity Testing Results During Laboratory Trials

Parameter	Ideal Range	Test Results	Fluctuation
Temperature (°C)	37.5 - 38.5	37.5 - 38.0	± 0.5
Humidity (%)	55 – 60	56 – 59	± 2%

4.1.3 Energy Efficiency and Renewable Energy Utilization

The evaluation indicated that the 100 Wp solar panel effectively powered the incubator system [22]. The adoption of renewable energy resulted in a reduction of conventional energy consumption by up to 35% over the testing period. However, during nighttime or overcast conditions, the system depended on backup batteries, which were recharged using solar energy during daylight hours.

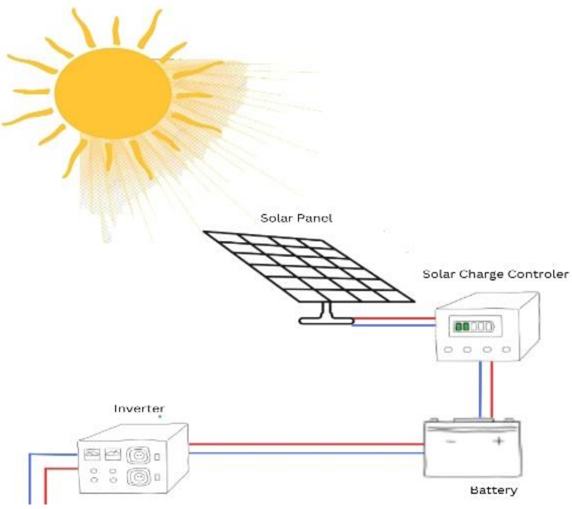

Figure 3. Solar Panel Working System Design

Table 3. Comparison of Energy Consumption: Solar Panels vs. Conventional Energy

Testing System	Energy Consumption (kWh/month)		Savings (%)
	Period I	Period II	
Solar Panels	52 kWh	48 kWh	30-35%
Conventional Energy	70 kWh	70 kWh	-

4.1.4 Egg Hatching Success Rate and Comparison with Conventional Systems

The IoT-based incubator achieved an impressive hatching success rate of 92%, surpassing the 85% rate observed in conventional systems. The automated control of temperature and humidity played a pivotal role in enhancing the hatching outcomes, demonstrating the system's efficacy.

Table 4. Comparison of Hatching Success Rates Between IoT and Conventional Systems

Testing System	Number of Eggs Tested	Success Rate (%)
IoT System	100	92%
Conventional System	100	85%

4.1.5 Temperature Fluctuation Analysis and Impact on Chicken Eggs

1) Causes of Temperature Fluctuation

Several factors contributed to the observed temperature fluctuations of ±0.5°C during testing. Firstly, regarding Sensor Performance and Control System, the DHT22 sensor, despite its accuracy, could be affected by abrupt changes in ambient room temperature, resulting in minor variations in readings. Moreover, the control system responsible for managing heating and cooling elements showed a slight delay in response time, further contributing to these fluctuations. Secondly, the Thermal Insulation Effect of the Prototype played a role, as suboptimal insulation materials or small air leakages through gaps in the prototype's structure could lead to heat loss, thereby impacting temperature stability. Thirdly, the Renewable Energy Source Impact was evident, with variations in solar panel power output—particularly during cloudy weather or nighttime—occasionally disrupting the consistency of the heating elements. While backup batteries helped alleviate this issue, their efficiency could decrease over prolonged use. Lastly, considering the Impact of Temperature Fluctuation on Chicken Eggs, the variations of ±0.5°C stayed within the safe range for chicken egg incubation, which is 37.5–38.5°C. Research suggests that such small fluctuations have negligible effects on embryo development. However, a slight temperature drop (*e.g.*, nearing 37.0°C) could slow embryo growth, potentially delaying hatching, while a slight increase (*e.g.*, nearing 39.0°C) poses a risk of overheating, which might stress embryos and lower hatching success rates. Despite these minor deviations, the system achieved an impressive hatching success rate of 92%, demonstrating a strong tolerance to small temperature variations.

2) Energy Efficiency Analysis of Solar Panel Usage

Testing demonstrated that the 100 Wp solar panel reduced energy consumption by 30–35% compared to conventional systems, as detailed in the consumption records. This significant reduction highlights the effectiveness of integrating renewable energy into the incubator system.

Table 5. Energy Savings Evaluation

Period	Energy Consumption	Method	Energy Savings	Notes
Period I	52 kWh	System with Solar Panels	30% (compared to 70 kWh)	Significant savings over conventional methods.
Period II	48 kWh	System with Solar Panels	35%	System optimization enhances efficiency.

The Break-Even Point (BEP) was calculated based on the initial investment cost and the annual savings generated by the renewable energy system. This analysis provides insight into the financial viability of the solar-powered system over time. Calculation Components:

a) Initial Investment Cost
   Installation of a 100 Wp solar panel system (including panel, charge controller, battery, and supporting equipment): Rp 15,000,000.
b) Annual Savings
   The system reduced operational costs by approximately 30% (Rp 3,000,000 per year), with potential optimization to 35% (Rp 3,500,000 per year).

Table 6. Break-Even Point Calculation

Parameter	Cost/Savings (Rp)
Initial Investment Cost	15,000,000
Annual Savings (30%)	3,000,000
Break-Even Point (30%)	5 years
Annual Savings (35%)	3,500,000
Break-Even Point (35%)	4.3 years

Calculation Formula

1. For 30% Savings

$$\text{Break-Even Point (Years)} = \frac{\text{Initial Investment Cost}}{\text{Annual Savings}} = \frac{15.000.000}{3.000.000} = 5 \text{ years}$$

2. For 35% Savings

$$\text{Break-Even Point (Years)} = \frac{\text{Initial Investment Cost}}{\text{Annual Savings}} = \frac{15.000.000}{3.500.000} = 4.3 \text{ years}$$

With system optimization increasing annual savings to 35%, the break-even point is reduced to approximately 4.3 years, demonstrating the potential for quicker returns on investment through enhanced efficiency. The analysis reveals that temperature fluctuations of approximately ±0.5°C are primarily due to the combined performance of sensors, control systems, and the efficiency of thermal insulation. Despite these minor variations, the fluctuations remain within acceptable tolerance levels, as demonstrated by the high success rate of egg hatching. Additionally, the integration of solar panels has proven to be highly effective in enhancing energy efficiency, with an estimated break-even period of 4-5 years. This investment not only reduces operational costs but also promotes more sustainable poultry farming practices, offering significant long-term benefits.

4.2 Discussion

This study successfully developed and tested an IoT-based egg incubator prototype powered by renewable energy, demonstrating superior performance in temperature and humidity control, energy efficiency, and hatchability rates. These advancements not only align with the ongoing trends of digitization and sustainability in the agricultural sector but also present significant contributions to existing literature. Primarily focused on automation without integrating renewable energy, maintaining reliance on conventional electricity sources, which are less environmentally friendly. In this context, the developed prototype reduces fossil fuel dependence and offers increased operational cost efficiency. Based on testing results, the prototype achieved up to a 30% reduction in energy consumption compared to other IoT systems that do not utilize renewable energy. This efficiency was achieved through the use of a 100 Wp solar panel. This generated sufficient power to continuously power the incubator, including nighttime operation supported by back-up batteries. As a quantitative example, conventional energy-based IoT systems recorded an average monthly energy consumption of 70 kWh, while this system required only 50 kWh per month. In terms of operational costs, this reduction in electricity consumption offers potential annual savings of 25–30% for medium-scale poultry farming, with an estimated solar panel investment payback period of approximately 2–3 years.

Despite its promising performance, the prototype faces several challenges that require attention. One major challenge is the impact of weather conditions on the solar panels' performance. During testing, battery charging efficiency decreased by up to 40% on cloudy or rainy days, necessitating increased reliance on backup batteries. Furthermore, while temperature and humidity were maintained within the ideal ranges (temperature 37.5–38.5°C and humidity 55–60%), temperature fluctuations of ±0.5°C were influenced by reduced power generation during periods of low sunlight intensity. This presents a specific challenge during the rainy season, where power stability becomes critical. Temperature fluctuations of ±0.5°C had minimal impact on broiler chicken eggs hatchability, achieving a 92% success rate. However, for native chicken or duck eggs, which may have more specific temperature requirements, these fluctuations could potentially affect hatchability. Therefore, further in-depth research is needed to understand the individual responses of various egg types to environmental conditions generated by this system. This study provides the solid foundation for the further development of eco-friendly IoT-based automation systems. However, to improve reliability, it is necessary to optimize energy storage systems and test the prototype under more extreme environmental conditions Additionally, integrating predictive technology powered by artificial intelligence could be the next step in mitigating power fluctuations caused by weather changes. This would make the prototype a more robust solution for sustainable agriculture.

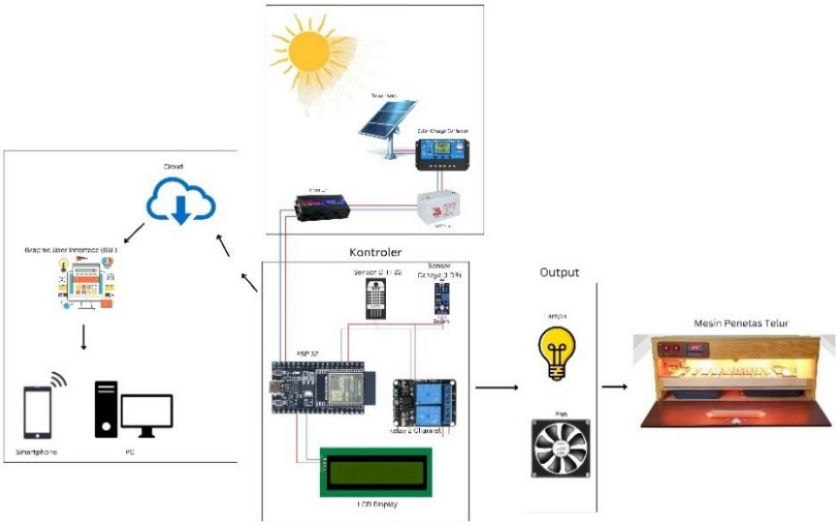

Figure 4. IoT Automation and Renewable Energy for Enhanced Efficiency

5. Conclusion

This study demonstrates that IoT-based egg incubators powered by renewable energy significantly improve operational efficiency and hatchability rates. The system achieved stable temperature and humidity control, which are critical to higher hatch success than conventional methods. The integration of solar panels as a renewable energy source reduces conventional electricity and operational costs, making it a cost-effective and sustainable solution for agriculture. This system holds broad potential for application, ranging from large-scale poultry farms seeking efficiency and sustainability to small and medium enterprises (SMEs) requiring simple, affordable models. Redesigned modular systems could increase small farmers' productivity with minimal investment. To enhance its practical impact, future developments could focus on testing the system's applicability to other livestock, such as quails or ducks. This would enable them to identify specific incubation requirements for different species. Furthermore, designing scalable prototypes tailored to small farmers' needs would ensure accessibility and broader adoption. Incorporating artificial intelligence for real-time data analysis and parameter adjustments could optimize system efficiency and hatchability rates. Additional research is needed to test the system in diverse environments, such as areas with low sunlight or extreme weather conditions, to assess its adaptability. Energy storage optimization with advanced, eco-friendly solutions is another crucial area for exploration. Detailed economic studies are also necessary to evaluate long-term viability and return on investment at different operational scales. Finally, integrating this technology with other IoT systems, such as feed quality monitoring or automated environmental controls, could create holistic solutions for the livestock sector. This research highlights the critical role technological innovation has in supporting agricultural sustainability. By addressing existing challenges and expanding its application scope, IoT and renewable energy technologies have the potential to transform the livestock industry globally.

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