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## Performance analysis of solar panel energy utilization in coffee drying applications

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**ABSTRACT**

Coffee farmers in Cimenyan Village face significant challenges in the post-harvest drying process due to high rainfall, which reduces quality and lowers income. This research aims to evaluate the performance of an IoT-based coffee-drying system powered by photovoltaic energy, using global solar atlas data. The designed system is a 2 kWp coffee dryer house, which was simulated to assess energy performance, drying efficiency, economic aspects, and environmental impact. The simulation results indicate that the photovoltaic system achieves conversion efficiencies of 80-88% under high irradiance. Drying efficiency reached 54% at an optimal temperature of 50°C, with a specific energy consumption of 0.4-0.6 kWh/kg of water evaporated, which is lower than conventional electric dryers that reach approximately 1.0 kWh/kg. From an economic standpoint, the investment payback period is estimated to be 1.5-3 years with a benefit-cost ratio of 1.4-1.5. Additionally, this system has the potential to reduce $CO_2$ emissions by 0.5-1.5 tons per year per unit. The system's ability to reduce operational costs, improve product quality, and support sustainable energy transitions in rural Indonesia. Although initial costs and limited technical skills may constrain farmer adoption, cooperative-level implementation, hybrid energy integration, and ongoing training offer promising avenues for future development.

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***ABSTRAK***

Petani kopi di Desa Cimenyan menghadapi tantangan besar dalam proses pengeringan pascapanen akibat tingginya curah hujan, yang menyebabkan penurunan kualitas dan berkurangnya pendapatan. Penelitian ini bertujuan untuk mengevaluasi kinerja sistem pengeringan kopi berbasis IoT yang didukung energi fotovltaik dengan memanfaatkan data global solar atlas. Sistem yang dirancang berupa rumah pengering kopi berkapasitas 2 kWp dan disimulasikan untuk menilai kinerja energi, efisiensi pengeringan, aspek ekonomi, serta dampak lingkungan. Hasil simulasi menunjukkan bahwa sistem fotovoltaik memiliki efisiensi konversi sebesar 80-88 % pada kondisi iradiasi tinggi. Efisiensi pengeringan mencapai 54 % pada suhu optimal 50 °C, dengan konsumsi energi spesifik sebesar 0,4-0,6 kWh/kg air yang diuapkan, lebih rendah dibandingkan pengering listrik konvensional yang mencapai sekitar 1,0 kWh/kg. Dari sisi ekonomi, periode pengembalian investasi diperkirakan 1,5-3 tahun dengan rasio manfaat-biaya sebesar 1,4-1,5. Selain itu, sistem ini berpotensi mengurangi emisi $CO_2$ sebesar 0,5-1,5 ton per tahun per unit. Kemampuan sistem dalam menekan biaya operasional ini, meningkatkan kualitas produk, serta mendukung transisi energi berkelanjutan di pedesaan Indonesia. Meskipun adopsi oleh petani dapat terkendala biaya awal dan keterampilan teknis, penerapan pada skala koperasi, integrasi energi hibrida, serta pelatihan berkelanjutan menawarkan potensi pengembangan yang menjanjikan di masa depan.

***Kata Kunci:*** *energi bersih terjangkau; fotovoltaik; Internet of Things; ketahanan ekonomi; pertanian berkelanjutan*

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## INTRODUCTION

The use of solar energy in agricultural processing has grown rapidly in recent years as a sustainable way to reduce dependence on fossil fuels, lower operating costs, and cut greenhouse gas emissions (Rizalman et al., 2023; Kimaro et al., 2024). Coffee drying, a crucial stage in post-harvest handling, remains one of the most energy-demanding processes. Conventional dryers that rely on electricity or diesel not only increase production costs but also significantly contribute to environmental impacts (Suherman et al., 2020; Mirzaei et al., 2023). The development of renewable energy-based drying technologies, therefore, plays an essential role in advancing sustainable agriculture and supporting the resilience of rural economies.

Indonesia, as the world's fourth-largest coffee producer, possesses abundant solar energy potential, particularly in highland rural areas such as Cimenyan, West Java, where coffee farming is a key source of livelihood (Silalahi et al., 2021). To harness these natural resources effectively, it is essential to conduct detailed performance assessments of photovoltaic (PV) systems under local climatic conditions. Preconstruction modeling and feasibility studies of solar energy systems have benefited from the high-resolution irradiance and photovoltaic potential information provided by the World Bank Group's Global Solar Atlas (link: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/729411496240730378/solar-resource-and-photovoltaic-potential-of-indonesia).

Previous studies have demonstrated the technical viability of solar-assisted drying. Hybrid solar dryers for coffee beans achieved collector efficiencies of up to 54%. The hybrid dryer they tested was more energy-intensive than a typical modern conventional dryer. Its primary advantages were a drastically reduced drying time compared with open sun drying (26 hours vs. 7-10 days) and improved bean quality, rather than superior energy efficiency compared with conventional mechanical dryers (Suherman et al., 2020). Hybrid solar dryers with enhanced thermal management strategies could reduce operational costs and achieve payback periods of as little as 2 years (Suherman et al., 2024; Jha & Tripathy, 2021). Complementary reviews also emphasized that solar dryer technologies have advanced rapidly between 2016 and 2023, with improvements in efficiency, energy management, and integration of digital tools such as IoT (Saini et al., 2024). Despite these advances, the integration of Internet of Things (IoT) enabled monitoring and control with Global Solar Atlas-based performance simulation in the Indonesian coffee sector has rarely been investigated.

The performance of photovoltaic-powered drying systems is commonly evaluated using indicators such as PV efficiency, specific energy consumption, payback period, and benefit-cost ratio. These parameters are widely applied in solar drying research to assess technical performance, energy demand, and economic feasibility (Suherman et al., 2020). In this study, these indicators were used to quantify the energy savings, financial viability, and environmental benefits of an IoT-enabled solar-powered coffee-drying system.

IoT technology offers distinct advantages in agricultural drying systems by enabling real-time monitoring of temperature, humidity, and solar irradiance, as well as automated control of fans and heating elements to maintain optimal drying conditions (Dhonde et al., 2022; Suprianto et al., 2022). Previous studies have shown that IoT-enabled dryers can improve product quality, reduce energy waste, and enable predictive control using weather data. For example, another study demonstrated improved drying stability and reduced energy loss in a hybrid solar dryer employing a Proportional-Integral-Derivative (PID) control technique (Arifin et al., 2024). Similarly, a study developed an IoT-enabled innovative greenhouse coffee dryer with fuzzy control that improved drying uniformity while reducing energy consumption (Suprianto et al., 2022). However, most applications remain confined to experimental prototypes rather than integrated performance modeling using site-specific resource data.

The novelty of this study lies in combining high-resolution solar resource data from the Global Solar Atlas with IoT-based control strategies to design a replicable and sustainable coffee drying system for rural Indonesia. By linking digital monitoring with site-specific solar energy simulations, the framework provides a more reliable basis for decision-making in both technical and economic dimensions. Compared with studies of rural solar-assisted drying


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reported in the literature, the proposed coffee dryer exhibits notably improved conversion and operational performance. Published hybrid solar dryer experiments commonly report solar collector efficiencies near 32-46% for 40 60°C for Arabica and Robusta coffee types and payback periods on the order of 1-2.5 years (Suherman et al., 2024). Systematic reviews also document widespread socioeconomic benefits and measurable $CO_2$ mitigation potential from solar dryers in smallholder settings, while highlighting variability in technical performance across regions. Therefore, this study aimed to evaluate the performance of a proposed IoT-based coffee drying system in Cimenyan Village by simulating photovoltaic output and drying efficiency using Global Solar Atlas data. The analysis focused on specific energy consumption, economic feasibility assessed by the payback period and benefit-cost ratio, and $CO_2$ mitigation potential. The projected performance was compared with that of conventional dryers to demonstrate the advantages of integrating renewable energy in rural postharvest processing. In line with the Sustainable Development Goals, the study advances the larger agenda of Sustainable Agriculture, Economic Resilience, and Affordable and Clean Energy by tackling these goals.

## Literature Review

### Solar Energy Systems for Agricultural Drying

The proposed system consists of a monocrystalline photovoltaic (PV) array with a maximum capacity of 2 kWp. The panels are oriented northward (0° azimuth) and tilted at 15°, which represents the optimal configuration for maximizing solar energy absorption in southern hemisphere locations (Soulayman & Sabbagh, 2015). This PV array supplies power to a coffee drying house that operates under an Internet of Things (IoT) control framework. The drying chamber includes key components, including an axial fan for air circulation, a backup electric heater to maintain a stable temperature, and temperature and humidity sensors for continuous, real-time monitoring. For performance comparison, data from a conventional electric coffee dryer of similar capacity, powered by the State Electricity Company (PLN), were used as a benchmark.

Solar drying technologies have been widely explored as sustainable alternatives to conventional drying methods in agriculture. Solar energy provides a clean, low-cost heat source that can enhance product quality while reducing postharvest losses. Solar-assisted drying systems improve energy efficiency and temperature uniformity in food drying applications (Thirunavukkarasu et al., 2023). Solar dryers can significantly reduce drying time and improve product quality through controlled thermal environments (Nematchoua et al., 2021). In the broader context of agriculture, various studies have examined solar drying configurations, including cabinet dryers, greenhouse dryers, and hybrid systems, consistently demonstrating their advantages over traditional open-air solar drying. These studies provide a comprehensive overview of solar drying devices, highlighting improved heat transfer, controlled air movement, and space design that contribute to better drying uniformity and humidity control (Fernandes & Tavares, 2024). Similarly, another study emphasizes that hybrid solar dryers and greenhouse-type dryers provide greater protection against contamination and environmental variability, thereby maintaining higher hygiene standards and improving product quality (Etim et al., 2024). Comparative analyses in other studies confirm that solar tunnel dryers and greenhouse dryers outperform open drying by reducing spoilage, improving consistency, and minimizing post-harvest losses (Agarwal et al., 2024). Collectively, these findings underscore that solar thermal systems not only enhance drying efficiency but also address critical issues of hygiene, consistency, and moisture control in agricultural applications.

### Photovoltaic (PV) Performance, Orientation, and Environmental Influences

The performance of photovoltaic modules is strongly influenced by array orientation, tilt angle, and environmental conditions. Northward orientation with moderate tilt angles maximizes solar absorption at southern-hemisphere sites, aligning with the system design proposed in this study (Soulayman & Sabbagh, 2015). Multiple studies have quantified the effects of temperature on PV performance. PV module efficiency is strongly influenced by operating


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temperature, with higher cell temperatures reducing performance and necessitating ventilation strategies in agricultural installations. PV system efficiency in tropical climates was examined, and it was confirmed that temperature rise significantly reduces conversion efficiency, underscoring the importance of cooling and airflow management (Eze et al., 2024). Southeast Asia, with its relatively consistent irradiance, is well suited to the deployment of photovoltaic (PV) solar panels in agricultural contexts, although environmental heat remains a challenge (Rozak et al., 2023). Building on these findings, another study analyzed solar panel performance in equatorial Indonesia and reported that humidity and cloud cover can reduce energy output by up to 18%, underscoring the need for continuous monitoring and adaptive strategies in agro-industrial PV applications (Susanto et al., 2022). Collectively, these studies demonstrate both the promise and the climatic constraints of PV-powered agriculture in tropical regions

**Solar Powered Dryers and Hybrid Photovoltaic-Thermal Applications**

Hybrid photovoltaic thermal systems are increasingly recognized for their dual capacity to generate electricity and thermal energy, making them suitable for agricultural applications. The potential for integrating thermal photovoltaic systems with agricultural processing units, including dryers and greenhouse structures (Samykano, 2023). In drying applications, forced-convection dryers powered by thermal photovoltaic systems achieve faster and more uniform drying rates than natural-convection systems, thereby increasing efficiency in agricultural product storage (Chouikhi & Amer, 2023). A study on coffee reports that hybrid solar dryers reduce water content more consistently and lower operational costs for small-scale coffee farmers (Duque-Dussán et al., 2023). Collectively, these findings underscore the growing role of hybrid PV and solar drying systems in advancing sustainable agro-industrial practices.

**Energy Efficiency Metrics and Thermal Performance Indicators**

Energy performance evaluation is a critical aspect of the design of solar drying systems, with Specific Energy Consumption (SEC) widely used as the primary metric of the energy required to remove 1 kg of moisture. Lower SEC values correlate with higher energy efficiency in greenhouse dryers for agricultural products (Desa et al., 2021). Complementary indicators such as thermal efficiency and collector efficiency have also been emphasized. Solar drying systems show that selective absorber coatings and optimized channel geometry significantly improve heat capture (Sandali et al., 2019). Additionally, real-time monitoring systems with IoT-based sensors can track fluctuations in temperature, humidity, and light intensity, helping to maintain efficient energy use in solar drying facilities (Hidayat et al., 2024). Collectively, these metrics provide a robust foundation for evaluating the performance of PV-powered dryers in operational agricultural settings.

**Solar Applications for Coffee Processing and Quality Preservation**

Solar technology is increasingly being applied in the post-harvest process of coffee. Recent studies show that controlled solar-drying environments can preserve aromatic compounds and reduce fungal contamination compared with drying under open sunlight. Drying methods significantly affect the physicochemical, sensory, and microbiological quality of coffee, with solar dryers improving safety and flavor retention (Abreu et al., 2025). Optimized solar dryers improve uniformity of moisture content and reduce labor requirements in tropical regions (Meja et al., 2025). The integration of solar energy can shorten drying duration while improving product quality (Sharma et al., 2009). Collectively, these studies suggest that coupling photovoltaics with solar drying chambers offers a high-value opportunity for quality improvement and cost reduction in coffee production chains


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# METHODS

This study simulated the operation of an IoT-based solar-powered coffee drying system under environmental conditions representative of Cimenyan Village, West Java, Indonesia (6.8799° S, 107.6638° E; 835 m elevation), a major coffee-producing area with high solar potential (1,729 kWh/m²/year). The system employs a 2 kWp monocrystalline PV array oriented northward (0° azimuth) and tilted at 15°, which is considered optimal for maximizing solar capture in southern hemisphere locations. The PV array supplies electricity to a drying chamber equipped with an axial fan, a backup electric heater, and temperature-humidity sensors, all controlled by an IoT framework. The performance of this system was compared with that of a conventional PLN-powered electric dryer of similar capacity.

Solar radiation data were obtained from the Global Solar Atlas, which provides long-term monthly and hourly datasets suitable for locations where pyranometer measurements are unavailable. Duffie et al., in the book titled "*Solar Engineering Of Thermal Processes, Photovoltaics And Wind*," explain that hourly clear-sky profiles were statistically filtered to reduce cloud variability and provide realistic PV input conditions. System performance was then evaluated through photovoltaic (PV) conversion efficiency and drying efficiency. PV efficiency (ηpv) was calculated as the ratio of DC output power (Pout) to the incident plane of array irradiance multiplied by panel area (A):

$$\eta pv = \frac{P_{out}}{G_{POA} \times A} \times 100\%$$

Drying efficiency (ηEfficiency) was determined by comparing the latent heat required to evaporate water from the coffee beans with the total electrical energy consumed at an operating temperature of 50 °C. Here, $m_w$ is the mass of water removed (kg), $h_{fg}$ Is the latent heat of vaporization (≈ 2,260 kJ/kg), and $E_{total}$ is the total energy input (kJ):

$$\eta_{Efficiency} = \frac{mw \times hfg}{E_{total}} \times 100\%$$

Mujumdar, in the book titled "*Handbook of Industrial Drying*" states that energy performance was further quantified using Specific Energy Consumption (SEC), which represents the energy required to remove 1 kilogram of water from the beans. This study compared SEC values between the IoT-based solar dryer and the conventional dryer:

$$Specific\ Energy\ Consumption = \frac{Mass\ of\ Water\ Removed\ (kg)}{Total\ Konsumsi\ Energi\ (kWh)}$$

Economic performance was assessed through the Payback Period and Benefit-Cost Ratio (BCR), which serve as quantitative indicators of financial feasibility. The Payback Period was calculated as:

$$Payback\ Period\ = \frac{Initial\ Investment}{Annual\ Energy\ Savings}$$

Based on information from the International Energy Agency (IEA) in 2020, the Benefit-Cost Ratio (BCR) assumes a system lifespan of 25 years and a discount rate that reflects local economic conditions (link access: *https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec-2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf*). Where n is the project duration (years), r is the discount rate, $C_t$ is the cost in year t, and $B_t$ represents the benefit in year t. A benefit-to-cost ratio greater than 1.0 indicates that the project is economically viable and yields a positive return on investment.

$$BCR = \frac{\sum_{t=1}^{n} \frac{Bt}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Ct}{(1+r)^t}}$$

The environmental benefits of the proposed system were assessed through the potential reduction in greenhouse gas emissions. Based on information from the Ministry of Energy and Mineral Resources in 2019, the annual reduction in $CO_2$ emissions is estimated by multiplying the total electricity generated by the photovoltaic (PV) system by the



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emission factor of Indonesia's national electricity grid, which is 0.85 kg $CO_2$/kWh (link acces: https://gatrik.esdm.go.id/assets/uploads/download_index/files/96d7c-nilai-fe-grk-sistem-ketenagalistrikan-tahun-2019.pdf). This indicator reflects the project's contribution to climate action (SDG 13) by quantifying its ability to offset fossil fuel based electricity consumption. The equation for determining the $CO_2$ emission reduction is as follows:

$$CO_2\ Emission\ Reduction = Annual\ PV\ Energy\ (kWh) \times Emission\ Factor\ (kg\ CO_2/kWh)$$

To evaluate robustness under varying installation conditions, a sensitivity analysis was conducted by varying azimuth and tilt by ±15° and ±10°, respectively, relative to the baseline configuration. Additional scenarios included ±10% annual irradiance and ±5 °C variations in ambient temperature. Irradiance for each scenario was modeled using a standard transposition approach to compute plane-of-array values. Changes in PV yield were then reassessed for their effects on SEC, Payback Period, and $CO_2$ reduction, allowing a comprehensive evaluation of system stability under practical installation variabilities. Field validation with local coffee farmer cooperatives is planned as future work.

## RESULTS AND DISCUSSION

### Photovoltaic Performance

According to Cimenyan Village's modeling results, the 2 kWp PV system produced an average annual output of approximately 2,900-3,200 kWh, consistent with Global Solar Atlas estimates for West Java. Under clear-sky conditions, the PV collector efficiency ranged from 80% to 88%, as shown in **Figure 1.** Seasonal variation was observed, with efficiency declining during the rainy months due to lower irradiance and intermittent cloud cover. However, the IoT system compensated for fluctuations by dynamically regulating fan speed and auxiliary heater operation to maintain stable drying conditions.

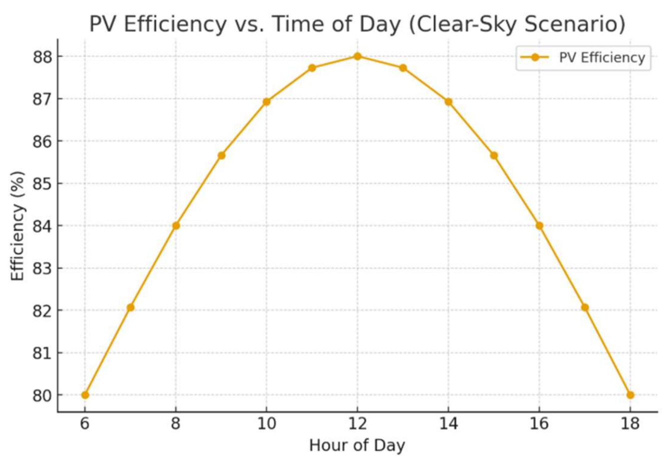


**Figure 1.** Photovoltaic Performance
*Source: Global Solar Atlas data processed through the author's simulation.*

### Drying Efficiency

The drying house achieved an efficiency of approximately **54%** at the optimal setpoint of 50 °C. The IoT-based monitoring system enhanced process stability by preventing overheating or under-drying, both of which are common in traditional sun drying



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**Specific Energy Consumption**

The IoT PV drier used between 0.40 and 0.60 kWh of energy per kilogram of water removed, as shown in Figure 2, oT-PV results (blue) vs. Conventional system (gray), which was significantly lower than the ~1.0 kWh/kg recorded for the benchmark grid-powered dryer. The lower Specific Energy Consumption implied not only reduced operational costs but also higher energy efficiency, contributing to improved profitability for smallholder farmers.

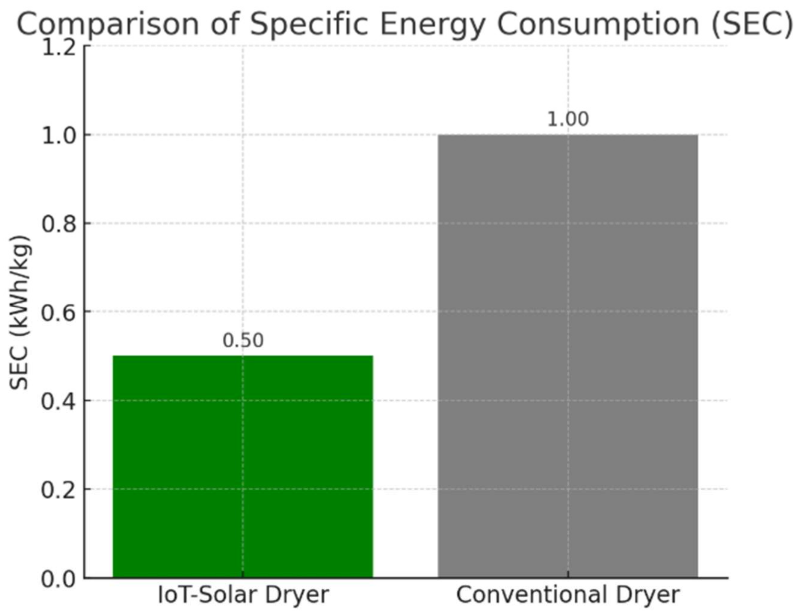


**Figure 2.** Comparison of Specific Energy Consumption between IoT-PV Dryer and Conventional Electric Dryer
*Source: Global Solar Atlas data processed through the author's simulation.*

**Economic Performance**

The system's payback period was 1.5-3 years, according to an economic study, depending on assumptions of electricity tariffs and PV system capital costs. The Benefit Cost Ratio was calculated in the range of 1.4-1.5**,** indicating financial feasibility. These findings demonstrate that solar-powered drying could be a viable investment for smallholder farmers, particularly when supported by cooperative ownership or microfinance schemes.

**Carbon Emission Reduction**

Based on Indonesia's grid emission factor (0.85 kg $CO_2$/kWh), the system reduced annual emissions by approximately 0.5-1.5 tonnes of $CO_2$ per unit. This reduction was proportional to the displacement of grid electricity and was consistent with carbon savings reported for other agro processing solar PV projects in tropical regions. These findings highlighted the system's compliance with Sustainable Development Goal (SDG) 13 (Climate Action).

**Sensitivity to Panel Orientation**

The sensitivity analysis showed that deviations in panel orientation significantly affected annual PV energy yield. A tilt variation of ±10° resulted in an energy change of −4% to +3%, while azimuth shifts of ±15° reduced output by up to 6%. However, the overall impact on *Specific Energy Consumption* and payback period remained within ±7%, demonstrating that the system was robust to moderate installation errors. This flexibility is critical in rural deployments where installation precision may be limited.


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**Discussion**

The integration of IoT-based control with site-specific solar resource data demonstrated substantial advantages over conventional dryers. Energy efficiency improved by more than 40%, operating costs decreased through reduced Specific Energy Consumption, and the system yielded tangible climate benefits through carbon mitigation. The novelty of this study lies in applying Global Solar Atlas datasets for system performance modeling and integrating them with IoT predictive control. This approach has been rarely investigated in the Indonesian coffee sector. Previous studies have reported improvements in thermal efficiency and product quality using solar drying technologies, yet most relied on static configurations or lacked adaptive controls. For example, fixed-tilt PV-powered dryers improved energy utilization but did not address temporal variability in solar irradiance (Elwakeel et al., 2025). Similarly, conventional passive and hybrid solar dryers achieved meaningful yet limited efficiency gains compared to mechanical drying (Rana et al., 2024). Studies on coffee drying have reported improved bean quality but still rely on manual operations and non-optimized airflow or thermal profiles (Abreu et al., 2025). In contrast, the present system's IoT-driven real-time optimization enabled dynamic regulation of airflow and heating based on solar potential forecasts, addressing key limitations identified in earlier research. This study, therefore, extends the body of knowledge by demonstrating that predictive solar data integration and automated control can significantly outperform prior solar-based coffee-drying configurations across both energy and quality metrics. The novelty of this study lies in applying Global Solar Atlas datasets for system performance modeling and combining them with IoT predictive control, a framework rarely investigated in the Indonesian coffee sector, and the performance summary is shown in **Table 1**.

**Table 1**. Performance Summary IoT PV dryer

| Parameter | IoT-Solar Dryer | Conventional Electric Dryer |
|---|---|---|
| **PV Efficiency (%)** | 80-88 | N.A |
| **Drying Efficiency (%)** | ≈54 | 50-54 |
| **Specific Energy Consumption (kWh/kg)** | 0.40-0.60 | 0.99 - 2.57 |
| **Payback Period (years)** | 1.5-3.0 | N.A |
| **Benefit-Cost Ratio (BCR)** | 1.4-1.5 | N.A |
| **$CO_2$ Savings (tonnes/year)** | 0.5-1.5 | N.A |

N.A: Not Available
*Source: Global Solar Atlas data processed through the author's simulation.*

These results confirmed that solar-powered IoT dryers could enhance product quality**,** reduce dependency on fossil fuels, and strengthen rural economic resilience. The results demonstrated their potential as scalable solutions for sustainable agro-processing in low-income countries and aligned with SDGs 7 (Affordable and Clean Energy), 12 (Responsible Consumption and Production), and 13 (Climate Action).

The implementation of a PV-based IoT coffee-drying system was not without technical and non-technical challenges. One of the main constraints was the relatively high capital expenditure (CAPEX). Despite favorable payback periods, adoption barriers, including upfront costs, limited access to financing, and a lack of technical training, remain significant challenges. Incentives such as green microloans, cooperative-based investments, and government subsidies could accelerate adoption. The system's scalability also depends on regional solar potential; simulations for lower-irradiance regions indicate up to a 10% reduction in efficiency, which remains within feasible operational thresholds. Furthermore, strong policy support for clean energy transition and the availability of green financing mechanisms presented additional opportunities for broader adoption of this technology in rural contexts.


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## CONCLUSION

This study evaluated the performance of a PV-powered, IoT-based coffee-drying system in Cimenyan Village. By integrating Global Solar Atlas data with IoT-controlled monitoring, the system demonstrated high conversion efficiency, effective drying performance, and a substantial reduction in specific energy consumption compared with conventional dryers. The economic analysis indicated that investment in the system is viable, with a relatively short payback period and favorable benefit-cost outcomes. In addition, the system demonstrated substantial environmental benefits by reducing carbon emissions per unit. The findings confirm that solar PV IoT coffee dryers not only enhance post-harvest processing efficiency and product quality but also contribute to national clean energy transitions and climate action goals. Future implementation should emphasize scalability through cooperative-level adoption, integration with hybrid energy sources, and sustained farmer training to ensure long-term impact and resilience.

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