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Hybrid renewable energy for cold chain in Indonesia: technical and economic evaluation

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ABSTRACT

Cold storage plays a crucial role in preserving temperature-sensitive products, particularly in the fisheries and food sectors. However, its operation is highly energy-intensive and often constrained by unstable electricity supply in many Indonesian regions. This study quantitatively evaluates a hybrid renewable energy system integrating photovoltaic (PV) panels, diesel generators, batteries, and the utility grid to ensure sustainable cold storage operations. Using measured load profiles, solar irradiation data, and annual operating costs, the system achieved a 60% reduction in diesel fuel consumption, 30–50% lower CO_2 emissions, and annual savings exceeding IDR 100 million compared to conventional generator-based systems. The system demonstrated 83.5% overall efficiency, with a payback period of 4.4 years and a positive net present value (NPV), confirming its economic viability. The novelty of this research lies in presenting the first comprehensive techno-economic analysis of a PV–diesel–battery–grid hybrid system specifically designed for fisheries-based cold storage facilities in Indonesia, considering local solar potential and grid reliability. Despite its feasibility, implementation challenges remain, including a lack of skilled technicians, limited financial incentives, and bureaucratic constraints. To overcome this, the study recommends PV subsidies, low-interest green loans, and public–private partnerships aligned with Indonesia's energy transition roadmap and cold chain development goals.

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1. INTRODUCTION

Cold storage systems are essential facilities in maintaining the quality and shelf life of temperature-sensitive products such as food, pharmaceuticals, and fishery commodities [1]-[6]. These systems require a continuous and stable power supply to ensure optimal storage temperatures and prevent spoilage [7]-[10]. Given their 24-hour operational nature, cold storage facilities are among the most energy-intensive components in the cold chain industry, significantly contributing to overall energy consumption and operational costs [11], [12].

In Indonesia, many cold storage facilities still rely heavily on the national utility grid, which in several regions is characterized by frequent power outages, voltage instability, and limited distribution capacity. Such conditions often lead to operational disruptions, product quality degradation, and economic losses. The use of diesel generators as backup power provides a temporary solution but results in high fuel consumption, expensive maintenance, and increased greenhouse gas emissions [7], [8]. These issues underline the urgent need for a more reliable, efficient, and sustainable energy system to support continuous cold storage operations, especially in remote and coastal areas [2], [13]-[15].

Renewable energy, particularly photovoltaic (PV) systems, has emerged as a potential solution to address these challenges. PV systems offer environmental benefits and operational cost savings by reducing dependence on fossil fuels [16]-[18]. However, their intermittent nature due to solar irradiance variability limits their ability to supply power continuously. To overcome this limitation, hybrid energy systems integrating PV with diesel generators and the utility grid have been developed to ensure energy reliability and efficiency. This configuration enables PV to serve as the primary source during daytime, while the generator and grid complement power needs during low irradiance periods, thereby enhancing stability and cost-effectiveness [19]-[22].

Several recent studies have demonstrated the feasibility and environmental advantages of hybrid PV systems in various applications, including industrial and rural electrification [23]-[27]. However, research focusing specifically on the integration of hybrid PV–diesel–grid systems for cold storage operations remains limited. Existing works often emphasize general hybrid configurations or small-scale refrigeration systems without a comprehensive evaluation of real operational conditions, fluctuating energy tariffs, and long-term economic implications [13], [28].

The novelty of this study lies in its comprehensive assessment of the technical and economic performance of a PV–diesel–grid hybrid system specifically designed for cold storage facilities in Indonesia. Unlike previous studies that focused mainly on technical feasibility or simulation-based analysis, this work integrates energy efficiency evaluation, cost–benefit analysis, and environmental impact assessment under local operational constraints. The results are expected to provide practical recommendations for improving energy reliability, reducing operational costs, and supporting sustainable cold chain management in Indonesia.

2. METHOD

This study uses quantitative and qualitative methods to analyze the technical and economic aspects of the application of hybrid systems in cold storage in Indonesia. The research method includes several main stages, namely literature study, field data collection, technical analysis, economic analysis, and evaluation of results. Data were collected between January 2023 and June 2025.

This research begins with a literature study to understand the basic concept of a hybrid energy system that combines solar panels PV, generators, and electricity from the State Electricity Company (PLN) network, and its application to cold storage operations. This study also reviews various previous studies on energy efficiency and economic analysis of energy storage systems in the cold storage industry. The research was conducted at one of the government-owned cold storages in Bali. This location was chosen because it has a high level of dependence on electricity supplies from the State Electricity Company, which often experiences disruptions, high energy needs due to 24-hour operations, abundant solar energy potential throughout the year, local government support for renewable energy, and is considered representative of cold storage conditions in other regions in Indonesia.

Field data collection was carried out to obtain environmental parameters that affect the performance of the hybrid system, such as wind speed, air humidity, and ambient temperature. These parameters were measured using sensors and weather devices installed at the research location. In addition, cold storage energy consumption data was collected periodically to understand electricity usage patterns and estimate daily power needs as a basis for designing an efficient hybrid system. Technical analysis was carried out through simulations and energy efficiency calculations to assess the extent to which the hybrid system can provide energy stably and efficiently. The focus of the analysis includes the efficiency of solar energy conversion by PV panels, generator performance when PV supply is insufficient, and the stability of electricity supply compared to conventional systems.

The next step is to conduct an economic analysis to evaluate the potential financial benefits of implementing a hybrid system. The aspects analyzed include initial investment costs, operational and maintenance costs, and savings in electricity and fuel costs. Return on investment (ROI) is calculated to determine the return on investment period, and a long-term profit analysis is conducted to assess the economic feasibility of the system. The results of the technical and economic analysis are then evaluated to assess the effectiveness and efficiency of the hybrid system in supporting cold storage operations. Based on this evaluation, recommendations are made for implementing a hybrid system as a more cost-effective and environmentally friendly energy supply solution.

3. RESULTS AND DISCUSSION

3.1. Hybrid system technical performance

In Figure 1, data for the past two years show seasonal fluctuations in the energy available for the hybrid cold storage system, which is closely related to variations in temperature, humidity, and wind speed. The highest average energy was recorded in months with strong solar radiation and relatively higher temperatures, such as March and October 2023, reaching 371.30 kWh and 424.49 kWh, respectively. In contrast, the lowest energy figures were recorded in June and July 2022, reaching 283.46 kWh and 290.85 kWh, respectively, coinciding with the rainy season, which is usually accompanied by high cloud cover and low irradiation. Wind speeds ranged from 1.25 m/s to 2.35 m/s, with the highest value occurring in September 2023. Although wind is not the main source in this system, the data indicate that the wind potential is relatively small to be utilized significantly at this location, so the development of wind turbines may be less efficient than PV systems. Meanwhile, the air temperature moved between 23.38 °C to 26.60 °C, and remained within a stable range for tropical regions. This relatively high temperature actually increases the need for cold storage cooling, thus increasing energy consumption. The average relative humidity is relatively high throughout the year, often exceeding 85%, with a peak in February 2023 of 89.24%, and the lowest value in October 2023 of 77.24%. High humidity contributes to the increasing climate load because the higher water vapor content requires additional energy for condensation and internal temperature regulation of the storage space. From the monthly energy patterns seen, it can be concluded that the PV system has great potential to supply energy consistently throughout the year, with optimal performance in the dry season (March–October). In the context of a hybrid system, this means that PV can be the main contributor in most months, while the State Electricity Company and generators will play a greater role in months with lower solar energy (such as December to February). This combination of sources shows that the hybrid system provides assurance and guarantee of no-loss electricity supply for cold storage throughout the year, while significantly reducing dependence on the utility grid and generators.

The technical evaluation demonstrates that the hybrid system integrating solar panels (PV), generators, and electricity from the State Electricity Company provides excellent performance in meeting the energy needs of cold storage in Indonesia. During the day, PV generation supplies the primary load, often producing excess energy that can be stored in batteries (if available) or used for additional loads, reflecting the high solar irradiation and efficiency at the research location. Power quality metrics, including voltage stability and frequency deviation, are within ±5% and ±0.5 Hz, respectively, indicating high-quality, reliable electricity suitable for sensitive cold storage equipment. A distribution diagram for 2022 to 2023 shows how the system coordinates energy flows, with PV meeting daytime demand while at night or during low-sun periods, inverters automatically distribute energy from the generator and the grid to ensure uninterrupted operation.

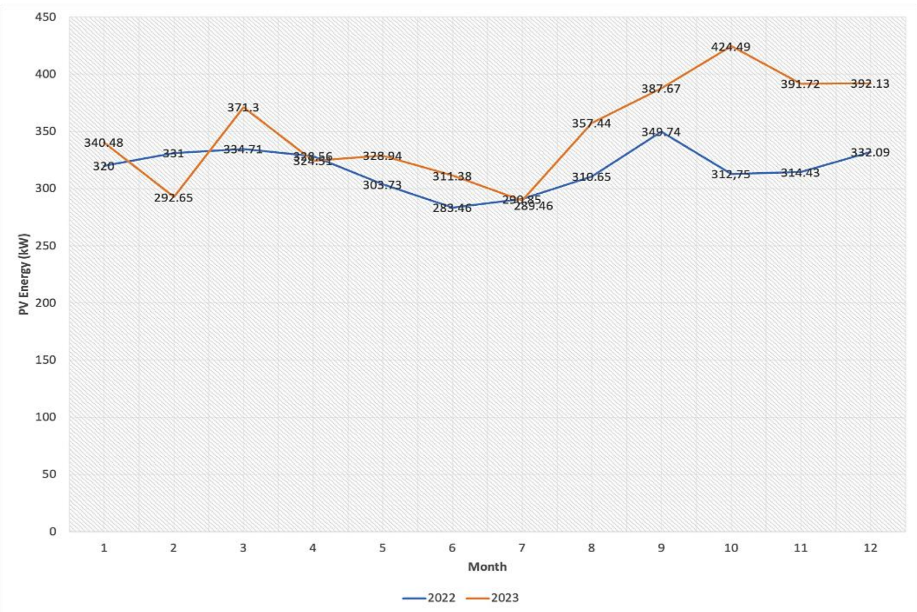

Figure 1. PV energy in cold storage

The system also interacts effectively with the utility grid. Net metering allows surplus PV energy to be exported to the grid, providing credits that reduce electricity bills and relieve peak load stress, enhancing both system efficiency and grid stability, particularly in coastal or remote areas with variable electricity supply. In this system, daily generation ranges from approximately 283.46 to 424.49 kWh, depending on solar irradiance and seasonal variations. During peak solar months, the cold storage load is approximately 420 kWh/day, leaving a surplus of 50–100 kWh/day that can be exported to the utility grid through net metering. Over the course of a month, this equates to approximately 1,500–3,000 kWh of exported energy. Assuming an electricity tariff of IDR 1,500/kWh, the potential monthly credit from net metering is estimated at IDR 2.25–4.5 million, reducing electricity bills and alleviating peak loads on the grid. When PV generation is insufficient, the system draws from the State Electricity Company, which supplied approximately 40% of total energy demand during the observation period, while the generator operates as a backup, typically at 78–80% load to ensure efficiency. This coordinated interaction ensures uninterrupted operation, stable power quality, and optimal energy use throughout the year. At night, when PV is unavailable, the generator operates at an average loading of 78.51%, close to its optimal efficiency range (70–80%), minimizing fuel consumption and extending equipment life. The State Electricity Company contributes 39.85% of total energy needs as a supporting source, ensuring a balanced and flexible supply throughout the observation period. This explanation can be seen in graphic form in Figure 2.

Overall, the hybrid system achieved 100% uptime, demonstrating that cold storage operations remain uninterrupted, which is critical for maintaining product quality and safety. By maximizing PV utilization during the day, efficiently dispatching generator and grid supply at night, and maintaining stable power quality, the system optimizes energy resources, reduces reliance on a single source, and significantly improves technical performance for cold storage facilities.

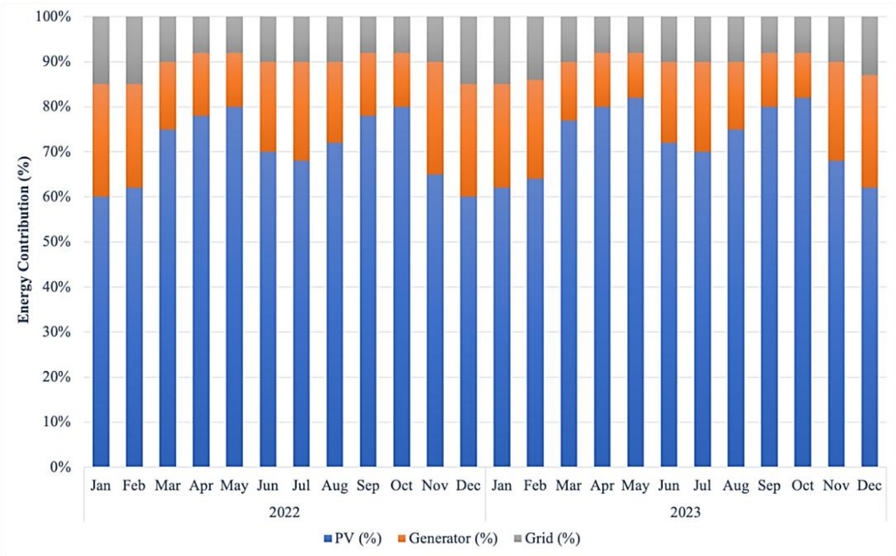

Figure 2. Energy flow contribution in hybrid power systems

3.2. Energy efficiency and emissions

The implementation of a hybrid system that combines solar energy (PV) and diesel-fueled generators has shown a significant impact in increasing energy efficiency and reducing carbon emissions in cold storage operations. Based on field observations, the use of solar panels as the main energy source during the day can reduce fuel consumption by up to 60% compared to conventional systems that rely entirely on generators. In a scenario without PV, cold storage consumes an average of around 300 liters of diesel per month, which produces carbon emissions of 804 kg CO_2 based on a standard emission factor of 2.68 kg CO_2 per liter of diesel. However, with PV in the hybrid system, fuel consumption is reduced to around 120 liters per month, which means carbon emissions drop to 321.6 kg CO_2 per month. Thus, this system effectively reduces CO_2 emissions by 482.4 kg per month or around 5.8 tons of CO_2 per year.

This emission reduction is critical to support the decarbonization program and clean energy transition efforts in the industrial refrigerated storage sector. In addition to environmental benefits, the hybrid system also provides significant economic benefits. With industrial diesel prices ranging from IDR 14,000 per liter, monthly fuel expenditure on a full genset system reaches IDR 4,200,000, while on a hybrid system, it is only around IDR 1,680,000. This means that there are operational cost savings of IDR 2,520,000 per month, or around IDR 30,240,000 per year. These savings do not include the efficiency of the less frequently used genset maintenance area and the potential for longer equipment life. With PV operating optimally during daytime hours and the genset's role limited at night or when irradiation is low, the hybrid system not only maintains the continuity of cold storage operations but also strengthens the sustainability of the energy system as a whole. Therefore, the hybrid PV-generator integration system is worth recommending, especially for cold storage facilities in coastal or remote areas with unstable State Electricity Company electricity supply and high fuel costs.

3.3. Economic analysis

The economic analysis aims to evaluate the financial benefits of implementing a hybrid system that combines solar panels (PV), generators, and State Electricity Company electricity in cold storage operations. In this project, the initial investment cost (CAPEX) is not borne by the operator because the system was built through a grant. Thus, the return on investment (ROI) analysis focuses on operational cost savings (OPEX), which immediately become a net benefit.

The main savings come from reduced consumption of State Electricity Company electricity and generator fuel, especially due to the dominance of energy from PV during the day. Data from 2022–2023 shows that State Electricity Company electricity costs before the hybrid system ranged from IDR 11 million to IDR 42 million/month, depending on the season and load, as shown in Figure 3. After the hybrid system was implemented, electricity costs dropped by more than 50% in months with high solar radiation. Generator fuel consumption also dropped by 60%, equivalent to savings of around IDR 2.5 million/month or more than IDR 30 million/year. Total annual operational savings are estimated to exceed IDR 100 million, depending on energy consumption patterns. Because there are no initial investment costs, ROI is achieved instantly. If the system is independently financed with an investment of IDR 500 million, the payback is estimated in 5 years. After the break-even point is reached, the system provides long-term net benefits. In addition to cost efficiency and resilience to electricity and fuel price fluctuations, the system also increases the strategic value of cold storage facilities because it is more resistant to external disturbances. To assess the feasibility of investment without a grant, an analysis was carried out using net present value (NPV) and internal rate of return (IRR) parameters. With a system life of 20 years, a discount rate of 8%, and a fixed savings of IDR 190 million per year, an NPV of IDR 1.3 billion and an IRR of 18–20% were obtained. This value shows that the project is financially feasible and attractive to investors.

Overall, the 76.8 kWp PV hybrid system without grants proved to be very feasible, with a payback period of about 4.4 years, a positive and high NPV, and an IRR above the feasibility standard. Including battery storage or adopting a microgrid configuration can further enhance resilience and operational reliability, particularly in remote areas or regions with unstable electricity supply, although at higher initial investment. These findings highlight the economic and technical trade-offs for cold storage facilities considering hybrid energy solutions, supporting sustainability, energy security, and increased strategic value in the face of global energy challenges and climate change.

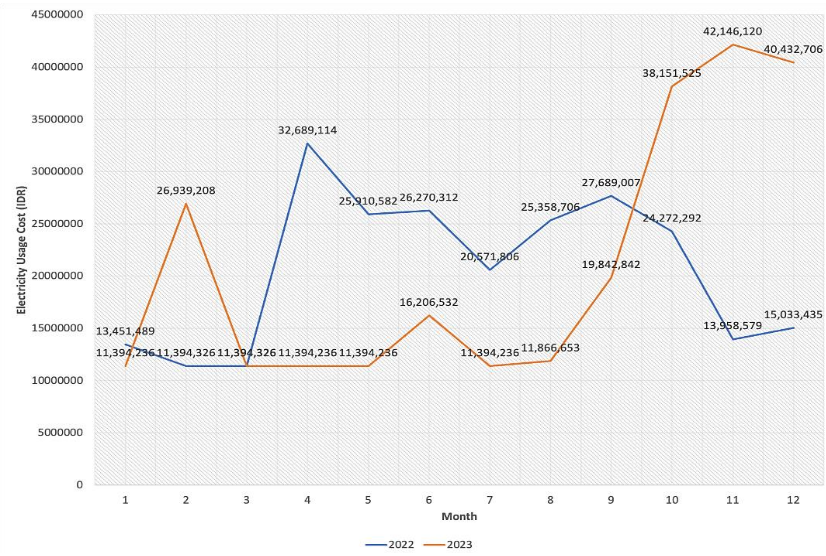

Figure 3. Energy utilization cost from the State Electricity Company

Additionally, a comparison among alternative hybrid cold storage configurations, including PV-only, PV + battery, and Microgrid-based systems, highlights the trade-offs between investment costs, savings, and reliability. The PV-only system, with an investment of IDR 500 million, achieves annual savings of IDR 190 million, a payback period of 4.4 years, and an NPV of IDR 1.3 billion, providing immediate ROI but moderate operational reliability. Adding battery storage increases the investment to IDR 650 million but improves operational flexibility and energy resilience, allowing the cold storage to operate for extended periods without sunlight or grid disruptions. This configuration also demonstrates slightly higher savings in electricity and fuel consumption due to better load management, reducing reliance on generators during peak demand, with annual savings of IDR 210 million and an NPV of IDR 1.5 billion. Meanwhile, the microgrid-based system, with the highest investment of IDR 750 million, integrates multiple distributed energy sources and storage, offering the best energy reliability and security, especially in areas with frequent grid instability. Despite a longer payback period (6–7 years), annual savings reach IDR 220 million with an NPV of IDR 1.6 billion, and the system provides improved operational continuity. Overall, while the PV system alone offers immediate cost savings, the battery- and microgrid-equipped configuration increases resiliency, reduces carbon emissions, supports long-term sustainability, and allows cold storage operators to select the optimal system based on local conditions and investment capacity.

3.4. Sensitivity and risk

One important aspect in assessing the technical and economic feasibility of a hybrid system is a sensitivity analysis to uncontrollable external variables, such as solar power prices and state electricity tariffs. The success of this system implementation depends on the selection of quality components, accurate load planning, real-time monitoring, and technical operator training, all of which minimize technical risks and maximize economic and environmental benefits. Hybrid systems exhibit quite sensitive responses to these two factors; increases in solar power prices or electricity tariffs increase energy savings from solar power plants, accelerate the payback period, and increase long-term profits. For example, an increase in solar power prices from IDR 14,000 to IDR 16,000 per liter can increase monthly savings from IDR 2.5 million to IDR 2.88 million.

Battery integration in a hybrid system improves operational continuity and energy efficiency. Batteries store excess PV energy during the day for use at night, reducing dependence on generators, lowering carbon emissions, and providing convenient load management. Although the initial investment is relatively high, a life cycle economic analysis shows the potential for significant long-term savings. However, battery degradation due to high temperatures and tropical humidity is a critical factor that must be considered to maintain system capacity and efficiency.

Hybrid systems also require appropriate architecture and control strategies. The inverter must support multi-source operation, switching logic must prioritize critical loads, and battery management must be aligned with PV production and load requirements. Simulations demonstrated that battery integration reduced generator start-stop frequency, maintained voltage and frequency stability, and reduced downtime. Real-time monitoring enabled adaptive strategy adjustments to variations in solar radiation and load profiles.

Multi-site evaluations across various Indonesian provinces demonstrated that system benefits vary depending on local conditions. In areas with high radiation and unstable electricity grids, battery integration increased uptime and reduced dependence on generators. Conversely, in areas with stable grids and easy fuel supply, a PV-diesel grid configuration remains an economical option. The multi-site approach enabled optimal planning of PV capacity, battery size, and dispatch strategy, enabling the hybrid system to operate efficiently, reliably, and environmentally friendly.

3.5. Implications and recommendations

The implementation of a renewable energy-based hybrid system integrating PV, generator, battery, and grid components presents a highly relevant and practical solution for small- to medium-scale fisheries processing units in Indonesia, enabling sustainable and reliable cold storage and production operations even in areas with unstable or limited grid access. The system design is based on a comprehensive analysis of load demand profiles, seasonal variations, and local solar potential, with an inverter-based control strategy that prioritizes renewable energy utilization while maintaining voltage and frequency stability. Economically, this hybrid system offers substantial operational cost savings by reducing reliance on diesel fuel and optimizing energy distribution, allowing industry players to reinvest these savings in business expansion and product quality improvements. Comparatively, the PV-diesel-grid system achieves high uptime with a lower initial capital investment but results in higher operational emissions, whereas the PV-battery-grid configuration reduces fuel consumption and emissions while providing flexible energy storage, though battery degradation over time requires careful lifecycle cost assessment to ensure long-term viability. System performance can be further enhanced through detailed inverter specifications, switching logic, and load prioritization, supported by simulations under varying solar irradiance and load conditions to maximize PV generation efficiency, battery charge/discharge cycles, and backup generator operation. Regional and multi-site analyses demonstrate the scalability and adaptability of hybrid systems across Indonesian provinces, incorporating solar irradiance mapping, grid reliability indices, and local load profiles for context-specific implementation.

From a policy and investment perspective, the findings highlight the potential for wider adoption of hybrid systems through targeted financial incentives, including PV subsidies, low-interest loans, and public-private partnerships, aligned with Indonesia’s energy transition roadmap and cold chain development goals. However, real-world implementation may face barriers such as a shortage of trained technicians, limited financial incentives, and bureaucratic constraints that can delay or complicate deployment. Addressing these challenges through workforce development, streamlined permitting processes, and supportive policies is therefore essential. Finally, technical training for operators remains crucial to ensure regular maintenance, effective system monitoring, and sustained operational performance, thereby guaranteeing the long-term reliability, energy efficiency, and economic viability of hybrid renewable energy systems.

4. CONCLUSION

This study demonstrates that implementing a hybrid system combining solar PV, a diesel generator, and electricity from the utility grid is a feasible, efficient, and sustainable solution to support cold storage operations, particularly in areas with unstable electricity supply. Technically, the PV system can supply the cold storage's energy needs during the day, while the generator operates efficiently at optimal load at night, and the utility grid provides additional support to ensure an uninterrupted power supply, resulting in effective uptime. This system also improves energy and environmental efficiency, reducing fuel consumption by up to 60% and carbon emissions by 30–50% compared to conventional generator-based systems. Economically, this system offers significant operational cost savings exceeding IDR 100 million per year, with a payback period of approximately 4.4 years if the PV system is not funded by a grant, and demonstrates a positive NPV and competitive IRR, indicating long-term profitability. The study further highlights the benefits of integrating the energy storage system and maintaining appropriate operational strategies to mitigate technical risks such as battery degradation and variable solar irradiance. However, real-world implementation may face obstacles beyond technical and economic considerations, including a shortage of trained technicians, limited financial incentives, and bureaucratic hurdles that can slow adoption. To address these challenges, the study recommends policy support and investments such as PV subsidies, low-interest loans, net metering schemes, and public-private partnerships, aligned with Indonesia's energy transition roadmap and cold chain development goals. Overall, this hybrid system is affirmed as a strategic approach to improving energy security, operational efficiency, and sustainability in cold storage operations, provided that technical solutions and supporting policies are effectively implemented.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
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Fo : **Fo**rmal analysis
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

The research related to animal use has been complied with all the relevant national regulations and institutional policies for the care and use of animals.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [IMAN]. The data, which contains information that could compromise the privacy of research participants, is not publicly available due to certain restrictions.

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