

Application of a Solar Photovoltaic System for Ventilation of a Livestock Farm in Southern Perú

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Article Info	Abstract
Received 30/11/2024	Despite high solar irradiance in southern Peru, the adoption of photovoltaic technology in rural areas remains limited. This study examines the application of an isolated solar photovoltaic system for the ventilation of a livestock farm in southern Peru. First, the analysis parameters were identified, including geographical location, local solar irradiance, and the ventilation equipment's operating time and energy requirements. A technical-economic analysis was conducted to size the photovoltaic system and assess its feasibility. As a result, the characteristics and specifications of the system components were defined. Additionally, three economic indicators were evaluated: net present value (NPV), levelized cost of energy (LCOE), and payback period. Over five years of operation, the proposed photovoltaic system shows potential for implementation, yielding favorable economic results, including a positive NPV, a moderately competitive LCOE, and a payback period of 3.8 years. The system also avoids approximately 0.165 metric tons of CO ₂ emissions per year, demonstrating the environmental viability of using renewable energy for ventilation systems.
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1. Introduction

In recent years, concerns about climate change and the need to adopt sustainable practices have driven the integration of renewable energy into various sectors, including agriculture. Livestock farms must ensure optimal environmental conditions for animal welfare, which requires efficient ventilation systems. Traditionally, these systems rely on conventional energy sources, leading to high electricity demand and contributing to the release of polluting gases [1]. The use of solar energy to power these systems represents a promising alternative, as it takes advantage of a clean, abundant, and potentially economical source.

Several studies have shown that integrating solar-powered ventilation systems can significantly reduce conventional energy consumption and, consequently, the carbon footprint of livestock farms. For example, evaluations of ventilation system performance indicate that incorporating photovoltaic technologies contributes to meaningful energy savings while enhancing overall facility operation [2]. Other studies emphasize the need to continue advancing sustainable energy applications in agroindustry, noting that combining solar systems with automated control strategies improves internal environmental conditions, increases comfort for livestock and

workers, and further decreases dependence on the traditional electrical grid. On the other hand, the United Nations established sustainable development goals (SDGs) to achieve sustainable, cleaner and environmentally friendly energy production in the future [3]-[5]. Photovoltaics [6] is among the most promising renewable energy technologies for mitigating climate change and plays a central role in global decarbonization efforts. Current innovation in photovoltaic technology focuses on developing more durable materials, simplifying installation, increasing energy output, and improving long-term maintainability [7]. Likewise, recent technological advances in photovoltaic systems have shown notable improvements in efficiency, cost, thermal management, and energy storage capacity [8], [9]. In rural areas, solar photovoltaic minigrids have emerged as a viable alternative for delivering a reliable electricity supply [10]. Recent interest in rural electrification has emphasized the importance of linking its development with productive uses for poverty reduction and massification of energy [11], [12]. This is necessary to accelerate rural electrification and mitigate the energy crisis facing developing nations [13], [14].

On the other hand, agricultural activities are crucial and provide several benefits to society, including food, farmer income, and

the creation of attractive rural areas, as well as production practices, such as livestock grazing, that contribute to biodiversity [15]. The integration of agriculture and livestock with efficient energy production can provide viable solutions amid increasing competition for land resources [6]. Such interaction addresses all aspects of sustainable development in social and economic terms and enhances farm productivity through the adoption of modern technologies [16], [17]. On a farm, energy is typically allocated to lighting, mechanical ventilation, water pumping, milk production, and refrigeration for the storage of agricultural products [18]. However, there is limited information regarding the energy costs associated with ventilation systems in livestock facilities, although they are estimated to account for around 20% of total energy use [19]. On the other hand, at an international level, the agricultural sector caused 26% of global greenhouse gas (GHG) emissions between 2006 and 2016. In addition, this sector is a significant source of nitrogen, phosphorus, and pesticides, contributing to both air and water pollution [15]. Among renewable energy sources, solar energy is among the most adaptable, with applications on farms and significant potential to reduce greenhouse gas emissions [20]. However, the deployment of photovoltaic projects on farms remains constrained by several economic, technical, and social barriers [21]. Therefore, it is of utmost importance to develop a renewable energy system that meets the needs of farms and enables farmers and ranchers to be independent of energy problems and protected from long-term supply disruptions [22].

In the literature, several researchers have developed projects for photovoltaic systems with an emphasis on agriculture and livestock, since they make efficient use of available land and can significantly reduce electricity purchased from the grid, help smooth power demand peaks, and minimize transmission losses [20]. Maammeur et al. [18] conducted a 12-month field study in northeastern Algeria, using a family farm as a reference. Through an economic analysis of a photovoltaic project, they showed that 49% of the farms' total electricity consumption was met by renewable energy. Romli et al. [23] optimized the energy storage system of a photovoltaic system through numerical and field studies conducted in rural areas of Malaysia, resulting in reduced stress and consequently less wear on the system components. Mendoza et al. [24] conducted a study in Texas to evaluate the feasibility of using renewable energy, including solar energy, for livestock and agricultural activities. Their results showed that regions with "Direct Normal Irradiance" values greater than 7 kWh/m² have a high potential for using photovoltaic energy. Amer et al. [25] conducted a field study on a farm in Egypt, comparing photovoltaic technology and anaerobic digestion to assess their economic viability. The results indicated that both projects are affordable exclusively for small-scale farms. Nawab et al. [26] proposed a microgrid incorporating photovoltaic and biogas technologies, based on a field study conducted in Pakistan. They concluded that the system is technically and economically viable, as indicated by the payback period and the internal rate of return. Boukebous et al. [27] implemented a photovoltaic system in Algeria to supply livestock water and irrigate crops. They achieved very good performance values due to the large volume of water provided by the system. It should be noted that

they received better operating performance in the winter and spring seasons. On the other hand, in a city in northern Switzerland, Lahlou et al. [28] developed a flexible photovoltaic system that can be converted into a Savonius turbine, increasing the system's power output by up to 175%. Oliveira et al [29] evaluated the potential of using renewable energies, considering photovoltaic, biomass, and wind through the implementation of an artificial intelligence algorithm. It was found that using these renewable energy sources, particularly photovoltaics, would reduce CO₂ emissions by 435.23 tons per year. Al-Lababneh [30] conducted a study on the implementation and impact of a photovoltaic system in a remote area in northeastern Jordan. The result was improved profitability by reducing diesel generator costs and providing an alternative for people in areas far from the national electricity grid. Gholami et al. [31] conducted a feasibility analysis of renewable energy generation options for a dairy farm in Shahroud, Iran. The techno-economic study was conducted based on the renewable resources available on site, including solar, wind, and biomass, as well as the farm's energy consumption. The results showed notable values across the economic parameters evaluated, as well as a reduction in greenhouse gas emissions. Several of these studies have obtained significant impacts regarding the energy efficiency of the system and the decarbonization generated by each of them. Most of them have been conducted using software for the sizing, design, and evaluation of photovoltaic or hybrid systems in rural areas.

Advances in agricultural and livestock techniques powered by photovoltaic energy are increasing [10], including efforts to promote rural tourism [32], particularly in countries whose economies depend primarily on this sector [13]. In Perú, the regulations promote the sale of RER (Renewable Energy Resources) energy through auctions, although this refers to a macro level. Currently, Peruvian legislation lacks specific regulations for photovoltaic systems connected to the self-consumption grid, which rely on energy supplied by electric companies as a backup. On the other hand, ventilation is a fundamental component of livestock farms [19], so effective energy management through renewable energy sources would reduce their total electricity consumption. In addition, South America, particularly in countries such as Bolivia, Chile, Peru, and Argentina, has substantial solar energy potential [33]. Furthermore, renewable energy sources are inherently safer, eliminating the risk of accidents such as explosions or fires commonly associated with fossil fuels [34]. Although fossil fuels remain the primary source of electricity generation in many countries, this trend is expected to shift over the coming decades, with renewable energy—particularly photovoltaic systems—projected to become a dominant source of electricity [35].

In this context, the present study analyzes the application of a photovoltaic system to meet the ventilation demand of a livestock farm in the city of Arequipa, Peru. A 12-month meteorological dataset for the case study was used to evaluate system performance and feasibility. The analysis examines the technical, economic, and environmental benefits of implementing solar-powered ventilation, demonstrating that integrating renewable energy in agricultural buildings can

improve energy efficiency, reduce operational costs, and lower carbon emissions. The results presented are theoretical but supported by previous studies demonstrating the applicability of this technology in real operating conditions. There is limited research evaluating solar-powered ventilation systems for livestock farms in high-irradiance regions such as southern Perú, particularly integrating technical performance, economic viability, and environmental benefits within a single framework.

2. Methodology

In this section, a photovoltaic system capable of meeting the ventilation load in a livestock farm is implemented. First, the input data were parameterized, including the meteorological conditions of the study area and the ventilation system's energy consumption. Then, the configuration of the photovoltaic system was presented, with components described and the design considerations used to size the photovoltaic array. Finally, the financial variables for the system's viability were identified, and the project's environmental impact was defined to reduce greenhouse gas emissions associated with conventional systems.

2.1. Parameterization of the case study

This study was conducted at a livestock farm in the southwestern region of Peru, in the city of Majes, Arequipa Department. The study area is located at latitude -16.331651 and longitude -72.266068 , with an estimated height above sea level of 1420m.

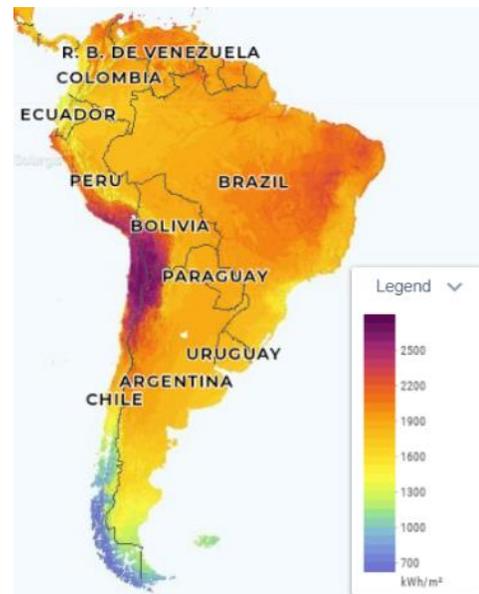
For meteorological data, NASA's Prediction of Worldwide Energy Resources (NASA-POWER; power.larc.nasa.gov) will be used, which provides meteorological information relevant to architecture, energy systems, and agrometeorology. The study period will be one year. The monthly averages of the "All-sky surface shortwave downward irradiance" parameter were calculated for 5 years (2018–2022) as shown in Table 1, obtaining a value of $6.297 \text{ kWh/m}^2 \cdot \text{day}$. Likewise, considering the maps in Figs. 1(a) and 1(b), obtained from the Global Solar Atlas, show that the western region of South America exhibits the highest annual global horizontal irradiance levels (red and orange colors). Furthermore, Arequipa (see Fig. 1(b)) has high solar energy potential relative to other regions in South America, indicating strong suitability for photovoltaic development.

To conduct an adequate energy analysis, it is necessary to account for all relevant energy requirements, including the number of devices in operation, their power consumption, and their daily operating time. Table 2 shows the devices considered in the system. The ventilation system has an estimated maximum daily energy demand of 556 kWh/day and an installed power of 118 W .

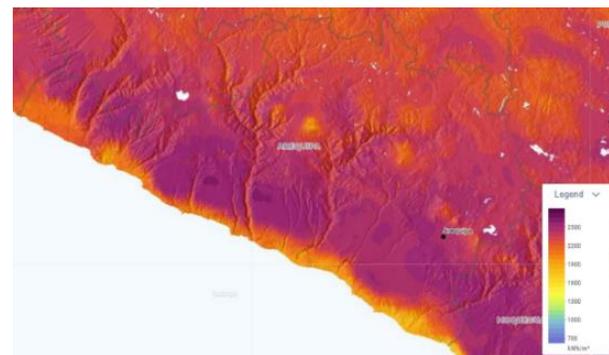
2.2. Photovoltaic system configuration

Until recently, only utility companies were legally authorized to generate and distribute electricity in many countries. As a result, the predominant electricity model worldwide is based on large power plants that supply electricity to consumers through

extensive transmission and distribution networks. In recent years, the situation has changed, and some countries have advanced their legislation to allow the installation of renewable energy systems by individuals and companies. These systems can generate energy for self-consumption or for injection into the electrical grid. In Arequipa, there is still no regulation governing excess energy injected into the grid or establishing compensation mechanisms for users. For this reason, an isolated system will be considered to guarantee "zero injection", and the equipment used in the installation must include remote monitoring capabilities and allow for specific configuration settings.



(a)



(b)

Figure 1. Map of annual global horizontal irradiation in the department of (a) South America and (b) Arequipa in Perú [36]. Copyright statement: Adapted from Global Solar Atlas, by Global Solar, 2024 (<https://globalsolaratlas.info/>). CC BY 4.0.

Table 1. Solar irradiance in kWh/m²-day from 2018 to 2022.

Month	2018	2019	2020	2021	2022
January	7.42	6.6	6.34	7.55	7.28
February	7.03	6.27	6.6	7.47	7.21
March	6.72	6.93	6.33	6.77	6.6
April	6.1	6	6.43	5.9	6.24
May	5.43	5.32	5.25	5.26	5.29
June	4.34	4.79	4.71	4.75	4.85
July	4.18	4.89	5.25	4.86	4.78
August	5.45	5.72	5.48	5.51	5.78
September	6.55	5.97	6.14	5.93	6.37
October	6.81	6.92	6.93	6.93	7.65
November	7.94	7.19	7.93	7.57	7.87
December	7.84	7.9	7.37	6.81	7.52

Source: NASA’s Prediction of Worldwide Energy Resources

Table 2. Power load specification of devices.

Description	Quant.	Power (W)	Usage (h-day)	Consum. (Wh-day)
Air extractor Volker	01	10	6	60
Air extractor Karson	02	10	6	120
Air extractor Broan	02	18	6	216
Temperature sensor	01	0.8	24	19.2
Ammonia sensor MQ-135	01	0.8	24	19.2
Methane sensor MQ-4	01	0.9	24	21.6
Light alarm OPALUX	01	20	2	40
Audible alarm OPALUX	01	30	2	60

The photovoltaic system will consist mainly of a set of solar panels to convert solar radiation into valuable electrical energy, an inverter that transforms the direct current produced by the photovoltaic system into alternating current so that it can be supplied to the components, a set of batteries for storing electrical energy, and a solar charge controller which protects the battery from overcharging by regulating the voltage and current supplied by the solar panels. Likewise, the components of the ventilation system will be operated through a real-time monitoring system, and the overall configuration is shown in Fig. 2.

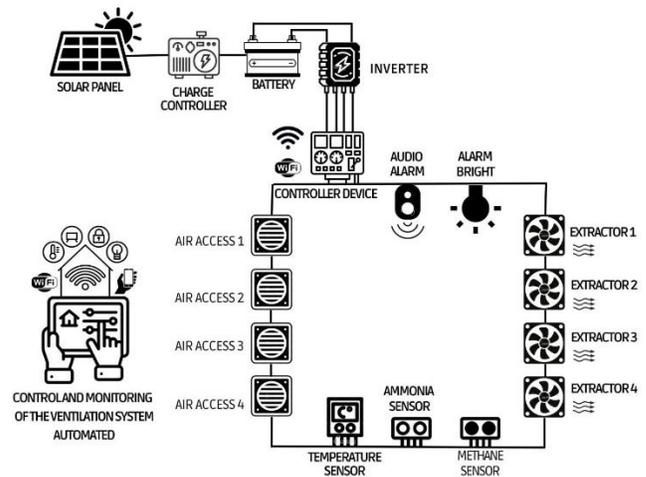


Figure 2. Schematic diagram of the PV system for the ventilation system.

The sizing of the photovoltaic installation may depend on external factors and the devices and equipment used. In this study, a sizing method already used in photovoltaic installations of this type [37] will be employed. The load capacity will be taken as the reference, defined as the ventilation system's daily consumption in amperes and the photovoltaic system's autonomy in days. The RJ100P5 photovoltaic panel was used with a peak power of 100W and a short-circuit current of 6.18A. Likewise, the inverter size must always be 30% greater than the actual wattage to ensure safety [22]. Therefore, the VE12250IEC inverter was selected with a peak power of 400W and an efficiency of 87%. GB12-150 batteries with a charging capacity of 150 Ah were used. The BSMPPT7515 controller can deliver a charging current of up to 15 A and a photovoltaic panel voltage of up to 75V. Fig. 3 depicts the electrical system.

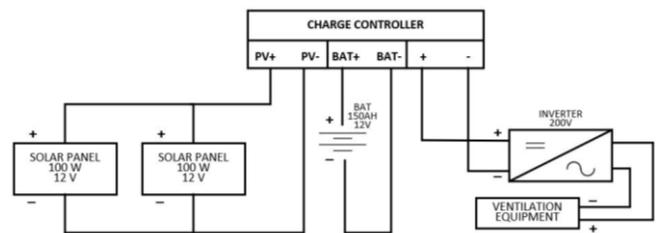


Figure 3. Schematic diagram of the electric system.

The charging capacity is obtained from (1) where C is the estimated maximum daily consumption of the ventilation system, η is the efficiency of the inverter, V is the voltage at which the photovoltaic system is being configured, which in this case is 12V, ψ is a safety factor of the inverter, in this case we will use a recommended value of 1.2. K is a loss coefficient defined in (2), where D denotes the days of autonomy, which in this case is 1 day.

$$Y = \frac{\psi M}{\eta V K} \tag{1}$$

$$K = 0.7 - 0.0058D_a \tag{2}$$

The energy generated by the solar panels is calculated using Equation (3). In this expression, σ represents the safety factor, which accounts for additional energy demand during periods of

sunlight; a value of 1.2 was adopted in this study. I denotes the current of the selected photovoltaic module; for a 100 W, 12 V panel, this corresponds to 8.33 A. H refers to the solar irradiance received by the panels, expressed as peak sun hours. Based on these parameters, the required number of panels connected in parallel and in series is determined using Equations (4) and (5), respectively.

$$E = \sigma IH \quad (3)$$

$$N_{pp} = \frac{Q}{E} \quad (4)$$

$$N_{ps} = \frac{V_b}{V_p} \quad (5)$$

For the sizing of the battery array, (6) represents the battery capacity for one day of autonomy. Where P is the depth of discharge, which, according to the manufacturer, will be considered as 0.6. The number of batteries in parallel and in series is denoted by (7) and (8), respectively.

$$C_{battery} = \frac{QD_a}{P} \quad (6)$$

$$N_{batteries-parallel} = \frac{C_b}{C_{no}} \quad (7)$$

$$N_{batteries-series} = \frac{V_b}{V_{no}} \quad (8)$$

For controller sizing, the current through this device is shown in (9). Where γ denotes the controller safety factor, we use the recommended value of 1.1. I_{sc} is the short circuit current of the solar panel, and N_r is the number of branches in the solar panel array.

$$I_{controller} = \gamma I_{sc} N_r \quad (9)$$

2.3. Economic parameters

When evaluating a project's share, the first indicators we usually use are Net Present Value (NPV) and Payback (PB). In the energy sector, it is not sufficient to consider only these two metrics; it is also crucial to account for the energy produced by the variety of existing generation technologies and the capacity of each type. Therefore, a more comprehensive and effective metric was adopted to parameterize and compare projects. This indicator, called the Levelized Cost of Energy (LCOE), facilitates the calculation of the breakeven price at which the asset's electricity must be marketed to cover total production costs over its life cycle.

Net Present Value (NPV) is the present value of the after-tax cash flow discounted to the first year using the nominal discount rate.

$$NPV = \sum_{n=0}^N \frac{R_n}{(1+S_n)^n} \quad (10)$$

where R_n is the after-tax cash flow in year n , N is the analysis period in years, and S_n is the nominal discount rate.

The overall life-cycle costs of a project, expressed in cents per kilowatt-hour of electricity produced over its lifetime, are known as the levelized cost of energy (LCOE).

$$LCOE = \frac{\sum_{n=0}^N \frac{C_n}{(1+S)^n}}{\sum_{n=0}^N \frac{Q_n}{(1+S)^n}} \quad (11)$$

where C_n denotes the annual cost of the project in year n , Q_n denotes the electricity generated by the system in year n , N denotes the analysis period in years, and d denotes the discount rate.

The payback of the PV system was calculated as

$$\begin{aligned} CF \text{ for payback in Year } n > 0 = & \\ & \text{Value of electricity savings} \times (1 - \\ & \text{Effective Tax Rate}) + \text{State Tax Savings} + \\ & \text{Federal Tax Savings} + \\ & \text{Total PBI (Production based incentives)} - \\ & \text{Debt Interest Payment} \times \text{Effective Tax Rate} - \\ & \text{Total Operating Expenses} \end{aligned} \quad (12)$$

3. Results

3.1. Technical Performance

In Perú, there is currently no specific national regulation governing the design of photovoltaic minigrids. This work was based on a methodology for sizing small-scale isolated photovoltaic systems, underscoring the need to develop clear national design standards. With this, it is possible to determine the total number of modules required, the total installed power, the number of branches in parallel, the number of modules per branch, the power and voltage per branch, the nominal capacity and voltage of the controller, the number of batteries in series, the maximum current that the controller must withstand on the generation side and on the load side, and the minimum nominal power of the inverter. Table 3 summarizes the operating characteristics of the photovoltaic system. Likewise, Table 4 summarizes the specifications of the photovoltaic system components.

Photovoltaic technology is a promising alternative for reducing costs because, unlike conventional generation technologies, its unit cost and conversion efficiency remain largely independent of system size. Since users can independently generate a portion of the energy they consume, this system is an excellent option, making it a practical alternative for lowering electricity expenses [6]. Table 5 presents the monthly and miscellaneous consumption costs of the local electricity supply company expressed in Peruvian currency (PEN). The total expenditure over five years amounts to 9,321.00 PEN. Consequently, Table 6 presents the component details and values required for the implementation of the photovoltaic system. The total investment required is 6,071.00 PEN, and an annual maintenance cost of approximately 4% is assumed, given the system's small scale [22].

Table 3. Characteristics of the sizing of the isolated system for generating electricity through solar radiation.

Parameter	Value	Units
Daily energy consumption in AC	639.08	Wh-day
Maximum electrical load of the installation	92.62	Ah-day
Nominal current of the photovoltaic panel	8.33	A
Electric charge per photovoltaic panel	47.16	Ah-day
Number of panels in parallel	2	-
Number of panels in series	1	-
Battery capacity for the system	154.37	Ah
Number of batteries in parallel	1	-
Number of batteries in series	1	-
Input current to the controller	13.6	A
Power required in the inverter	163.45	W

3.2. Economic Evaluation

Using the data in Tables 5 and 6, we can derive economic indicators such as NPV, PB, and LCOE. For the first case, the net present value (NPV) is the present value of the after-tax cash flows, discounted to the first year at the nominal discount rate. In practical terms, NPV is the present value of future cash inflows minus future cash outflows over the evaluation period. A positive net present value indicates that a project is economically viable. According to the flow presented in Table 7, the value obtained for 5 years is 1,118.69 PEN.

The total life-cycle cost of the project, expressed in cents per kilowatt-hour of electricity produced over its useful life, is known as the levelized cost of energy (LCOE). In this case, the input data for this analysis are presented in Table 8, yielding a value of 0.88 US\$/kWh (assuming an exchange rate of 1 US\$ = 3.77 PEN). This value is comparable to those reported for small-scale systems in other regions [17], [32]. Although Arequipa benefits from high solar irradiance, the LCOE is also affected by the limited system size and the relatively high cost of imported equipment, as locally manufactured equipment is more expensive.

Table 4. System component specifications.

Component	Parameter	Value	Units
Inverter	Power	200	W
	Efficiency	87	%
	Voltage	12	V
	Short circuit current	10.36	A
Photovoltaic panels	Peak power	100	W
	Efficiency	18.4	%
	Open circuit voltage	21.6	V
	Voltage at the maximum power point	17.8	V
	Short circuit current	6.18	A
	Nominal current	5.62	A
Battery	Voltage	12	V
	Load capacity	160	Ah
Charge controller	Nominal power 12 V	220	W
	Efficiency	98	%
	Maximum open circuit voltage	75	V
	Nominal charging current	15	A

Table 5. Monthly cost of consumption of a local electricity supply company in local currency.

Description	Value (in PEN)
Ventilation system	132.00
Public lighting	6.09
Fixed charge	3.84
Compensatory interest	11.00
Maintenance and replacement	1.43
Tariff adjustment	0.99

Table 6. Investment in photovoltaic system components.

Component	Value (in PEN)
Air extractors	880.00
Temperature sensor	124.00
Ammonia sensor	170.00
Methane sensor	165.00
Light alarm	150.00
Audible alarm	82.00
Encapsulation	350.00
Electronic controller	420.00
Charge controller	750.00
Solar panel	1,060.00
Batteries	820.00
Power inverter	850.00
Annual maintenance	250.00

Payback is the number of years required for an investment in a specific project to generate annual profits or savings. In conventional analyses, the payback period accounts for factors such as electricity generation, revenue or savings, depreciation, and operating costs, as summarized in Table 9. For this autonomous system, only the electricity generated and the

corresponding savings were considered, yielding a payback period of 3.8 years.

Table 7. Cash flow per year.

Year	Profitability per month (PEN)	Discount rate (%)	NPV per year (PEN)
1	650.00	8.91	615.19
2	1,300.00	8.91	1,095.99
3	1,950.00	8.91	1,509.49
4	2,600.00	8.91	1,848.00
5	3,250.00	8.91	2,121.02

Table 8. Details for obtaining the LCOE.

Description	Value	Units
Project capacity	639.08	Wh-day
Initial investment	6,071.00	PEN
Maintenance cost	250.00	PEN
Annual production	233 264.20	Wh
Analysis time	5	Years
Total production	1 166 321.00	Wh

Table 9. Details for obtaining the payback period.

Description	Value	Units
Electricity savings value	3,350	PEN
Discount rate	8.91	%
Annual savings	650.00	PEN
Total expenses	6,071.00	PEN

3.3. Environmental Benefits

Another important factor today when implementing a renewable power plant is the resulting carbon footprint. In recent years, greenhouse gas emissions have contributed to significant health problems and even deaths. Conventional fossil-fuel-based energy sources are the primary contributors to these harmful emissions [38], [39]. Based on the annual production of 233.26 kWh in Table 8, 0.165 metric tons of CO₂e are obtained [40]. This CO₂-equivalent does not appear to be significant for a large-scale project; however, in a future carbon market in Latin America, it could benefit large and medium-sized livestock farms, as they also emit other greenhouse gases from their livestock.

4. Discussions

The present study adds specificity and extends the scope of previous research on the integration of renewable energy into ventilation systems on livestock farms. For example, Fan et al. compare the efficiency of ventilation systems on farms that integrate renewable energy. Their study reported notable gains in energy efficiency and lower operational costs. However, the research presented here extends this approach by incorporating key factors, such as local climate variability and the role of

energy storage, thereby enhancing system reliability and broadening its applicability across diverse regions [41].

On the other hand, Maia et al. proposed a theoretical model for solar-powered ventilation systems on farms, demonstrating the concept's viability under high-solar-radiation conditions. While their results are consistent with those obtained in this study, this study further contributes by examining the technology's performance under fluctuating environmental conditions and its implications for sustainable farm operation, offering a more integrated perspective for the agricultural sector [42].

The performance of the photovoltaic system is primarily explained by the high solar irradiance in Arequipa, which supports stable energy generation throughout the year. The economic indicators, including a 3.8-year payback period and an LCOE of 0.88 US\$/kWh, are primarily influenced by the small scale of the installation and the relatively high cost of imported equipment. Although the total CO₂ reduction is modest given the system's limited size, these savings become increasingly meaningful when scaled to larger livestock operations. These results highlight the technical and economic suitability of small PV systems for agricultural ventilation, particularly in regions with strong solar resources.

This study presents several limitations that should be acknowledged. The analysis is based on simulated performance rather than real-time operational data, and system behavior under transient or extreme weather conditions could not be fully assessed. The load profile of the livestock farm was assumed constant, although actual ventilation demand may vary with animal density, season, and environmental conditions. Economic parameters, such as component prices and exchange rates, may fluctuate over time, thereby affecting long-term cost projections. In addition, battery degradation and maintenance requirements were not explicitly modeled, which could affect system reliability.

5. Conclusions

Two photovoltaic panels will be required to supply electricity to the farm's ventilation system, based on average consumption. Photovoltaic energy systems have not been widely adopted in rural areas of southern Peru. Still, they can be implemented when properly sized and planned, even in rural areas where additional agricultural machinery may increase overall energy demand. To calculate the components of the isolated system, accurate geographic information, equipment load profiles, local solar irradiance, and the technical specifications of the selected PV modules are required. Photovoltaic solar energy, as a renewable energy source, is a reliable and cost-effective alternative to conventional energy sources on livestock farms. The results of this study show that photovoltaic panels can be implemented in rural areas of Arequipa, including the livestock facility analyzed. We can also validate the feasibility of implementation by comparing the results obtained with those of an investigation that aligns with evidence from rural electrification projects worldwide, demonstrating the effectiveness of small-scale solar systems, particularly domestic PV installations. The economic importance of

photovoltaic systems is increasing due to ongoing price declines and experience with their deployment in other sectors, including social infrastructure, community services, agriculture, and other productive activities that support rural development.

The economic study showed that, despite being a small-scale installation, the return on investment is not sustained over an extended period, unlike that of large investment projects. Likewise, this also helps mitigate emissions from livestock operations, where greenhouse gases are produced in proportion to herd size. The massification of this type of project could consolidate the legal framework for renewable energy in Peru, to expand electrification in remote or underserved regions.

Future research should focus on validating the proposed system under real operating conditions, particularly by monitoring seasonal variations in ventilation demand and photovoltaic performance. In addition, integrating hybrid configurations—such as PV–battery–biogas or PV–wind systems—could further enhance energy reliability on livestock farms with variable loads. The incorporation of predictive control strategies for ventilation, supported by environmental and animal-welfare data, may also improve operational efficiency. Finally, assessing the economic impact of emerging carbon markets in Latin America would provide a more comprehensive view of the long-term sustainability and financial potential of solar-powered agricultural systems.

Abbreviations

C	Annual project cost (PEN)
D	Days (-)
E	Energy received by photovoltaic panels per day (Ah-day)
H	Irradiance (W/m ² -day)
I	Current (a)
K	Loss coefficient (-)
LCOE	Levelized cost of energy (US\$/kWh)
N	Number (-)
NPV	Net present value (PEN)
M	Maximum daily consumption of the system (Wh-day)
V	Voltage (V)
R	Net cash flow (PEN)
S	Discount rate (%)
P	Depth of discharge of battery (-)
Q	Electricity generated by the system (Wh)
Y	Charging capacity (Ah-day)
ψ	Safety factor for the inverter (-)
η	Efficiency of inverter (%)
σ	Safety margin for energy consumption (-)
γ	Safety factor for the controller (-)

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Willian Leiva Huarcaya: Research proposal, Conceptualization, methodology, formal analysis, and writing—original draft.

Yuri Silva Vidal: supervision, resources, project administration, writing, review, and editing.

José Canazas Rodríguez: writing—review and editing, data curation, methodology, and validation.

All authors have read and agreed to the published version of the manuscript.

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