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Energy Efficiency and Environmental Sustainability in Rural Buildings: A Life Cycle Assessment of Photovoltaic Integration in Poultry Tunnels—A Case Study in Central Italy

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Featured Application: The implementation of energy efficiency solutions in poultry farming, particularly those based on renewable energy sources, plays a crucial role in promoting more sustainable agricultural practices across rural territories. This study contributes to current research by providing empirical data on the real-world effectiveness of integrating photovoltaic systems into layer hen poultry tunnels. By grounding the analysis in real-world agricultural infrastructure and combining technical assessment with territorial relevance, the study contributes original insights into scalable, sustainable interventions for rural development.

Abstract: Livestock buildings in rural areas are increasingly recognized for their environmental impact, yet few studies provide applied, scenario-based evaluations to guide retrofit interventions. While the existing literature acknowledges the environmental burden of livestock facilities, it often lacks operationally grounded analyses applicable to real-world agricultural contexts. This paper proposes an original integration of experimental climatic monitoring and life cycle assessment (LCA) to evaluate retrofit scenarios for energy efficiency in real poultry farming contexts. Based on an accurate climatic monitoring campaign conducted on-site during the spring and summer periods, relevant data were collected on air temperature, humidity, wind speed, and solar radiation affecting two poultry tunnels in central Italy, highlighting the need for thermal mitigation. The comparison between the observed operational scenario and the hypothesized improved scenario, involving energy supply from photovoltaic sources, evaluated using the PVGIS tool, demonstrated a significant reduction in environmental impact, with a 33.4% decrease in global warming potential and a 26.1% reduction in energy consumption. This study combines experimental on-site climatic data collection with comparative environmental evaluation using LCA methodology. The LCA approach, which guided the entire study, highlighted how the energy efficiency gained through solar panels adequately offsets their production and maintenance costs over the long term. These findings offer a replicable model for energy retrofits in rural livestock facilities, contributing to both environmental goals and rural resilience.

Keywords: life cycle assessment; renewable energy; environmental impact; energy retrofit; photovoltaic systems; rural buildings; poultry farming; sustainable agriculture; sustainable; rural architecture; climatic monitoring

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1. Introduction and Background

This introductory section is structured in two parts: the first outlines the socio-environmental context and research motivations, while the second presents the scientific background and research framework supporting the experimental phase.

The urgency imposed by environmental issues is progressively leading the fields of architecture and engineering to broaden their fields of interest, expanding toward new sectors, including agriculture and energy [1]. In this regard, the well-documented challenges associated with (and resulting from) energy procurement currently represent the driving force behind the global acceleration that, since the Kyoto Protocol, has increasingly influenced production sectors [2].

Energy consumption in the residential and agricultural sectors constitutes a significant component of overall energy demand, both in Italy and in the European Union. In 2022, households accounted for 27.3% of final energy consumption in European countries, while agriculture represented approximately 3% [3]. In the agricultural sector, crude oil represents the main energy source, accounting for about 60%. Electricity and natural gas accounted for approximately 12% each, while renewable energy contributed 10% [4].

This phenomenon is gradually shaping scientific research and fostering extensive and multi-layered academic attention to the development of new experimental applications for improving the energy efficiency of buildings, regardless of their intended use [5]. This trend has now become well established within the disciplines of architecture and engineering, which have recently begun to reconsider the role of industrial buildings. This shift has led to growing interest in the development of energy efficiency models and techniques for rural constructions, promoting sustainability in buildings used for agriculture and livestock [6].

1.1. Energy Efficiency in the Agricultural Sector

Despite the growing interest in sustainable construction, few studies have focused on rural livestock buildings with high energy demand and their potential for scalable retrofit solutions. The attention previously mentioned is widely justified by the impact that the agricultural sector generally exerts on the territorial and landscape levels, particularly considering the role that certain types of production play in shaping the "development trajectories" of entire territorial systems [7]. Indeed, while rural buildings typically respond to specific business needs—both in terms of typology and settlement patterns—through a largely standardized construction process, these buildings also impact local land use and ecosystems. These effects stem both from the intensive use of natural resources and from the significant energy demands that certain entrepreneurial practices require.

Moreover, the need for energy efficiency in rural construction does not pertain exclusively to residential buildings or the restoration of rural dwellings [8]. Rather, it primarily concerns productive structures and livestock farms, which are particularly energy-intensive. These facilities require substantial energy for heating, cooling, ventilation, and water supply to ensure the well-being of the farmed animals. Technologies associated with sustainable construction [9], along with the integration of renewable energy production systems—such as photovoltaic panels and solar thermal systems—offer concrete opportunities to make livestock buildings autonomous and self-sufficient. Additionally, they contribute to improving the landscape integration of productive structures. On innovative technologies, green roofs have been shown to reduce peak heat flux by up to 60%, depending on insulation layers and climate conditions [10], while also enhancing their profitability, operational sustainability, and appeal to tourism sectors that promote sustainable rural development [11].

The technological aspects outlined above suggest that the sustainability of construction, particularly in rural contexts, should also take into account the social and economic implications underlying environmental concerns. Investing in the energy efficiency of rural buildings can serve as a strategic tool to support the integration of more balanced economic development models, enriching decision-making processes in areas affected by depopulation.

The socio-economic implications referenced here should not be regarded as merely theoretical considerations; rather, they have also informed the selection of the case study analyzed in this research. The two poultry tunnels examined, in fact, represent a common production model in rural areas at risk of marginalization [12]. As previously noted, energy retrofit interventions can generate tangible benefits not only in environmental terms, but also in enhancing local economic resilience [13].

This assessment will focus on evaluating the benefits of reducing energy consumption and economic assessment methods based on life cycle analysis, including life cycle assessment (LCA). These methodologies provide comprehensive tools for assessing the environmental impact associated with the operation of the analyzed buildings, thereby identifying scientifically grounded, sustainable, and long-term solutions [14].

1.2. Life Cycle Analysis of Poultry Tunnels: A Proposal for an Alternative Experimentation

Among the different factors influencing the actual sustainability of buildings designed to accommodate this industrial segment, the energy consumption of poultry tunnels plays a crucial role in the specific objectives of this research. Ventilation systems required to ensure animal welfare, along with lighting, climate control, cooling, and heating (where applicable), account for the vast majority of the energy costs that entrepreneurs in this sector must manage [15].

On the other hand, it is undeniable that the technologies commonly used for constructing such tunnels generally consist of commercially standardized components, rarely resulting from dedicated engineering or design processes. Consequently, they lack the integrated systems or architectural considerations that typically provide other building types—whether residential or industrial—with effective responses to the urgent demand for sustainability in construction. This approach could draw from experiences in other construction fields, embracing the NZEB (Nearly Zero Energy Building) ambition that has long characterized the building industry [16].

Among the various operational scenarios, solar energy appears to be the most universally applicable solution across different geographical contexts, making it particularly relevant for poultry housing. The widespread adoption of this renewable energy source in agriculture in recent years has been primarily aimed at reducing CO_2 emissions and decreasing reliance on fossil fuels [17]. The integration of photovoltaic systems in the agricultural sector represents a strategic choice to ensure self-sufficient energy production, thereby improving productivity within the industry [18].

However, this proposed scenario requires careful evaluation, considering both the geographical location of the facility—along with its specific environmental conditions [19]—and the life cycle of the structure under analysis. A rigorous methodological approach is therefore necessary, combining life cycle assessment (LCA) with expedited analyses based on reliable, on-site data collection, at least for the physical and climatic variables impacting the building's energy requirements and consumption. In particular, this includes parameters such as air temperature, relative humidity, and solar radiation affecting the building envelope.

In this perspective, the present study aims to assess the energy efficiency scenarios for poultry tunnels through an analysis of climatic conditions and an LCA-based evaluation of operational strategies based on energy audits. While both LCA and photovoltaic retrofits have been explored independently, this study contributes a novel perspective by applying LCA to real experimental data collected on-site from functioning poultry tunnels, an underexplored typology, thereby bridging empirical measurement and environmental simulation.

1.3. Climate Factors and Energy Demand

Addressing the evaluation of operational scenarios for achieving complete energy self-sufficiency in a building requires consideration not only of its constructional, morphological, and typological characteristics, but also of the environmental factors to which it is subjected, depending on its geographical location. The latter specifically refers to climatic variables that directly influence the building's energy performance, such as air temperature, humidity, and solar radiation.

While it is certainly reasonable to experiment with efficiency scenarios based on predetermined characteristics identified according to geographic zones, the ability to monitor these factors through dedicated sensor technology enables the attainment of more precise and forward-looking results specifically tailored to the case study [20]. Moreover, the descriptive capabilities offered by modern sensor technology, when applied during the preliminary study phase of the experiment, allow for a detailed mapping of the variables that most significantly impact the thermal response of building envelopes [21].

A detailed understanding of the solar radiation affecting a building and the thermal transmittance of its envelope are essential parameters for the technological design of windows and vertical closures (both transparent and opaque) [22]. Additionally, knowledge of the solar energy available in a given environment allows for maximizing passive thermal gains through the use of specific materials [23].

Optimal thermal conditions in poultry tunnels range between 18 and 24 °C, with relative humidity under 70% to prevent heat stress and respiratory issues [24]. Sound levels should remain below 65 dB, and appropriate natural lighting or 10–20 lux artificial lighting is recommended to ensure animal welfare [25].

Building on previous research conducted by other authors for comparable purposes [26–28], this study identifies the key variables that contribute to accurately mapping the responsiveness of a building to the climatic conditions it is subjected to. These variables include air temperature, relative humidity, wind speed, and the thermal fluxes measurable at the roof and ground slab levels.

As previously stated, if these characteristics are properly monitored, they can yield valuable results in two key areas. Firstly, they provide an initial research outcome in the form of precise climatic data and the responsiveness variables of the building envelope. Secondly, they enable the definition of tailored operational efficiency scenarios specific to the building under investigation, without relying on standardized data for geographic zones similar to the case study. This distinction allows for the evaluation of customized and precise scenarios, avoiding assessment errors in LCA analysis that could arise from the extensive use of predetermined characteristics [29].

1.4. The Life Cycle of Agricultural Buildings

With its specific production and climatic characteristics, the agricultural industry requires an integrated approach to reduce environmental impacts and the sustainable management of buildings used for livestock and other agricultural activities [30]. In this context, the life cycle assessment (LCA) of agricultural buildings is an indispensable tool for evaluating their life cycle, from design and construction to operation, maintenance, and decommissioning [31]. This approach enables identifying and quantifying the most relevant contributing elements, thereby providing a basis for improvement interventions aimed at energy consumption and reducing operational costs [32]. In the literature, numerous studies have been conducted on energy audits of industrial activities [33–35] and accommodation activities [36,37], while research focusing on rural building heritage, especially that associated with high-energy-consumption activities, is less frequent [38]. A detailed energy audit allows for a structured analysis of consumption profiles, identifying both critical issues and opportunities for intervention in terms of energy efficiency, reducing environmental impact, and optimization of costs [39], enhancing the economic competitiveness of enterprises and reducing greenhouse gas emissions.

In the context of agricultural and livestock buildings, there are numerous applications of LCA, encompassing aspects such as construction materials, the use of renewable energy, and the control of the indoor microclimate through mechanical systems [30]. Some authors have analyzed the use of local materials to reduce environmental impact and transportation costs [40]. At the same time, other researchers have examined the possibilities of recycling agricultural waste materials as construction materials, such as rice straw, olive stones, hemp, etc., within a circular economy framework [41–43]. Other studies have focused on the benefits of sustainable materials to enhance the energy efficiency of buildings [44–46]. These analyses highlight that the environmental impact of construction materials becomes more significant as the operational phase plays a minor role, particularly in low-energy buildings [47]. Conversely, in the case of buildings used for high-energy activities, the operational phase becomes predominant, and interventions on systems, especially those involving renewable energy sources, prove to be the most effective in reducing environmental impact [38]. From this perspective, numerous studies have focused on analyzing the opportunities of using renewable energy sources in livestock buildings, including solar energy and bioenergy [48]. Other research has addressed the issue of ventilation, a significant aspect in livestock buildings, to effectively remove excess humidity and heat through the use of passive cooling systems [49]. Depending on external climatic conditions, these strategies can be implemented through hybrid systems that combine natural and mechanical ventilation or by employing high-efficiency mechanical ventilation systems [48]. Other studies have analyzed indoor air quality, although this aspect is rarely correlated with environmental impact assessments. Regarding studies on poultry houses, some have focused on the evaluation of pollutants and the indoor microclimate [50], while others have examined potential improvements in heating and ventilation systems [51].

1.5. Hypothesis and Research Thesis

Despite the growing number of LCA applications in rural buildings, few studies provide detailed experimental validation of retrofit scenarios in real livestock structures. Most rely on simulated data or focus on material production rather than operational energy flows. Furthermore, the integration of PV systems is often evaluated without considering climate-adaptive strategies based on local monitoring.

As observed in the preceding paragraphs, the sustainable management of agricultural buildings plays a crucial role in strategies aimed at reducing environmental impacts and improving energy efficiency. This is particularly relevant given the high energy consumption of such structures and their frequent placement in environmentally and scenically valuable contexts. The adoption of life cycle assessment (LCA) methods, as briefly outlined in Section 2.2, allows for a comprehensive evaluation of a building's entire life cycle—from construction and operation to decommissioning—by identifying the most critical phases in terms of environmental impact. This, in turn, enables the development of strategies to mitigate energy consumption [52].

Within this framework, the hypothesis underlying this investigative work is that integrating renewable energy sources, along with potential technological and material modifications to the building envelope of agricultural structures, can significantly reduce the environmental impact of livestock buildings compared to current construction standards [53].

Specifically, this study, through a direct experimental approach, aims to test the hypothesis that implementing photovoltaic systems for energy storage can effectively reduce greenhouse gas emissions in the livestock sector, thereby lowering primary energy consumption without compromising indoor air quality, the overall functionality of the building, or animal welfare [54].

The central thesis of this research is based on the conviction that transitioning to renewable energy sources in livestock facilities not only generates environmental benefits by reducing global warming potential (GWP) and other impact indicators, but also provides economic advantages directly proportional to lower operational costs. The objective is to demonstrate that, despite the increased environmental impact associated with the production, installation, and maintenance of photovoltaic panels, the overall operational impact is significantly reduced compared to the measured baseline standard.

The findings from this study are intended to address the research questions driving this investigation, which are summarized in Table 1 below.

Table 1. Research questions underpinning the investigative study—© authors.

Code	Research Questions
RQ1	How and to what extent does the implementation of photovoltaic energy supply systems reduce the environmental impact of a livestock building compared to the construction standard that relies solely on energy supply from the national grid?
RQ2	Which phases of the life cycle of a livestock facility have the greatest impact on its overall environmental footprint, and how can property management be optimized through improvement and energy qualification scenarios?
RQ3	What is the potential replicability of operational scenarios derived from other case studies already present in rural environments for different building types, and what strategies could ensure their large-scale adoption?

From this perspective, this paper aims to contribute to the state of the art in scientific research on energy efficiency within a specific sector—namely, the rural environment—by demonstrating how the use of renewable energy sources represents a viable solution for ensuring the sustainability of livestock farms. This analysis considers the entire life cycle of agricultural production facilities, emphasizing long-term sustainability for such structures. The theoretical and contextual premises outlined above converge on the hypothesis that photovoltaic integration can be a key lever for reducing operational environmental impacts in high-consumption livestock facilities, such as poultry tunnels. The following sections present the experimental methodology adopted to test this assumption.

The contextual and scientific premises discussed above establish the framework within which this research is positioned and justify the methodological choices outlined in the next section.

2. Research Subject

The contextual and scientific premises outlined above define the framework for the present study and directly inform the methodological choices described in the following section.

In line with the scientific framework outlined in Section 2, the objective of this research is to assess the ecological footprint and energy consumption of a poultry farm where solar energy is integrated as the primary source. The study compares the projected results with those of a conventional scenario entirely powered by grid electricity. This evaluation, conducted through life cycle assessment (LCA), examines the impact of the proposed operational choices in terms of reduction in CO_2, energy savings, and the actual economic and financial sustainability of the enterprise. The assessment follows international standards as established by ISO 14040 [55] and ISO 14044 [56], and is structured into five distinct phases, as illustrated in Figure 1 below.

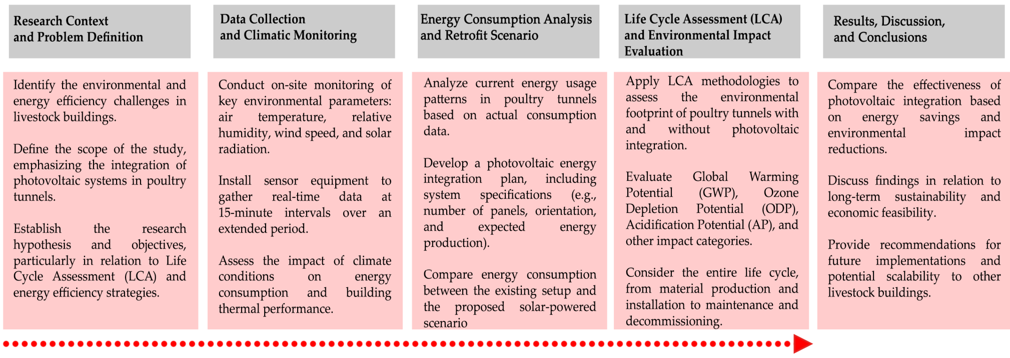


Figure 1. Applied scientific investigation method—© authors.

In relation to the aspects outlined above, this section aims to highlight the key elements of the case study employed for the experimental analysis. It presents the characteristics of the environment in which the study is conducted, the type of monitoring carried out to collect climatic data from the context, and the analysis of the actual energy consumption sustained by the enterprise.

2.1. Case Study Introduction

As observed in the previous paragraphs, the sustainable management of agricultural buildings can play a crucial role in scenarios aimed at reducing environmental impacts and improving energy efficiency. This is particularly relevant given the high energy consumption of such structures, which are often located in environmentally and scenically valuable areas.

In order to test expedited LCA analysis scenarios for livestock buildings—specifically evaluating the impact of photovoltaic energy supply on farming structures throughout their entire life cycle—a case study was selected for experimental application, deemed particularly representative of the topic. The study focuses on two poultry tunnels located in the municipality of Montefiascone, a town in northern Tuscia, within the province of Viterbo, situated not far from Italy's capital, as illustrated in Figure 2 below.

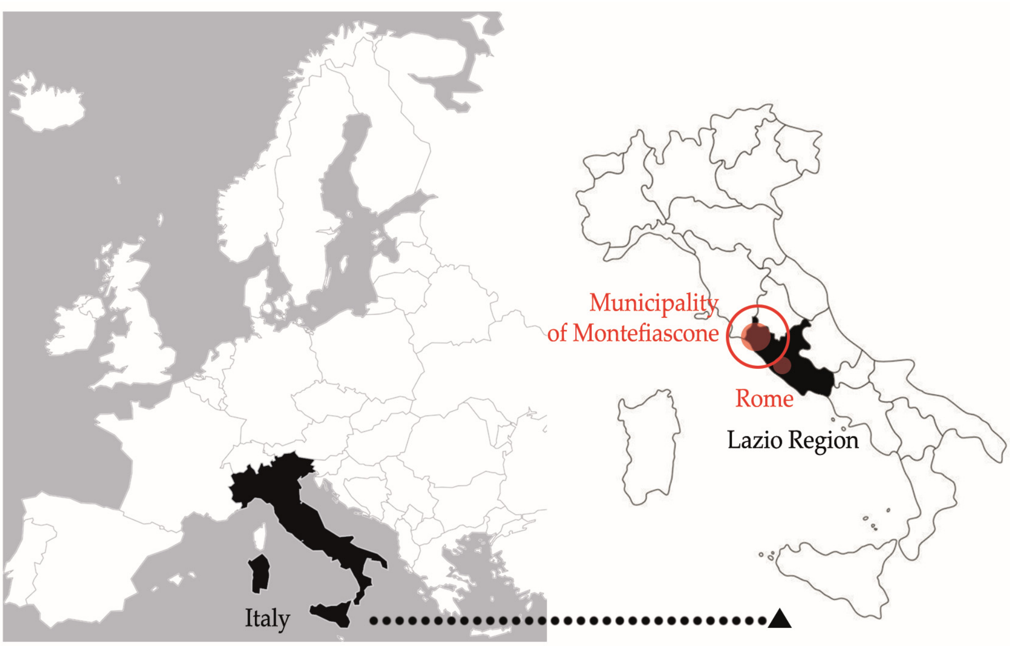


Figure 2. Geographical identification of the selected case study for experimental application—© authors.

In compliance with the landscape protection regulations established by the Cultural Heritage and Landscape Code [57], and in accordance with the Regional Landscape Territorial Plan (PTPR) approved by the Lazio region, the area where the case study is located is classified, according to Table A, as an agricultural natural landscape. It is situated among wooded areas and traversed by a dense network of waterways, as illustrated in Figure 3.

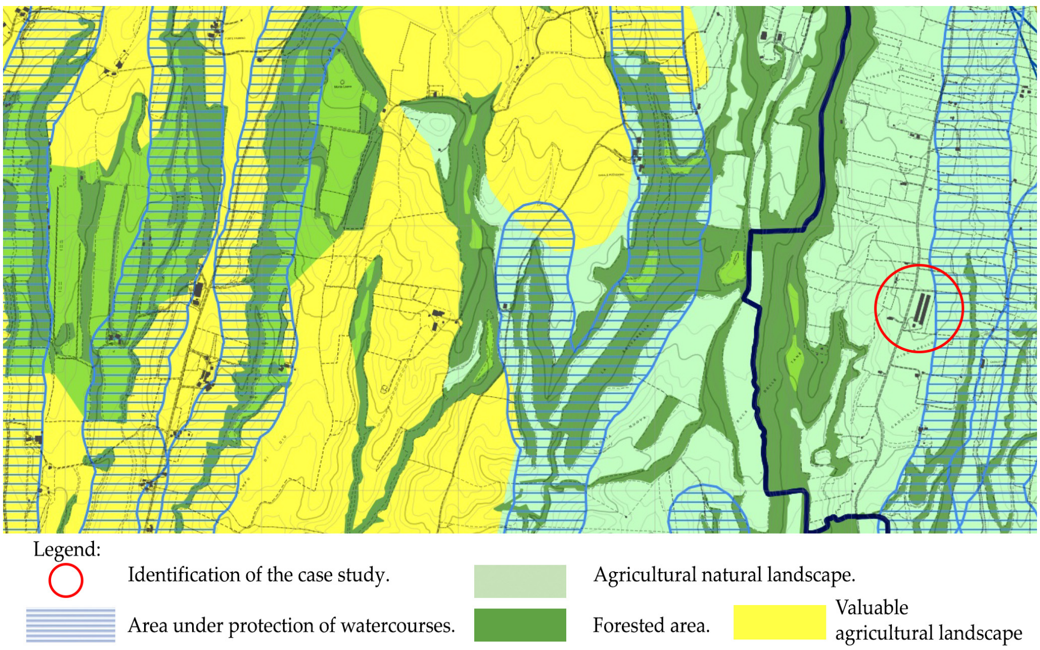


Figure 3. Classification of the agricultural landscape surrounding the case study, according to table A of the PTPR—© authors.

Although the landscape immediately surrounding the poultry tunnels under investigation is not classified as requiring direct protection, the adjacent areas are listed in Table B of the same PTPR as environmentally valuable zones deserving conservation measures. Specifically, the geographic area where the two poultry tunnels are located is characterized by the presence of waterways and forested landscapes, which are subject to specific regulatory protection, as illustrated in Figure 4.

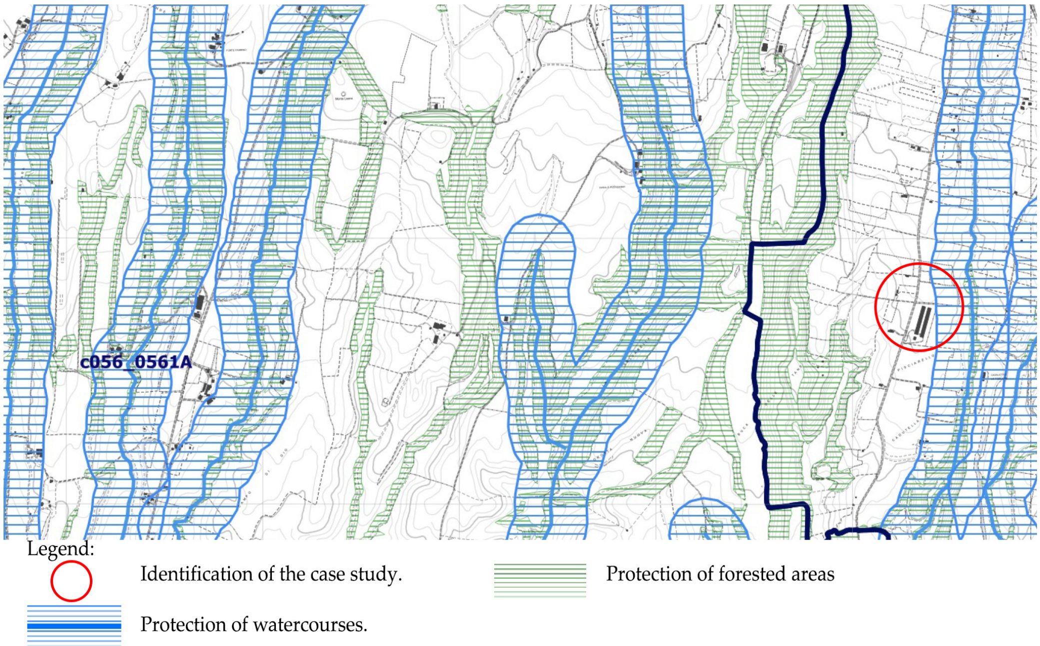


Figure 4. Classification of areas subject to regulatory protection, according to table B of the PTPR—© authors.

At the municipal level, the area where the two tunnels are located is also designated as an agricultural area of primary importance, pursuant to implementing the technical regulations of the current General Regulatory Plan. The cartographic reduction in this designation is presented in Figure 5 below.

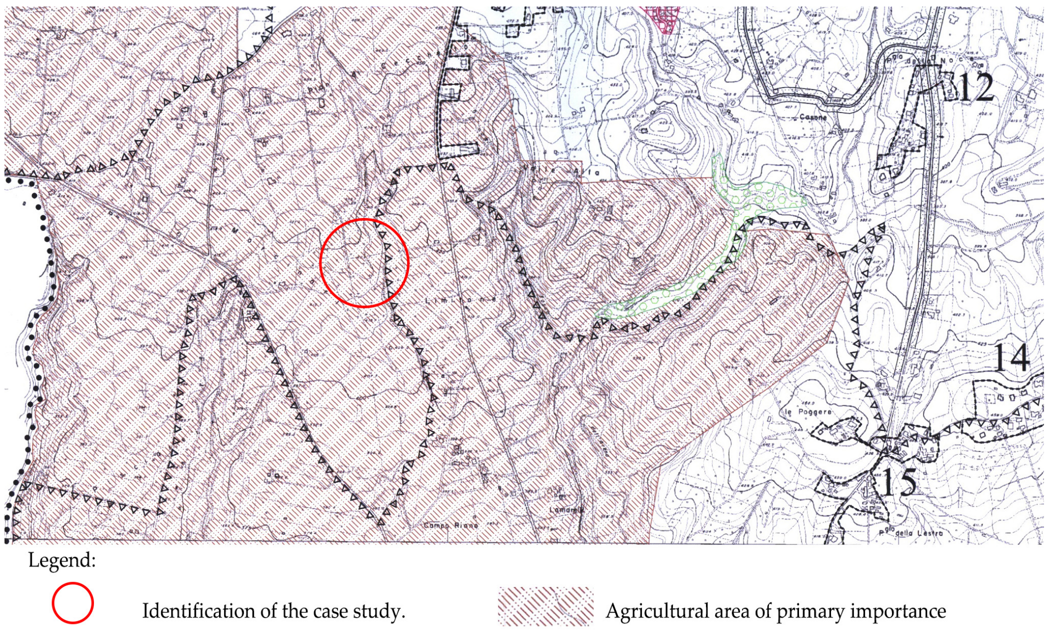


Figure 5. Classification of the case study area according to the provisions of the current municipal general regulatory plan. Cartographic reduction and reworking: author's elaboration—© authors.

The area is classified as a lowland agricultural territory, predominantly characterized by arable crops, with the possibility of irrigation systems due to the presence of shallow water tables. Within this zone, the construction of storage buildings for agricultural products, farm shelters, and livestock stables is permitted.

2.2. Technological Characterization and Environmental Standards

The two poultry tunnels are characterized by a spatial organization strictly aligned with the entrepreneurial purpose of egg production, serving solely as livestock housing for poultry farming. Similarly, the construction technology employed follows the standard commercial approach commonly used for similar structures, lacking artisanal refinements or architectural strategies aimed at minimizing the environmental impact of the two structures within their context, as illustrated in Figure 6.

Figure 6. The physical structure of the two poultry tunnels in relation to the surrounding environment—© authors.

This case is therefore highly emblematic of the scenarios outlined in the scientific background discussed in Section 2 of this study. It represents a structure located in an area of significant landscape value, where the settlement typology is primarily oriented toward maximizing productive activities. From a technological perspective, it is entirely attributable to the characteristics of commercial construction.

The case concerns two nearly identical structures, both in terms of construction and technological plant systems. These poultry tunnels, each housing 18,000 birds all-year-round, are characterized by a base structure measuring 120 m in length and 12 m in width. The load-bearing system consists of a steel frame with rectangular-section columns and a primary structure composed of truss beams. The vertical enclosures are likewise made of prefabricated steel-finished panels, as shown in the typical cross-section illustrated in Figure 7. The building envelope, which defines both the vertical and horizontal closures of the structure, is entirely composed of prefabricated technological components commonly used in agribusiness for cost-efficiency purposes.

Given the considerable environmental impact of similar structures, a thorough and unbiased assessment is necessary to explore strategies for mitigating their effects, both in terms of landscape integration and energy consumption.

To gain a better understanding of the behavior of the opaque enclosures in the case study, a dedicated monitoring system was installed to track relevant environmental parameters. The sensor specifications are summarized in Table 2 and further detailed in terms of positioning in Figure 8 below.

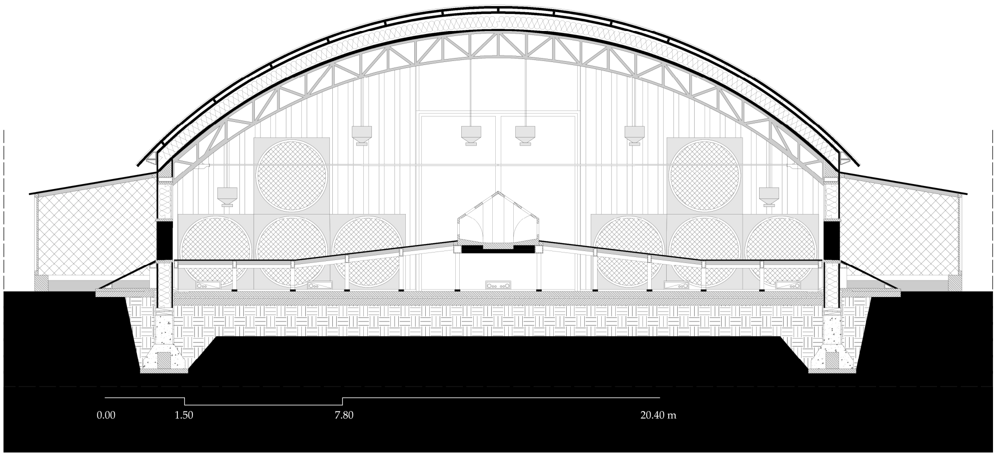


Figure 7. Typical section of the tunnel building selected as case study, highlighting the construction technology employed—© authors.

Table 2. Sensors used for monitoring environmental determinants—© authors.

Code	Type Model—Manufacturer	Designation	Accuracy
1A	CR1000X—Campbell Scientific	16-channel logger with eight I/O ports, complete with 4G router for remote control, two ethernet ports, and Wi-Fi capabilities	±(0.04% of reading + offset)
1B	CR300_422—Campbell Scientific	Basic six-channel logger with two I/O ports, integrated RF422 radio remote communication, complete with antenna	±(0.1% of measurement + offset)
1C	HFP01—Hukseflux	Heat flux plates	±3% (k = 2, standard ISO 17025)
1D	HygroVUE10_35M—Campbell Scientific	Air thermo-hygrometer. Complete with one spare sensitive element	±0.1 °C
1E	RAD10—Campbell Scientific	Protection for thermo-hygrometer, naturally ventilated multi-plate type	-
1F	LPPYRA10—Delta OHM	Spectrally flat class A (secondary standard) pyranometer according to ISO 9060:2018 [58]	±0.5%
1G	WindSonic_op1—Gill distributed by Campbell Scientific	2D sonic anemometer with RS232 interface	±2% of reading at 12 m/s
2A–2B	NR01—Hukseflux	Net radiometer with four elements (two global radiation and two infrared radiation)	±2.4%
3A	LoggerNet	Software for the comprehensive management of Campbell Scientific loggers	-

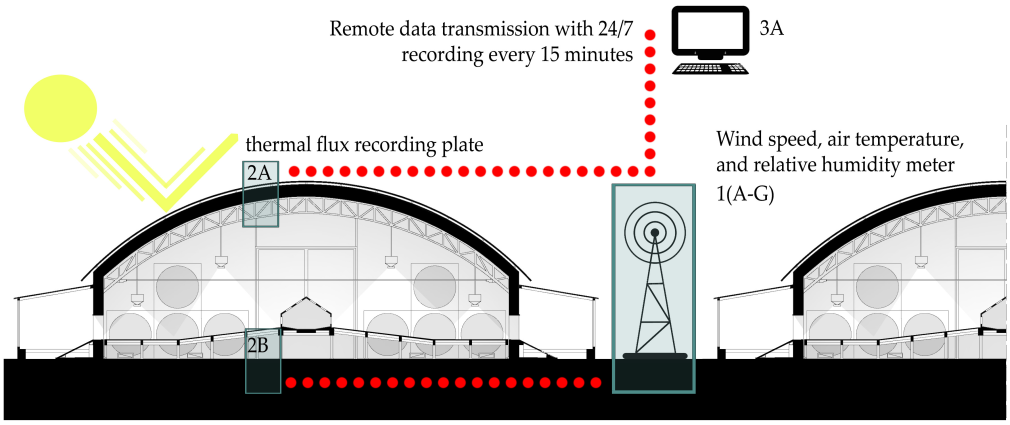


Figure 8. Localization of the various sensors positioned in the case study to capture the environmental determinants necessary for assessing the actual climatic conditions—© authors.

The meteorological sensors for wind speed, air temperature, and relative humidity were mounted on a metal tower positioned at a distance of approximately 3 m from the closest poultry tunnel. Although the proximity to the structures may introduce some localized disturbances—such as partial wind deflection or shading effects—this location was the only available open space on the property that met basic installation safety and accessibility requirements.

The sensors were installed at a height of 1.5 m above ground level, consistent with recommendations from the World Meteorological Organization (WMO) and standard agronomic practices for microclimate monitoring in agricultural environments [59].

While minor gap effects cannot be completely ruled out, the open corridor between the buildings (14 m wide) and the unobstructed vertical clearance at the tower's position ensured a reasonable degree of representativeness of ambient outdoor conditions relevant to the operational environment of the poultry tunnels.

2.3. Collection and Evaluation of Energy Consumption

Energy consumption has been derived through the acquisition and analysis of electricity supply bills. These energy demands arise from various sources within the livestock, including controlled mechanical ventilation and cooling systems, which ensure an optimal indoor microclimate for both the animals and the working staff. In addition, consumption is driven by lighting and electronic control systems, which maintain suitable environmental conditions for the livestock and support the overall management of operations. The energy consumption data are presented in Table 3. The table illustrates the monthly energy consumption in the current state scenario (SDF), where the livestock operates without renewable energy sources. Consequently, all electricity demand is met through the national energy mix supplied by the grid.

Table 3. Monthly energy consumption in the baseline scenario (SDF) measured on the electricity bills—© authors.

Energy Consumption (Electricity)	January	February	March	April	June	July	August	September	October	November	December
Electricity bills [kWh]	3503	3953	4714	4752	4671	6278	6931	6658	4566	3840	4247

The assessment of electricity consumption for the retrofit scenario (RIQ) was conducted by calculating the energy potentially generated by a fixed photovoltaic system installed on the building's roof, after assessing the load-bearing capacity of the roof to support the new photovoltaic system. For this analysis, the Photovoltaic Geographical Information System (PVGIS) was used, an online tool developed by the European Commission's Joint Research Center (JRC) to assess solar energy potential and photovoltaic (PV) system performance worldwide [60]. The results of this evaluation are presented in Figure 9 in terms of monthly energy output from fixed-angle PV systems and monthly in-plane irradiation. The calculation assumes the installation of 80 photovoltaic panels, each with a peak power of 410 W, evenly distributed between the southwest-facing (40 panels) and southeast-facing (40 panels) roof slopes. The analysis estimates an average annual energy production of 16,926 kWh for the southeast-facing slope and 16,385 kWh for the southwest. The productivity of the east pitch roof is slightly higher than that of the west pitch each month. The highest production occurs during the summer months, with a peak in June and July. In contrast, productivity is approximately one quarter of the summer values during the winter months of December and January.

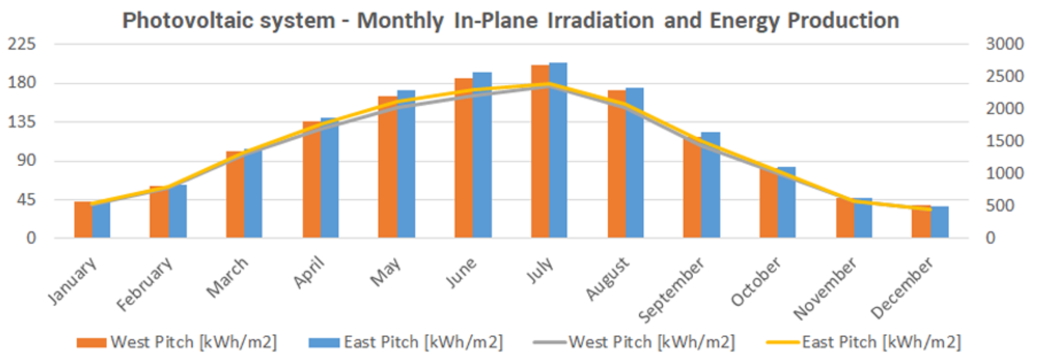


Figure 9. Monthly energy output from fixed-angle PV systems and monthly in-plane irradiation evaluated for the retrofit scenario (RIQ)—© Authors.

The results described above were assessed considering a system loss of 14% for both the east and west pitches, a change in output due to angle of incidence of 4.07% for the east pitch and 4.3% for the west pitch, spectral effects of 0.80 and 0.81, respectively, and temperature/low irradiance losses of 10.83% (east) and 11.12% (west), resulting in total losses of 25.85% for the east pitch and 26.26% for the west pitch.

The assessment of monthly energy consumption for the retrofit scenario (RIQ) is presented in Figure 10, comparing it with the monthly data for the current state (SDF). This histogram highlights the natural reduction in energy consumption following the installation of the photovoltaic system. It should be specified that this refers to the consumption of electricity supplied by the grid. From January to April, the gap between the two scenarios progressively increases, peaking in April. Although energy consumption rises due to cooling and mechanical ventilation during the spring and summer months, a significant reduction is observed in the RIQ. In autumn and winter, overall energy consumption gradually decreases, and the gap between the SDF and RIQ narrows due to the lower energy production of the photovoltaic system. The monthly data were subsequently used in the LCA analysis to assess the operational stage of each scenario.

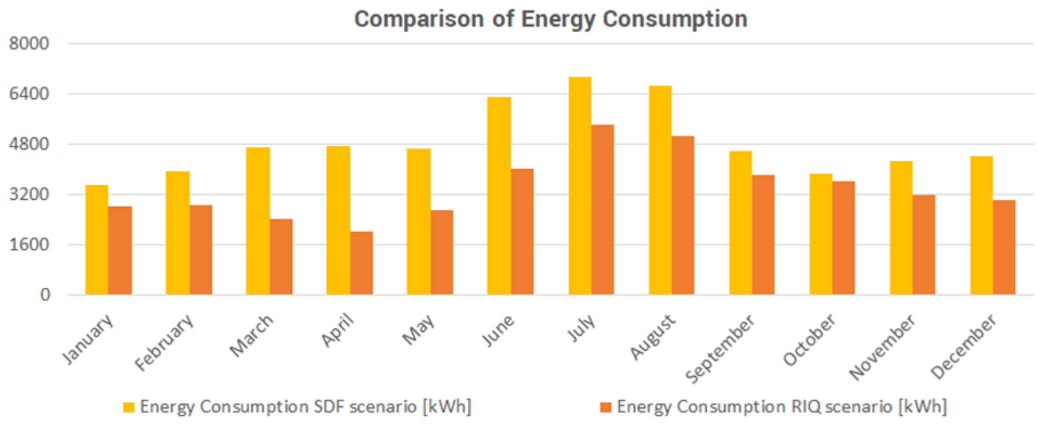


Figure 10. Comparison of monthly energy consumption in the baseline scenario (SDF) and the retrofit scenario (RIQ)—© authors.

3. Materials and Methods

3.1. The Monitoring Results in the Spring and Summer Cases

Based on the sensor system installed, as detailed in Section 3.2 of this research study, continuous monitoring was conducted throughout the spring and summer periods—identified as the most critical seasons for poultry tunnels geographically located in this area. By recording data at 15 min intervals, it was possible to assess the actual trends of air temperature, relative humidity, and solar radiation impacting the building envelope of the poultry tunnels (both at the roof and floor levels), as well as wind speed.

These data are graphically represented in Figures 11–15.

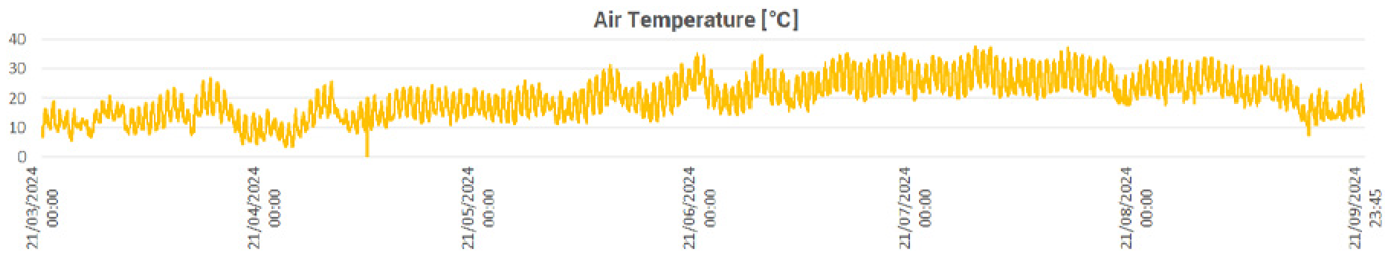


Figure 11. Environmental monitoring results: air temperature values recorded on-site every 15 min between 21 March 2024 and 21 September 2024—© authors.

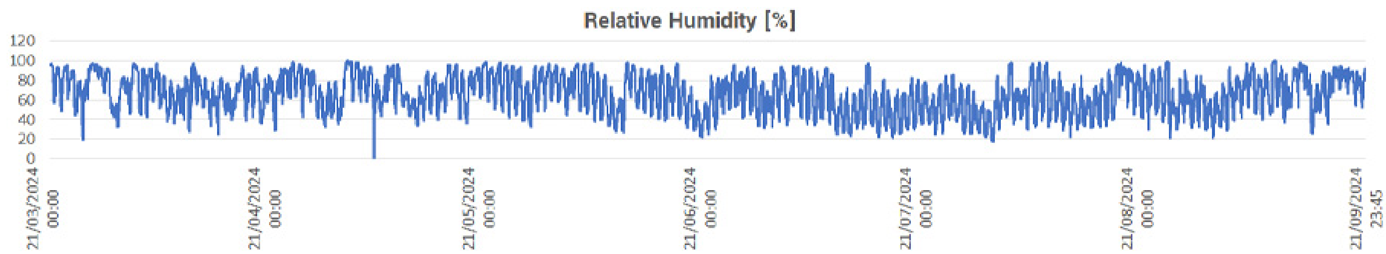


Figure 12. Environmental monitoring results: relative humidity values recorded on-site every 15 min between 21 March 2024 and 21 September 2024—© authors.

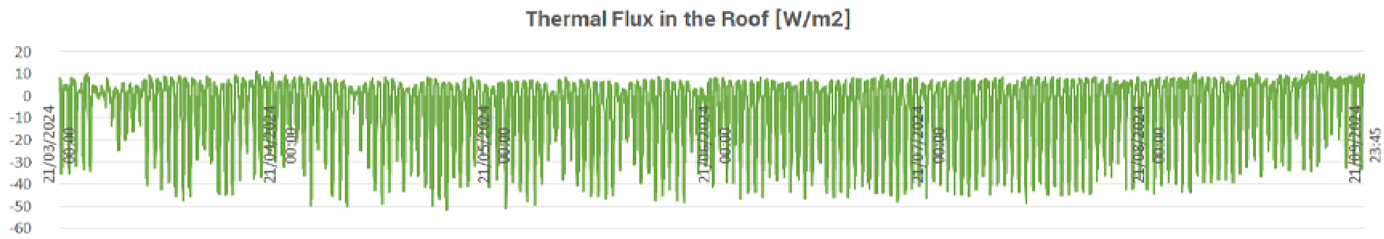


Figure 13. Environmental monitoring results: thermal flux values on the roof recorded on-site every 15 min between 21 March 2024 and 21 September 2024—© authors.

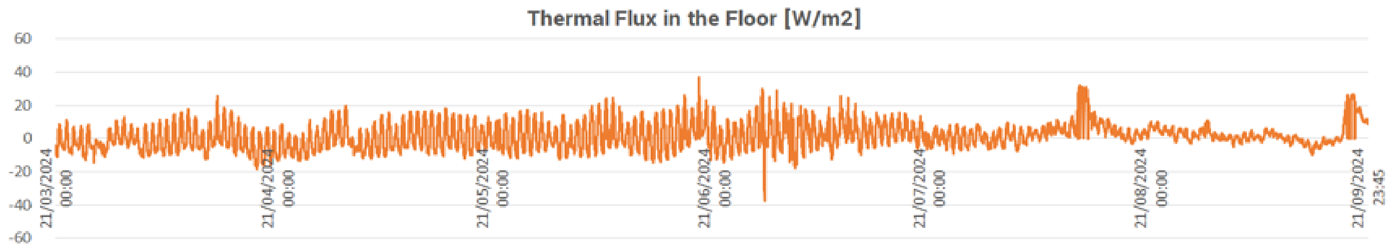


Figure 14. Environmental monitoring results: recorded on-site floor heat flux values every 15 min between 21 March 2024 and 21 September 2024—© authors.

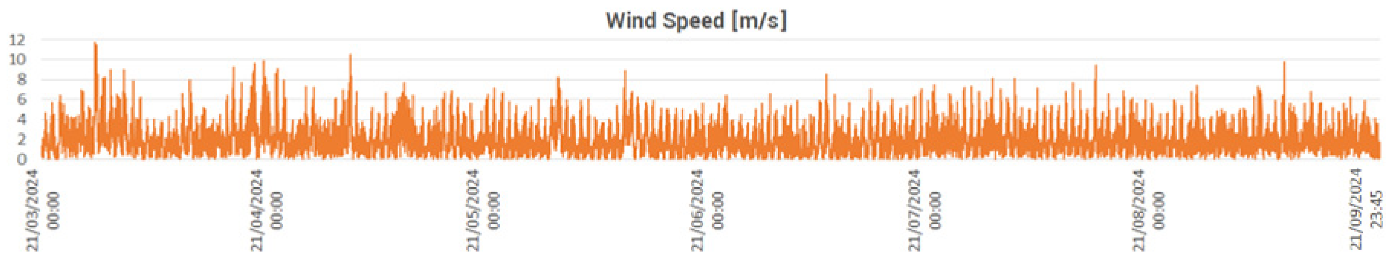


Figure 15. Environmental monitoring results: on-site wind speed values recorded every 15 min between 21 March 2024 and 21 September 2024—© authors.

The collected data, as highlighted in the aforementioned graphs, effectively represent the state of the art concerning the climatic conditions in which the poultry tunnels are located. This dataset itself constitutes an initial and original research output, directly derived from the environmental monitoring results. The data unequivocally reveal the critical trends of the summer period, which significantly affect the thermal and aerodynamic environment of the poultry tunnels.

Air temperature (Figure 11), in particular, follows the expected seasonal trend, remaining within the average range for the geographic area of reference. However, the peak values recorded in summer indicate potential criticalities for animal welfare. This concern is further compounded by variations in relative humidity (Figure 12), which may pose risks of thermal stress. These findings highlight the need to consider alternative envelope solutions beyond the commercially standardized ones, taking into account local specificities.

Similarly, solar radiation appears to confirm the hypothesis of significant thermal loads on the structure, particularly on the most exposed roof surfaces (Figures 13 and 14). This finding reinforces the feasibility of photovoltaic technology implementation within a potential operational scenario aimed at retrofitting livestock structures. While temperature-related criticalities may find some mitigation through the observed variations in ventilation (Figure 15), the intensity of solar radiation further substantiates and justifies the proposed operational scenarios for analysis. It is important to highlight, from the outset, that in the construction of a thermal model and for an accurate assessment of potential energy improvement scenarios, the contribution of rooftop photovoltaic panel installation to the actual reduction in thermal load must also be considered. The heat flux recorded and shown in Figure 13 would, in fact, be significantly different if solar radiation were partially absorbed by an additional element such as the PV system itself. The resulting shading effect on the structure, albeit partial, can lead to a reduction in the energy demand for ventilation and indoor cooling.

Such analyses, as previously mentioned, should be conducted using the LCA approach to define the long-term management strategies for the poultry tunnels throughout their entire life cycle.

3.2. Thermal Parameters Defining the Performance of the Building Envelope

The thermal performance of the building envelope is determined by a set of parameters that describe both steady-state and dynamic heat transfer phenomena. These indicators are essential for evaluating the energy efficiency, thermal comfort, and moisture behavior of opaque building components. The following parameters were assessed for the case study building components.

Thermal transmittance, commonly referred to as the U-value [W/m^2K], quantifies the steady-state rate of heat transfer through a building element per unit area and per unit temperature difference between the internal and external environments. It is calculated as the reciprocal of the total thermal resistance of the element, including both surface resistances. The total thermal resistance is the sum of the resistances of individual material layers, each computed as the ratio between layer thickness and its thermal conductivity, plus the internal and external surface resistances.

The surface mass represents the mass per unit area of a multilayered building component. It is calculated by summing the products of the density and thickness of each individual layer, expressed as kg/m^2. This parameter is particularly significant for evaluating the thermal inertia of opaque envelope elements, as greater surface mass contributes to improved thermal lag and attenuation of daily temperature fluctuations.

Periodic thermal transmittance, denoted as YIE, characterizes the dynamic behavior of a building envelope component under sinusoidal temperature variations, typical of day–night cycles. It is defined as the amplitude of the heat flow rate entering the internal environment per unit temperature variation on the external surface, under periodic conditions.

The attenuation factor, indicated as f, measures the capacity of an opaque component to reduce the amplitude of thermal waves between the exterior and interior surfaces. It is defined as the ratio between the periodic thermal transmittance (YIE) and the steady-state transmittance (U-value). This dimensionless coefficient ranges from 0 to 1, where lower values denote a better ability to attenuate heat flow fluctuations.

The thermal wave phase shift, or time lag ($\Delta\tau$), expressed in hours (h), quantifies the delay between the peak temperature on the external surface of a building element and the corresponding peak on the internal surface. It is obtained from the argument (phase angle) of the complex transfer function used in dynamic thermal analyses and is expressed in hours.

Permeance expresses the capacity of a building component to transmit water vapor through its thickness under a given vapor pressure difference. It is calculated as the inverse of the total vapor resistance [kg/m^2sPa].

4. Results and Discussion

This section is dedicated to the preliminary analysis and subsequent discussion of the results obtained through environmental monitoring and the application of the LCA methodology to the selected case study. By interpreting the data collected during the spring and summer phases—considered in itself an original research output—the impact of local climatic conditions on the actual energy performance of the poultry tunnel under study is evaluated, identifying potential criticalities related to both thermal management and energy consumption. The comparative analysis between the scenario based on actual energy consumption data and the expedited scenario representing a potential retrofitting process (focused on photovoltaic system implementation) allows for an estimation of the reduction in ecological footprint and operational costs of the livestock facility. The findings provide replicable options for the effective energy efficiency improvement of similar livestock farming structures.

4.1. Life Cycle Assessment

The LCA analysis conducted in this study aims to investigate the short- and medium-term environmental impacts associated with the current state of livestock (SDF) and an energy retrofit scenario (RIQ), which includes the installation of 80 photovoltaic panels on the roof, with a total peak power of 32.80 kW. This study was conducted using the OneClick LCA software in accordance with the EN 15978:2011 standard [61]. An evaluation period of 30 years is considered, encompassing the stages of production (A1–A3), transportation (A4), construction (A5), end-of-life (C1–C4), material-related use phases (B4–B5), and operational energy phases (B6). These assessments are presented in terms of global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), formation of lower atmosphere ozone (FO), and primary energy consumption (PE). In order to obtain an average assessment of environmental impacts related to scenarios, generic materials from the OneClick LCA database were employed for the production stage (A1–A3) and the Italian energy mix for the operational phase (B6).

The analysis was conducted using the gross floor area (in square meters) as the functional unit, considering a total surface of 1695 m^2. Both the building envelope materials (external walls, floors, and roof) and the structural components (steel frame and foundation), as well as the photovoltaic panels, were included in the analysis. In particular, only the photovoltaic modules were included in the analysis, while the metal substructure, inverters, storage batteries, and other components were not considered. In addition, doors, windows, furnishings, finishes, materials external to the building (vegetation, fences, pavements, temporary cabins, etc.), and mechanical systems (heating, cooling, mechanical ventilation, lighting, and machinery) were excluded. The quantities of construction materials are detailed in the bill of materials (Table 4).

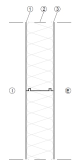
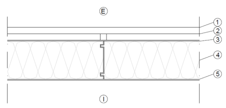
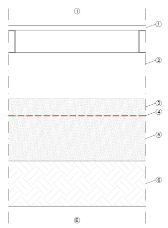
Table 4. Bill of main material quantities included in the assessment—© authors.

Description	Unit	Quantity	Description	Unit	Quantity
Steel frame	t	57.79	Wooden formwork	m^2	108.52
Rebar	t	29.09	PVC roofing elements	kg	3096.98
Concrete C 16/20	m^3	135.60	EPS insulation	kg	4464.36
Concrete C 25/30	m^3	506.40	Steel sheeting	t	54.40
Gravel	m^3	339.00	Raised floor system	kg	8284.10
Bentonite membrane	t	11.75	Photovoltaic panels	m^2	120.00

The production phases (A1–A3) include the extraction and transportation of raw materials to the manufacturing site, their processing, and the treatment of generated waste. Material quantities are expressed per square meter of envelope surface, following the stratigraphies detailed in Table 5. The transportation (A4) and construction (A5) phases are modeled using standard scenarios from the OneClick LCA database. The use phase (B3–B4) and end-of-life phase (C2–C4) are estimated based on standard processes from the

OneClick LCA database, accounting for both repair and replacement activities, as well as the machinery required for processing material waste by weight. The operational phase (B6) is assessed using energy consumption data outlined in the previous section, along with environmental profiles specific to the Italian context from the OneClick LCA database, derived from the Italian electricity mix based on IEA 2022 data.

Table 5. Stratigraphy of main elements of the building envelope, where Th.: thickness; Th. Cn.: thermal conductivity; Th. Rs.: thermal resistance; Ms.: mass; SH. Cp.: specific heat capacity; Vp. Rs.: vapor resistance; U-value: thermal transmittance; Tot. Th.: total thickness; S. Mass: surface mass; Yie: periodic transmittance; f: attenuation factor; Δτ: thermal wave phase shift; W: permeance—© authors, 2024.

	ID	Layer	Th.	Th. Cn.	Th. Rs.	Mass	SH. Cp.	Vp. Rs.
External Wall								
			[mm]	[W/m K]	[m^2 K/W]	[kg/m^3]	[kJ/kgK]	[-]
	1	Steel plate	0.50	52.0000	0.000	7800	0.45	9,999,999
	2	EPS foam board	120.00	0.0310	3.871	15	1.45	60
	3	Steel plate	0.50	52.0000	0.000	7800	0.45	9,999,999
		U-value	Tot. Th.	S. Mass	Yie	f	Δτ	W
		[W/m^2 K]	[mm]	[kg/m^2]	[W/m^2 K]	[-]	[h]	[10^{-12} kg/sm^{2}Pa]
		0.246	121	10.0	0.245	0.996	−0.6	0.020
Roof								
	ID	Layer	Th. [mm]	Th. Cn. [W/m K]	Th. Rs. [m^2 K/W]	Mass [kg/m^3]	SH. Cp. [kJ/kgK]	Vp. Rs. [-]
	1	PVC cladding	20.00	0.1700	0.118	1390	0.90	50,000
	2	Ventilated cavity	20.00	0.1250	0.160	-	-	-
	3	Steel plate	0.50	52.0000	0.000	7800	0.45	9,999,999
	4	EPS foam board	120.00	0.0310	3.871	15	1.45	60
	5	Steel plate	0.50	52.0000	0.000	7800	0.45	9,999,999
		U-value	Tot. Th.	S. Mass	Yie	f	Δτ	W
		[W/m^2 K]	[mm]	[kg/m^2]	[W/m^2 K]	[-]	[h]	[10^{-12} kg/sm^{2}Pa]
		0.232	161	37.0	0.226	0.973	−1.6	0.018
Ground Floor Slab								
	ID	Layer	Th. [mm]	Th. Cn. [W/m K]	Th. Rs. [m^2 K/W]	Mass [kg/m^3]	SH. Cp. [kJ/kgK]	Vp. Rs. [-]
	1	Perforated raised floor	20	52.0000	-	7800	0.45	-
	2	Ventilated cavity	300.00	-	-	-	-	-
	3	Concrete screed	80.00	0.3800	-	1000	1.00	-
	4	Waterproofing membrane	6.00	0.1700	-	1050	1.00	-
	5	Reinforced concrete slab	200.00	2.5000	-	2400	1.00	-
	6	Coarse gravel	300.00	0.7000	-	1500	1.00	-
		U-value	Tot. Th.	S. Mass	Yie	f	Δτ	W
		[W/m^2 K]	[mm]	[kg/m^2]	[W/m^2 K]	[-]	[h]	[10^{-12} kg/sm^{2}Pa]
		0.886	887	1020.0	0.025	0.028	−17.9	0.040

The results presented in the following section exhibit a series of methodological limitations arising from various factors, as they are based on the specific assumptions adopted in this study. However, it is important to highlight that variations in some of these initial assumptions could significantly affect the final outcomes. In particular, the LCA evaluation is highly sensitive to the assumptions regarding photovoltaic productivity, which in turn depends on the environmental conditions. In this research, the actual conditions of the surroundings of the case study were considered, which is located in a warm temperate climate area (Cfa), according to the Köppen classification, corresponding to climate zone E as defined by Italian regulations [62]. However, changes in the climatic zone could significantly affect the photovoltaic productivity. Within the Italian context, for instance, productivity could decrease by approximately 30% in alpine regions and increase by about 25% in Sicily, compared to the values estimated for the case study [60]. In addition, variations in the climatic zone would also have a significant impact on the building loads, which could either increase or decrease depending on the external climatic conditions. Moreover, factors such as the roof slope, its orientation with respect to north, and the presence of shading would considerably influence the system's productivity. In this study, two roof pitches inclined at 35° and oriented towards east and west, respectively, were considered, assuming no shading due to the absence of nearby buildings or tall vegetation. Nonetheless, variations in these parameters could also significantly affect the results.

The second type of limitation concerns certain assumptions related to the LCA. The emissions associated with energy consumption refer to the current Italian context and may vary depending on the national context considered. Moreover, these emissions were assumed to remain constant throughout the entire study period, whereas it is likely that they will gradually decrease over time as the national energy mix becomes progressively decarbonized.

Similarly, the photovoltaics' productivity was assumed to be constant over the study period, although panel efficiency typically decreases during the service life, with an annual degradation rate ranging from approximately 0.1% to over 1.0%, according to different studies [63]. Finally, another source of uncertainty lies in the use of generic data related to the Italian context for the building materials. While this choice is advantageous for clearly defining the boundaries of the analysis, it simultaneously introduces an additional geographical variable, which should be considered if attempting to extrapolate general results to case studies located in different contexts.

4.2. Life Cycle Assessment (LCA) Results

The graphs present the results of LCA comparing two scenarios: the current state (SDF) and a refurbishment scenario (RIQ) achieved through the installation of photovoltaic panels. The evaluation has been conducted over a 30-year analysis period per square meter of gross floor area (GFA) to assess the cost-effectiveness of energy efficiency measures in the short to medium term. The results indicate that introducing photovoltaic technology leads to substantial reductions in all environmental impact parameters evaluated.

The first diagram (Figure 16) compares the environmental impacts of each indicator in percentage terms relative to the first baseline scenario. From this overall assessment, it is possible to demonstrate a substantial reduction in environmental impact in the retrofitted scenario (RIQ) compared to the baseline (SDF). The photovoltaic system significantly decreases the global warming potential (GWP) by 33.44%. Furthermore, reductions are observed across other impact categories: ozone depletion potential (ODP) (11.60%), acidification potential (AP) (28.57%), eutrophication potential (EP) (22.84%), formation of ozone in lower atmosphere (FO) (17.78%), and primary energy demand (PE) (26.11%).

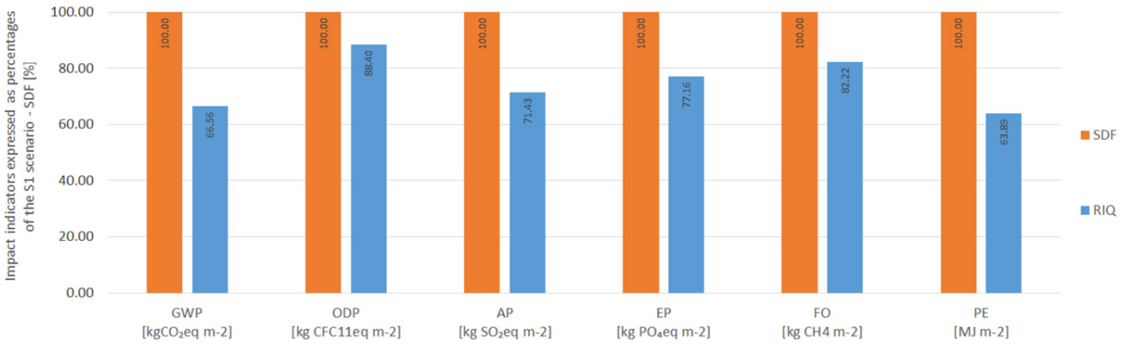


Figure 16. Environmental impacts in terms of GWP, ODP, AP, EP, FO, and PE for each of the two evaluated scenarios—© authors.

The second graph (Figure 17) depicts the environmental impacts in each life cycle assessment (LCA) stage, with each color representing a specific analysis phase. In this way, it is possible to obtain a detailed comparison of the contributions from each phase under the current state (SDF) and the refurbishment scenario (RIQ) enabled by photovoltaic panel installation. In the SDF, the operational stage (indicated in blue) contributes a significant portion of the overall impact. With the introduction of photovoltaic panels in the RIQ, there is a significant reduction in the environmental burden associated with energy consumption in each parameter evaluated: GWP by 33.43%, ODP by 11.60%, AP by 28.57%, EP by 22.84%, FO by 17.78%, and PE by 36.11%. Part of the reduction in environmental impacts avoided through the use of electricity generated by photovoltaic panels is offset by the higher emissions resulting from the extraction and production processes required for panel manufacturing (A1–A3): GWP by 0.80%, ODP by 13.06%, AP by 0.82%, EP by 1.82%, FO by 2.73%, and PE by 0.65%. In addition, the environmental impacts associated with maintenance are also higher in the RIQ, as the service life of the photovoltaic panels has been considered to be 20 years, which is shorter than the evaluation period (30 years). As a result, maintenance accounts for 2.69% of GWP, 15.44% of ODP, 1.97% of AP, 2.74% of EP, 5.96% of FO, and 2.73% of PE. These data underscore the importance of durability in assessing environmental impacts at the building scale, particularly when incorporating components with a lifespan shorter than the building in which they are installed [64]. However, the increase in environmental impacts from the product stage (A1–A3) and use stage (B4–B5) remains lower than the reduction occurring in the operational stage (B6), underscoring the environmental benefits of retrofitting existing high-energy-consuming structures with photovoltaic panels.

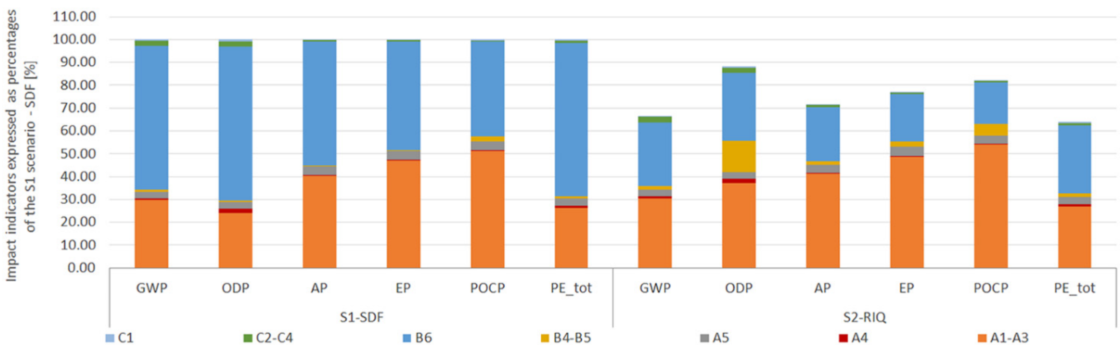


Figure 17. Contribution of each life cycle stage in determining the overall environmental impacts in terms of GWP, ODP, AP, EP, FO, and PE for each of the two evaluated scenarios—© authors.

In addition to the significant reduction in environmental impact demonstrated through the LCA, it is worth emphasizing that the energy retrofitting of structures such as poultry tunnels can strengthen the economic competitiveness of agricultural enterprises and contribute to the vitality of rural areas [65], in line with the considerations introduced in Section 1.1.

This phenomenon has also been observed by other authors and is well established within the scientific debate, within which this study positions itself [66,67].

5. Conclusions

This study demonstrates that integrating photovoltaic systems into livestock buildings, supported by empirical climatic monitoring and life cycle assessment, can significantly reduce environmental impacts—achieving a 33.4% decrease in GWP and a 26.1% reduction in energy use.

The results of this research confirm the critical role that energy efficiency improvements in the existing building stock play, even in rural contexts, including structures that architecture and engineering disciplines have often overlooked. In particular, the study highlights how the integration of photovoltaic systems significantly reduces both the environmental impact and operational costs of buildings traditionally designed solely to maximize available space for livestock farming while prioritizing minimal construction costs.

In addition, the comparative LCA analysis highlights that the RIQ consistently performs better than SDF across all assessed impact indicators. This significant decrease is primarily attributed to the shift from conventional energy sources to renewable photovoltaic energy, underscoring its potential for reducing carbon footprint and mitigating long-term operational impacts. This long-term environmental advantage in the operational phase positions PV systems as a key solution for sustainability and mitigating operational carbon in rural buildings characterized by high energy consumption through building-scale energy interventions. The adoption of renewable photovoltaic energy plays a crucial role in the transition from fossil fuels and the effective reduction in environmental impacts. This is particularly relevant in rural areas, where implementing systemic solutions can be challenging due to the often fragmented and heterogeneous nature of the built environment. Through the life cycle assessment (LCA) methodology, this study reinforces the well-known benefits of photovoltaic energy, demonstrating the effectiveness of the proposed solution. Furthermore, the study highlights its potential replicability in other livestock farming and rural production contexts, offering a scalable approach to more sustainable energy practices.

Replicability should be understood strictly in methodological terms, as the specificity of this study is based on the accuracy of environmental parameters. While these parameters may be comparable to the geographical standards commonly used in similar energy simulations, they have allowed for a preliminary assessment of the actual conditions to which the two poultry tunnels are subjected.

It should be clarified that these reflections are based on the activities carried out and therefore on the evaluation of a specific case study, already geographically defined and internally characterized in terms of energy balance (given that the presence of 18,000 livestock units remained constant throughout the monitoring period). The fact that the poultry tunnel selected as a case study is located in the temperate Mediterranean zone has led to the early consideration of spring and summer conditions as the most critical, in line with the standard management practices of livestock facilities in central and southern Italy.

While the experimental method can, in principle, be directly replicated, the environmental characterization specific to this case may substantially influence the outcomes when applied to similar facilities located in geographically distant and climatically different regions from that of Tuscia Viterbese. Though this consideration may seem self-evident to those engaged in energy assessment, and perhaps redundant in the overall structure of this paper, it is nonetheless deemed necessary to emphasize the intrinsic relationship between a built structure and its context. Highlighting the relevance of site-specific features is not trivial, particularly within the framework of a multidisciplinary research project such as the one presented here

The adopted approach, which results from a direct combination of empirical data and comparative analysis, opens up new research scenarios primarily focused on evaluating the actual environmental responsiveness of livestock structures. While this initial research has considered environmental impacts and energy consumption, the recorded climatic variables prompt further reflection on the building envelope and the necessity of moving towards a non-standardized design, one specifically tailored to meet the precise needs of the given context.

It is also important to highlight that the results obtained appear to support findings from portions of the literature cited throughout this paper, which suggest that energy efficiency strategies based on renewable energy sources—such as the one analyzed in this study—not only represent an effective solution from an environmental perspective, but also serve as tools for economic and social enhancement in rural contexts. In this regard, interventions on existing productive structures may thus be regarded as strategic levers for strengthening both the resilience of agricultural enterprises and the processes of sustainable development in marginal areas of the inner territories.

Future research and development efforts must acknowledge that, alongside operational and business considerations, there is a need to establish a fundamental architectural principle for livestock facilities. This specifically refers to the need to address the design of the building envelope and the materials used, ensuring that vertical closures are consistent with local environmental determinants and promoting the use of materials that are more coherent with the rural landscape. This approach would help avoid the indiscriminate use of prefabricated steel elements, regardless of the specific characteristics of the site. While limited to specific climatic conditions and operational scenarios, the results offer a solid foundation for future research and practical guidelines to promote sustainable retrofits in rural agricultural infrastructure.

Moreover, beyond assessing the environmental impact of certain materials during their production phase, attention should also be given to the esthetic and contextual integration of livestock buildings, particularly in areas of high natural value. It is crucial to consider how these structures can engage in a meaningful dialog with their surroundings, contributing to the quality of the agricultural landscape. These aspects are not only relevant to the entire life cycle of the building, but also to the well-being of the environment in which it is situated. These considerations will shape the next steps in research and development.

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