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Energy Sustainability in the Ripening of Traditional Cheese: Renewable Energy Sources and Internet of Things Based Energy Monitoring

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Abstract

Improving the energy efficiency of traditional production methods while preserving their cultural and economic value is a challenge aligned with the Sustainable Development Goals of the 2030 agenda. Refrigeration during cheese maturation is particularly energy-intensive, contributing significantly to greenhouse gas emissions and operating costs. An approach to make traditional cheese production more sustainable, through the development of a prototype ripening chamber with a natural refrigerant-based refrigeration system powered by renewable energy was studied. A dedicated system based on an Internet of Things architecture was developed using low-cost sensors, microcontroller units, and single-board computers to enable real-time measurement and monitoring of environmental variables and energy consumption throughout the ripening process. A comparative analysis was conducted using ewe's milk cheese, produced and ripened with Protected Designation of Origin conditions, in both the prototype and the conventional chambers over four weeks, quantifying energy consumption and evaluating product quality. Results demonstrate the technical feasibility of energy efficient and sustainable refrigeration systems, as well as the possibility of retrofitting installed cheese ripening chambers with affordable IoT monitoring systems, while maintaining traditional cheese quality standards.

Keywords: cheese production; sustainability; energy; IoT in dairy industry; color analysis; sensory analysis

1. Introduction

According to archaeological studies, the production of cheese dates back to 7000–6500 BC, when pottery was used for milk storage and ceramic sieves for molding cheese [1]. The classical agronomists of Ancient Rome were the first to document the importance of cheese, including a detailed description of cheese making by Columella [2]. Actually, over 500 commercial types of cheese may be found worldwide [3], including a large variety of tastes, textures, scents, rinds, and shapes, resulting from the different biochemical composition, manufacturing technique, ageing process and cultural background [4].

In the European Union, quality schemes protect those cheeses linked to a specific geographical origin, with unique characteristics and where the knowledge is supported by a long tradition, namely Protected Denomination of Origin (PDO) and Protected Geographical Indication (PGI). In Portugal, there are 13 cheeses with PDO and 1 cheese with PGI, mostly produced in small-scale facilities and using milk from small ruminants, such as cheese Queijo Serpa (Portugal) produced from raw ewe's milk [5].

The production of this cheese starts with the filtration of the milk, followed by heating to about 30 °C inside the coagulation vat, then an aqueous solution of Cynara cardunculus, is added for the enzymatic coagulation of casein. After 1 h, curd is cut, drained from the whey, molded into a cylindrical shape, salted and placed inside the ripening room [2].

Ripening time is a minimum of 30 days, during which a set of biochemical alterations, caused by the native microflora, will influence the texture, aroma, and flavor, increasing the sensory complexity of the cheese [3,6]. Nonetheless, environmental conditions inside the ripening room, such as temperature and humidity [7], must be controlled over time to lead to the desirable characteristics [8] and to meet the mandatory regulations of PDO cheeses [9].

The most common process for temperature control inside the ripening room is the vapor-compression refrigeration system (VCRS), invariably on-grid and using three-phase electric power, representing up to 40% of the energy consumed during the production process [10].

The need for sustainable development, in a process that "meets the needs of the present without compromising the ability of future generations to meet their own needs" [11], gave rise to the international commitments that have gone through the United Nations Millennium Development Goals (MDGs) [12] and evolved into the Sustainable Development Goals (SDGs) defined in the 2030 Agenda for Sustainable Development [13]. Achieving sustainable production systems is a global challenge aligned with the SDGs that promote the shift towards more energy-efficient industries: SDG 12 on promoting responsible consumption and production; SDG 9 on promoting sustainable industrialization; SDG 7 on the adoption of affordable, reliable, and clean energy; and SDG 13 on combating climate change [13–16]. Improving the energy efficiency of traditional production methods while preserving their cultural and economic value is essential to obtain a more sustainable and resilient dairy industry. While new energy-efficient technologies and production processes can be implemented, this may also be achieved with small, affordable changes to systems already in place, which is the case in installed cheese ripening chambers at production plants [10,17,18].

Refrigeration plays a crucial role in the dairy industry, particularly during the ripening phase of traditional cheese production, which requires strict environmental control over temperature, humidity, and airflow [11]. However, conventional refrigeration systems are typically energy-intensive, contributing significantly to greenhouse gas emissions and operational costs [12]. In recent years, increasing emphasis has been placed on developing sustainable refrigeration technologies that reduce environmental impact while maintaining the high standards required for food safety and quality [13,14].

Traditional refrigeration systems in cheese maturation rely heavily on vapor compression cycles powered by electricity [15,16]. These systems are not only energy-demanding but also often use hydrofluorocarbon (HFC) refrigerants, which have high global warming potentials (GWPs) [19]. Studies have shown that refrigeration can account for up to 60% of total energy consumption in dairy processing facilities [7]. The need for continuous operation and precise control further amplifies the energy burden.

To address the environmental concerns associated with conventional refrigerants, significant research has been directed towards the adoption of natural refrigerants which have negligible or zero GWP [20]. CO_2-based transcritical systems have gained attention in medium- and large-scale food refrigeration applications due to their thermal efficiency and safety profile [21].

The integration of photovoltaic (PV) systems with refrigeration has become increasingly feasible due to falling solar panel costs and advancements in power electronics. Hybrid systems that combine solar power with conventional electricity grids can help offset peak energy loads in cheese maturation facilities. Several case studies report the successful implementation of solar-assisted cooling systems in rural dairy farms, demonstrating both environmental and economic benefits [20,22].

Despite these advancements, the adoption of sustainable refrigeration technologies in traditional cheese production remains limited, particularly among small and medium-sized producers. Cultural and economic barriers, combined with the complexity of retrofitting existing infrastructure, have slowed the transition. However, pilot studies have demonstrated that retrofitting aging ripening chambers with automated control and variable-speed compressors and advanced insulation materials can reduce energy usage by up to 30% without compromising cheese quality [23].

The Internet of Things (IoT) is a network of interconnected physical devices, the "things", which have sensing and/or actuation capabilities, are potentially programmable, and have processing and communication capabilities. IoT devices can collect, exchange, and process data, making use of various communication technologies, always including Internet connectivity [24]. IoT architectures present several common characteristics: communication, including the Internet; low-cost off-the-shelf electronic components, namely sensors, actuators, and communication modules; and low-power data processing systems, namely Microcontroller Computing Units (MCUs) and Single Board Computers (SBCs) [25–27].

The use of IoT in the dairy industry, particularly in cheese production, has shown the potential to improve product quality, operational efficiency, and make the industry more efficient and sustainable. Sensor networks enable precise control and monitoring of critical parameters, such as temperature and humidity, as well as resource consumption. Their use within IoT architectures, which combine with peripheral computing and cloud computing, enables the optimization of the production process, resulting in energy savings and a reduced carbon footprint. However, several challenges must be considered, including scalability, interoperability, data security, and economic viability [23,28–34].

An innovative ripening chamber prototype was developed and implemented at the Polytechnic Institute of Beja, integrating renewable energy sources (solar, wind, and biomass) to improve energy efficiency in artisanal cheese production. A dedicated IoT

system was conceived and developed for real-time monitoring of environmental variables (temperature and humidity) and energy consumption, adapting advanced sensor technology to the traditional ripening process.

The study conducted a comprehensive comparative analysis between the sustainable prototype and conventional chambers in ewe's cheese production, quantifying energy consumption in both systems and evaluating the impact on final product quality through sensory and colorimetric analyses. The results demonstrate the technical and economic feasibility of sustainable refrigeration systems in the dairy industry, as well as the retrofitting of conventional chambers with an IoT system architecture, contributing to the Sustainable Development Goals related to clean energy, sustainable industrialization, and climate change mitigation.

2. Materials and Methods

The system developed aims to enable cheese production through the exclusive use of renewable energy sources, thereby fostering the transition of the dairy industry toward a fully sustainable and decarbonized model [13,20,35]. The whole process integrates wind energy, solar thermal and photovoltaic systems, and biomass with thermal regulation supported by Phase Change Materials (PCMs). This approach, following similar approaches in other sectors [36,37], seeks to minimize fossil fuel dependency during both cheese production and maturation phases, while ensuring product quality and process reliability [22]. However, the scope of the article is limited to the evaluation of the impact of using new, and more sustainable, refrigeration technologies, powered by solar photovoltaic systems, in the ripening phase.

The system architecture is structured around three core functional levels: (i) energy consumption, (ii) energy conversion and storage, and (iii) energy generation.

The energy consumption level includes the electrical load associated with the ripening chambers, which are conditioned using refrigeration systems. The cheese ripening process is subdivided into two stages, with a tightly controlled environment: the first at a lower temperature and higher relative humidity, and the second at a higher temperature, but lower relative humidity. These environmental conditions are critical to ensure the organoleptic properties of the final product.

The energy conversion and storage stage encompasses a refrigeration cycle composed of a compressor, condenser, and heat exchanger. This level also includes a battery bank for storing excess energy produced during low-demand periods, an inverter, and auxiliary electrical components required for system operation.

The energy generation stage is responsible for supplying electrical energy based on process requirements. The subsystem includes a photovoltaic system. This renewable energy powers the electrical loads through an integrated control panel and energy management system. A grid connection is maintained as a backup measure to ensure system reliability in the event of renewable source unavailability.

The prototype ripening chamber, using a CO_2-based transcritical compressor, is compared with one working with conventional technology, using an R404A-based [38] compressor. Both chambers have a volume close to 28 m^3. The prototype demands approximately 2.2 kW, and the conventional 1.8 kW, of electrical power under standard operating conditions. The photovoltaic production system is based on an array of 5.8 kW total maximum power output, using 580 W modules [39]. Made with N-type tunnel oxide passivated contacts (TOPCon) technology, they feature higher output (580 W over 2.58 m^2) and efficiency (22.5%), better degradation resistance, and enhanced energy yield in hot climates, compared with other PV technologies [40].

To evaluate the system's performance, an energy monitoring infrastructure was developed and implemented both in the prototype (renewable-powered) ripening chamber and in a traditional ripening chamber using conventional technologies. Real-time monitoring of electrical consumption was conducted across all relevant equipment and process stages. The resulting data enabled a comprehensive assessment of energy usage across and renewable energy production during the cheese ripening. This comparative analysis provides a technical basis for identifying energy-saving opportunities and validating the benefits of integrating renewable energy and energy-efficient technologies into traditional dairy processes.

2.1. Measurement and Monitoring System

The measurement and monitoring system was designed and developed using an IoT architectural approach. The system uses local measuring modules with communication capabilities, built with sensors and actuators suitable for measuring and controlling the relevant physical quantities. The modules are connected to a local data aggregator, built on a Debian Linux 12 server [41,42], running in headless mode on a Raspberry Pi 4 [43] SBC. The local aggregator, which includes an integrated Mosquitto MQTT broker [44], orchestrates the data collection from the measuring modules, performs data pre-processing, provides access to data visualization in real-time, and records all the relevant information in local and remote databases.

The data measurement system is organized into three specialized subsystems to monitor (1) the environment within the ripening chamber and pilot plant; (2) the outdoor environment; and (3) the energy consumption of the ripening chamber. A detailed description of each subsystem, including its corresponding function diagram (Figures S1–S3) and the technical specifications of its sensors and variables (Tables S1–S3), is provided in the Supplementary Material text, figures and tables.

The Ripening Chamber Environmental Variables Measurement Subsystem is responsible for monitoring the ripening chamber and pilot plant environment. It uses a custom module built around the Espressif ARM-based ESP32-S2 MCU [45,46] in a development board and various sensors. The SHT20 (Sensirion AG, Stäfa, Switzerland) digital humidity–temperature sensor is used to measure the chamber temperature and relative humidity. If the chamber relative humidity is above a user-defined Humidity SetPoint, the MCU opens the electro valve of the humidifier sprinkler system during a predefined time. The water flow is measured with a YF-S201 (Shenzhen Maoye Electronics Co., Ltd., Shenzhen, China) sensor, which consists of a plastic valve body, a water rotor with a magnet, and a Hall effect sensor. The number of pulses detected has a linear relation to the water volume. The pilot plant temperature and relative humidity are measured with the DHT22 (Aosong Electronics Co., Ltd., model, Guangzhou, China) digital humidity–temperature sensor.

The Outdoor Environmental Variables Measurement Subsystem is responsible for monitoring the outdoor environment. All the outdoor environmental variables are acquired with a low-cost SBS-WS-600 (Steinberg Systems expondo GmbH, Berlin, Germany) weather station (WS). It integrates a temperature sensor, a relative humidity sensor, a protective radiation shield, a cup anemometer, a wind vane, a tipping-bucket rain gauge, and a light sensor. The WS sensor data are encoded and sent in a 968 MHz, frequency shift-keying (FSK) modulated, RF signal. A software-defined radio (SDR) module is used to capture the RF signal and recover the encoded datapack.

The Electrical Energy Consumption Measurement Subsystem is responsible for monitoring the ripening chamber's energy consumption, using Shelly Pro Series modules (Shelly, Sofia, Bulgaria) [47,48] to track the electrical load of the compressor, condenser, evaporator, and controller. The modules have RMS voltmeters for each phase, and RMS ammeters

via clamp-on Current Transformer (CT) for each phase/neutral. All the units process the acquired signals to obtain the relevant electrical quantities: instant voltages, currents, and power; maximum, minimum, and average values, and energy consumption, over a determined time.

All the data captured during each measurement cycle is formatted and encoded into a JSON packet that is both published in the local MQTT broker and stored in a local SQLite database (version 3.46). A copy of the local database is sent to a remote server for processing.

The aggregator's functionality is implemented through several Python (version 3.13) scripts, managed as persistent background processes using systemd services. Environmental and water consumption data is captured redundantly via the serial port and by subscribing to the local MQTT broker. Resilience against potential network or serial connection failures is increased this way. For outdoor environmental data emitted by the weather station using RF signals, a script decodes the signals captured by a USB RF receiver. This data is then published to the MQTT broker. Energy consumption data from the Shelly devices is acquired through three parallel methods for increased reliability: directly from the devices on the local network via JSON-RPC over HTTP; by subscribing to the MQTT broker; and redundantly from the Shelly Cloud with REST API. The data from all these sources is processed and stored locally in a SQLite [49] embedded database for immediate access. For long-term storage and advanced analytics, the data is also forwarded to a remote PostgreSQL [50] database server. Real-time monitoring is facilitated by a Node-RED instance running on the aggregator, which provides interactive web-based dashboards.

A dedicated local module, with a touch screen, allows operators to monitor and adjust the humidity in the ripening chamber. This module consists of another Raspberry Pi running FullPageOS [51], a specialized Linux operating system distribution that launches a full-screen web browser on startup. The browser's starting URL is pointed to the Node-RED dashboard hosted on the data aggregator, providing an intuitive, on-site interface for operators to view live data and interact with system controls without needing a separate computer.

All modules are connected via a local network based on a MikroTik router (RB960PGS and RBwAPG-5HacT2HnD-BE, Riga, Latvia) [52,53] with wireless capabilities, using either WiFi or Ethernet. The aggregator module connects to a remote server via the Internet for data backups and further analysis.

The illustrative diagram presented in Figure 1 shows the system's primary functional blocks and their hardware components.

The Node-RED-based graphical user interface provides the ripening chamber operators with real-time monitoring and control through data subscription/publication in the data aggregator's MQTT broker. A ripening chamber dashboard, as shown in Figure 2 with the "Câmara 1" tab, displays the temperature and relative humidity inside the curing chamber, and their respective set points, as well as the temperature and relative humidity in the pilot plant where the chamber is operating. In addition to environmental data, the dashboard presents the electrical power consumption of the main components of the refrigeration system: the compressor, the condenser fan (outside), and the evaporator fan (inside). The interface is interactive, allowing an operator to directly modify the chamber humidity set point through the Local Monitoring touch screen.

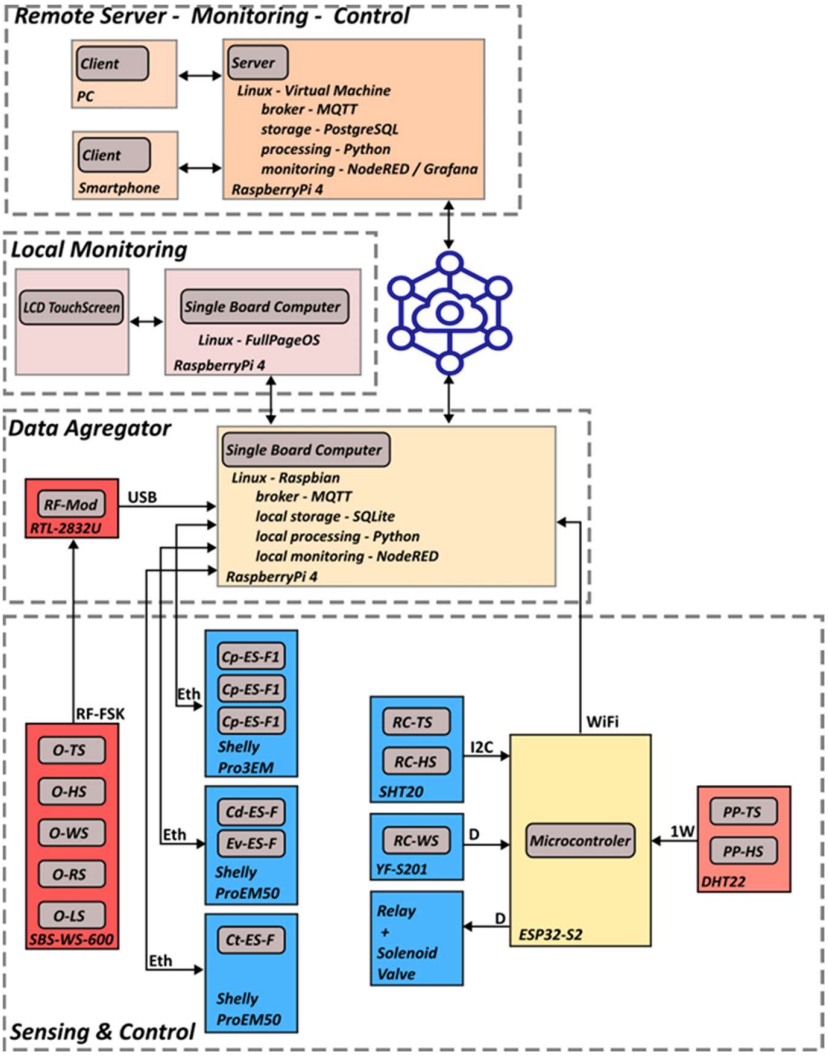

Figure 1. IoT measurement and monitoring/control system: illustrative diagram with the primary blocks and their hardware components.

Figure 2. Monitoring/control system graphical user interface: the Node-RED-based dashboard provides real-time data visualization for environmental variables and electrical energy consumption. Câmara 1 tab, shows the ripening chamber temperature and relative humidity, the pilot plant temperature and relative humidity, and the compressor, condenser, and evaporator electrical consumptions. The dashboard includes interactive elements allowing an operator to modify system parameters, such as the humidity setpoint, shown here at 80%.

2.2. Cheesemaking

A batch of 60 semi-hard cheeses was produced using raw sheep's milk, coagulated with aqueous extract of *Cynara cardunculus* L. flower at 30 °C for 1 h. Then, the gel was cut, the whey was drained off, and the curd was collected and pressed inside cylindrical plastic molds. Each cheese presented 110 mm diameter, 60 mm height, and around 300 g weight. Cheeses were divided into two groups of 30 units each and placed into each one of the ripening chambers for 4 weeks. The group coded "P" was placed inside the prototype ripening chamber, powered with PV energy, while the group coded "C" was placed inside the ripening chamber working with conventional technology, working entirely on-grid, as described previously.

2.3. Color Analysis

The instrumental evaluation of the appearance of the rind and paste of cheeses, at the end of ripening time, was performed through the measurement of RGB color channels of digital images, on a scale from 0 to 255. The digital image acquisition of the rind and paste of cheeses was conducted according to [54] and analyzed with ImageJ software version 1.52d (National Institute of Health, USA) for the measurement of RGB components. Samples were analyzed in quintuplicate.

2.4. Sensory Analysis

Sensory analysis was conducted following the procedure described by [55], with adaptations for this study. A total of 54 assessors (38 females and 16 males; mean age 40 years, range 15–63) participated voluntarily. Recruitment was carried out among staff and students at the National Institute for Agricultural and Veterinary Research (INIAV) and the Polytechnic Institute of Beja (IPBeja). The panel was composed primarily of naïve consumers but also included participants with previous training in general sensory evaluation and more than 500 h of experience in food-related sensory panels, ensuring a balance between consumer-oriented responses and consistent evaluation. All participants provided informed consent before the test.

The sessions were conducted in sensory analysis rooms designed in accordance with ISO 8589:2007 [56]. Each assessor was seated in individual booths under uniform white lighting and controlled temperature conditions. Cheese samples ripened in the prototype chamber (P) and in the conventional chamber (C) were cut into standardized pieces ($\approx 2 \times 2 \times 2$ cm), served at 18 ± 1 °C, and presented in randomized order in Petri dishes coded with three-digit numbers to ensure blind evaluation. Water and unsalted crackers were provided for palate cleansing between samples.

Assessors evaluated five attributes—Appearance, Paste Color, Texture, Flavor/Aroma, and Overall Liking—using a 9-point hedonic scale (1 = "dislike extremely," 9 = "like extremely") [57]. Panelists received instructions on how to apply the scale prior to the test. After data acquisition and validation, statistical analysis was performed as described in Section 2.5.

2.5. Statistical Analysis

The average values, standard deviation, and 0.95 confidence interval values were evaluated. Experimental data were subjected to one-way ANOVA (pairwise comparison of means with Scheffé test) for comparison of the average values of cheeses produced in the conventional ripening room and in the prototype of a ripening room using solar energy. All statistical analysis was carried out using StatisticaTM v.8.0 software from StatSoft [58].

3. Results and Discussion

3.1. Cheese Ripening

3.1.1. Environmental Variables

Environmental parameters (temperature and relative humidity) were monitored throughout the four-week ripening period in both chambers (conventional and prototype) as well as outdoors, with results presented in Table 1. During the first and second week of ripening time, temperature in both rooms ranged from 10.6 °C to 10.8 °C, while during the third and fourth weeks it ranged from 11.3 °C to 13.0 °C, with no significant differences between conventional and prototype. Relative humidity during the first and second week was around 99%, decreasing during the third and fourth week to values from 85% to 98%. Outdoor conditions exhibited expected fluctuations throughout the monitoring period.

Table 1. Temperature and relative humidity during 4 weeks for conventional technology ripening chamber and prototype ripening chamber with outdoor parameters.

Ripening Week	Temperature (°C)			Relative Humidity (%)		
	Conventional	Prototype	Outdoor	Conventional	Prototype	Outdoor
1	10.6 ± 0.1^{a}	10.7 ± 0.1^{a}	10.3 ± 1.2^{a}	99.9 ± 0.1^{a}	99.7 ± 0.4^{b}	73 ± 11^{a}
2	10.6 ± 0.1^{a}	10.8 ± 0.1^{a}	12.1 ± 0.7^{b}	99.9 ± 0.0^{a}	99.9 ± 0.0^{b}	84 ± 12^{a}
3	11.3 ± 0.2^{b}	12.9 ± 0.5^{b}	13.0 ± 1.3^{b}	96.5 ± 6.1^{ab}	98.2 ± 1.9^{b}	84.8 ± 3.9^{a}
4	12.3 ± 0.7^{c}	13.0 ± 0.0^{b}	13.4 ± 1.2^{b}	86 ± 11^{b}	85 ± 11^{a}	77 ± 11^{a}

Average ± standard deviation by one-way ANOVA; the same letter superscript in the same column means no significant differences using Sheffé test, $p < 0.05$ and $n = 7$, the smallest average values with "a" superscript letter.

Besides the differences, both ripening rooms present environmental conditions similar to previous works on this type of cheese, fundamental for the development of the traditional light yellow color of the rind and the buttery texture [59,60].

3.1.2. Electrical Energy Consumption

Table 2 presents the values obtained from the analysis of daily electric energy consumption data, both for the prototype and the conventional technology ripening chambers, and of daily electric energy production data from the photovoltaic system. The plot in Figure 3 displays those daily energy consumption values for both ripening chambers, and the value of the energy consumed from the grid for the prototype chamber.

Table 2. Values obtained from the analysis of daily electric energy consumption data for both ripening chambers and daily solar fraction, during the 4-week ripening time.

Ripening Week	Electricity Consumption (kWh/day)		Solar Fraction (%)	
	Conventional	Prototype	Conventional	Prototype
1	1.41 ± 0.14^{a}	7.04 ± 0.78^{a}	0	97.5 ± 1.2^{a}
2	1.58 ± 0.22^{a}	7.43 ± 0.10^{a}	0	96.1 ± 2.8^{a}
3	2.37 ± 0.85^{ab}	7.33 ± 0.99^{a}	0	93.8 ± 9.8^{a}
4	3.4 ± 1.3^{b}	7.86 ± 0.40^{a}	0	96.6 ± 1.4^{a}

Average ± standard deviation by one-way ANOVA; the same letter superscript in the same column means no significant differences using Sheffé test, $p < 0.05$ and $n = 7$, the smallest average values with "a" superscript letter.

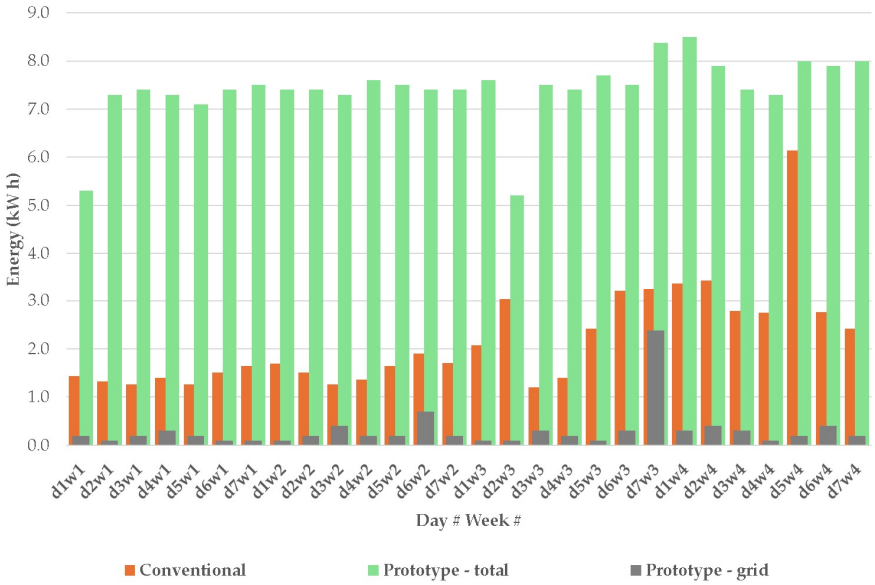

Figure 3. Electrical energy consumption of conventional technology chamber and prototype: though the prototype chamber has a higher energy demand (green bars) than the conventional technology one (orange bars), the part that comes from the grid (grey bars) is much lower. Most of the prototype used energy comes from PV energy production.

During the first and the second weeks of ripening time, the electric energy consumption in the conventional system was around 1.41 kWh/day and 1.58 kWh/day, increasing later to around 2.37 kWh/day and 3.38 kWh/day in the third and the fourth weeks. Such values were significantly lower than those in the prototype for the same time, where consumptions between 7.04 kWh/day and 7.86 kWh/day were observed. This difference might be related to different technological features in the two systems, such as the need for higher pressure in the refrigeration system of the prototype, due to the use of CO_2 as a refrigerant. However, as the prototype ripening chamber is powered by the PV energy system, which provided daily energy values from 5.5 kWh to 28.8 kWh (Figure 3), representing a share from 93.8% to 97.5% of the total energy consumption, the value of the energy consumed from the grid for the prototype chamber is much lower.

3.1.3. Electrical Energy Production

The comparison of daily PV energy production with daily illumination values computed from the IoT system data confirms what was expected. Figure 4 shows a plot of the daily illuminance (lighter green bars and right axis) compared to the daily PV energy production (darker green bars and left axis). The daily illuminance was computed by integrating the values obtained from the WS in real time (each 16 s) over each day.

The radiation data from the common off-the-shelf, low-cost WS are from light intensity (illuminance) measurements, which contain only the visible part of the solar radiation spectrum (with a peak at ~555 nm, green). PV production is predicted with solar irradiation data [61] that covers the entire solar spectrum, but it depends on much more expensive and accurate equipment. Daily irradiation values, during the same and from a nearby location, were computed from real-time data (each 60 s) obtained with an ISO Secondary-Standard pyranometer (Kipp & Zonen CMP11, Sensitivity = 9.15 μV/(W m^{-2}) [62]). A plot of the daily irradiation (yellow bars and right axis) is compared to the daily PV energy production (darker green bars and left axis), in Figure 5, showing a slightly better agreement. However, the approach used is sufficient to estimate PV energy production values for monitoring purposes, as can be confirmed in Figure 6, which shows the daily PV energy production as a function of illuminance.

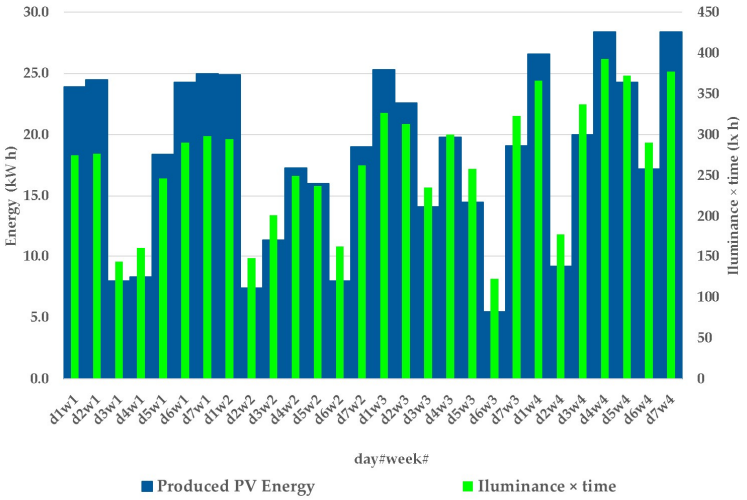

Figure 4. Daily PV Energy Production and illuminance: the produced daily PV energy values (dark bars, left-side axis) are plotted with the measured illuminance values from the weather station integrated over each day (light bars, right-side axis).

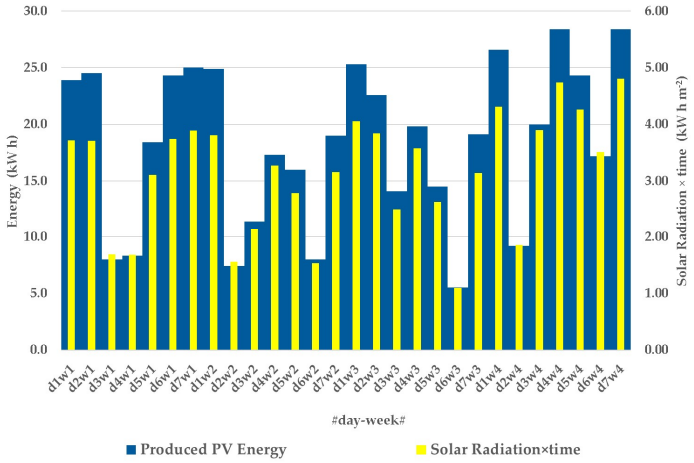

Figure 5. Daily PV Energy production values compared to the daily solar total irradiation values obtained from local calibrated irradiation measurements.

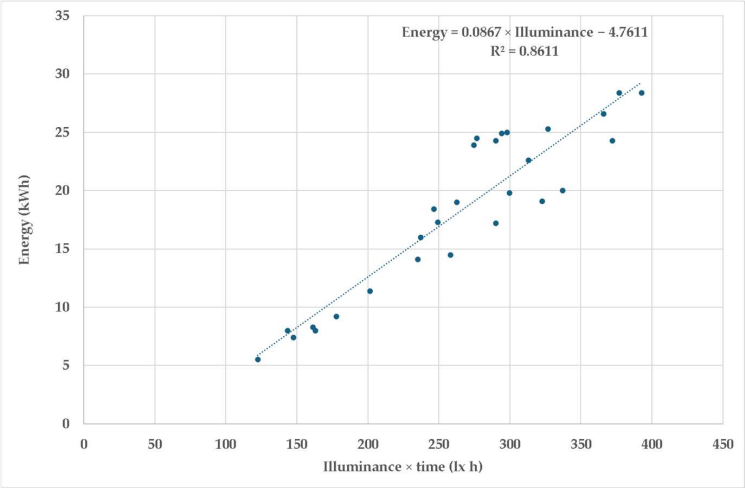

Figure 6. Daily PV energy production as a function of illuminance: the plot displays daily PV energy production against corresponding daily illuminance values. The linear regression analysis confirms that the data from the WS can be used to estimate PV energy production.

3.2. Cheese Analysis

3.2.1. Color Analysis

Table 3 presents the results for cheeses ripened in the conventional technology chamber (C) and the prototype chamber (P). The obtained results are comparable to previous works [29], where the RGB values for rind are typical of a yellowish color and the RGB values of the paste are typical of an ivory white color, identified as the usual features for this type of cheese. No significant differences were observed between the cheeses ripened in the conventional and in the prototype.

Table 3. The digital image acquisition of the cheese's rind and paste (n = 5) in RGB system. C: conventional technology ripening chamber; P: prototype ripening chamber.

		C	P	*p*-Value
Rind	R	245.4 ± 1.4	242.5 ± 5.3	0.3318
	G	238.1 ± 1.6	233.4 ± 5.4	0.1514
	B	161.7 ± 3.6	154.5 ± 5.5	0.0718
Paste	R	243.9 ± 5.6	240.7 ± 2.9	0.3568
	G	221.4 ± 15	217.3 ± 10.8	0.3171
	B	249 ± 4.3	246.6 ± 2.4	0.3694

The appearance of cheese, such as the color of the rind or the presence of cracks, may affect consumers' decisions. Nevertheless, both outside and inside quality attributes are relevant when looking for reliable methods for assessing quality. Considering the most frequent criteria of choice in the food industry, color gives a hint for many of their attributes like taste, freshness, ripeness, and motivates buyers' options. Given that human evaluation of food quality has been shown to provide inconsistent choices, functional assessments based on computational approaches are a reliable complement to human evaluation [63].

3.2.2. Sensorial Analysis

Figure 7 presents the sensory analysis results for the cheeses ripened in the conventional technology chamber (C) and the prototype chamber (P). Overall, the panelists rated both groups positively, with scores above 6 in a 9-point scale in all parameters. The appearance was the only parameter showing a significant difference at $p < 0.05$, according to the Scheffé test, and was rated higher in the samples produced in the conventional chamber.

The data obtained from the sensory analysis panel indicates that no significant differences were detected between the samples produced in the two chambers in the parameters of overall rating (p = 0.960), flavor/aroma (p = 0.822), texture (p = 0.555), and paste color (p = 0.130). The only statistically significant difference was observed in the appearance parameter (p = 0.001). The significant difference observed in the appearance attribute likely reflects the influence of environmental control on rind development. Although instrumental color analysis did not reveal measurable differences between chambers, consumer perception is highly sensitive to surface irregularities, minor cracks, and variations in rind uniformity that may result from slight differences in humidity cycles and air circulation during ripening. The prototype chamber, despite maintaining temperature within the PDO requirements, exhibited marginally less stable humidity regulation than the conventional chamber. This could have promoted subtle drying effects, leading to a less homogeneous rind appearance. Importantly, all other sensory attributes (paste color, texture, flavor/aroma, overall liking) were scored positively and showed no significant differences, indicating that the renewable-powered system preserved the core sensory qualities of the cheese.

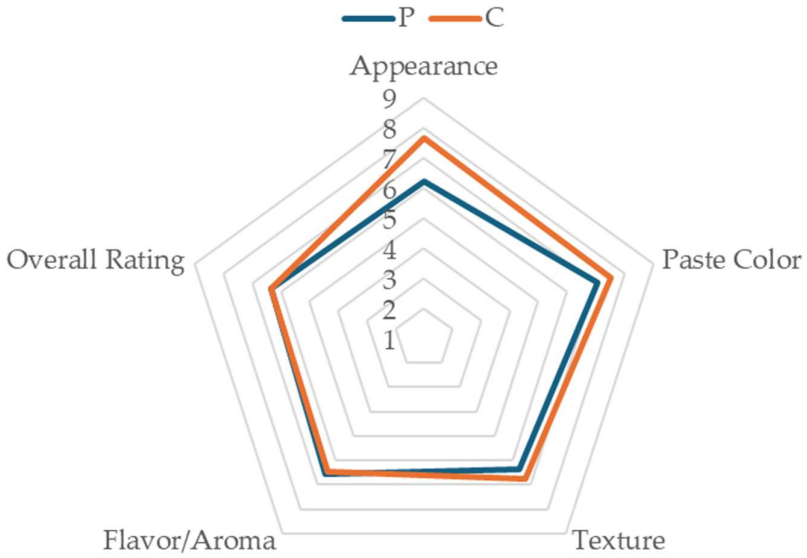

Figure 7. Mean values of the sensory analysis attributes of cheeses ripened in the conventional technology chamber (C) and in the prototype chamber (P). Only the appearance parameter showed a significant difference at $p < 0.05$, according to the Scheffé test. Assessors evaluated five attributes—Appearance, Paste Color, Texture, Flavor/Aroma, and Overall Liking—using a 9-point hedonic scale (1 = "dislike extremely," 9 = "like extremely") [57].

Sensory evaluation plays a central role in validating technological innovations in cheese ripening, since consumer perception ultimately determines market acceptance. Whether conducted with naïve consumers, as in this exploratory study, or with trained panels, sensorial assessment provides essential insight into product quality that cannot be fully captured by instrumental analyses alone. While our approach focused on consumer-oriented acceptability, future work may complement these findings with descriptive evaluations to better characterize subtle differences between ripening systems.

4. Conclusions

Cheese ripening is an energy-intensive process that requires precise control of temperature and humidity, particularly for Protected Designation of Origin (PDO) cheeses, where deviations can lead to declassification and economic losses. Conventional ripening chambers add to this challenge by relying on refrigerants with very high Global Warming Potential (GWP); for instance, R404, used in the reference chamber of this study, has a GWP nearly 4000 times higher than CO_2, the refrigerant adopted in the prototype system.

Although the prototype system exhibited higher total energy consumption than the conventional one—due to the high operating pressures required by its CO_2 transcritical refrigeration cycle—its grid energy consumption was significantly lower, as it is powered by a photovoltaic system.

Overall, the renewable-powered ripening chamber maintained the essential sensory qualities of the cheese, with only minor differences in appearance that can be attributed to humidity regulation and rind formation. These findings indicate that while further optimization of environmental control may be beneficial, the prototype successfully preserves product quality while advancing sustainability goals. Future studies should also assess other parameters, such as the cheese's rheological and physicochemical properties.

Our findings demonstrate that a demanding process can be replaced with a more globally efficient alternative, significantly reducing environmental impact from refrigerant gases while preserving product quality, as confirmed by sensory and color analyses.

Moreover, the IoT-based monitoring system developed proved both effective and affordable, offering a scalable solution for retrofitting existing cheese ripening chambers while upholding traditional quality standards.

Looking ahead, this approach presents strong potential for wider application not only in the dairy sector but also in other fermented foods, contributing to the transition toward more sustainable production systems without compromising product identity or consumer expectations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/dairy6060063/s1, Figure S1: Ripening chamber and pilot plant environmental variables measurement subsystem; Table S1: Ripening chamber and pilot plant environmental variables measurement subsystem: sensors and variables, with ranges, accuracy and resolution; Figure S2: Ripening chamber outdoor environmental variables measurement subsystem; Table S2: Outdoor environmental variables measurement subsystem: input variables with ranges, accuracy and resolution [53]; Figure S3: Ripening chamber electrical energy consumption measurement subsystem; Table S3: Ripening chamber electrical energy consumption measurement subsystem: input variables with ranges, accuracy and resolution.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the sensorial analysis study.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

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