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Electrification of a Remote Rural Farm with Solar Energy—Contribution to the Development of Smart Farming

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Abstract: Rural farms constitute a vital component of a country's agricultural landscape, traditionally reliant on energy installations known for their reliability yet notorious for their energy-intensive and inefficient characteristics. While the smart farm concept, integrating renewable energy sources and resource management technologies, has seen widespread adoption in domestic and industrial sectors, rural farms have been slower to embrace these innovations. This study presents a groundbreaking solution, deployed on a rural farm in Portugal, resulting in an impressive 83.24% reduction in energy consumption sourced from the grid. Notably, this achievement translates to a substantial reduction in CO_2 emissions, aligning with the growing need for environmentally sustainable farming practices. The technical intricacies of this pioneering solution are comprehensively described and juxtaposed with other scientific case studies, offering valuable insights for replication. This initiative represents a vital first step towards the integration or combination of conventional farming with photovoltaic energy production, exemplified by agrivoltaic systems. In conclusion, this research showcases the potential for rural farms to significantly enhance energy efficiency and financial viability, thereby contributing to a more sustainable and cost-effective agricultural sector. These findings serve as a model for similar endeavors, paving the way for a greener and more economically viable future for rural farming practices.

Keywords: agrivoltaics; photovoltaic energy; renewable energy; smart farm; sustainable farms; SCADA; PLC

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1. Introduction

The pursuit of sustainable development (SD) aims to meet current sustainability needs without jeopardizing the ability of future generations to meet their own needs. This need, recognized as an urgent reality, warns of the urgency of climate phenomena which globally affect not only the economic dimension but also the social and environmental dimensions. On the other hand, the dependence on traditional energy sources contributes to the worsening and increasing impact of fossil fuels on the ecological balance of the planet where the prices of oil, coal, and natural gas are continuously increasing due to the decrease in fuel reserves and to political conflicts. Portugal, which is not self-sufficient in energy terms, imports a substantial part of the energy it consumes, with the consequent expenditure of large sums that, under other conditions, could be channeled to the social sector, and, above all, to the environmental sector.

Recently, the European Environment Agency [1] announced that the average temperature at ground level has varied, in the last decade, between 1.13 and 1.17 °C above the preindustrial level. However, in Europe, the variation of terrestrial temperature was more pronounced, increasing between 2.04 and 2.10 °C, which compromises the Paris Agreement of 2015 that limited the increase to 1.5 °C, making it also impossible to comply with the global temperature limit of a maximum increase of 2 °C by 2050. Although these data are already quite alarming, global temperature forecasts are much darker, as it is predicted that temperatures could increase from 2.1 to 3.5 °C by the end of the 21st century. Figure 1 (left) shows a comparison between 1960 and 2022, and Figure 1 (right) shows the estimate for temperatures around 2080.

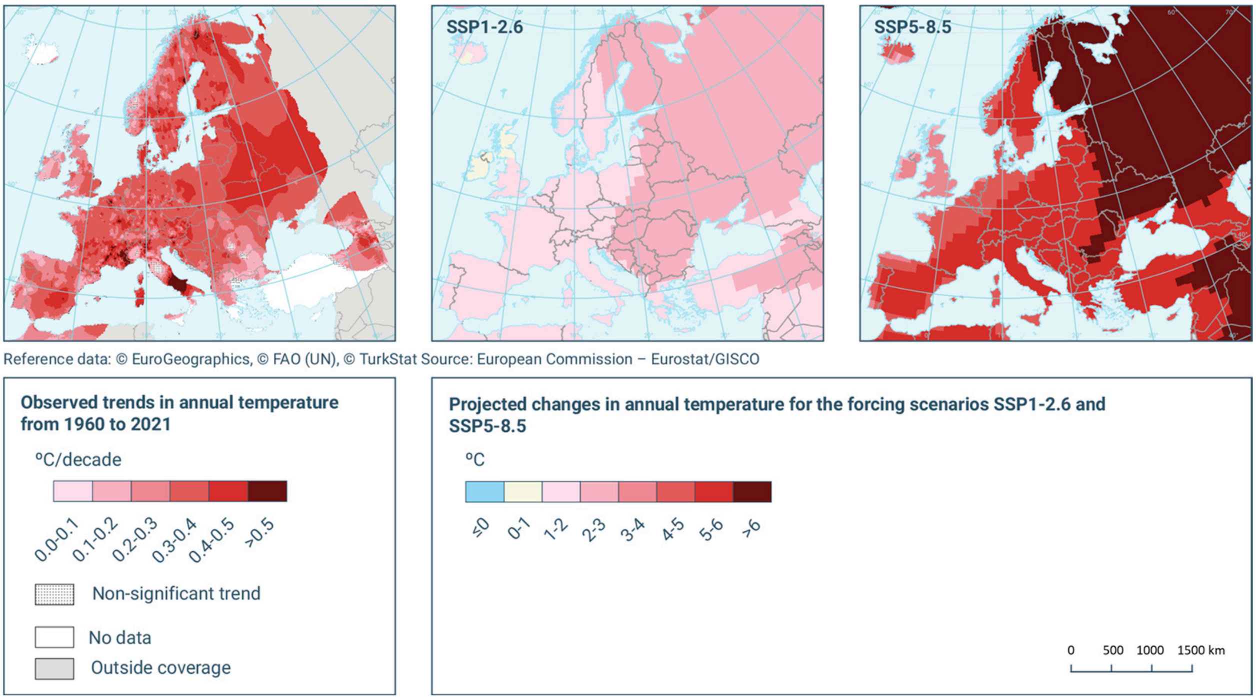

Figure 1. Annual average temperature trend from 1960 to 2022 (left panel) and projected temperature for the 21st century (right panels) [1].

It must be borne in mind that the commitment made in Paris will not be easy to realize if we maintain current patterns of consumption of energy resources, predominantly of fossil origin (nonrenewable and with high carbon emission rates), water (surface and underground, increasingly less renewable due to extreme droughts and uncontrolled consumption), and food (increasingly scarce due to droughts, farm abandonment, and lack of restructuring of agricultural areas). The Sustainable Development Goals (SDGs), defined by the United Nations (UN) in the 2030 Agenda for Sustainable Development [2], aim to ensure the globalization of actions focusing on three dimensions of sustainable development (social, economic, and environmental) that promote peace and justice according to a common vision for humanity.

In fact, the reality we are currently experiencing, the increase in temperature that manifests itself in most sectors, affects not only the energy but also the agricultural sector. If, on the one hand, greater exposure to the sun allows us to increase the production of solar energy, on the other hand, it raises questions that require a global response that demonstrates a capacity to adapt to this change.

It is easy to understand that the production of solar energy benefits from this increase in temperature, but agricultural crops follow a literally opposite path. Exposure to the sun increases evaporation from the soil, reducing growth conditions and, consequently, productivity. Therefore, the highest yield will be obtained with a supply of water and fertilizers and the adoption of new technologies [3]. Climate change, such as extreme precipitation, high temperatures, and frost (low night temperatures), are key factors to the destruction of the agriculture sector [4].

Therefore, the objectives set for this implementation were to develop a system capable of reducing electricity consumption on a rural farm through the application of a photovoltaic (PV) system and to develop a control system aimed at managing existing devices and equipment used in agriculture. This work also analyzes environmental factors and possible impacts, considering both negative and positive factors, which will enable the development of new sustainable solutions for rural farms, always with the aim of reducing CO_2 emissions.

The system presented in this document is a contribution to addressing each of the specific SDGs below:

- SDG2: promote food and sustainable agriculture. The farm has areas for cultivation and pasture capable of providing food (vegetables and legumes) as well as dairy products and meat (cattle, chicken, sheep, etc.) and water for irrigation;
- SDG6: availability of clean water and sanitation. The system has a 10,000 L underground tank whose capacity ensures sanitary and bathing consumption. This capacity depends on the amount of rain that is stored annually;
- SDG7: affordable, reliable, and renewable energy. The rural farm is supplied based on clean alternative energy. It consists of a photovoltaic system supported by a mini hydro and a wind turbine. In the absence of any of the aforementioned renewable energy sources, the farm will continue to operate, as it is connected to the Portuguese electricity distribution network, with an alternative energy source;
- SDG9: industry, innovation, and infrastructure. This system is innovative. The rural farm is fully automated. The implemented system allows remote access to rural farm owners and users, where it is possible to control and monitor, in real time, the proper functioning of domestic and rural equipment associated with the farm and the rural house;
- SDG11: sustainable cities and communities. This project contributes to this SDG through the use of renewable and sustainable energy, which reduces the negative environmental impact per capita in the area where it operates. In addition, it is adapted to climate change due to the reduction of the carbon footprint of the agricultural products. This allows one to make it a smart grid.

This paper explores the possible pathways for different modes of energy production in a rural environment, considering the SDGs proposed for a sustainable future after 2030. It describes the development of the photovoltaic system and compares the solution obtained with other installations implemented worldwide. This study also considers the economic impacts of the installation and the possible trajectories for different forms of rural energy production, i.e., the trajectory towards an agrivoltaic system (AVS).

2. Development of Sustainable Farms

Renewable solar energy systems are one of the key elements to help fight climate change and carbon neutrality, with photovoltaics technology being the most used in this field [5]. However, and given its increasing domestic and industrial use, the production of electricity on a large scale requires large land areas, leading to a decrease in farmland [6]. On the other hand, and not only because of this, this energy source has raised great interest in rural farms, which has led to considerable development in recent decades.

The electricity sector is currently facing challenges in terms of sustainability and the need to explore new energy sources that are alternative to fossil resources, as well as the quality of supplies in view of the growing needs and competitiveness of the electricity sector.

The solutions to these challenges will make it possible to increase the integration capacity in the electrical networks—of distributed production systems based on renewable energy sources—of an intermittent and variable nature. Among the energy sources available on the planet, solar is the main one because it is a practically inexhaustible and constant resource.

Compared to other European countries, Portugal is one of the countries that has the best conditions for taking advantage of this resource, as it has an average of 2200 to 3000 h per year of sunshine (mainland) and good temperatures with low humidity, while Germany, for example, has only between 1200 and 1700 h per year of sunshine [7], as can be seen in Figure 2.

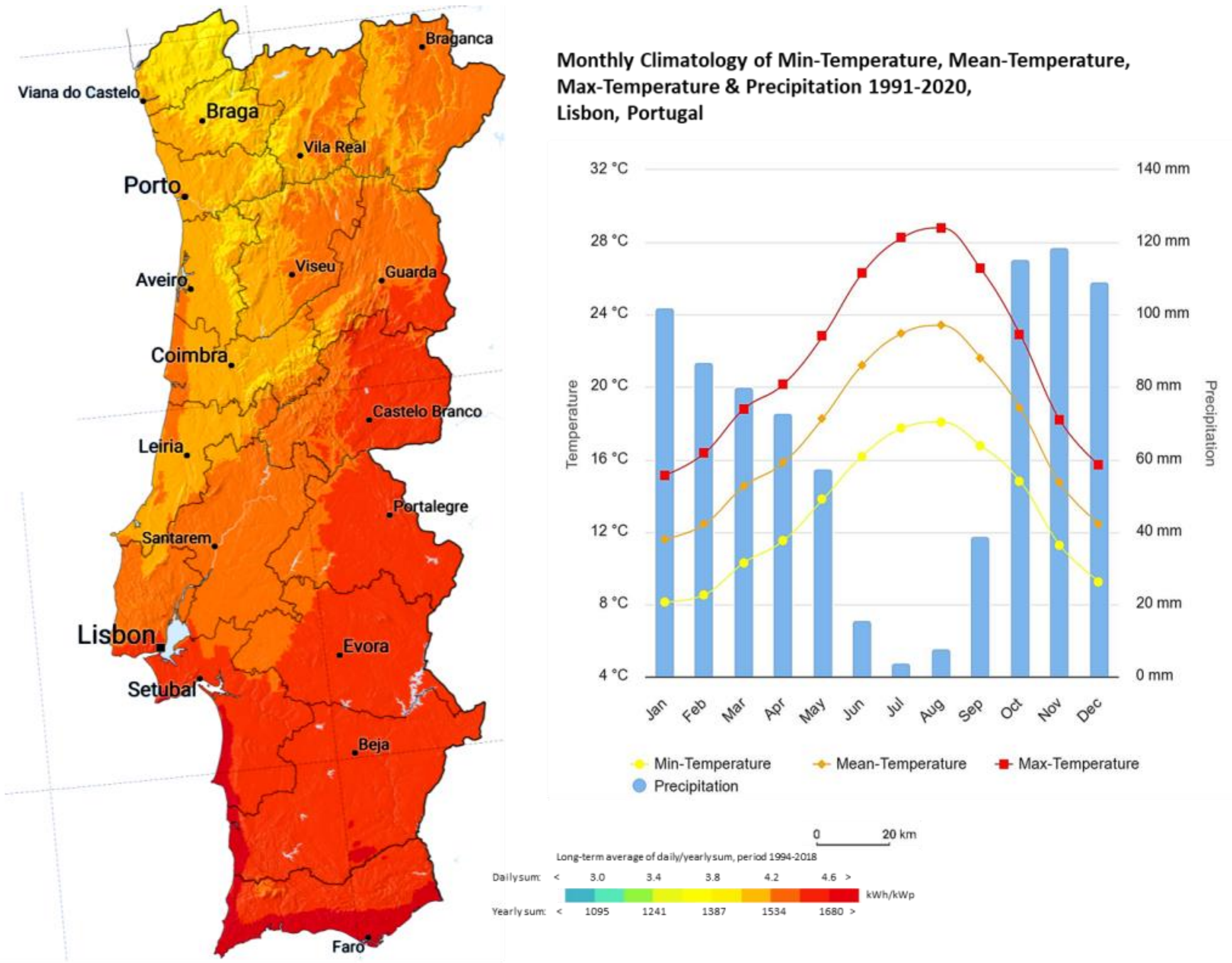

Figure 2. Solar resource map of Portugal (left panel) [8] and current climate of Lisbon (right panels) [9].

Despite the solar characteristics that exist in Portugal and all the possibility of producing electricity, the truth is that national consumption represents a very large burden on the monthly expenses of a family. These expenses are mainly related to the use of electric stoves to prepare meals, which can reach 40% [10], associated with a consumption of around 30% in buildings in cities as well as in rural areas. Therefore, an immediate response should be carried out in order to reduce this consumption, taking into account solutions that respond to the demand for electricity supply, such as an efficient approach to optimal real-time charging [11]. Solutions such as decentralized energy production and localized generation of good-quality electricity through the combination of different types of energy resources, such as photovoltaics and wind turbines [12], cannot be discarded. However, since decentralization is an interesting option from the point of view of production, other questions can be raised regarding control and intercommunication between the various instances. This could also be stated in terms of its applicability to the farm sector, taking as a starting point the discussion on the use of the Internet of Things (IoT) suggested by Soufi et al. [13]. These researchers presented the concept of smart farm exploring, in an incremental way and the sharing of data in so-called Agriculture 4.0, while Yahya [14] extends this same concept (A4.0) to the use of drones, robots, artificial intelligence (AI), and solar energy. Thus, the introduction of solar energy in a rural environment transforms it into a production unit that, in turn, is also a consumer, i.e., a "prosumer", capable of adapting its consumption according to the energy generated and buying or selling the surplus according to its specific needs [15]. Therefore, these new paradigms and the integration of digital technology in rural practices open ways to achieve increased productivity, cost reduction, and a minimization of the use of water, fuels, and fertilizers. This will be the path to sustainability in agriculture, where the main challenges are the efficient use of land and water (reducing operating costs and electricity bills to maximize productivity) as well as soil and biodiversity management.

Aiming at the efficient management of resources and diversity, other authors have presented new ways that intend to complement the production of electric energy in rural farms with agricultural production. This solution (the integration of photovoltaic energy production with agriculture in an agrivoltaic system (AVS)) offers strategies to respond to the needs of global and local demand for renewable energy and sustainability [16] and contributes to an effective reduction in water consumption. This is another one of the tools that farmers possess to adapt to climate change. As far as solar-based energy production is concerned, this can be seen as the main means of producing photovoltaic energy and as a complement to the installed systems. AVS systems help farmers stabilize growth conditions such as temperature, soil moisture, the intensity of the light falling on crops [17], or pasture-based photovoltaics (PPVs) [18]. On the other hand, in regions where there is a scarcity of nonarable land available for the implementation of PV systems, the use of agrivoltaic systems—combining energy production with greenhouses used for food production—increases farmers' income, controls the interior temperature and water requirements, and makes agriculture more attractive [19].

This project was created to respond to these needs. It uses the capabilities of intelligent electricity management systems to promote the reduction of electricity consumption in a farm home with the aim of integrating energy production from renewable sources, namely, photovoltaic solar energy, with the use of automation equipment incorporated into the home. In addition, the management system implemented must be able to incorporate all the complexity inherent in the control environment developed and must include links between the various devices and with the various intelligent functionalities and communication requirements. So, the use of automation equipment is extremely important for efficient, safe, and comfortable energy management for the user and the household.

The solutions for smart farms are intrinsically complex. Various studies have been carried out on this subject. In our previous work [7], an economic analysis was presented. This paper presents technical solutions and details of the implemented system.

Outlined below are the primary objectives pursued and the attained outcomes of the endeavor focused on the development and implementation of a photovoltaic system for a rural farm in an agrivoltaic configuration.

Main Objectives:

- Development and implementation of a photovoltaic system for rural and residential automation aimed at real-time control and monitoring of the installation's equipment.
- Reduction of energy consumption in the rural farm and residence, eliminating dependence on traditional energy sources obtained through fossil means or the conventional electrical grid.
- Continuous monitoring of significant electrical quantities at the farm and residence through real-time visualization pages, enabling analysis and application of corrective measures to maximize the performance of the photovoltaic system.

Achieved Results:

- Description of the development and implementation of a photovoltaic automation system for real-time control and monitoring of equipment.
- Emphasis on the difficulty of comparing the development and implementation of renewable energy solutions due to the lack of access to confidential technical data.
- Based on comparative analysis with similar solutions, no identical solution exists with the results and technologies obtained through this configuration, allowing for the addition of other renewable energy sources such as wind and hydroelectric power.
- Discussion on the migration, transformation, and implementation of agrivoltaic photovoltaic systems, highlighting the most significant starting points for their construction.
- Evaluation of possible constructions, objectives, problems, and added value in the implementation of agrivoltaic photovoltaic systems.

3. Case Study

The rural farm is located in Aveiras de Cima, a Portuguese parish in the municipality of Azambuja, covering an area of 26.16 km^2. The town of Aveiras de Cima had 4762 inhabitants according to the 2011 census, making it the second-most populous parish after the municipal seat. The estate features a water pumping system, a garage at the entrance, and agricultural land use and includes a villa with a ground floor that has a total footprint area of 185 m^2. Additionally, there is an annex with a total area of 36 m^2.

The rural farmhouse located in the center of Portugal will be referred to as System A in this document. According to a previous consumption study, the monthly costs of electricity consumed on the farm were very high [7]. This situation allowed for the development of a large-scale pilot project that combined a photovoltaic renewable energy system with other possible sources of renewable energy, such as support systems (mini hydro and wind), and the automation of the farmhouses so that they can be more energy efficient. The population living on the farm consists of eight people who essentially devote their daily activity to agriculture. This rural holding takes advantage of the natural resources available (artesian well), particularly in terms of water supply for irrigation and domestic consumption. The corresponding problem was high energy consumption and, consequently, a high energy bill (an annual bill of EUR 5000 for a daily consumption of 89.43 kWh/day). The system developed includes a photovoltaic generator, energy storage batteries, and a microgrid monitoring and control system. The project includes the sizing of the different components, the sizing of the cables, and the entire protection systems.

3.1. Case Implementation

The photovoltaic system implemented allows the loads to be controlled and connected to the existing photovoltaic system or via the grid (in the event of a power failure). Control is via three inverters connected to the grid, one of which (the master) gives orders to control the operation of the loads. For the photovoltaic generator, 72 photovoltaic modules were planned with six azimuth axis trackers with 15.28 m^2 of photovoltaic module area per tracker, for a total catchment area of 91.68 m^2, inclined at 36°. Sunny Boy inverters were installed on each tracker. These modules were chosen due to their quality/price ratio, which allowed us to present an adequate budget to obtain a return on investment as quickly as possible. The inverters in question (Sunny Island 5.0) have a 5-year guarantee, with a possible extension of a further 10 years. There is no other brand of inverter on the market with the characteristics of the Sunny Island 5.0. This system enables the integration of additional renewable energy sources, such as wind and hydroelectric power, as depicted in Figure 3. Figure 4 presents the photovoltaic system implementation diagram [20].

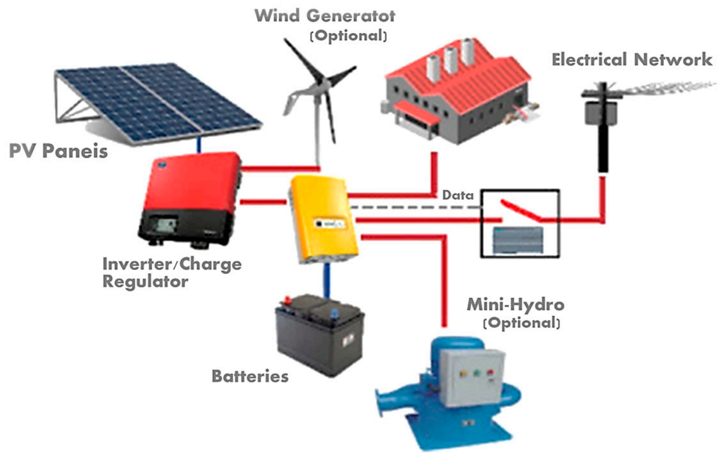

Figure 3. Diagram illustrating the energy generation system [20].

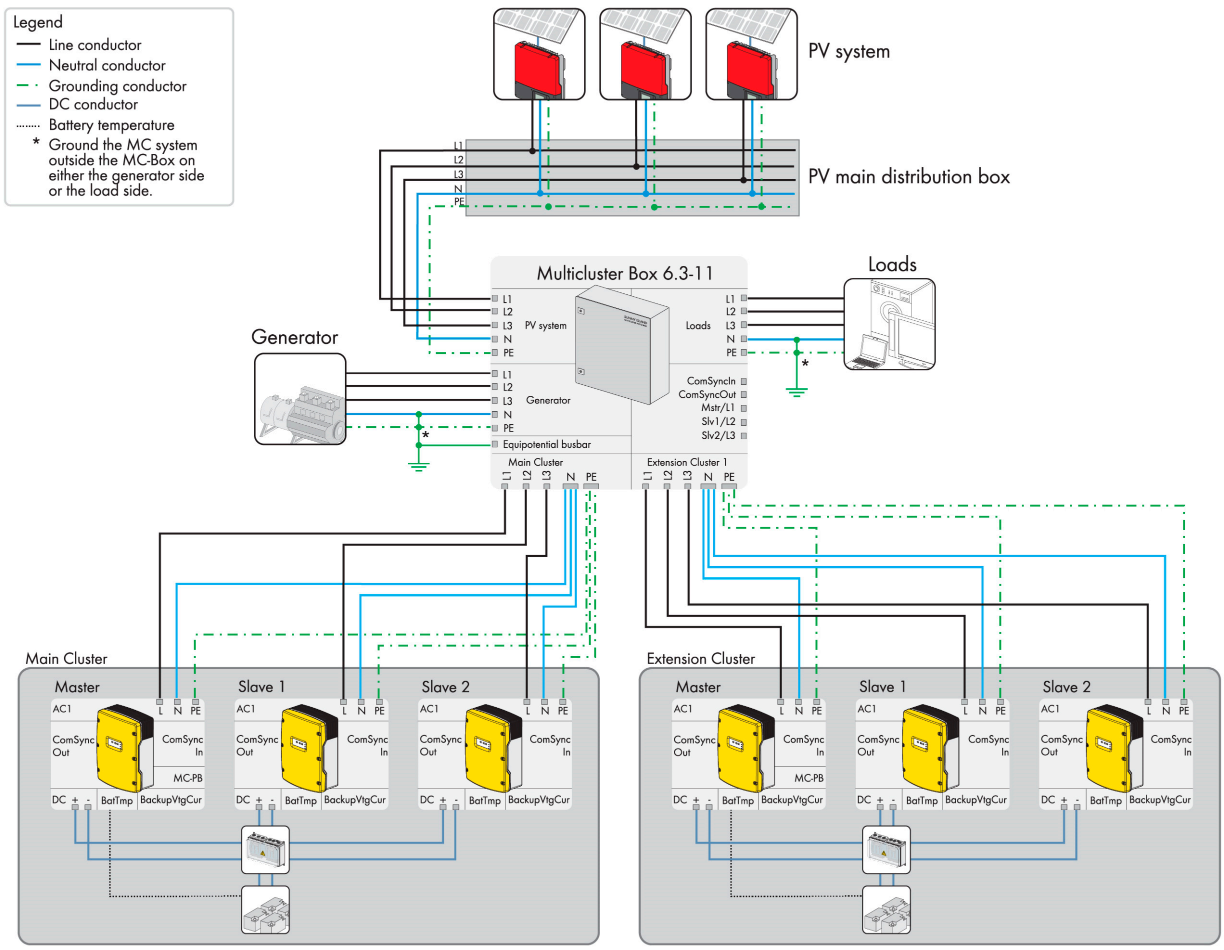

Figure 4. Block diagram of the implemented photovoltaic system [20].

At the same time, it was also planned to install a monitoring system interconnected to the inverter via an RS485 communication port, capable of monitoring the installation and making the data available locally (via LCD), via the Web or via a smartphone app. The Sunny Island inverters were connected to a panel called Multicluster 6.3 using channeled and buried cables in order to take advantage of part of the manholes in the external electrical infrastructure. As far as the Multicluster 6.3 panel is concerned, there is nothing similar on the market with the quality/price ratio of the product in question, so no other possible solutions are presented. In terms of automation, the system allows the end user to, among other things:

- Activate or deactivate loads in the house, such as the pump motor that allows water to be collected from underground;
- Activate or deactivate loads such as lighting, blinds, irrigation system, etc.;
- Checking the operation of certain equipment and/or devices at home and abroad;
- Checking the working condition of the various pieces of equipment that make up the house;
- Generate warning signals if any anomaly occurs;
- Send SMSs in case of fire or another anomaly.

3.2. Photovoltaic Generator Sizing

The implemented photovoltaic system consists of six solar trackers made up of 18 photovoltaic modules each. The autonomous system was dimensioned using PVGIS (ver. 5.2) software, and an annual production of around 27 MWh was obtained. The following input parameters were adopted for the photovoltaic system implemented:

- Nominal power of the photovoltaic generator: 13.0 kW (crystalline silicon);
- Estimated losses due to temperature and low irradiation: 10.8% (using local ambient temperature);
- Estimated loss due to angular reflection effects: 2.6%;
- Other losses (cables, inverters, etc.): 14.0%;
- Losses from the combined photovoltaic system: 25.3%;
- Optimal tilt angle: 36°.

3.3. Photovoltaic System Implemented

The system is made up of 12 photovoltaic modules, enough to meet the farm's energy needs, associated with six solar trackers, as shown in Figure 5a, as well as a set of 24 batteries (type OPzS 2V), as shown in Figure 5b.

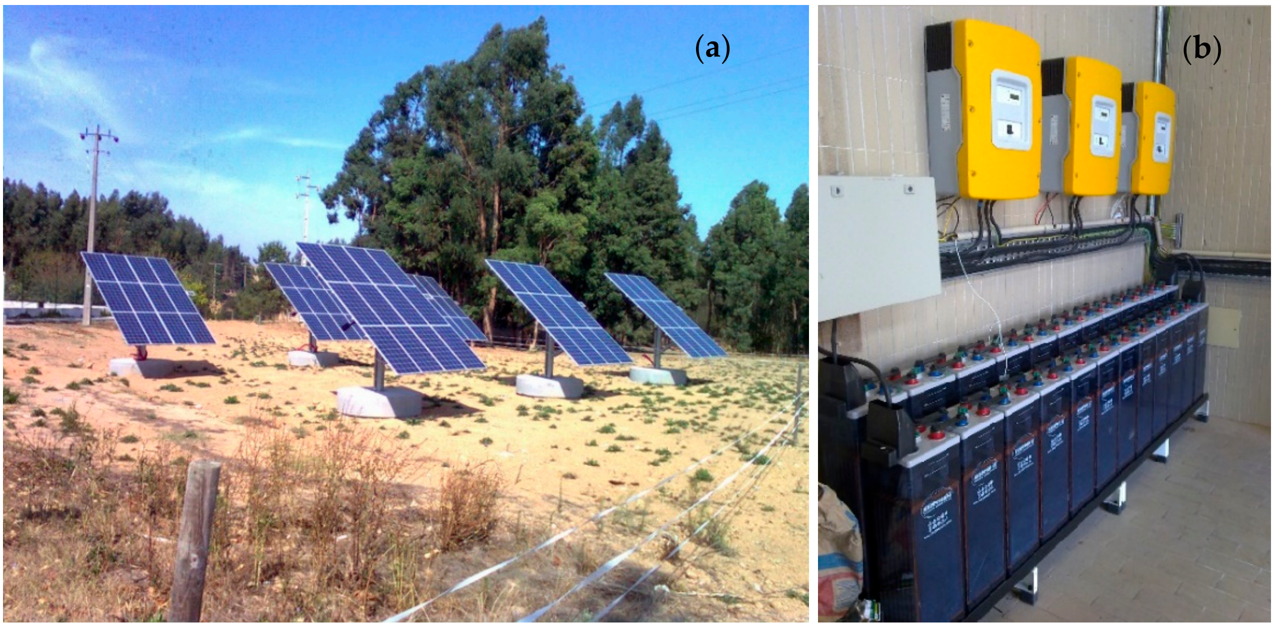

Figure 5. (**a**) Photovoltaic system with 6 solar trackers; (**b**) set of batteries [21].

We chose this range of batteries (OPzS Solar) because they offer excellent performance in industrial applications for both medium and high power. The system has lead batteries with an acid electrolyte and a very low level of maintenance. They are very robust, which means they have a long-life cycle, making them ideal for storing renewable wind and solar energy. They are also widely used in telecommunications as emergency elements (e.g., in the Unity Power System).

It should be noted that the system is equipped with a Multicluster MC-Box 6.3 control box for connecting and controlling the loads. This is supported by a PLC which is used as a monitoring and control system running the supervision application. Table 1 summarizes the equipment that makes up the photovoltaic system and its monitoring and control system.

Table 1. List of equipment that makes up the photovoltaic system.

Equipment List	Quantity
SILIKEN panels with 180 Wp peak power	72
Structure for fixing the panels to the ground, with ETTATRACK 1500 solar tracker system (for 12 panels each)	6
Sunny Boy 3800 V inverters (up to 95.6% efficiency)	3
Battery inverter (off-grid): Sunny Islands 5048 (efficiency up to 95%)	3
(3 × 8) batteries: 8OPzS 800 Elem.2 V-1166 Ah/C120 h	24
Battery shelf	1
Material earth protection system, modules, junction boxes, electrical wiring, circuit breakers, electrical panels, etc.	1
Multicluster MC-Box 6.3	1
Monitoring option: Sunny WebBox	1
Router	1

3.4. Equipment That Composes the Implemented Photovoltaic System

The installation of the photovoltaic park has a monitoring system capable of collecting the energy generated, in kWh and in real time, including the voltages and currents of the string as well as the input power (DC) and output power (AC) of the inverters, among other equipment. Data monitoring was visualized on an OMRON N5 console, although any brand and console available on the market could have been used. This choice was not conditioned by any special feature of the console but, rather, was a question of optimizing and speeding up the project, since its presence at the distributor reduced not only the time taken to complete the photovoltaic system project but also the final cost of the installation. With this in mind, and adopting a standardized approach, we opted to use PT-100 temperature probes with their respective transmitters. These could have been purchased from any other manufacturer, but we opted to stick with the manufacturer's initial choice. We chose to use a set of PT-100 probes from OMRON with the same company's 0–10 V transmitters (LKM 224 transmitters). One of the probes was used to monitor the temperature of the photovoltaic system's battery pack, while the others were assigned to the photovoltaic generators system.

Since photovoltaic installations must achieve maximum energy efficiency as quickly as possible, the monitoring and diagnostic equipment from the manufacturer Phoenix Contact, called SOLARCHECK Photovoltaic/Solar, was used. With this equipment, it is possible to detect errors and effectively monitor the power losses of individual branches, which can be caused, for example, by damaged panels or faulty contacts and wiring, allowing appropriate measures to be taken in good time. Thus, the solar monitoring module should be made up of various devices capable of measuring current and voltage and a correspondent communication module capable of transmitting them in real time. The communication module will therefore make it possible to:

- Connect and collect measurement values from up to eight measurement modules;
- Prepare data for transmission to higher commands;
- Supply power to the connected measurement modules;

The current measurement modules allow:

- Eight-channel current measurement up to 20 A DC;

- Detection of reverse currents up to 1 A;
- Four-channel add-on modules for 20 A DC;
- Digital input for monitoring, from the remote signaling contacts of the surge protection modules;
- Power supply via the communication module;

The voltage measurement modules allow:

- Voltage measurement up to 1500 V DC in any grounded photovoltaic system;
- Connection and supply normally via the analog input provided by the eight-channel current measurement;
- Solar check current measurement module;
- Output of the voltage measurement value as an analog signal.

The communication module collects the measured values from the current measurement modules and forwards them to a higher-level controller via RS485 MODBUS. A maximum of eight current measurement modules of any type can be connected to one communication module. A communication cable consisting of two stranded conductors is used to supply the necessary current to the measurement modules at the same time as it is used for reading data. Any alternative power supply is therefore unnecessary. All measured values can be read via the communication module's open registers. The CP1L-EM PLC with built-in Ethernet port and two analog input expansion cards was used. An RS-485 communication board was also incorporated into the front of the PLC to enable RS-485 communications between devices.

3.5. Economic Analysis of the Implemented System

The annual expenses incurred by the user amounted to approximately EUR 5000, reflecting a relatively high expenditure. The contracted power stands at 20.7 kVA. Figure 6 illustrates the energy consumption and production of the examined system (A).

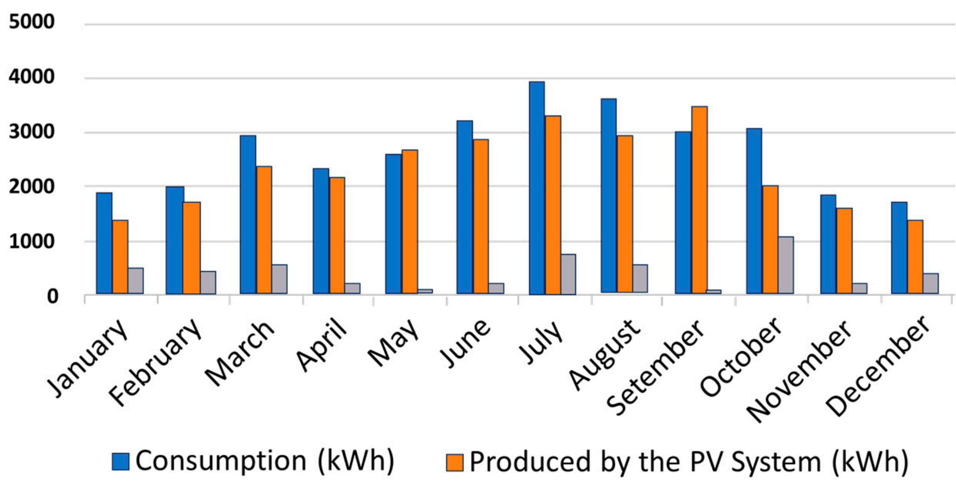

Figure 6. The energy consumed and produced subsequent to the implementation of System A.

The economic feasibility study data are summarized as follows. The cost of the photovoltaic system amounts to EUR 32,434.00 (VAT excluded), with an estimated annual production of 27,000 kWh. Additionally, the operation and maintenance (O&M) cost stands at EUR 324.34 per year (VAT excluded).

The installation of this photovoltaic system is expected to bring benefits centered on reducing the cost of electricity purchased from the national distribution network. The expected gross value is obtained by multiplying the energy produced by the purchase price, considering an average value of 0.1566 EUR/kWh (EDP source) that is subject to expected average annual variations of 5.8% in the following years as a result of inflation. The operational maintenance costs (OMCs) of the photovoltaic system will remain fixed over the years of operation, considering that all the equipment used has the same life cycle during its operational cycle. The expected net revenue from implementation was then estimated considering the profits made and the system's operating costs, namely, the solar park's OMCs. On the basis of these operating parameters, the NPV (net present value) and the profits obtained, depending on the investment, over the operating time, shown in Figure 7, were calculated.

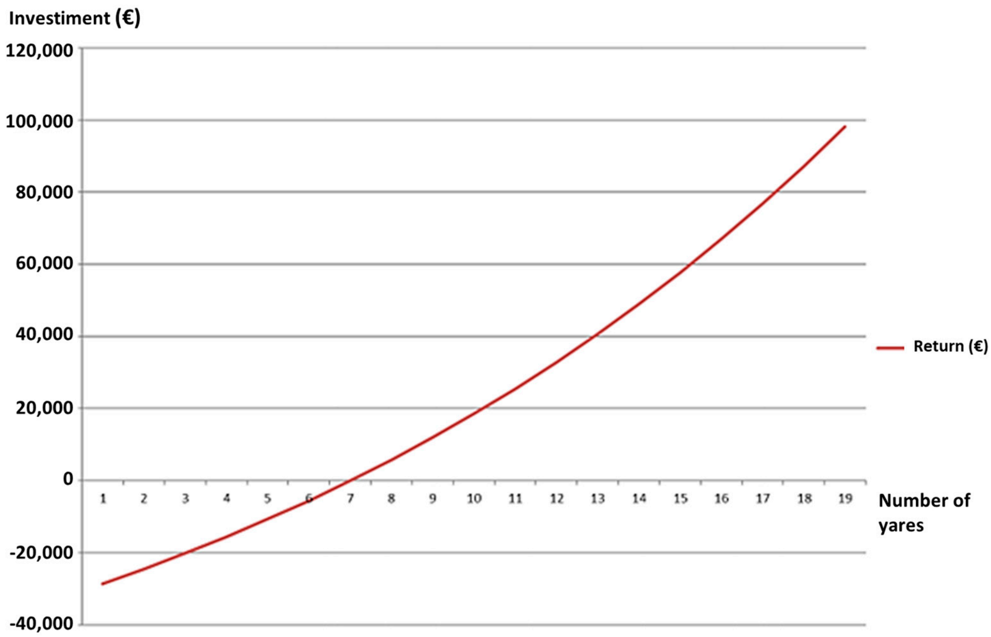

Figure 7. Financial return considering the number of years (EUR versus years).

Analyzing the graph presented in Figure 7, it can be seen that the initial investment will be quickly recovered, meaning the project will be viable. We can also see that a positive NPV can be calculated for an internal rate of return (IRR) of around 6% for a return period of around 6.5 years.

4. Discussion

4.1. Comparison with Similar Cases

Based on our research, we found that there are few cases reported in the scientific literature. In fact, in the scientific literature, there are very few cases of smart farms reported that can be compared with the data obtained in our case study, which will be referred as System A. Soufi et al. [22] describes the sizing of a solar panel and its energy storage system (battery) for a stand-alone photovoltaic system (PVS) capable of supplying the necessary electricity to a rural farm in Algeria, hereinafter referred to as System B. Salihu et al. [23] presented a photovoltaic system disconnected from the national distribution network for the rural electrification of a farm in Nigeria, which will henceforth be referred as System C. The work carried out centered on the construction and implementation of a small photovoltaic network. On the other hand, Ibrik [24] focused his work on aspects related to the impact of using solar photovoltaic systems in a rural microgrid located in Palestine, which will henceforth be referred as System D. Table 2 shows some of the most important characteristics of the solutions studied and proposed in the aforementioned works, comparing them with the characteristics of the research case proposed in this study.

Table 2. Characteristics of the previously proposed solutions compared to the case study.

Equipment List	System A (Case Study)	System B	System C	System D
Peak power of the installed photovoltaic system (Wp)	13,000	56	24,000	10,000
PV System—fixed or solar tracker	Solar tracker	Fixed	Fixed	Fixed
Energy consumption per day (kWh)	89.43	121	54.64	36.2
Installed battery size (Ah)	1166	85	1202	1800
Own production	Yes	Yes	Yes	Yes
Local and remote control/monitoring system ability	Yes	No	No	No
Prepared to include a wind generator or mini hydro	Yes	No	No	No
Automatic energy selection from own production or external grid network	Yes	No	No	No
Batteries autonomy in days for the installed power without sun	5/6	n.a.	n.a.	n.a.
Reduction energy from grid (%)	83.24%	n.a.	n.a.	86%
Percentage (%) of load rate/batteries' autonomy for the installed power	86	n.a.	n.a.	n.a.
Type of automation (PLC or other)	Yes	No	No	No
System uses HMI or other equipment for monitoring and controlling the system	Yes	No	No	No
Automation able to optimize/reduce consumption	Yes	No	No	No
System must comply with the IEC 60364-7-712 standard [25]	Yes	n.a.	n.a.	n.a.
Peak power of the installed photovoltaic system (Wp)	13,000	56	24,000	10,000
PV system—fixed or solar tracker	Solar Tracker	Fixed	Fixed	Fixed
Energy consumption per day (kWh)	89.43	121	54.64	36.2
Power energy source choice with automatic control	Yes	No	No	No

n.a.—not applied.

4.2. Critical Analysis

Analyzing all the solutions presented in Table 2, it is easy to see that not all the solutions described meet a set of specifications that, in our opinion, are important. The developed solution has important differentiating factors, namely:

- System A supplies energy to the farm equipment and the farmhouse, while System D supplies energy only to the farmhouse. In addition, System A has a high degree of automation of the house and the photovoltaic system implemented, which allows for a significant reduction in the cost of the monthly energy bill;
- System A manages two alternative renewable energy sources, one solar photovoltaic and the other wind or mini hydro. System D has a diesel generator, i.e., a nonrenewable energy source. In addition, System A makes it possible to use the national electricity grid as a backup source of energy in the event of a failure in the supply of any of the renewable energy sources;
- System A will have a lower battery replacement cost in the future, since the installed capacity is lower than that of System D. In addition, System A has a higher capacity percentage (%) of the battery charge rate, with an autonomy for the installed power of 5/6 days, which is very good;
- System A has local/remote control and monitoring for the photovoltaic system as well as for the automated equipment on the farm and in the rural dwelling. System D does not have a degree of automation, remote access, or integrated controls.

To summarize, it can be seen that systems A and D have some similarities. However, System A stands out not only for the level/degree of automation, but also for the type of control and monitoring, as well as its versatility. The support system has been designed to integrate various renewable energy sources, always considering the automation of the various types of agricultural equipment. It allows remote control and access to data and the system. These features are a very important contribution to sustainability, with many economic benefits, considering the indirect costs of fossil fuels [26] and the social, comfort, and human health benefits [26,27]. The system's autonomy can reach 5 to 6 days on batteries alone. It has the capacity to supply up to 85% of the load in a farm or rural home.

4.3. Adaptation to Agrivoltaic Systems

The evolution of rural electricity production extends beyond the mere utilization of unused land for cultivation; it necessitates a nuanced consideration of the visual impact of energy transport on rural landscapes [28,29]. Farmers will have to adapt to and resist climate change, contributing to minimal emissions, considering their activities and how they relate to population growth, changes in diets, and factors related to farm interactions and extension. Therefore, different types of farmers will need different means of adapting to the sustainable development of agriculture in its various types of management according to different rural developments [30]. This distinction is a function of the starting point, which must be defined according to the different agricultural facilities, global trends, and, last but not least, the size of the farm, the contributions to decision making, and the farm's choices [4]. This awareness and the move towards more sustainable agriculture is an important step towards combating competition between electricity production and food production in the use of arable land. Agrivoltaic systems emerge as a solution mitigating land use conflicts arising between electricity and food production by integrating both seamlessly [31], i.e., satisfying electricity demand while avoiding land use conflicts [32]. Thus, the resolution of land use conflicts (over land that is used for electricity production and agricultural production) involves the use of photovoltaic installations on pastures, integrating agriculture and PV [18]. In this way, actions such as the electrification of agricultural wells on large tracts of farmland, supported by PV, will be one of the solutions for not only increasing energy efficiency through the use of renewable energies but also for creating sustainable and intelligent agriculture [33]. An example of these interactions is those that take place on large areas of dry land used for grazing cattle, sheep, pigs, and other animals [34]. These areas include the extensive properties in the Alentejo, where water is a strategic factor to consider in the sustainability of livestock farming. So, the PVs used to pump groundwater become shading elements (eliminating direct solar influence on the land) which, combined with the pumped water, improve the quality of the land and pasture growth [18].

Although agriculture photovoltaic (APV) systems, also called agrivoltaic systems (AVSs), are not required to be a good solution to all agricultural challenges, they are a sensible choice when used in regions where the level of solar radiation is high. In essence, the APV's function is to manage sunlight considering the specific characteristics of each crop and create a sustainable and productive growing environment. On the other hand, it is important to emphasize that sunlight is crucial for the robustness of crops and that excess sunlight can have the opposite effect. It is also known that photosynthesis increases with light intensity, but when maximum light is reached, saturation is reached, and photosynthetic efficiency stops increasing [35]. The use of APVs helps minimize the incidence of direct solar radiation on cultivated areas during the hottest hours of the day, creating a more favorable, sustainable, and profitable growth environment that allows for the development of more varied crops with higher yields, reducing crop losses [36].

Considering the above and what has been described, the transition/adaptation or complementation of renewable energy production on a rural farm based on photovoltaic agriculture (AVS) depends on the means initially made available [37], i.e., the relationship between renewable energy production and agricultural profitability, taking into account strengths and weaknesses, future opportunities, and threats [38]. In this case, an approach should be considered that aims to mitigate the impacts of pollution and seek management practices that resolve them [39]. Thus, in this case study, both the transition and the complementation of photovoltaic systems depend on the means of energy production available, considering the size of the farm and all the energy consumption of the farm and the household.

In this case, given that a photovoltaic solar energy production system has already been installed on nonagricultural land, in addition to the entire support structure for the panels, new equipment can be purchased if necessary, or surplus AVS energy can simply be directly injected into the national grid. In this sense, the starting point centers on the dimensions of the system, considering a topological and structural approach that can consist of a greenhouse structure [40] (panels placed and leaning against each other in the configuration of a roof) or a "branch" [16,41] where the panels are scattered around the farm area with the same orientation and alignment.

Considering the scenarios presented, the first case focuses on crops' protection from exposure to the weather, considering phytosanitary protection and, consequently, reducing harvest losses [36] and maximization production [42]. For instance, while greenhouses offer protection to crops, the alignment of solar panels within them may not always optimize energy consumption [43].

Alternatively, solar orientation is contingent upon the orientation of building elements, compromising the attainment of ideal angles. To ensure efficient solar movement tracking, the use of solar trackers becomes imperative [44].

5. Conclusions

This work describes the development and implementation of a photovoltaic system of a rural and residential automation system capable of controlling and monitoring, in real time, all the equipment that makes up the installation as well as the residential equipment. The main objective of this installation is to reduce the consumption of the farm, eliminating the dependence on traditional sources of energy obtained by fossil means or the electricity distribution network. The monitoring of the system was achieved through the creation of several visualization pages, in real time, of the most significant electrical quantities of the farm and home. The online consultation of these elements makes it possible to carry out an analysis of the photovoltaic system and, based on the data visualized, to apply corrective measures aimed at maximizing the performance of the installation. In summary, the present work highlights the difficulties of comparison in terms of development and implementation of this type of energy production and renewable solutions. The authors superficially addressed the economic impact of the installation on the basis of the technical data of the installed system, as these cannot be always accessed. This superficiality is due to the fact that the data, in many situations, are confidential, which makes the comparison of similar solutions also superficial or difficult to carry out. The migration, transformation, or implementation of agrivoltaic photovoltaic systems is also addressed, focusing attention on the most significant starting points for their construction. An assessment is made of the possible construction, objectives, problems, and added value of their implementation.

In this paper, we endeavor to present, in the form of a list, some of the most used components in photovoltaic installations and their requirements and technical specifications, highlighting the details and conditions of implementation, considering that this document will be one of the many other contributions to the scientific dissemination of the subject as well as to the development and implementation of photovoltaic systems.

6. Future Work

The future work and challenges in the field of agrivoltaic systems may encompass:

- System optimization: developing enhanced design and deployment techniques for agrivoltaic systems to maximize energy production efficiency while supporting diverse types of crops and varying environmental conditions.
- Economic feasibility studies: conducting comprehensive and detailed analyses on the economic viability of agrivoltaic systems across different scales, considering costs, benefits, and long-term financial impacts for farmers.
- Environmental impact research: investigating environmental impacts, including life cycle assessments, potential carbon emission reductions, and comparative analyses with other renewable energy sources and conventional agricultural methods.
- Adaptation and technological integration: advancing technologies tailored and integrated to enhance the harmonious coexistence of agricultural production and solar energy generation, including innovations in solar tracking systems, support materials, and energy efficiency.

- Standardization and policies: establishing technical standards and guidelines for agrivoltaic system implementation as well as formulating governmental policies and incentives that promote the adoption and expansion of these technologies.
- Monitoring and case studies: conducting detailed studies and long-term monitoring in agrivoltaic farms and test areas to evaluate performance, resilience, and social, economic, and environmental impacts over time.
- Education and awareness: investing in educational programs and awareness campaigns for farmers, rural communities, and policymakers about the benefits, challenges, and best practices related to agrivoltaic systems.
- Addressing technical challenges: tackling technical challenges such as integrating different renewable technologies, energy storage, and smart grid management to optimize the operation of agrivoltaic systems.

In our next iteration or in future work, we aim to incorporate more precise and quantitative data that illustrate the discrepancy in the adoption of smart farming technologies within various sectors. This endeavor might encompass statistical insights concerning the deployment of particular technologies, such as automation, agricultural IoT, and other tools, across rural, domestic, and industrial domains. The inclusion of such quantitative data is intended to offer a more lucid and substantiated understanding of the adoption gap, thus providing a stronger rationale for additional research in this field.

Continuous research in these areas can significantly contribute to the advancement and widespread adoption of agrivoltaic systems, fostering effective integration between agriculture and renewable energy production.

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References

1. European Environment Agency. Global and European Temperatures, June 2023. Available online: https://www.eea.europa.eu/ims/global-and-european-temperatures (accessed on 1 August 2023).
2. United Nations. Resolution Adopted by the General Assembly on 6 July 2017, Work of the Statistical Commission Pertaining to the 2030 Agenda for Sustainable Development. Available online: https://digitallibrary.un.org/record/1291226 (accessed on 29 July 2023).
3. Ilahi, H.; Hidayat, K.; Adnan, M.; Rehman, F.U.; Tahir, R.; Saeed, M.S.; Shah, S.W.A.; Toor, M.D. Accentuating the Impact of Inorganic and Organic Fertilizers on Agriculture Crop Production: A Review. *Indian J. Pure Appl. Biosci.* **2021**, *9*, 36–45. [CrossRef]
4. Stringer, L.C.; Fraser, E.; Harris, D.; Lyon, C.; Pereira, L.; Ward, C.; Simelton, E. Adaptation and development pathways for different types of farmers. *Environ. Sci. Policy* **2020**, *104*, 174–189. [CrossRef]
5. Olabi, A.; Abdelkareem, M.A. Renewable energy and climate change. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112111. [CrossRef]
6. Lee, S.-I.; Choi, J.-Y.; Sung, S.-J.; Lee, S.-J.; Lee, J.; Choi, W. Simulation and analysis of solar radiation change resulted from solar-sharing for agricultural solar photovoltaic system. *J. Korean Soc. Agric. Eng.* **2020**, *62*, 63–72. [CrossRef]
7. Pereira, F.; Caetano, N.S.; Felgueiras, C. Increasing energy efficiency with a smart farm—An Economic Evaluation. *Energy Rep.* **2022**, *8*, 454–461. [CrossRef]
8. Solargis—Solar Resource Maps of Portugal. Available online: https://solargis.com/maps-and-gis-data/download/portugal (accessed on 6 August 2023).
9. Climate Change Knowledge Portugal—For Development Practitioners and Policy Makers. Available online: https://climateknowledgeportal.worldbank.org/country/portugal/climate-data-historical (accessed on 6 August 2023).

10. Toshiba. Induction Heating: The Technology Driving Efficiency in HOME Cooking Appliances. Available online: https://toshiba.semicon-storage.com/content/dam/toshiba-ss-v2/master/en/semiconductor/design-development/innovationcentre/whitepapers/TCM0542_GT20N135SRA.pdf (accessed on 29 July 2023).
11. Faria, P.; Vale, Z. Demand response in electrical energy supply: An optimal real time pricing approach. *Energy* **2011**, *36*, 5374–5384. [CrossRef]
12. Guerrero, J.M.; Blaabjerg, F.; Zhelev, T.; Hemmes, K.; Monmasson, E.; Jemei, S.; Comech, M.P.; Granadino, R.; Frau, J.I. Distributed Generation: Toward a New Energy Paradigm. *IEEE Ind. Electron. Mag.* **2010**, *4*, 52–64. [CrossRef]
13. Spanaki, K.; Karafili, E.; Despoudi, S. AI applications of data sharing in agriculture 4.0: A framework for role-based data access control. *Int. J. Inf. Manag.* **2021**, *59*, 102350. [CrossRef]
14. Yahya, N. Agricultural 4.0: Its Implementation Toward Future Sustainability. In *Green Urea: Green Energy and Technology*; Springer: Singapore, 2018; pp. 125–145. [CrossRef]
15. Brusco, G.; Burgio, A.; Menniti, D.; Pinnarelli, A.; Sorrentino, N. Energy Management System for an Energy District with Demand Response Availability. *IEEE Trans. Smart Grid* **2014**, *5*, 2385–2393. [CrossRef]
16. Lee, S.; Lee, J.-H.; Jeong, Y.; Kim, D.; Seo, B.-H.; Seo, Y.-J.; Kim, T.; Choi, W. Agrivoltaic system designing for sustainability and smart farming: Agronomic aspects and design criteria with safety assessment. *Appl. Energy* **2023**, *341*, 121130. [CrossRef]
17. Pascaris, A.S.; Schelly, C.; Burnham, L.; Pearce, J.M. Integrating solar energy with agriculture: Industry perspectives on the market, community, and socio-political dimensions of agrivoltaics. *Energy Res. Soc. Sci.* **2021**, *75*, 102023. [CrossRef]
18. Zhang, J.; Wang, T.; Chang, Y.; Liu, B. A sustainable development pattern integrating data centers and pasture-based agrivoltaic systems for ecologically fragile areas. *Resour. Conserv. Recycl.* **2023**, *188*, 106684. [CrossRef]
19. Schallenberg-Rodriguez, J.; Rodrigo-Bello, J.-J.; Del Río-Gamero, B. Agrivoltaic: How much electricity could photovoltaic greenhouses supply? *Energy Rep.* **2023**, *9*, 5420–5431. [CrossRef]
20. SMA Solar Technology. Installation—Connection Overview, Multicluster Box 6.3-11. Available online: https://www.europe-solarstore.com/download/sma/sunnyisland/MC-BOX-6-IAU-en-10W.pdf (accessed on 29 July 2023).
21. Pereira, F.; Oliveira, M. *Curso Técnico Instalador de Energia Solar Fotovoltaica*, 2nd ed.; Publindústria: Porto, Portugal, 2015.
22. Soufi, A.; Chermitti, A.; Mostafa, B.M.; Zehor, A. Investigating the Performance of Chosen Models for the Estimation of Global Solar Radiation on Horizontal Surface—A Case Study in Terny Hdiel, Tlemcen of Algeria. *J. Eng. Sci. Technol. Rev.* **2014**, *7*, 45–49. [CrossRef]
23. Salihu, T.; Akorede, M.; Abdulkarim, A.; Abdullateef, A. Off-grid photovoltaic microgrid development for rural electrification in Nigeria. *Electr. J.* **2020**, *33*, 106765. [CrossRef]
24. Ibrik, I. Micro-Grid Solar Photovoltaic Systems for Rural Development and Sustainable Agriculture in Palestine. *Agronomy* **2020**, *10*, 1474. [CrossRef]
25. *IEC 60364-7-712:2017*; Low Voltage Electrical Installations—Part 7-712: Requirements for Special Installations or Locations—Solar Photovoltaic (PV) Power Supply Systems, 2.0 ed. International Electrotechnical Commission: Geneva, Switzerland, 2017.
26. Alharbi, S.J.; Alaboodi, A.S. A Review on Techno-Economic Study for Supporting Building with PV-Grid-Connected Systems under Saudi Regulations. *Energies* **2023**, *16*, 1531. [CrossRef]
27. Lo, K.; Kibalya, B. Electric cooperatives and the political economy of rural electrification in Africa: Insights from Uganda. *Electr. J.* **2023**, *36*, 107238. [CrossRef]
28. Devine-Wright, P.; Batel, S. Explaining public preferences for high voltage pylon designs: An empirical study of perceived fit in a rural landscape. *Land Use Policy* **2013**, *31*, 640–649. [CrossRef]
29. Poggi, F.; Firmino, A.; Amado, M. Planning renewable energy in rural areas: Impacts on occupation and land use. *Energy* **2018**, *155*, 630–640. [CrossRef]
30. Di Felice, V.; Batista, E.R.d.J.S.B.; Mancinelli, R.; Batista, J.G.F.; Campiglia, E. Rurality and agroecosystem sustainability: A case study at farm-field level in Terceira Island (Portugal) and in Viterbo Province (Italy). *Renew. Agric. Food Syst.* **2014**, *29*, 265–276. [CrossRef]
31. Nakata, H.; Ogata, S. Integrating Agrivoltaic Systems into Local Industries: A Case Study and Economic Analysis of Rural Japan. *Agronomy* **2023**, *13*, 513. [CrossRef]
32. Wagner, M.; Lask, J.; Kiesel, A.; Lewandowski, I.; Weselek, A.; Högy, P.; Trommsdorff, M.; Schnaiker, M.-A.; Bauerle, A. Agrivoltaics: The Environmental Impacts of Combining Food Crop Cultivation and Solar Energy Generation. *Agronomy* **2023**, *13*, 299. [CrossRef]
33. Moradi, M.A.; Salimi, M.; Amidpour, M. Evaluation of agriculture wells electrification policy and development of a long-term sustainable energy strategy. *Smart Energy* **2023**, *10*, 100101. [CrossRef]
34. Enel Green Power: Agrivoltaics: The World of Agriculture Can Reap Numerous Benefits. Available online: https://www.enelgreenpower.com/media/news/2022/12/agrivoltaics-benefits-world-agriculture (accessed on 20 October 2023).
35. Liu, W.; Omer, A.A.A.; Li, M. Agrivoltaic: Challenge and Progress. *Agronomy* **2023**, *13*, 1934. [CrossRef]
36. Ramesh, D.; Chandrasekaran, M.; Soundararajan, R.P.; Subramanian, P.P.; Palled, V.; Kumar, D.P. Solar-Powered Plant Protection Equipment: Perspective and Prospects. *Energies* **2022**, *15*, 7379. [CrossRef]
37. Monteiro, C.; Saraiva, J.; Miranda, V. Evaluation of electrification alternatives in developing countries-the SOLARGIS tool. In Proceedings of the Mediterranean Electrotechnical Conference-MELECON, Tel Aviv, Israel, 18–20 May 1998; Volume 2, pp. 1037–1041. [CrossRef]

38. Martinho, V.J.P.D. Interrelationships between renewable energy and agricultural economics: An overview. *Energy Strat. Rev.* **2018**, *22*, 396–409. [CrossRef]
39. Martinho, V.J.P.D. Best management practices from agricultural economics: Mitigating air, soil and water pollution. *Sci. Total. Environ.* **2019**, *688*, 346–360. [CrossRef]
40. Agrovoltaic, Preserving the Farming Culture: Solar Greenhouses. Available online: https://agrovoltaic.org/solar-greenhouses/ (accessed on 20 October 2023).
41. Patel, U.R.; Gadhiya, G.A.; Chauhan, P.M. Case Study on Power Generation from Agrivoltaic System in India. *Int. J. Environ. Clim. Chang.* **2023**, *13*, 1447–1454. [CrossRef]
42. Yajima, D.; Toyoda, T.; Kirimura, M.; Araki, K.; Ota, Y.; Nishioka, K. Estimation Model of Agrivoltaic Systems Maximizing for Both Photovoltaic Electricity Generation and Agricultural Production. *Energies* **2023**, *16*, 3261. [CrossRef]
43. Cieślak, K.J. Multivariant Analysis of Photovoltaic Performance with Consideration of Self-Consumption. *Energies* **2022**, *15*, 6732. [CrossRef]
44. Ceballos, M.A.; Pérez-Higueras, P.J.; Fernández, E.F.; Almonacid, F. Tracking-Integrated CPV Technology: State-of-the-Art and Classification. *Energies* **2023**, *16*, 5605. [CrossRef]