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Increasing energy efficiency with a smart farm—An economic evaluation

Filipe Pereira[a,*], Nídia S. Caetano[a,b,c], Carlos Felgueiras[a]

[a] *CIETI - Centre of Innovation on Engineering and Industrial Technology/IPP-ISEP, School of Engineering, R. Dr. António Bernardino de Almeida 431, 4249-015 Porto, Portugal*

[b] *LEPABE-Laboratory for Process Engineering, Environment, Biotechnology and Energy, Faculty of Engineering, University of Porto, R. Dr. Roberto Frias S/N, 4200-465 Porto, Portugal*

[c] *ALiCE - Associate Laboratory in Chemical Engineering, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal*

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Abstract

Rural farms are typically energy-intensive facilities with relatively low energy efficiency. In this sector, the introduction of renewable energies and integrated resource management technologies has been slower than in the domestic and industrial sector. The introduction of renewable energy sources was an important step in the past, but they are currently insufficient, as they do not allow for adequate energy management. The development of new solutions with integrated energy control is especially attractive for these installations as they present the least limitations in terms of space and adaptation to new technologies.

This work describes a solution that was developed and implemented in a farm located in central Portugal. The results show that 83.2% reduction in energy from the grid can be achieved, with 5527 kg CO_2 savings, and the return on investment (of € 32,434) is about 8 years. However, this period can be shortened if evolutionary options are taken, such as upgrading to electric driven agricultural equipment.
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1. Introduction

In 1987, Sustainable Development concept sought to meet the needs of current generations without compromising the ability of future generations to meet their own needs. This widely accepted definition implies a global approach, which brings together economic, social and environmental dimensions in order to allow their mutual reinforcement [1]. Recently, the United Nations 2030 Agenda, adopted by world leaders in 2015, set 17 Sustainable Development

* Corresponding author.
E-mail address: fal@isep.ipp.pt (F. Pereira).

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Goals (SDGs), constituting the new global framework for sustainable development. The commitment made is aimed at eradicating poverty and achieving sustainable development by 2030 around the world, ensuring that no one is left behind. The SDGs set specific targets for the next 15 years, ensuring a balance between the three dimensions of sustainable development — economic, social and environmental, while focusing on a healthy planet. Those goals help to promote convergence between EU countries, within societies and with the rest of the world [2]. In this context, the main objectives of the present work were both to develop a system able to reduce energy consumption in a rural farm, using a photovoltaic (PV) system, and to develop a specific automation oriented to manage a set of existing devices within the infrastructure and equipment applied in agricultural use. This paper will also analyze environmental impacts, both positive and negative, and perform an economic analysis of the project viability. It is necessary to develop new solutions in rural farms, hence the relevance of the presentation of this innovative solution that will reduce CO_2 emissions.

This work brings an original contribution, as it presents a developed system for a rural farm that responds to some specific SDGs:

SDG 6 – Clean water and sanitation – The system features a 6500 L water reservoir, whose capacity will be sufficient for normal sanitary consumption, depending on the amount of rainfall that the farm will be able to collect annually;

SDG 7 – Affordable and clean energy – The rural farm is supplied at energy level based on clean renewable energies. The actual solution includes a photovoltaic system, although it was designed to also accommodate a wind turbine and a mini-hydro. Whenever any of the energy sources runs out, the farm will have the Portuguese national electricity grid as an energy backup;

SDG 9 – Industry, innovation, and infrastructure – This system is innovative, as it is fully automated, as well as energy efficient. It allows remote access and the farm user can monitor and control the proper operation of the equipment associated with the rural house and agricultural farm in real time;

SDG 11 – Sustainable cities and communities – This project is associated with energy sustainability, particularly in rural communities, which reduces the energy footprint, and consequently, the negative environmental impacts per capita, and is also adapted to climate change.

The global work has certainly taken into consideration various dimensions such as the selected technical options, or environmental and social impact among others, but this article is focused on the economic analysis, leaving additional justifications and demonstrations for future work.

The entire project of converting a regular farm into a smart farm comprehends several phases. The present work reports the economic study of the first phase that, in a simplified way, includes the control and monitoring infrastructure and the introduction of a PV system. The following phases will include the incorporation of energy from a mini-hydro generator and switching from diesel agricultural machines to electric ones.

2. Sustainable farms

The use of photovoltaic solar energy in agriculture has had considerable development in the last decade. Agriculture currently has more and more innovative technical and commercial solutions that improve the energy efficiency of farms which, consequently, lead to a reduction in costs, including that of the electricity bill. Sustainable intensification, the challenge of the efficient use of land and water, the importance of land management, the management of biodiversity and the importance of agriculture are all extremely important for a balanced territorial development.

In this context, the so-called smart grids, and particularly the micro-grids, allow the consumer to become a prosumer, (i.e. producer and consumer) capable of adapting his consumption according to locally generated energy, being able to buy or sell the energy surplus according to the needs of each moment [3]. This new paradigm presents the users as socially active elements, able to change their own behaviors in response to the use of renewable sources of energy that are intrinsically intermittent, and having impact in the balance between production and consumption [4,5]. Thus, an intelligent energy management system must include three main elements: (i) internal communication network, (ii) intelligent control systems and (iii) local automation. A smart farm [6,7] must include a central controller, a set of equipment with the capability of remote control and monitoring interface. Communication between users and devices can be made via the internet or mobile phone [8,9]. Smart farm management systems must be able to efficiently manage the consumption and participation in Demand Response (DR) events, such as dynamic energy cost [10,11]. Furthermore, the management system must accommodate a sufficiently complex environment including connection between devices with different intelligent functions. It is also important to consider an effective management of interaction with the user.

A smart farm is, therefore, a system that combines complex and strategic functionalities, based on the several energy resources available. Unfortunately, there is not an energy management infrastructure microgrid structured, normalized, with low price and widely and commonly accepted. In fact, solutions that have been exploited and implemented are frequently based on infrastructures that were developed for industry and therefore more expensive than the ones that certainly will take place when verifying the broad dissemination of its use [12].

3. Case study

The rural farm is located in Aveiras de Cima, center of Portugal, called System A. The farm had huge monthly electricity costs, which allowed the development of a large-scale project that combined a renewable energy source and automation of the house to make it energy efficient. The number of inhabitants of the rural farm is 8 people, who work mainly as farmers and cattle raisers, while some are delivery service workers. This farm has an artesian well that provides water to the farm and housing simultaneously.

The current problem lies in the high values of energy consumption, translated in the electricity bill. The house had a daily consumption of 89.43 kWh/day and an annual turnover of around €5,000.

3.1. Case presentation

The first part of the work was aimed at the conception, design, development, implementation and putting into service of an electric energy supply solution using six 1-axis solar trackers, in order to improve the efficiency of a photovoltaic system assembled in the locality of Aveiras. A monitoring system was installed in the facility, which collected all its data in real time, such as production in kWh, currents in the strings, voltages in the strings, DC power at the input and AC power at the inverter output, among others.

The second part of the work consisted of the automation and monitoring system of the house, installed in the farm in Aveiras, with the aim of improving its energy efficiency. For the respective automation, a system with a centralized architecture was created through a PLC, for the control/management of the operation of the pumping and irrigation system, shutters, lighting, garage door, air conditioning, security system, among others. All this was monitored in real time through a SCADA system. Fig. 1 shows the energy production system block diagram.

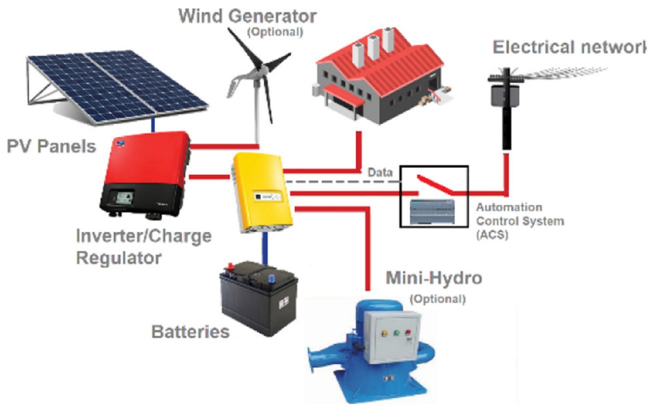

Fig. 1. (a) Block diagram of the energy production system.

The rural farm automation, monitoring and control system, shown in Fig. 2 allows, among others, the activation/deactivation of electrical loads in the home, such as pump motor, lighting, blinds, etc.; controlling of the operation of some equipment at home and beyond; monitoring the operating status of the various equipment that make up the home's automated system; generation of warning signals if any anomaly occurs.

Fig. 2. (a) PV System with 6 solar trackers with 18 photovoltaic modules; (b) batteries for energy storage.

3.1.1. Requirement's list

The implemented system should comply with the following requirements in order to be designed and installed:

- Reduction of energy consumption in the rural farm;
- Adoption of renewable energy sources instead of fossil fuels in use;
- Allowing for other renewable energy sources to be used in the future;
- Allowing for the automation of the farm, as well as for carrying out all its remote control and monitoring;
- Reduction of the levels of CO_2 emissions;
- Allowing the return on investment in a short period of time (a few years).

3.1.2. Technical solution presentation

The dimensioned photovoltaic system consists of 6 solar trackers with 18 photovoltaic modules each (Fig. 2) and has 24 OPzS 2 V batteries each (Fig. 2). The OPzS Solar range provides excellent results in medium and high-power industrial applications. These are lead–acid batteries with low-maintenance liquid electrolyte. Thanks to their robustness and longevity, they are ideally suited for use in solar and wind energy systems, as well as in telecommunications and emergency power supply applications. It should be noted that the system has a Multicluster MC-Box6.3 control box to interface and control the loads, and there is also control and monitoring through a PLC with a supervision application

3.2. Economic analysis

The case study developed throughout this study will serve, as already mentioned, to cover the costs associated with the consumption of electricity from the network. The implemented photovoltaic system will always be in service and only in exceptional cases, for example in the absence of battery charge, does the DC/AC converter switch and allow the electricity to come from the national electricity grid. The costs associated with supplying electricity from the grid were quite significant. Annually, the user had costs of about €5,000, which is quite high. The contracted power is 20.7 kVA. Fig. 3 shows the energy consumed and produced by the System under study (A).

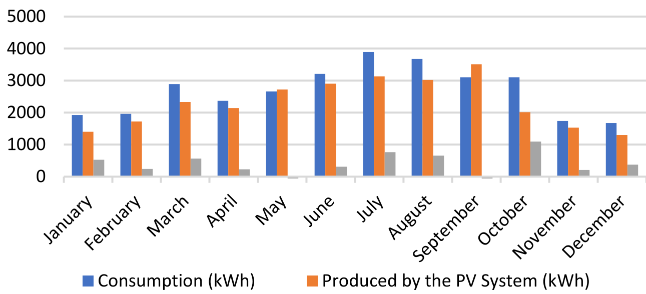

Fig. 3. Energy consumed and produced after the introduction of System A.

The expected benefit of installing the photovoltaic system was to reduce the costs of purchasing electricity from the National electricity grid. The calculation of the gross revenue is made through the product of the electric energy produced and the value of the remuneration for the purchase, considering the value of 0.1258 €/kWh for the first year. However, this value is not the same every year, as the cost of purchasing power from the grid will have a predictable average increase of 5.8% per year, as a result of inflation, over the lifetime of the project. The Operation and Maintenance (O&M) cost of all components remains fixed at a defined value for all years. It was considered that all equipment used in the photovoltaic system has a lifetime equal to the operating time of the system. It should be noted that the possible negotiation of insurance for the installation of the photovoltaic system was not considered.

The project's net revenue was calculated by the difference between the gross revenue and the facility's O&M costs. In order to allow for a comparative analysis, it was decided to consider the value of the initial investment without VAT and a discount rate of 7%. The main values are summarized in Table 1.

Table 1. Data for the economic feasibility study.

Data	Value
Photovoltaic system cost	€32,434.00 (VAT excluded)
Estimated annual production	27,000 kWh
Operation and maintenance (O&M) cost	€324.34/year (VAT excluded)

Based on the variables presented in Table 1, the Net Present Value (NPV) and Payback time were calculated, which are shown in Fig. 4.

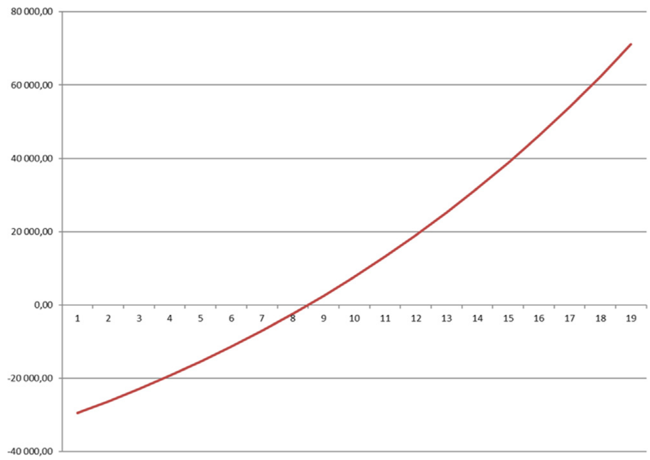

Fig. 4. Financial statement with number of years of return (Euros *versus* years).

With the data obtained, it was concluded that the investment capital is recovered, which is why the project is economically viable. It could also be concluded from Fig. 4 that, with the application of a rate of 7%, a positive NPV (VAL = 49,960 €) is obtained with an Internal Rate of Return (IRR) of 6% and a Payback Time of 8 years. In short, it is a viable project and there is no doubt that this will be the future in self-consumption with energy storage in smart farms.

3.3. Presentation of environmental benefits: CO_2 savings

Reducing CO_2 emissions helps protect the environment, thus reducing the greenhouse gas effect. During the production of electrical energy, the combustion of fossil fuels (coal, for example) causes the emission of CO_2. With electricity produced from renewable energy (Sun, wind, water, biomass, geothermal heat), no (additional) CO_2 is generated [13]. The greater the percentage of renewable energy in a country's energy mix, the lower the direct CO_2 emissions. As such, supplying the public grid with renewable energy sources like a PV system helps reduce the country's CO_2 emissions. The amount of CO_2 emissions that a PV system can avoid depends on the fuel used (gas, fuel oil, coal) or the conventional energy used (electricity, remote heat) in the country. In Portugal, the reference value in 2019 was 206.70 g/kWh or 0.20670 kg/kWh (Source: EDP – Portugal).

In Portugal, the electricity mix consists of approximately 50% renewables [14], and with this 13 kWp photovoltaic system, the average energy production of the farm would be 26,737 kWh of electricity per year. Electricity produced via photovoltaic system avoids a CO_2 emission of 26,737 kWh x 0.20670 kg/kWh = 5527 kg CO_2.

3.4. Comparison with similar cases

According to our research, there are few reported cases of smart farms with data that allow comparison with our case study — from now on called System A. Soufi et al. [15] presented a paper that scrutinized optimal sizing of solar array and battery in a stand-alone photovoltaic (SPV) system to provide the required electricity for a dairy cow farm located in Terny Beni hdiel in Tlemcen, Algeria — from now on called System B. Salihu et al. [16] presented an off-grid photovoltaic system for rural electrification in the village of Lajolo in Nigeria — from now on called System C. Their work presents the design and implementation procedure of the photovoltaic microgrid system carried out, with the main objective of providing clean electricity in order to increase its productive capacities and improve the quality of life in the remote areas of the village. Ibrik [17] conducted a study regarding the impact of using micro-grid solar photovoltaic (PV) systems in rural areas in the West Bank, Palestine — from now on called System D. The photovoltaic system to be implemented can be used as an alternative only to supply villages and isolated locations with energy, especially given that Palestine has a daily average of 5.6 kWh/m^2 of solar radiation and 3,000 h of sunshine per year [18], meaning that the region is well suited for photovoltaic installations [19]. The System D project has two PV irrigation systems for remote Palestinian communities. Table 2 summarizes some of the characteristics of the previously proposed solutions compared to the case study proposed in the present research.

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

System characteristics	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 accommodate another RES (e.g., wing, run-of-river)	Yes	No	No	No
Automatic selection from own production/ external grid	Yes	No	No	No
Energy savings in CO_2 (kg CO_2)	5527	n.a.	n.a.	6288
Reduction energy from grid (%)	83.24%	n.a.	n.a.	86%
Payback (years)	8	n.a.	n.a.	3.5
Village farm or Rural farm	Rural farm	Rural farm	Village farm	Village farm
Automation able to optimize/reduce consumption	Yes	No	No	No
System cost (€)	32,434.00	n.a.	n.a.	25,600.00

Comparing all of the aforementioned solutions, it can be concluded that not all of them respond to a set of important specifications. The developed solution in System A has some differentiating factors, as follows:

- System A supplies energy to agricultural equipment and rural housing while system D only supplies energy to rural houses. There is the automation of housing allowing a significant cost reduction in the monthly energy bill.
- System A allows the management of two alternative renewable energy sources being one the solar photovoltaic and another wind turbine or a mini hydro; System D has a diesel generator, i.e., non-renewable energy source.
- System A will present, in the future, a lower cost for the replacement of batteries, since the capacity installed is lower than that of system D.
- System A has a local/remote control/monitoring option for the photovoltaic system as well as the automated equipment in the rural farm; System D does not have remote access and control.

In summary, Systems A and D have many similarities, but System A stands out for its versatility, support from other renewable energy sources, automation of various farm equipment and allows for remote control and access that is important for sustainability, comfort and well-being of those who live there.

4. Conclusion

Motivated by the constant evolution of photovoltaic-based electricity production systems and by the need for systems to monitor and analyze the behavior of photovoltaic plants, as they have an intermittent operation due to the fact that solar irradiation is not always constant, this work was developed in order to provide a basic monitoring system and some useful analysis functions that can be implemented. As the implemented System A is framed in the so-called energy efficiency, it has in fact contributed to a significant improvement in the rural farm owner's monthly energy bill, thus making housing more efficient, ecological and automated. With an investment cost of 32,434.00 €, energy savings in CO_2 of 5527 kg CO_2 and 83.24% reduction in the energy consumption from the grid, the system has a payback time of 8 years. The obtained results with the implementation of this system met the initial expectations, not only due to its functionality, but also due to the comfort it brought to the client and, above all, the cost reduction it provided to the rural farm owners. It is important to emphasize that the selected technology is an industrial one, and therefore, significantly expensive. The development of technologies based on electronics is consistently low in prices while it has high potentialities. Thus, in the future, the use of technologies oriented for the smart farms will be more affordable and, therefore, with much more attractive payback. In addition, the completion of the following phases of the project, i.e., inclusion of a mini-hydro generator and change to electric agricultural machines, it is expected that will lead to an increase in the competitiveness of smart farm products.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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