Assessment of performance and scalability of a solar pumping system for sustainable agricultural irrigation in Uruguay.

Alejandra Morales[1]

[1] *Universidad Tecnológica del Uruguay (UTEC), Durazno (Uruguay)*

Abstract

This work analyzes a photovoltaic (PV) solar pumping system that uses solar energy to power water pumps, promoting the use of renewable sources and reducing maintenance requirements. In Uruguay, where livestock and agriculture are key economic sectors, this technology represents an efficient energy alternative for irrigation and livestock water supply, especially in rural areas with limited access to the electrical grid. PV water pumping offers a sustainable solution that reduces dependence on conventional energy sources and aligns with governmental incentives promoting its adoption. The study combines technical data collection with simulation-based analysis using COMPASS 3.1 software for system sizing and performance evaluation. The case study focuses on a solar pumping installation located in Lavalleja, Uruguay, and explores scalability scenarios, highlighting the potential benefits and the contribution of this technology to the development of a more sustainable agricultural sector.

Keywords: photovoltaic solar pumping, sprinkler irrigation, renewable energy, sustainable agriculture, rural development, water management

1. Introduction

1.1. Renewable Energies and Global Energy Transition

Climate change and the growing global demand for energy have driven the adoption of renewable sources as part of the transition toward a more sustainable energy model. Over the past decade, the development of these technologies has accelerated significantly, becoming a central axis for the decarbonization of energy systems and the promotion of sustainable development models.

In this context, as illustrated in Figure 1, Uruguay has positioned itself as an international benchmark in renewable energy, achieving one of the cleanest electricity matrices in the world, according to the Renewable Energy Policy Network for the 21st Century (REN21, 2023).

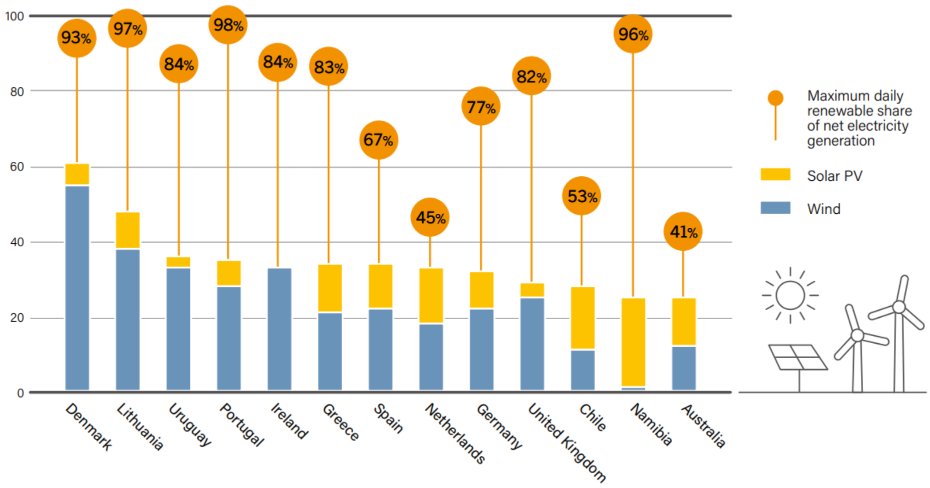

Figure 1: Countries with the highest share of variable renewable electricity generation and maximum daily share of renewable energy in Net Electricity Generation, 2022. REN (2023).

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According to the National Energy Balance 2023 (DNE, 2023), 78% of Uruguay's installed capacity comes from renewable sources, as shown in Figure 2, mainly hydropower, wind, biomass, and solar energy.

This structural transformation has made it possible to reduce dependence on fossil fuels, diversify electricity generation, and strengthen national energy security as a result of consistent public policies, infrastructure investments, and regulatory frameworks that promote the adoption of clean technologies (MIEM, 2023).

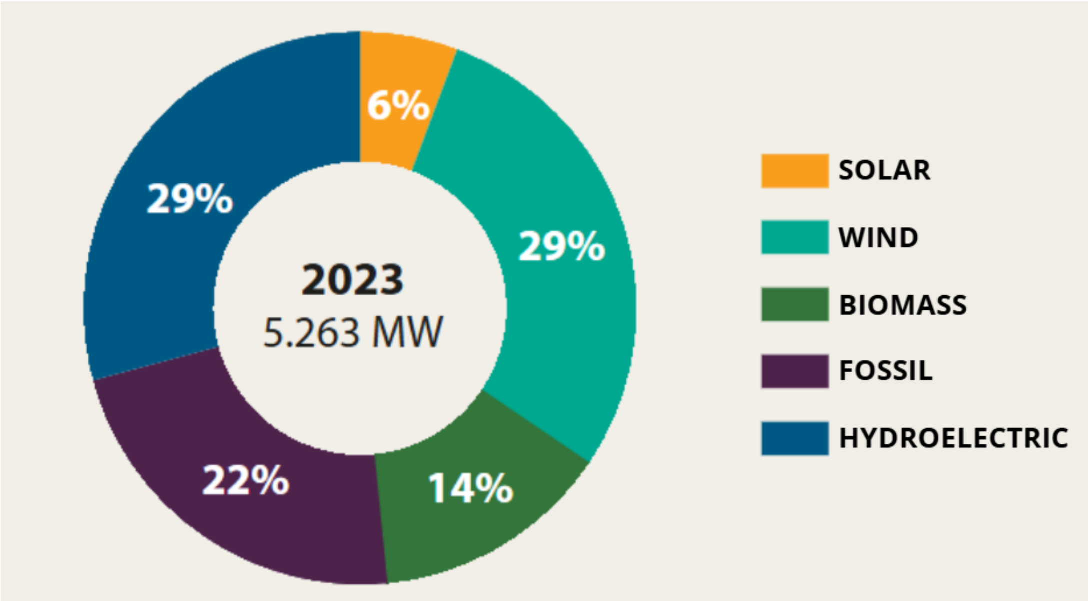

Figure 2: Installed power capacity by energy source. BEN (2023).

Uruguay's energy transition has also created new opportunities for rural and productive development, particularly in the agricultural sector. In a country where agricultural and livestock irrigation strongly depends on climatic conditions, the use of technologies such as photovoltaic (PV) water pumping improves profitability and reduces vulnerability to climate variability. According to Marisquirena (2018), this technology helps lower operating costs and, although it requires a high initial investment, it offers significant advantages over conventional systems: lower maintenance, higher efficiency, reduced environmental impact, and less dependence on fossil fuels.

In addition, national irrigation support policies have strengthened this process, promoting the adoption of renewable energy solutions in agriculture. These actions are aligned with the United Nations 2030 Agenda for Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) (UN, 2025).

1.2. Photovoltaic Solar Water Pumping

Photovoltaic solar water pumping is an advanced and sustainable technology that uses solar energy to drive water pumps, replacing conventional systems powered by fossil fuels. Its operating principle is based on the direct conversion of solar radiation into electrical energy, which continuously powers the pumping system through a controller that adjusts the available power to radiation conditions and water demand.

This allows the system to operate autonomously and efficiently, synchronizing water extraction with periods of higher solar irradiance (Rúa Ramírez et al., 2020).

The general operating scheme is shown in Figure 3, illustrating the integration between the PV array, controller, and irrigation network, which enables a direct water supply to the system without the need for intermediate storage.

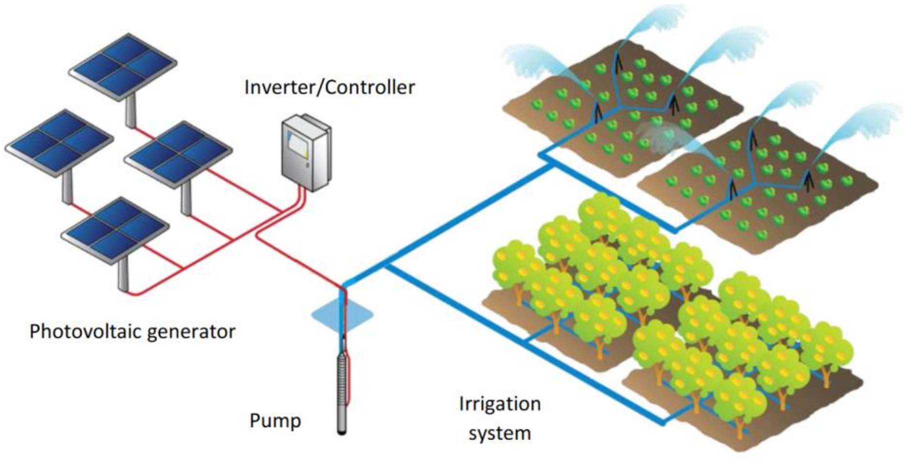

Figure 3: Diagram of a solar photovoltaic pumping system. Adapted from COMPASS 3.1.

Ramírez notes that, unlike traditional systems, PV water pumping does not require battery storage, since water production naturally synchronizes with solar radiation, coinciding with periods of highest irrigation demand.

This type of system offers low maintenance, reduced operating costs, and a minimal environmental impact, making it an efficient and economically viable alternative for water management in rural areas.

1.3. Relevance of Photovoltaic Solar Pumping in the Uruguayan Agricultural Sector

In Uruguay, where agriculture and livestock are pillars of the national economy, photovoltaic (PV) solar water pumping holds strategic importance. The agricultural sector represents between 6% and 7% of the Gross Domestic Product (GDP), including activities such as agriculture, livestock, and forestry; in contrast, the remaining 92% corresponds mainly to manufacturing industries and services (FocusEconomics, 2022).

When including activities linked to the agro-industrial sector, the total contribution of the agro-productive complex to the national economy rises to between 14% and 16% of GDP, highlighting its fundamental role in the country's productive development (Uruguay XXI, 2024).

This comparison is illustrated in Figure 4, which shows the proportion of the agricultural and agro-industrial sectors' contribution relative to the rest of the economic activities.

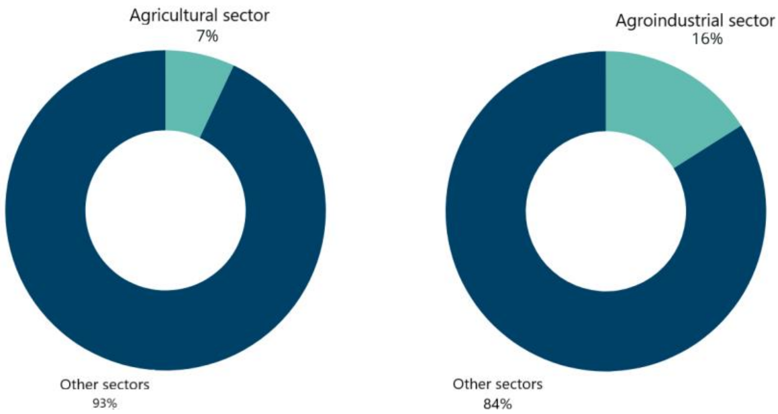

Figure 4: Share of the agricultural and agro-industrial sectors in Uruguay's GDP. Author's elaboration.

In this context, and given the strong dependence of irrigation on climatic conditions, solar water pumping systems make it possible to ensure efficient and sustainable access to water, particularly in rural areas with limited access to the electrical grid.

According to Marisquirena (2018), this technology helps reduce operating costs and, although the initial investment may be high, it offers significant advantages over conventional systems, such as lower maintenance requirements, greater energy efficiency, positive environmental outcomes, and a reduced dependence on fossil fuels.

In line with government incentives aimed at promoting clean production and energy efficiency, photovoltaic solar water pumping has become a key solution for the sustainable development of the agricultural sector, helping to improve productivity, optimize water resource use, and strengthen the sector's resilience to climate change (Abella and Romero, 2009).

2. Justification and Objective of the Study

As previously mentioned, in Uruguay, where agriculture and livestock are pillars of the national economy, photovoltaic solar water pumping represents an efficient and sustainable energy alternative for agricultural irrigation and livestock water supply, particularly in rural areas with limited access to the electrical grid.

In this context, the present study was conducted to evaluate the performance and scalability of a photovoltaic solar pumping system under real operating conditions.

The analysis focuses on a system installed in the department of Lavalleja, on a 10-hectare rural plot used for sprinkler irrigation of forage crops for livestock feeding. The installation includes a solar-powered pump sized to meet the crop's daily water requirements, with an average operation time of seven hours per day.

The study combines field measurements with simulations performed using the COMPASS 3.1 software, a tool developed by Lorentz for the design and energy assessment of solar pumping systems. This software integrates satellite meteorological databases, site-specific hydraulic data, and a wide range of equipment configurations, enabling system optimization and the generation of automated technical reports tailored to local conditions (Lorentz, 2025).

Figure 5 shows a satellite image of the analyzed site, located in the department of Lavalleja, Uruguay, at geographical coordinates 33°36'52.6"S and 54°36'02.8"W.

Figure 5: Satellite image of the study site in the department of Lavalleja, Uruguay. Source: Google Earth.

The main objective of the study is to determine the technical and operational feasibility of the system and to explore its potential application across different irrigation areas, contributing to the development of a more sustainable and resilient agricultural model.

3. Methodology

The study was based on the collection of specific information from an existing photovoltaic solar pumping installation located in the department of Lavalleja, Uruguay. Data were gathered on the available solar resource, the hydraulic characteristics of the terrain, the system's power, and the general operating conditions.

During the site visit, measurements were taken of pipe length, motor cabling, dynamic head, required flow rate, and type of irrigated crop, in order to evaluate the system's performance under real operating conditions.

The main hypothesis stated that the length of pipelines and the volume of pumped water increase proportionally with the irrigated area. To verify this relationship, data from the current installation were used as a baseline for scalability projections for areas of 5, 7.5, 15, 20, 30, 40, and 50 hectares.

System sizing and simulation were carried out using COMPASS 3.1 software, a tool developed by Lorentz that enables the simulation of solar pumping system performance based on hydraulic, electrical, and meteorological data.

The input data were based on a technical report of the baseline model provided by Kivoy, a company specializing in the installation of photovoltaic irrigation systems in Uruguay. This model corresponds to the actual system installed on a 10-hectare site, which was taken as the reference for the simulation.

The main parameters considered were: daily flow rate of 300 m³, total dynamic head of 16 m, pipeline length of 700 m, motor cable length of 35 m, and 5% losses due to dirt. The photovoltaic module selected, listed in the software database, was chosen because it is the most commonly used model by Kivoy in rural applications.

Finally, the number of PV modules and the technical characteristics of the system proposed by the software for each plot size were compared, considering energy efficiency and operational performance parameters.

4. Results and Discussion

4.1. Application of COMPASS 3.1 Based on the Current Case

The main hypothesis of the study allowed the baseline 4 kW system to be scaled to irrigated areas of 5, 7.5, 15, 20, 30, 40, and 50 hectares, assuming that both the pipeline length and the volume of pumped water increase proportionally with the irrigated surface.

For each scenario, the COMPASS 3.1 software determined the optimal configuration of pumps and photovoltaic modules, along with the daily energy performance and projected flow rates, enabling the evaluation of the system's technical scalability.

In the current 10-hectare installation, the system operates with a PS2-4000 C-SJ30-2 pump (Figure 6) rated at 4.0 kW, designed for medium-scale irrigation applications.

Figure 6: PS2-4000 C-SJ30-2 pump for a 10-hectare irrigation system.

This unit is powered by a photovoltaic configuration of 24 modules (8×3), as illustrated in the wiring diagram in Figure 7, ensuring a continuous water supply during the system's average daily operating hours.

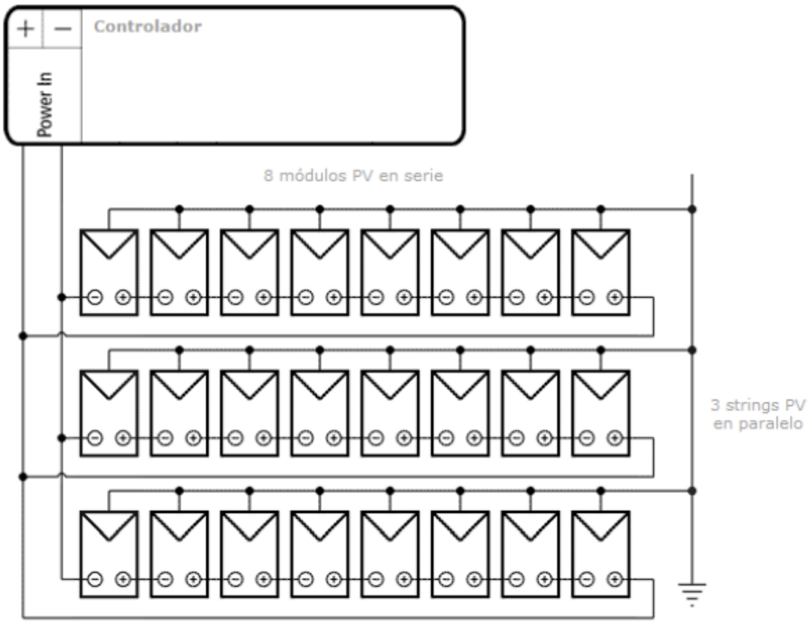

Figure 7: Configuration of photovoltaic modules for a 10-hectare system.

The photovoltaic modules used correspond to the LC325-P72 model (Figure 8), widely employed in rural installations due to their efficiency and durability. Each module has a nominal power of 325 Wp, with an efficiency of 16.7%, a maximum power voltage (Vmp) of 37.5 V, and a power current (Imp) of 8.67 A, values that ensure stable performance under the region's climatic conditions.

Figure 8. LC325-P72 photovoltaic module.

The results obtained show a strong correlation between the system's energy generation, the available solar radiation, and the crop's water requirements, validating the performance of the baseline system and its potential for replication across different production scales, as summarized in Table 1.

A seasonal pattern in energy generation is also observed, with lower values during months of reduced irradiance (winter) and a minimum of approximately 24 kWh in June. Solar irradiance peaks in summer, with an annual average of 5.0 kWh/m², while average precipitation shows moderate variability (3.1 mm annually) without significantly affecting energy output.

The annual average temperature is 17 °C, with higher values in summer and lower in winter, reflecting a direct relationship between irradiance, temperature, and system efficiency. The system achieves its best performance during months of higher solar radiation.

Table 1: Daily and average yield for 10 hectares.

Months	Energy (kWh)	Irradiation (kWh/m²)	Precipitation (mm)	Temp. (°C)
January	44	6.4	3.2	23
February	41	5.9	3.4	23
March	39	5.5	3.5	22
April	32	4.5	2.8	18
May	29	4.0	3.0	15
Jun	24	3.3	3.1	13
July	26	3.6	3.3	11
August	32	4.4	3.2	13
September	38	5.2	3.1	14
October	40	5.6	3.3	17
November	43	6.0	2.9	19
December	43	6.2	2.7	22

4.2. Comparison of Pumping Systems According to Irrigated Area

Table 2 presents the main characteristics of the simulated solar photovoltaic pumping systems for different irrigated areas (5 to 50 ha). A direct proportional relationship is observed between the irrigated area, pump power, and the number of modules required. As the area increases, so does the energy demand, and the system's sizing must be adapted to ensure sufficient flow and efficient operation.

Table 2: Characteristics of the pumping system according to the irrigation area.

Hectares	Pump power (kW)	Number of modules	Peak PV power (kWp)	Annual energy generated (kWh)
5	1.8	12	3.90	214
7.5	4	18	5.85	323
10	4	24	7.80	431
15	8.3	40	13.00	758
20	16	48	15.60	964
30	21	76	24.70	1365
40	21	108	35.10	1942
50	25	128	41.60	2301

Among the results, it is noteworthy that starting from 20 hectares, the pump power tends to stabilize around 21 kW, while the number of photovoltaic modules continues to increase. This behavior indicates that a higher photovoltaic capacity can compensate for the increased energy demand without requiring pumps of greater power, thus optimizing the overall efficiency of the system.

Figure 9 shows the relationship between the irrigated area, the pump power, and the number of photovoltaic modules required for each simulated scenario. A nearly linear growth between the variables can be observed until reaching a stability point around 20 hectares, where the pump power remains constant while the number of modules continues to increase. This behavior reflects an energy optimization of the system, as the additional photovoltaic capacity allows the required flow rate to be maintained without increasing hydraulic power.

Furthermore, the observed trend confirms the technical consistency and scalability of the design, demonstrating that the expansion of the irrigated area can be addressed through the modular expansion of the photovoltaic array, maintaining a stable relationship between electrical power and hydraulic demand.

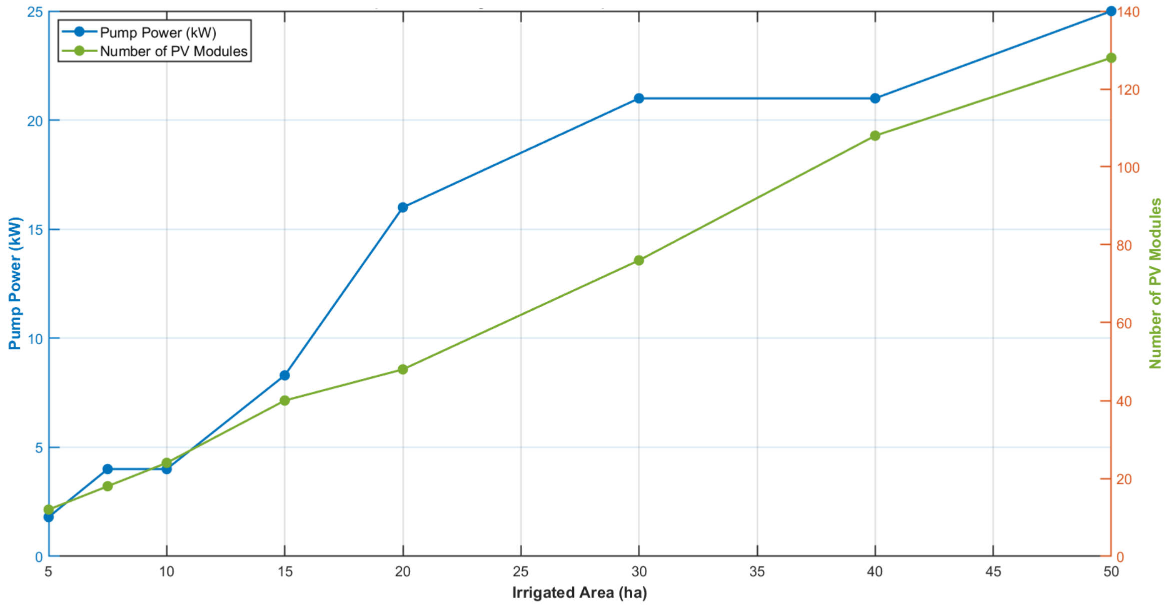

Figure 9: Relationship between Irrigated Area, Pump Power and Number of PV Modules.

On the other hand, Figure 10 shows the peak power of the photovoltaic system (kWp) as a function of the irrigated area. The relationship between both variables is practically linear, as indicated by the equation of the fitted line:

$$y = ax + b \qquad \textit{(eq. 1)}$$

where y represents the photovoltaic system power, x the irrigated area (ha), a the slope, which reflects the increase in required power with the expansion of the irrigated area, and b the intercept, corresponding to the theoretical base value of the system.

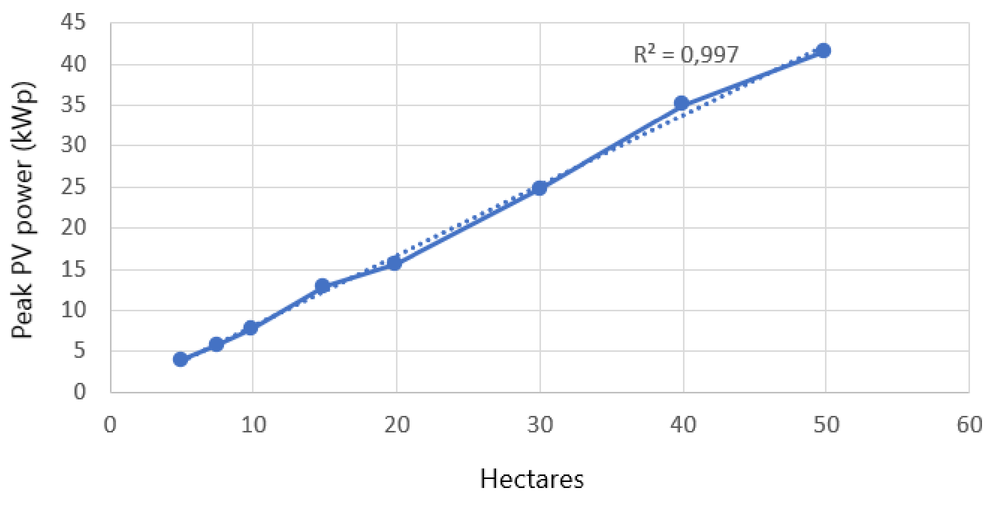

Figure 10: Peak power of the photovoltaic system (kWp) as a function of the irrigated area.

The coefficient of determination ($R^2 = 0.997$) suggests a high correlation between the two variables, validating the consistency of the model and the correspondence between the installed power and the system's energy requirements.

Similarly, Figure 11 presents the annual energy generated (kWh) as a function of the irrigated area (ha), adjusted through a linear regression represented by Equation 1. The resulting coefficient of determination ($R^2 = 0.9966$) indicates a strong and positive correlation between the energy generated and the irrigated surface, confirming both the consistency of the design and the technical validity of the system.

This behavior is consistent with the progressive increase in energy demand as the irrigated area expands, verifying the feasibility and scalability of photovoltaic solar water pumping across different productive scenarios.

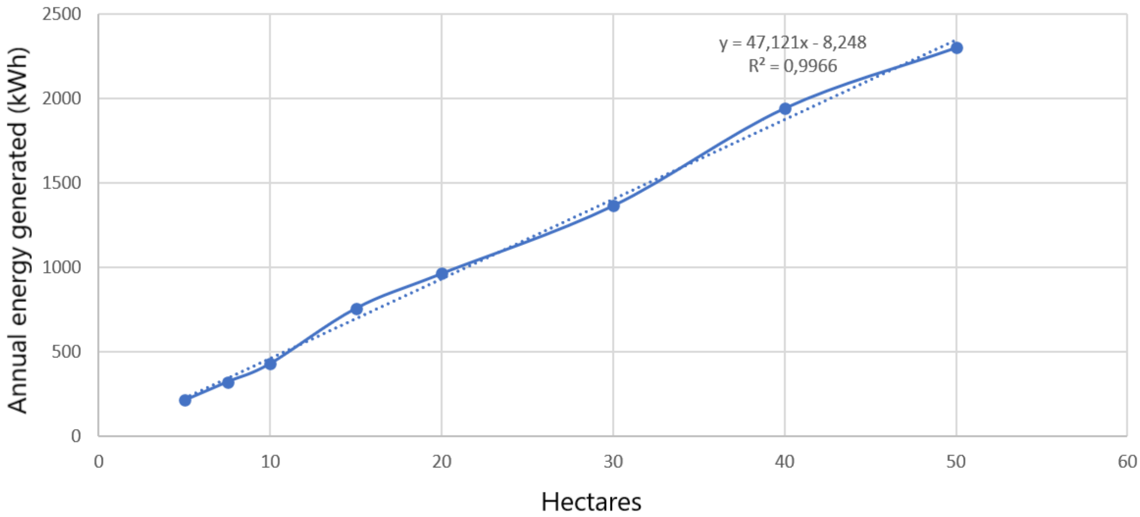

Figure 11: Relationship between the irrigated area and the annual energy generated (kWh).

4.4. Analysis of Advantages and Limitations

The photovoltaic solar water pumping system offers significant advantages over conventional alternatives, particularly due to its energy autonomy, low maintenance requirements, and reduced operating costs. Its independent operation from the electrical grid makes it an efficient and sustainable solution for water supply in the agricultural sector.

However, there are limitations associated with the high initial investment cost and the seasonal variability of solar radiation, which require proper equipment selection and appropriate irrigation planning to prevent water shortages during periods of low irradiance.

4.5. Recommendations on Expansion or Current Configuration

The comparative analysis showed that the PS2-4000 pump (4 kW) was maintained across different irrigation surface scenarios, suggesting that it may be oversized for smaller areas and undersized or properly adjusted for larger ones.

To optimize system performance, it is recommended to consider replacing the pump with an intermediate-power model or modularizing the photovoltaic installation by using higher-capacity PV modules, which would reduce the number of panels and simplify the electrical design without compromising efficiency.

For expansions beyond 20 hectares, it would be advisable to evaluate the integration of hybrid systems or multi-pump configurations to enhance operational continuity under varying climatic conditions.

5. Conclusions

The study validated the technical feasibility and scalability of photovoltaic solar water pumping applied to agricultural irrigation in Uruguay, demonstrating that this technology can effectively adapt to different surface areas and water demands.

The results show a stable and efficient system performance, with a direct relationship between irrigated area, energy generation, and installed power, confirming the design consistency and the accuracy of the simulations performed with COMPASS 3.1.

Furthermore, a potential for optimization was identified concerning both the pump selection and the unit power of the photovoltaic modules, since maintaining the same pump across different irrigation scales may lead to oversizing in smaller areas or undersizing in larger ones. In this sense, replacing the modules with higher nominal power units could reduce the number of panels and simplify the electrical configuration, thereby improving the overall efficiency of the system.

Overall, photovoltaic solar water pumping stands out as a sustainable, reliable, and replicable energy alternative for Uruguay's agricultural sector, contributing to productive autonomy, efficient water management, and enhanced climate resilience in rural areas.

Moreover, the methodological approach employed provides a solid foundation for future research and large-scale applications aimed at integrating renewable energy systems into agricultural production.

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