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ORIGINAL PAPER

Integrated photovoltaic system for rainwater collection and sustainable irrigation

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Abstract

The integration of photovoltaic systems with rainwater harvesting offers a promising solution for enhancing water and energy management in arid and semiarid agricultural regions."This study presents an agrivoltaic system where photovoltaic panels function both as energy source and as surfaces for runoff collection, directing rainwater into a storage reservoir for irrigation. A detailed analysis was conducted to evaluate different scenarios, for a period of ten years, including panel inclination, optimizing at 35°, and the expansion of the photovoltaic field, to enhance energy efficiency and water availability. The results demonstrate that this approach significantly reduces water shortages, reducing critical cases below 50% in first scenario, particularly during peak irrigation demand periods, while increasing the system's storage capacity and overall resilience to climate variability. The expansion of the photovoltaic system, which is scalable according to the application, demonstrates the overall reduction of critical cases in irrigation availability, increasing the reservoir capacity up to 60,000 m3, which can be combined with increased management of energy generated for the grid, or local generation in remote areas, in combination with improved water supply management. Additionally, the system improves energy sustainability by reducing reliance on external sources and lowering carbon emissions from agricultural activities. The findings highlight the potential of integrating photovoltaic systems into irrigation management as a scalable and replicable framework for enhancing resource efficiency and sustainability in water-scarce regions.

Introduction

Water scarcity and the growing global demand for food and energy require innovative solutions that integrate water, energy, and agricultural systems (Widmer et al. 2024). The potential of solar energy to meet global electricity demand is immense, but it requires extensive areas. There is growing concern that large renewable energy installations may displace other land uses, as farmland has a significantly high solar potential compared to other locations, averaging approximately 28 W/m^2 (Adeh et al. 2019).

Agrivoltaics, an innovative land-use strategy, combines agricultural production with photovoltaic energy generation on the same land. This approach optimizes the use of natural resources by harnessing solar radiation for both crop production and electricity generation. Unlike conventional photovoltaic systems, which occupy large land areas and may compete with agriculture, agrivoltaics enables a synergistic coexistence between both activities, providing economic and environmental benefits (Roxani et al. 2023; Arjun et al. 2023; Janota et al. 2023). Global energy demand could be offset by solar production if even less than 1% of farmland were converted into an agrivoltaic system (Adeh et al. 2019).

At the European level, the multifunctional use of land through agrivoltaics has the potential to make a significant contribution to achieving the goals set in the European Green Deal (EGD) (Chatzipanagi et al. 2022). Further research and development are still needed regarding energy aspects, agricultural and photovoltaic performance, biodiversity impacts, pilot projects, and system monitoring, all of which will be essential to obtain sustainable solutions for the future (Effect of climate change on reservoir water balance and irrigation water demand: a case of Gidabo irrigation project xxxx; Chatzipanagi et al. 2023; Shemer et al. 2023).

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Numerous studies have been conducted in recent years due to agrivoltaics potential in the food-energy nexus. Demonstration projects with new conceptual designs based on photovoltaic modules covering open fields have shown promising results in optimizing light availability while reducing irrigation needs and protecting against extreme weather events (Toledo and Scognamiglio 2021; Ye et al. 2023). However, the potential for optimizing water use within these systems remains unexplored.

Almanzora Valley, located in the province of Almería, is characterized by a semi-arid climate, with scarce rainfall and high temperatures throughout most of the year (Martín-Vide et al. 2021). Traditionally, this region has experienced hot, dry summers and mild winters with limited rainfall. In recent years, the effects of climate change have intensified these conditions, increasing aridity and leading to more extreme weather events (Bull et al. 2000; Sumner et al. 2003). A notable manifestation of this trend is the decline in annual precipitation, combined with an increase in the frequency of torrential rains (Camarasa-Belmonte et al. 2020). Recent data indicate that rainfall, which was previously more evenly distributed throughout the year, now occurs in isolated high-intensity events, discharging large volumes of water over short periods. This evolution of the meteorology creates the need for new water harvesting models and infrastructures to achieve sustainable technological development of water reserves for different sectors of society (Farmani et al. 2012, 2011; Memon et al. 2011; Ward et al. 2011; Butler et al. 2011; Aljohani et al. 2023; Albalawi et al. 2022).

Previous relevant scientific studies analyze the benefits of water harvesting in photovoltaic systems in geographical locations with torrential rainfall. In particular, by capturing and channeling rainwater in a controlled manner, solar panels help reduce uncontrolled surface runoff, which significantly contributes to preventing erosion and landslides. These water harvesting designs allow for a more even and targeted distribution of water flow, thereby reducing the direct impact of water on the soil and promoting more sustainable water resource management in areas with desert and extreme climates. Studies have focused on quantifying the effect of runoff following the installation of photovoltaic systems in agricultural regions (Cook LM, McCuen RH 2013). In order to take advantage of torrential waters for irrigation while also analyzing in an advanced way the different cases of erosion in the ground that these installations can cause, models have been proposed (Gullotta et al. 2023). Likewise, with the objective of analyzing the effect applied to the complexity of the orography, other models also analyze the effect of runoff and its application in the growth of agrovoltaic crops (Barnard et al. 2017).

Compared to previous studies, this study uses pipes at the ends of the photovoltaic panels, avoiding on-site construction, which entails greater economic and environmental impact. The proposed system is designed to accumulate the water collected in the existing reservoir, thus avoiding the use of the land beneath the photovoltaic installation. With this system's unique approach, it does not directly link water collection to the crop field, but instead uses a reservoir as a water reserve system to plan irrigation periods according to crop needs, significantly strengthening irrigation resilience. This study also optimizes the relationship between energy generation and water collection capacity. Furthermore, a scalable proposal for increasing the photovoltaic system offers different scenarios, including grid connection or local generation in remote areas. Therefore, this study proposes a novel method for collecting rainwater from the surfaces of photovoltaic panels integrated with an irrigation system. For the case of validation of the study, water is stored and used to irrigate almond crops, which are well adapted to arid and semi-arid regions. The system maximizes resource efficiency by aligning renewable energy production with sustainable water management practices.

The primary objective of this study is to evaluate and demonstrate the feasibility of an integrated photovoltaic system that combines solar energy generation and rainwater harvesting, aiming to enhance water and energy sustainability in arid and semi-arid agricultural regions where torrential rainfall occurs. This study proposes an innovative approach by utilizing the surfaces of solar panels as a tool for runoff collection, integrating renewable energy production with efficient water management practices. The key innovation lies in the design and evaluation of a multifunctional system that simultaneously optimizes energy performance and water storage, meeting the needs of high-aridity crops.

The structure of the manuscript is organized as follows: the introduction contextualizes the global water and energy challenges in relation to agriculture; the methodology describes the system design and evaluation methods; the results and discussion analyse the impacts of different configurations and scenarios, providing optimization for the proposed case. Finally, the conclusions highlight the benefits and future perspectives of the system.

Methodology

The design of the proposed system meets several key requirements to ensure its efficiency and viability. First, the collection of rainwater is designed to be optimized alongside electricity generation through photovoltaic systems. Additionally, it is essential to minimize installation and maintenance costs by optimizing the selection of materials and system configuration to reduce expenses without compromising functionality. Finally, the system must ensure a sufficient water supply for crop productivity, considering water demand based on crop type (MAPA

(Ministerio de Agricultura, Pesca y Alimentación) 2021; Romero et al. 2004).

To address these requirements, the proposed system design leverages synergies between solar energy capture and rainwater collection to optimize water resource use in agricultural fields. By utilizing the panel inclination along with a set of gutters and pipes, rainwater is collected and pumped into a central reservoir, increasing its effective capacity and ensuring water availability during dry periods. Subsequently, this water is distributed through a drip irrigation network, ensuring an efficient and sustainable water supply for crop development. The system falls within the rainwater harvesting method, which is applied for inducing, collecting, storing, and conserving local surface runoff for later use (Lasage and Verburg 2015).

Figure 1 illustrates the conceptual schematic of the system, highlighting its main components and the integration of the photovoltaic field within the agricultural facility. The system consists of the following components:

- Photovoltaic park: The photovoltaic panels are optimized in terms of inclination to enhance both solar energy capture and rainwater runoff collection.
- Channelling mechanism: Gutter systems are installed at the lower edges of the panels to direct collected rainwater into the piping system.
- Storage: The water is transported to a storage tank or central reservoir, dimensioned according to expected precipitation levels and irrigation requirements.
- Irrigation network: A drip irrigation system is designed to distribute the collected water to almond crops, ensuring efficient water use.

To assess the feasibility and efficiency of the rainwater collection system integrated into a photovoltaic park, a detailed analysis of climatic and energy conditions in a specific region in south of Spain was conducted. Historical data from local meteorological stations, including daily rainfall, were collected to estimate rainwater availability and its potential utilization. Agricultural water demand was defined based on the crop type in the area, allowing for the determination of the necessary water volume for efficient and sustainable irrigation (Agencia estatal de Meteorologia. 2025).

Additionally, the optimal inclination of the photovoltaic panels was evaluated, not only to maximize energy generation but also to optimize rainwater runoff collection, establishing a quantifiable relationship between energy production and water harvesting. For this purpose, the energy performance of photovoltaic panels was analysed through solar irradiation records and photovoltaic conversion models, integrating these data into the system planning. The combination of these variables enables the estimation of the overall efficiency of the proposed system, providing key information for its implementation and adaptation to different climatic and agricultural contexts.

Next, the characteristics and performance of a photovoltaic installation using 500 W solar panels were examined to determine their energy generation capacity for integration into the rainwater collection system. The panels used in this study are high-efficiency monocrystalline models, designed for photovoltaic park applications. The main specifications of these panels are presented in Table 1. The benefits of applying the system are aimed at improving irrigation systems where water supply can be critical due to remote areas or limited supplies. Similarly, the photovoltaic array is an off-grid system, although this same application would be

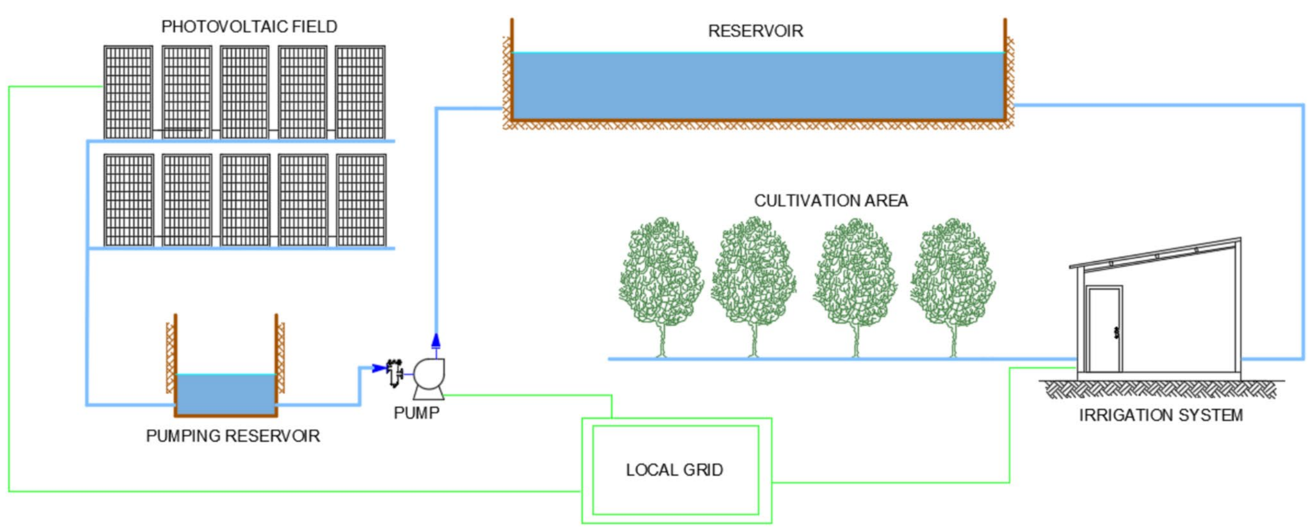

Fig. 1 Rainwater collection system design in a photovoltaic park

Table 1 Specifications of photovoltaic panels

Characteristic	Value
Photovoltaic park power	8.37 MW
Number of panels	16,740
Panel dimensions	2108 × 1048 × 35 mm
Panel weight	24 kg
Nominal Operating Cell Temperature (NOCT)	43 °C
Expected lifespan	30 years

scalable to grid-connected systems while maintaining the main advantages.

To evaluate the energy performance of the photovoltaic field in the study region in southern Spain, a detailed analysis was conducted considering different panel tilt angles. This approach allows for identifying the optimal configuration to maximize annual energy generation and understanding seasonal variations in system performance. Energy generation was analysed for tilt angles of 15°, 35°, 45°, and 60°, enabling a comparison of both monthly and annual accumulated values. The analysis was supported by the Photovoltaic Geographical Information System, the PVGIS tool (https://re.jrc.ec.europa.eu/pvg_tools/en/) (accessed on 20 January 2025). The Photovoltaic Geographical Information System (PVGIS) is a tool developed by the European Commission that provides solar irradiation data and estimates photovoltaic energy production using satellite-derived climate data and standard PV performance models. It calculates expected energy output based on geographical location, system configuration, and meteorological inputs. Figure 2 presents the analysis of solar energy generation, highlighting that a 35° tilt provides the highest annual accumulated energy generation, reaching values close to 14,000 MWh. From a first glance, this would be the optimal inclination value. Therefore, these values serve as an initial factor in optimizing the balance between energy generation and water collection, which is considered in the next section.

To evaluate the availability of water for irrigation throughout the year, a monthly water balance analysis was conducted, considering direct precipitation and crop demand under three different scenarios. This assessment was carried out in the Almanzora region, located in the north of the province of Almeria (Spain).

In a first scenario, the system was modelled without the additional collection of water through photovoltaic panels, allowing the evaluation of the storage capacity of the reservoir and water coverage solely from direct rainfall on the soil and the reservoir. This case study aims to analyze how rainfall and reservoir water supply meet irrigation needs, highlighting critical periods when water is insufficient to meet crop demand. The water level in the reservoir at the end of each month (V_t) is calculated using the following equation:

$$V_t = V_{t-1} + P_{t-1} \cdot A_b - D_{t-1} \tag{1}$$

where:

- V_{t-1} is the reservoir volume in the previous month,
- P_{t-1} is the precipitation recorded in the previous month,
- A_b is the reservoir catchment area,
- D_{t-1} is the irrigation demand of the previous month.

In a second scenario, the collection of rainwater through photovoltaic panels was incorporated, introducing an additional water input into the system. In this scenario, the analysis focuses on validating the increased water harvesting in

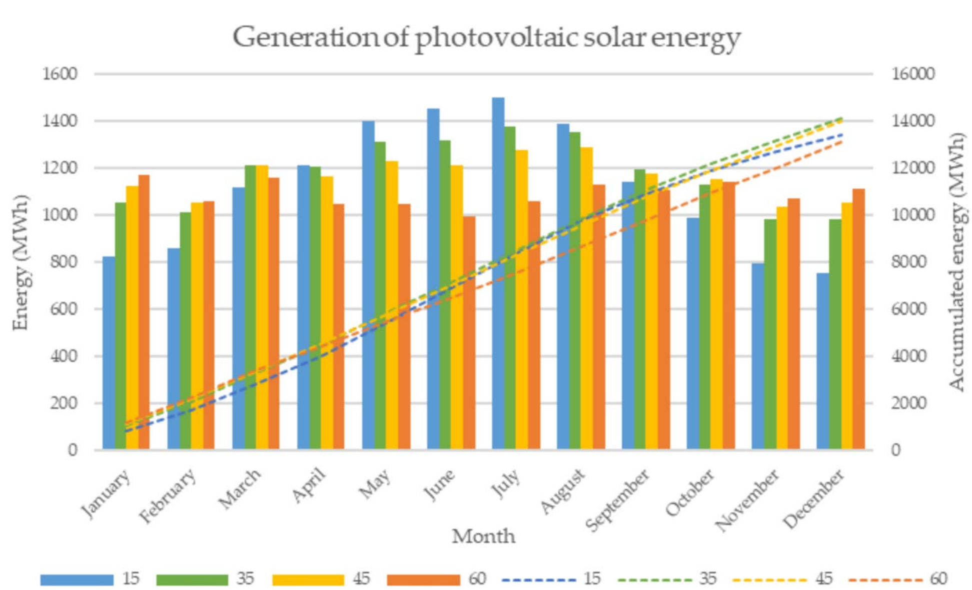

Fig. 2 Photovoltaic solar energy generation for different panel tilts

agrivoltaic systems to address the demand deficit from the previous scenario. In this case, the monthly volume of the reservoir (V_t) is adjusted considering the runoff captured by the panels, according to the following equation:

$$V_t = V_{t-1} + P_{t-1} \cdot A_b - D_{t-1} + P_{pv-1} \cdot A_{pv} \quad (2)$$

where:

- P_{pv-1} is the precipitation captured by the photovoltaic panels in the previous month,
- A_{pv} represents the total effective panel area, which is a function of the inclination angle.

This adjustment allows for evaluating the impact of water collection through photovoltaic panels on the system's water availability and determining the optimal inclination to balance water harvesting and solar energy generation.

The third scenario considers an expansion of the photovoltaic field, evaluating a threefold increase in the current panel surface area to enable additional rainwater accumulation in the reservoir. The expansion value represents the available installation area combined with a parameter reflecting the third case of the validation methodology. It ensures sufficient accumulated water volume and potential surplus in favorable rainfall conditions. This value is not universal, but scalable, allowing optimization based on rainfall, system configuration, water demand, and site availability. The application of this scenario is aimed at broadly addressing water demand during critical periods. It also proposes a scalable scenario where increased energy generation can contribute to self-consumption, grid connection, or local supply.

The Table 2 shows the scenarios analyzed in the results section, including the variables considered in each of them as well as the specific figure where the temporal evolution of the volumes of rain, storage and demand for each case can be seen, throughout the analyzed periods of ten years.

Results and discussion

This section presents the results obtained for the different analysed scenarios, for a period of ten years from 2014 to 2024. Figure 3 shows the results for the first scenario, illustrating the evolution of the reservoir volume and its

Table 2 Specifications of photovoltaic panels

	Rain (crop)	Rain (reservoir)	Rain (PV)	Water consumption	Reservoir volume	Reservoir volume with PV	Results
Scenario 1 (reservoir)	✓	✓		✓	✓		Figure 3
Scenario 2 (agrivoltaic + reservoir)	✓	✓	✓	✓	✓	✓	Figure 4
Scenario 3 (extended agrivoltaic + reservoir)	✓	✓	✓	✓	✓	✓	Figure 5

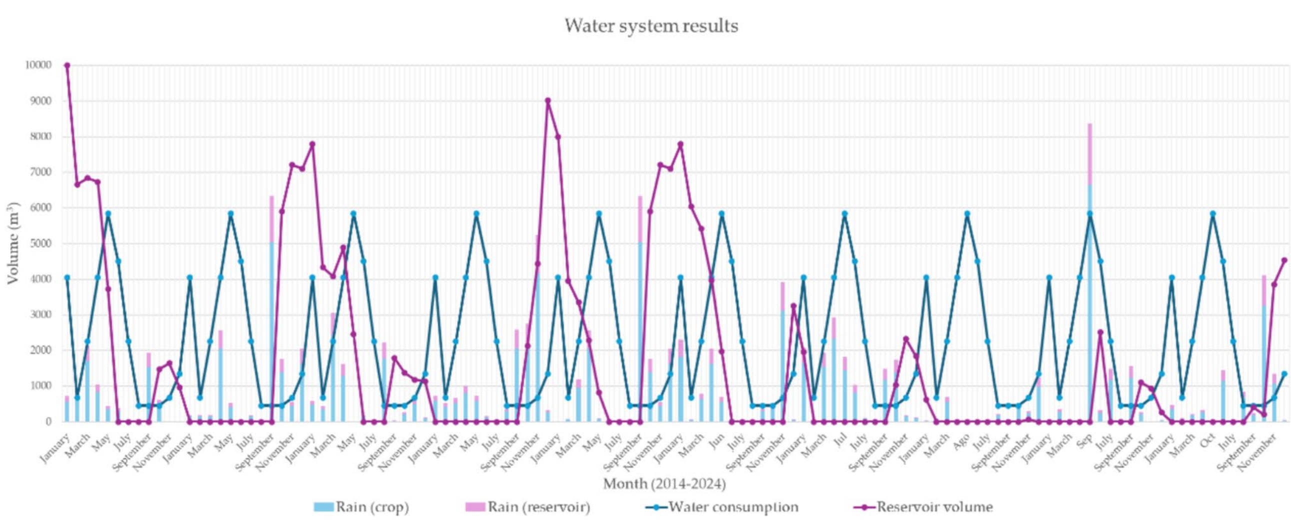

Fig. 3 Evolution of reservoir volume for the last ten years

relationship with monthly demand, allowing for the identification of periods in which water availability is insufficient to meet crop needs.

Figure 3 shows that the accumulated rainfall for the crop and the reservoir exhibits marked seasonality, along the ten years' period, with peaks in autumn and winter months, reaching over 6000 m^3, and minimum values in summer, with average values below 1000 m^3, highlighting the water system's dependence on seasonal rainfall for recharge. The monthly water demand follows a pattern consistent with the crop growth cycle, reaching its maximum during warm months such as spring and summer, when evapotranspiration rates are higher, with values around 5000 m^3, while in colder months, the demand is significantly lower, down to 500 m^3. The water consumption reported in the results also takes into account evaporation and filtration factors in the reservoir. The reservoir volume varies significantly throughout the year; during high precipitation months, the reservoir tends to recharge, up to 8000 m^3 for the best years, whereas in dry periods, especially in summer, the volume decreases considerably, often reaching critical levels. Thus, several periods are identified in which water availability is insufficient to meet crop needs, mainly in high-demand months such as July and August, underscoring the importance of optimizing stored water management and seeking complementary strategies to mitigate the impact of water deficits.

In the scenario 2, the impact of incorporating photovoltaic panels into the water system is evaluated. Figure 4 shows how the inclusion of photovoltaic panels positively affects the reservoir volume, providing an extra input of collected water during precipitation periods.

The reservoir volume with the integration of photovoltaic panels shows a significant increase compared to the baseline scenario, especially during high precipitation months such as autumn and winter, reaching over 9000 m^3. This additional input helps mitigate the water deficits that previously occurred in dry months like July and August in most cases. This is reflected in the results of water collection including the panels, which represent this system as a complementary source that reduces pressure on the existing water system. In this scenario the reservoir reach up to 15,000 m^3 for the best cases, while it mitigates the critical months of insufficient water reserves below 50% compared to the first scenario. Since the inclusion of water collection with photovoltaic panels reduces the number of critical cases regarding reservoir volume but does not entirely eliminate them, a third scenario is proposed, involving an extension of the photovoltaic field. Scenario 3 analyses the impact of expanding the photovoltaic field to improve both energy generation and rainwater collection. The photovoltaic field is expanded according to the available land area and optimized based on site-specific conditions such as rainfall, water demand, and system configuration. Figure 5 shows how this change significantly influences the water system's behaviour, completely mitigating periods when the reservoir volume reaches critical values.

The expansion of the photovoltaic field substantially increases the amount of water collected, directly contributing to maintaining more stable reservoir volume levels. The extent of the PV installation expansion depends on the land available and is adjusted to maximize water collection efficiency under local environmental and operational conditions. For the case study, the effective area in this case is tripled, thus affecting both water collection and energy generation. This may vary depending on the application area, as this is a scalable system. This improvement is

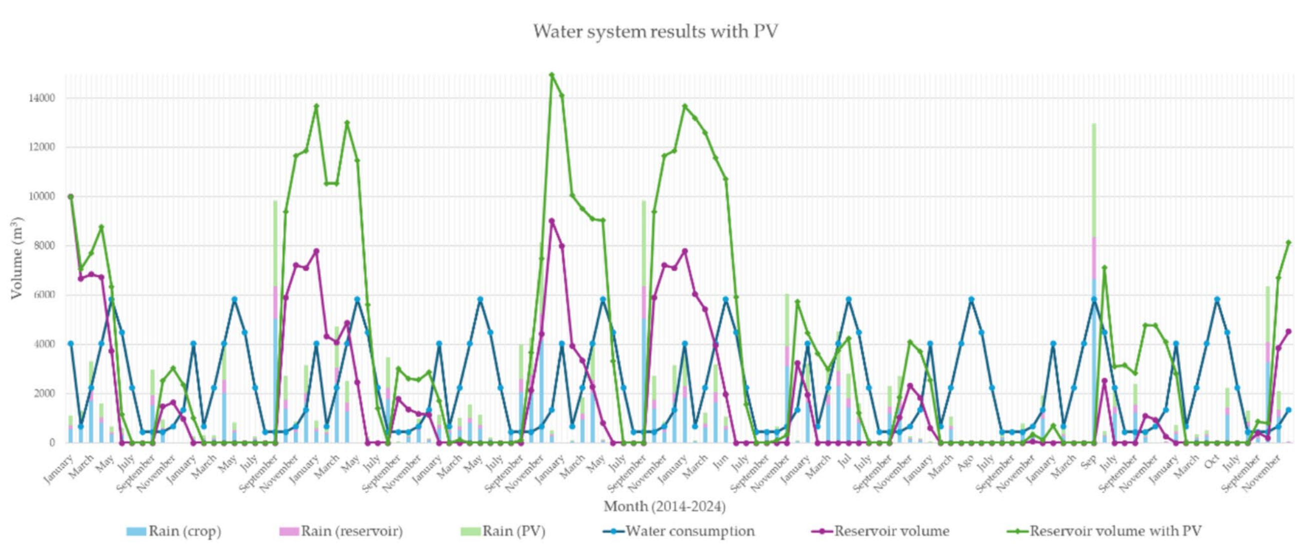

Fig. 4 Evolution of reservoir volume with photovoltaic water collection

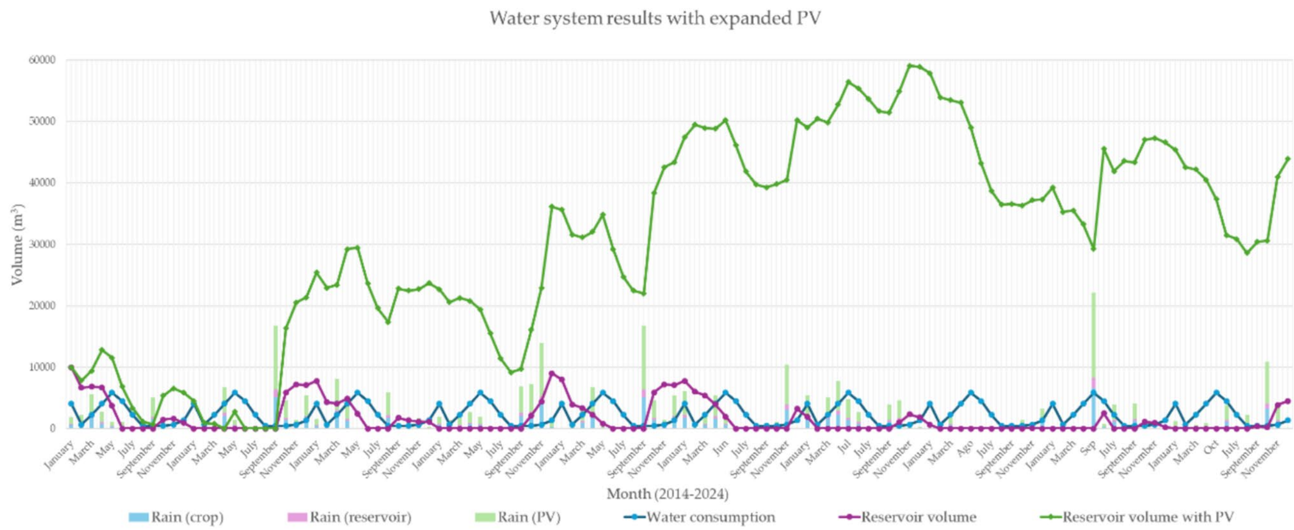

Fig. 5 Evolution of reservoir volume with extended photovoltaics

particularly notable in high water-demand months such as July and August, where the system previously experienced critical deficits. The increased collection capacity enables the system to respond more efficiently to crop needs, even under limited precipitation conditions. Additionally, a comparison with previous scenarios shows that expanding the photovoltaic field not only mitigates deficits but also provides a water security margin by increasing storage capacity during wet months, reaching reservoir volume up to 60,000 m^3. This ensures better water availability throughout the year, reducing dependence on external sources and providing a more consistent water supply that enhances system resilience against climate variability and increasing crop demands.

The final analysis evaluated the reservoir volume based on the photovoltaic panels' tilt angle, also considering the expansion of the photovoltaic field (+ in Fig. 6). This approach aims to determine the optimal angle that maximizes rainwater collection while ensuring efficient energy generation.

The analysis in Fig. 6 shows that the inclination of photovoltaic panels has a direct effect on reservoir volume, particularly in its ability to maintain stable levels over time. A lower inclination results in greater water collection due to the panels' more horizontal surface, which allows for increased runoff capture during intense rainfall periods. However, these lower inclinations can slightly reduce solar generation efficiency compared to steeper angles. At higher inclinations, water collection decreases slightly due to the panels' more vertical angle. Expanding the photovoltaic field significantly enhances the system's ability to address water deficits, particularly at intermediate inclinations such as 35° and 45°, which achieve a reasonable balance between water collection and solar generation (Fig. 2), with 35° being the optimal case under the study conditions, since 35° also produced the greatest solar generation. With the expanded

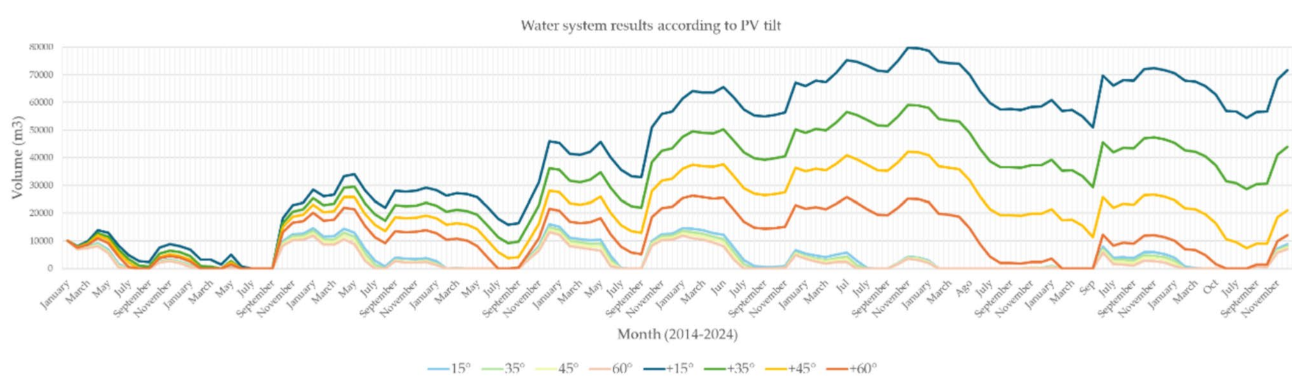

Fig. 6 Evolution of reservoir volume with different photovoltaic tilt angles

photovoltaic field, reservoir levels remain higher even during peak demand months like July and August, eliminating the critical deficits observed in scenarios without photovoltaic field expansion while ensuring both a large water reserve and optimal energy generation. These results can indeed be scalated to different regions as the increased water capacity is demonstrated within the expanded photovoltaics integration.

The economic viability of installing the system has been analyzed. Several factors are taken into account, including the cost of the material and its integration, as well as savings in water supply. It should also be noted that this application can be critical in regions with difficult water supplies. The amortization analysis is based on the initial investment required for the implementation of the water collection system. This includes material costs (such as piping and fittings), labor for installation, and other essential components necessary for system operation. The profitability threshold corresponds to the volume of water that would generate equivalent savings compared to conventional water acquisition sources. Therefore, system amortization is achieved when the accumulated collected volume compensates the initial investment through avoided water purchase costs. The annual accumulation of collected water is projected considering different photovoltaic panel tilt angles, influencing collection efficiency. Considering the different configurations of the first photovoltaic installation case, it is confirmed that the system can be amortized in less than 7 years, Fig. 7, while the optimized case of 35° is profitable from 5 years. Depending on the region and the water accumulation when the system is installed, these figures could even be improved. Therefore, in addition to a short economic recovery period, the system not only avoids the cost of water supply in remote areas, which has been proven in this work to be required to satisfy the demand of the plantation, but also avoids modifying the orography of the region when carrying out large-scale supplies, with the benefits in environmental impact that this entails. Regarding the payback from the expansion of photovoltaic panels, which can be scaled according to their application, several issues are worth noting. Since the installation material, its integration cost, the cost of water saved, and the volume of water collected are proportional, the payback is the same. This proportionality arises naturally, as scaling up the system entails a direct increase in materials, installation time, and water collection capacity. Although certain non-linear effects, such as minor efficiency variations or local cost differences, may occur, their influence is generally limited compared to the dominant impact of scaling. Therefore, this approximation is considered sufficiently robust for global scalability assessments, while more detailed, site-specific analyses can further refine the payback estimation if needed. It is important to keep in mind that an increase in photovoltaic generation must also have an application. If the agricultural plant does not have sufficient energy demand, two scenarios can be considered. On the one hand, grid connection, in areas where it exists, or the creation of a local grid with nearby facilities, to supply energy to more remote areas or those seeking to shift toward a more sustainable energy consumption model. Although this might increase CAPEX and affect financial indicators, the creation of a local grid provides a strategic benefit by enabling energy access in remote areas, which goes beyond short-term profitability.

The implementation of the integrated photovoltaic system is shown in Fig. 8, which illustrates the layout of the main components of this system. The photovoltaic system is strategically located and designed to maximize both solar energy capture and rainwater runoff collection. The panels are tilted at optimized angles that allow the

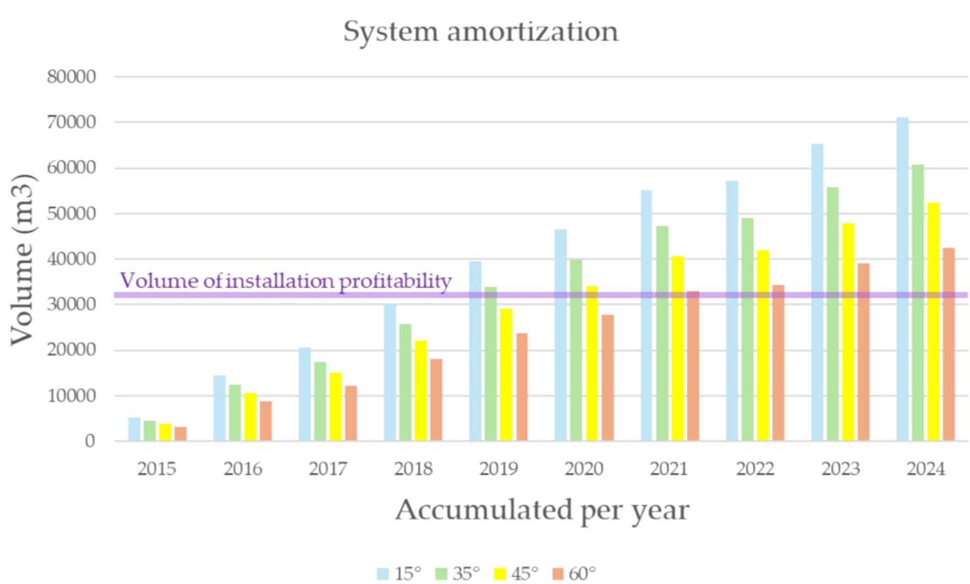

Fig. 7 Analysis of the system amortization

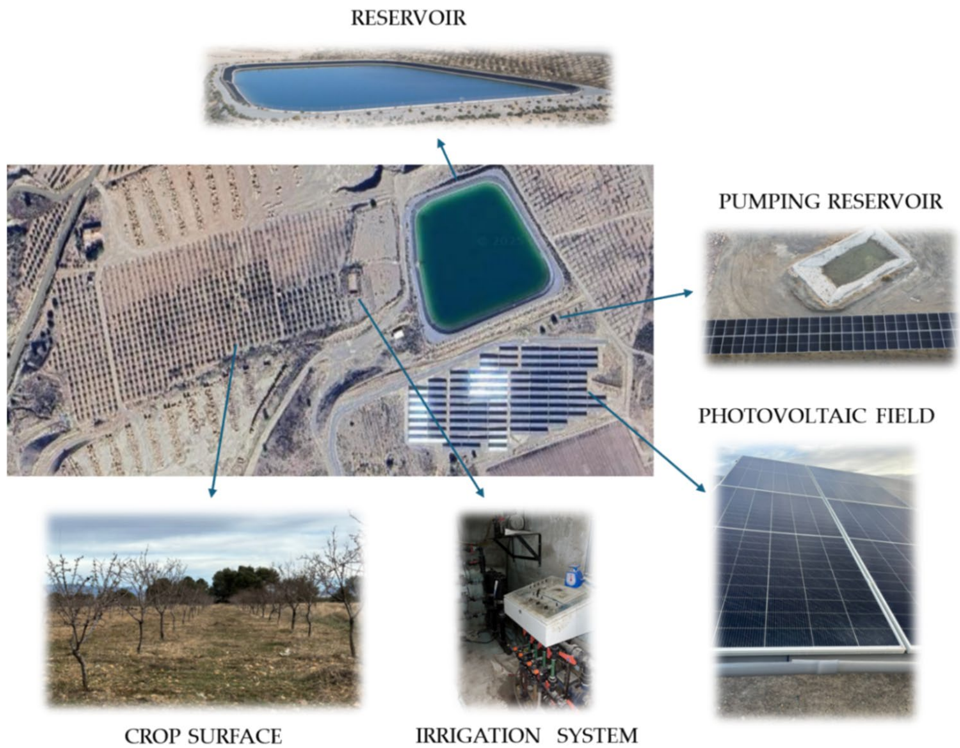

Fig. 8 Integrated irrigation system with photovoltaics and rainwater harvesting

collected water to be directed toward a storage system, which includes the main reservoir with sufficient capacity to ensure water supply during critical months of the year. This reservoir, receiving additional inputs from water collected by the panels, maintains stable levels even during high water-demand periods. Adjacent to the main reservoir is the pumping reservoir, which regulates water distribution. This design ensures efficient water management, reducing losses and guaranteeing a constant supply. The stored water is distributed through an irrigation system, which minimizes evaporation and optimizes resource use, adjusting to the specific needs of the crop.

The integration of this system into the cultivated area provides substantial benefits. Solar energy generation significantly reduces energy costs associated with agricultural operations, such as water pumping and other irrigation-dependent activities. Furthermore, rainwater collection ensures a stable water supply and reduces reliance on external sources, promoting greater water and energy autonomy. The implementation of this integrated photovoltaic system enhances crop resilience to climate variability conditions, such as drought periods or irregular rainfall. Its multifunctional design allows for efficient resource use, integrating environmental sustainability with agricultural productivity. Integration still allows for the incorporation of different plantations, on a smaller scale, with a reduced environmental impact. Additionally, this solution is replicable in other regions, adapting to their specific climate conditions, making it a valuable tool for transforming agriculture into a more sustainable and resilient model.

Conclusions

The results obtained in this study demonstrate that the integration of photovoltaic systems with rainwater harvesting is a technically viable and high-impact solution for water and energy management in arid and semi-arid regions. The ability of solar panels to function as runoff collection surfaces not only expands the functionality of traditional photovoltaic systems but also maximizes the utilization of existing infrastructure, creating synergies between renewable energy generation and water sustainability. The combination of energy generation and water collection makes photovoltaic panels an efficient and multifunctional solution. The objective of evaluating and demonstrating the feasibility of an integrated photovoltaic system that combines solar energy generation with rainwater harvesting has been successfully addressed. The results highlight the system's potential to improve water and energy sustainability in arid and semi-arid agricultural regions prone to torrential rainfall.

The detailed analysis of different scenarios and configurations, including panel inclination and the expansion of the photovoltaic field, confirms that it is possible to significantly reduce critical water deficits through this system. Specifically, for the evaluated case, the optimal inclination of 35°

not only ensures maximum annual energy performance but also provides sufficient water collection to meet the needs of almond crops, even during months of high water demand. Additionally, expanding the photovoltaic field considerably increases the reservoir's storage capacity, completely eliminating periods in which the available volume was insufficient in previous scenarios.

From an energy perspective, the integration of photovoltaic systems in an agricultural context not only reduces dependence on external energy sources but also minimizes emissions associated with the use of fossil fuels in agricultural activities. This makes agrivoltaic systems a key tool for the transition toward sustainable and climate-resilient agriculture. Furthermore, the proposed technical design, which includes gutters, pipes, and a highly efficient drip irrigation system, ensures that the collected water is distributed precisely, minimizing losses due to evaporation and infiltration. Their integration not only contributes to the energy sustainability of the system but also significantly improves the reservoir's water storage capacity, allowing crop demands to be met more efficiently even under climate variability conditions.

While additional water collection through photovoltaic panels reduces water deficits in initial scenarios, its impact is significantly amplified by increasing the installed photovoltaic surface area. This highlights the importance of considering scalability as an essential factor for implementing these systems in agricultural regions facing high water stress. In this context, this refers to the ability of agrivoltaic systems to increase their water collection and energy generation capacity by expanding the photovoltaic surface area, while maintaining their overall functionality and efficiency. Therefore, the framework is based on key considerations such as the installed photovoltaic capacity, the solar energy potential of the region, the rainwater harvesting and storage capacity, the crop water demand, the possible need to expand the agrivoltaic system, and the intended application of the generated energy.

In conclusion, this study provides solid evidence of the effectiveness of photovoltaics systems integrated within irrigation systems as a comprehensive solution to address the interconnected challenges of water and energy in agriculture. Additionally, it establishes a replicable framework for implementation in other regions with similar climatic conditions. The findings not only have practical implications for improving agricultural productivity and water sustainability but also contribute to global objectives of climate change mitigation and efficient use of natural resources. Future research should focus on the long-term validation of the system through pilot trials under real conditions and on further optimization of its technical and economic components to ensure its scalability and global feasibility.

Author contributions Conceptualization and methodology: A.M.R.P., C.A.R.G. and A.G.C.; validation, formal analysis, and investigation: C.A.R.G., J.J.C.M. and R.M.C.; writing—original draft: A.M.R.P. and A.G.C.; writing—review and supervision: R.M.C. and J.J.C.M. All authors have read and agreed to the published version of the manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

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