

Portable solar-powered irrigation control station into a container for sustainable agriculture

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Abstract

This study explores the design and adaptation of a shipping container into a portable irrigation control station for agricultural operations. The project leverages the structural durability and mobility of containers to offer a versatile and sustainable solution for irrigation management. By integrating irrigation equipment, control systems, and energy storage, this unit provides an efficient and cost-effective alternative to traditional irrigation stations. A key advantage of this innovation is its mobility, allowing the container to be easily relocated between farms using a crane truck. This feature optimizes its use in seasonal crop rotations and in agricultural operations spread across different locations. The system operates autonomously, harnessing photovoltaic solar energy stored in batteries, thereby eliminating reliance on fossil fuels and significantly reducing the environmental impact of agricultural irrigation. The system was designed to irrigate 4 hectares, with a pump flow rate of 26 L/s, a total power load of 3.47 kW, and the capacity to supply a crop area of up to 4 ha under typical operating conditions. Beyond its operational efficiency, the study emphasizes the environmental benefits of repurposing shipping containers, contributing to waste reduction and mitigating ecological degradation. This approach aligns with sustainability principles in agriculture, promoting the responsible and efficient use of water and energy resources in decentralized irrigation systems.

Key words: Sustainability; renewable energy; photovoltaics irrigation; water management.

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Introduction

The use of renewable energy in agriculture has gained significant relevance in recent years due to the need to reduce environmental impact and improve energy efficiency in agricultural operations. Among the various sources of renewable energy, solar energy is one of the most accessible and efficient, allowing electricity supply in rural areas without access to the power grid. In many agricultural regions, the lack of conventional electricity access hinders the operation of essential systems such as irrigation (Bhattacharjee *et al.*, 2024). In this context, photovoltaic solar systems, combined with storage batteries (Aziz *et al.*, 2024), offer a resilient alternative to energy supply even on days with low solar radiation (Pacesila *et al.*, 2016; Ibrahim, *et al.*, 2021).

The environmental impact of traditional irrigation systems, powered by internal combustion engines, poses a significant challenge in terms of greenhouse gas emissions and noise pollution in agricultural environments. Currently, many farms without access to the power grid rely on irrigation pumps driven by diesel or gasoline engines (Beerge *et al.*, 2024), which generate CO₂ emissions, nitrogen oxides (NO_x), and pollutant particles, contributing to climate change and affecting air quality. Moreover, these engines require a constant fuel supply, increasing operating costs and

dependence on fossil resources. In contrast, the system proposed in this study eliminates the need for fossil fuels by using photovoltaic solar energy, a renewable, clean, and sustainable source. The integration of solar panels with storage batteries ensures the system's energy autonomy without generating pollutant emissions, thus improving the sustainability of agricultural production and reducing its environmental impact (Al-Smairan *et al.*, 2024; Obalalu *et al.*, 2025).

Given these challenges, this study proposes the design of a modular transportable irrigation system based on a shipping container equipped with solar panels and batteries. This system is designed to operate in two locations with seasonal crops, alternating use every six months. These types of crops require high-cost irrigation installations, which remain completely unused for a large part of the year. This occurs with crops such as lettuce, arugula, escarole, cabbages, spinach, chard, radish, carrot, asparagus, artichokes, among others, which, even in geographically close regions like the case study, are subjected to very different climatic conditions depending on the season (Mainuddin *et al.*, 2015), making them seasonal crops (Fernández García *et al.*, 2020). These seasonal crops vary their water requirements depending on their location because the environmental conditions are different (Poddar *et al.*, 2021a; 2021b). Methods exist that allow predicting the water

requirements of crops based on their location, which are very useful tools for sizing irrigation systems (Poddar *et al.*, 2022). Thus, the cost and maintenance of a fixed installation is proposed to be replaced by a transportable installation designed in this study, also based on renewable energy sources. Its independence from the power grid makes it an efficient and sustainable alternative to ensure irrigation in remote areas, reducing operating costs and optimizing the use of water and energy resources in agricultural operations with seasonal usage conditions (Singla *et al.*, 2025). This project leverages the structural durability and mobility of containers to offer a versatile and sustainable solution for irrigation management, taking advantage of both natural and artificial water reserves (Poddar *et al.*, 2020). Its design allows relocation between different farms using a crane truck, optimizing its use in rotational crops (García *et al.*, 2024). Furthermore, the energy storage system ensures its operation even on days with low solar radiation, increasing its reliability in various agricultural environments. The optimization of energy use in this system is fundamental to maximizing its performance (Neethirasu *et al.*, 2024; Inada *et al.*, 2022). A novel review on the efficiency of nanomaterials for solar energy storage systems (Olivkar *et al.*, 2022; Irsha *et al.*, 2023). Advanced energy management strategies have been considered to improve the efficiency of storage and distribution of the energy generated by the solar panels (Rekioua, 2023; (Rana *et al.*, 2022; Obaideen *et al.*, 2022). Additionally, the integration of smart sensors and monitoring systems allows irrigation adjustments based on real-time crop water demand and climatic conditions, thus improving water use efficiency (Ghareeb *et al.*, 2023; El Mezouari *et al.*, 2022; Ndunagu *et al.*, 2022). Overall, the reviewed literature confirms the growing relevance of renewable energy for agriculture, showing that photovoltaic systems with battery storage can ensure off-grid water supply and that smart control strategies can improve irrigation efficiency. However, most reported approaches are conceived as stationary installations, focused on energy sizing, control optimization or sensor integration, but without addressing the problem of idle infrastructure in seasonal crops. As a result, farms that cultivate different plots at different times of the year are forced to either duplicate irrigation stations or leave them inactive for months, which increases costs and reduces system utilization. There is still a clear lack of modular, transportable irrigation solutions that combine hydraulic equipment, energy storage, and automated control in a single unit that can be relocated between sites while maintaining operational reliability. This gap limits the application of renewable irrigation systems in dispersed or rotation-based agriculture despite their proven technical potential.

The main innovation of this study lies in the combination of mobility, energy autonomy, and hydraulic efficiency in a transportable irrigation system. Unlike fixed infrastructures, this system allows optimized use in different locations according to crop seasonality. Moreover, the integration of renewable energy through an efficient photovoltaic design with battery storage eliminates dependence on fossil fuels and power grids, offering a sustainable and economically viable solution for agricultural operations in isolated environments (Emezirinwune *et al.*, 2024; García *et al.*, 2024; Augustyn *et al.*, 2021). The novelty of this study is demonstrated by the integration of mobility, energy autonomy and hydraulic efficiency into a single, fully operational unit that has been designed, implemented and validated under real agricultural conditions. Unlike most previous works, which approach photovoltaic-powered irrigation mainly from an energy or control perspective, this system combines all functional subsystems within a compact containerized station specifically engineered for seasonal

relocation between farms. It brings together a complete pressurized hydraulic network validated through EPANET modelling, a photovoltaic generation and battery storage system sized according to real crop water demands, and a programmable logic controller that coordinates irrigation and energy management to ensure stable operation under variable irradiance and battery states. The design process also included a detailed 3D model of the container to optimise the internal spatial arrangement, ensure accessibility for maintenance and anticipate mechanical interferences during assembly, enabling the system to be physically deployed as designed. Furthermore, the study provides a techno-economic comparison with conventional fixed irrigation sheds, demonstrating the advantages of the proposed solution in terms of investment costs, operational expenses and deployment flexibility. This comprehensive integration required reconciling the mechanical constraints of the container layout with hydraulic pressure uniformity and energy balance requirements, while guaranteeing reliable performance after each relocation. As a result, the proposed system not only operates autonomously off-grid but also minimizes infrastructure duplication and idle periods in seasonal agriculture, representing a significant advance from conceptual designs toward a deployable, field-tested solution for sustainable irrigation.

The main objective of this study is to design and analyze a modular autonomous irrigation system based on a repurposed shipping container (Wang *et al.*, 2024). This system incorporates a photovoltaic array with battery storage to ensure energy supply in agricultural operations without access to the power grid. To achieve this, several specific goals are established, such as the design and sizing of the solar system, the optimization of energy storage capacity, the integration of hydraulic and electrical components within the container, and the evaluation of its operational efficiency. The manuscript is structured as follows: the methodology section presents the design, case study, and analyzes consumption requirements. The results section evaluates the hydraulic model of the design, sizes the photovoltaic installation, experimentally validates the system's operation, designs the final distribution, and presents the 3D model of the installation. Finally, the conclusions of the study are presented.

Materials and Methods

The designed system integrates an irrigation solution within a shipping container, providing a versatile and sustainable approach that allows relocation to different sites according to the season while optimizing the use of energy and water resources in agricultural production. To ensure the mobility and efficiency of the irrigation system, a fully autonomous installation has been designed within the container. It includes a photovoltaic system that generates the electricity needed for irrigation, eliminating dependence on external energy sources. Additionally, the irrigation system includes a programmable logic controller (PLC), an irrigation pump, three fertilizer tanks for fertigation, and two sand filters to ensure the quality of the water used.

Figure 1 shows the schematic of the system inside the container, highlighting the main components:

- Photovoltaic solar panels, which supply the necessary energy.
- Power converter and inverter, responsible for regulating and transforming electricity.
- Storage batteries, allowing continuous operation even on cloudy days.
- Programmable Logic Controller (PLC), which manages irrigation and fertigation cycles.

- Irrigation pump, which drives water into the distribution network.
- Sand filters, which ensure water quality by removing impurities.
- Fertilizer tanks, which enable controlled nutrient application.

This modular and compact design optimizes the weight-volume-functionality ratio within the container, enabling efficient transport between agricultural sites while maximizing system sustainability. To optimize resource use and adapt the irrigation system to the climatic conditions of each region, a transportable system has been designed that will be installed in different locations depending on the time of year. From October to April, the irrigation station will be located in *Pulpí* (Almeria, Spain), while from May to September, it will be moved to *La Calahorra* (Granada, Spain). This distribution allows taking advantage of favorable climatic conditions for crops in each location, ensuring an efficient

and adequate water supply for the optimal development of the crops. Figure 2 shows the location scheme of the system, indicating the two areas where the irrigation system will be installed according to the season: *Pulpí* from October to April and *La Calahorra* from May to September. Thanks to this approach, the system maintains its mobility and versatility to operate in different agricultural farms throughout the year. With this, the aim is to facilitate irrigation management in seasonal crops, reducing infrastructure costs and maximizing efficiency in the use of water and energy resources.

The design of the irrigation system considers the water demand of different seasonal crops, allowing for the proper sizing of pumping capacity and energy consumption. In this study, seasonal crops where irrigation is not required year-round have been analyzed, such as lettuce, arugula, escarole, cabbages, spinach, chard, radish,

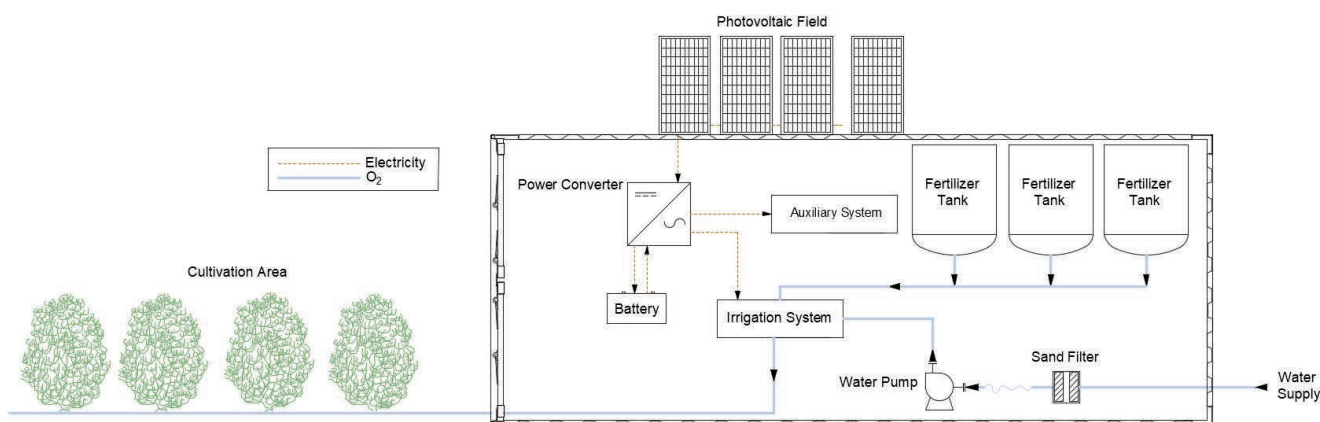


Figure 1. Schematic of the irrigation system inside the shipping container.

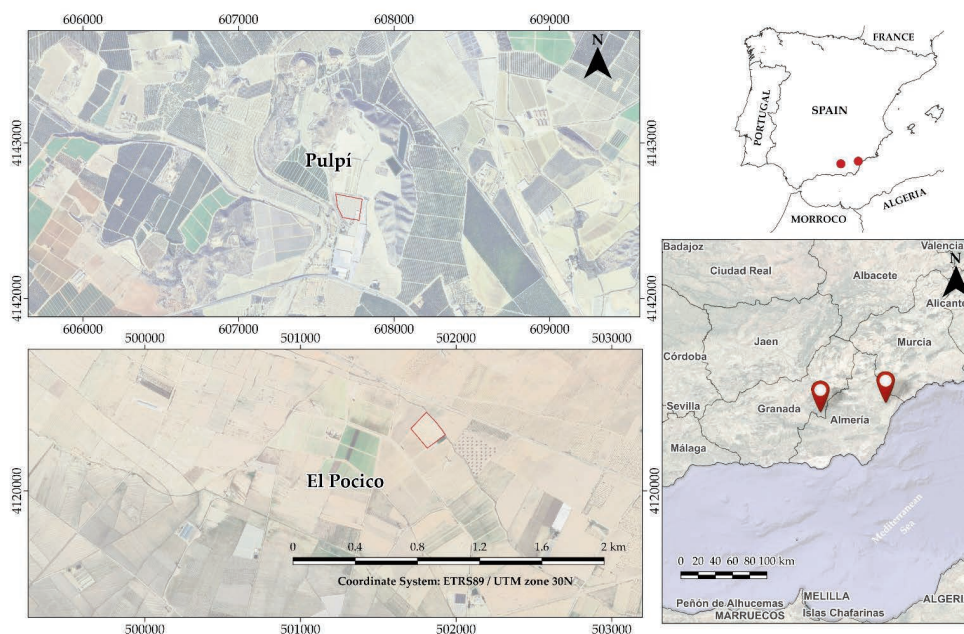


Figure 2. Location map of the transportable irrigation system.

carrot, asparagus, and artichokes. Their water requirements are detailed in Table 1, with values ranging from 1,150 to 6,000 m³/ha per year, depending on the crop. For the system design, lettuce was taken as a reference since it has the highest water consumption (45 m³/ha per day). This ensures that the designed system can meet the irrigation needs not only of this crop but also of all the others included in the analysis, as they have equal or lower consumption levels. To meet the irrigation demand, covering 4 hectares in the case study of this article, a total of 180 m³ of water per day is required. The plantation has been divided into two sectors of 2 hectares each. Each sector is irrigated during four periods of 35 minutes each, totaling 140 min of irrigation per day per sector. To meet the water demand of this crop, a constant flow rate of 10.7 L/s is needed during that time.

To provide the necessary irrigation conditions, an irrigation pump with a power of 3,100 W is required, along with a control automaton with a power of 350 W and system lighting with a power of 20 W, resulting in a total system power of 3,470 W. Based on the total power of the system, it is possible to determine the electrical demand required (I_{system}) in A from the battery, given that the supply voltage of the system components and the battery (V_{system}) is known. The following equation allows for the calculation of the required current (I).

$$I_{\text{system}} = P_{\text{system}} / V_{\text{system}} \tag{Eq. 1}$$

The battery capacity (C_{battery}) in Ah is determined based on the current demanded by the system (I) and the required operating time (t) (in hours, h) to ensure its functionality during a work shift.

$$C_{\text{battery}} = I_{\text{system}} \cdot t \tag{Eq. 2}$$

This energy demand is the design requirement for sizing the photovoltaic system and the battery bank, ensuring sufficient autonomy even under low solar radiation conditions.

Results and Discussion

System evaluation and control system

To evaluate the hydraulic performance of the designed irrigation system, a simulation was conducted using EPANET, a specialized software for modeling water distribution networks. The simulation allowed for the analysis of flow distribution and pressure levels in the system's pipes and drippers, ensuring that the design meets the crop's requirements.

Figure 3 presents the pressure map generated in EPANET, displaying the pressure distribution at various points within the irrigation network. As observed, the system maintains adequate values

Table 1. Main technical parameters and costs of the irrigation container.

Component	Technical specification	Cost (€)
Photovoltaic array	6000 Wp (12 × 500 Wp monocrystalline panels, 21% efficiency, 30° tilt)	1860
Inverter and controller	6 kW nominal power, integrated regulator	700
Battery storage	37 kWh (covering ~1 day of demand)	1900
Irrigation pump	3.1 kW, flow rate 26 L/s, pressure 11.8-35 mwc	900
Filtration system	Two sand filters	300
Fertilizer tanks	Three tanks for fertigation	400
Container adaptation	Modified 20 ft shipping container	1400

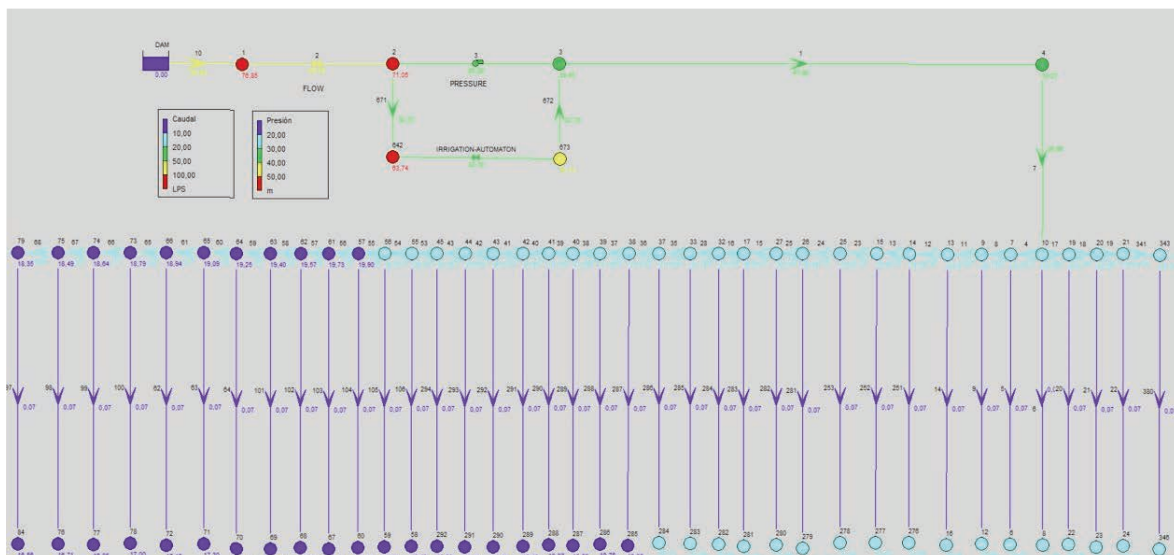


Figure 3. Pressure distribution in the irrigation network based on the EPANET simulation.

across all sectors, preventing excessive pressure losses and ensuring efficient water distribution. These results validate that the hydraulic design of the system has been optimized, enabling efficient and sustainable irrigation without compromising emitter pressure or causing water waste. The results obtained, applied to two hectares, show that the irrigation pump operates with a flow rate of 26 L/s and a pressure of 35 m of water column (mwc), ensuring uniform supply throughout the network. It is observed that pressure is higher in the pipes near the pump and gradually decreases toward the more distant sectors. However, even at the furthest points, the pressure remains at 11.8 mwc, guaranteeing optimal dripper operation without affecting irrigation uniformity. The evaluation was performed in EPANET under its standard hydraulic assumptions. The software solves the network under steady-state conditions, assuming fully pressurized and incompressible flow. Head losses along the pipes are calculated with the Hazen–Williams equation (default setting); a roughness coefficient $C=140$ was assigned to the PVC mains and manifolds, and $C=135$ to the polyethylene laterals (black LDPE drip lines). Minor losses at fittings and junctions are included through local loss coefficients. EPANET applies mass continuity at each junction and energy conservation along each loop, iteratively adjusting flows and pressures until convergence is reached. The pumping station was defined as a fixed-head boundary element, and the drippers were represented as emitter nodes with their characteristic discharge–pressure relationship. These assumptions are consistent with conventional pressurized irrigation networks and allow a realistic estimation of pressure distribution and flow rates throughout the system. Figure 4 shows the control logic diagram. The control runs on an industrial PLC installed inside the container. The logic is

executed cyclically with a scan time between 1 and 5 s and it commands the pump and the irrigation valves. The PLC reads Alarm as a digital composite of pressure and flow interlocks, drive thermal trips and tank levels. It acquires PV as the available photovoltaic power at the converter in W and SOC as the battery state of charge in percent, via the BMS over Modbus. The electrical demand of the hydraulic load is represented by P_{pump} in W. TIME_OK is a boolean generated by the PLC scheduler that is true when the current time lies within the operating window for irrigation. Hysteresis margins are used to avoid chattering: ΔPV is a power margin around P_{pump} that defines the safety band for deciding if PV comfortably covers the pump; P_{chg_min} is the minimum surplus power above P_{pump} required to authorize battery charging while pumping for irrigation; ΔCHG is the hysteresis associated with that charging authorization so that entry into the charging mode requires $PV \geq P_{pump} + P_{chg_min} + \Delta CHG$ while exit occurs when PV drops below $P_{pump} + P_{chg_min} - \Delta CHG$. Battery thresholds are defined as SOC_{min_run}, the minimum state of charge at which battery discharge is allowed during pumping, SOC_{cut}, the protection threshold that stops pumping to prevent deep discharge, and SOC_{max}, the upper limit at which charging is stopped. The logic revolves around a mode selector evaluated every scan. If TIME_OK is false or Alarm is true, the PLC forces S0 (OUT_OF_WINDOW): the pump is off and, whenever PV is greater than zero and SOC is below SOC_{max}, standby charging is enabled. When TIME_OK is true and no alarm is present, the system enters S1 (STANDBY_IN_WINDOW): the pump remains off and the battery charges in standby if $PV > 0$ and $SOC < SOC_{max}$. From S1 a single, mutually exclusive set of conditions selects exactly one of four operating states based on PV bands and battery

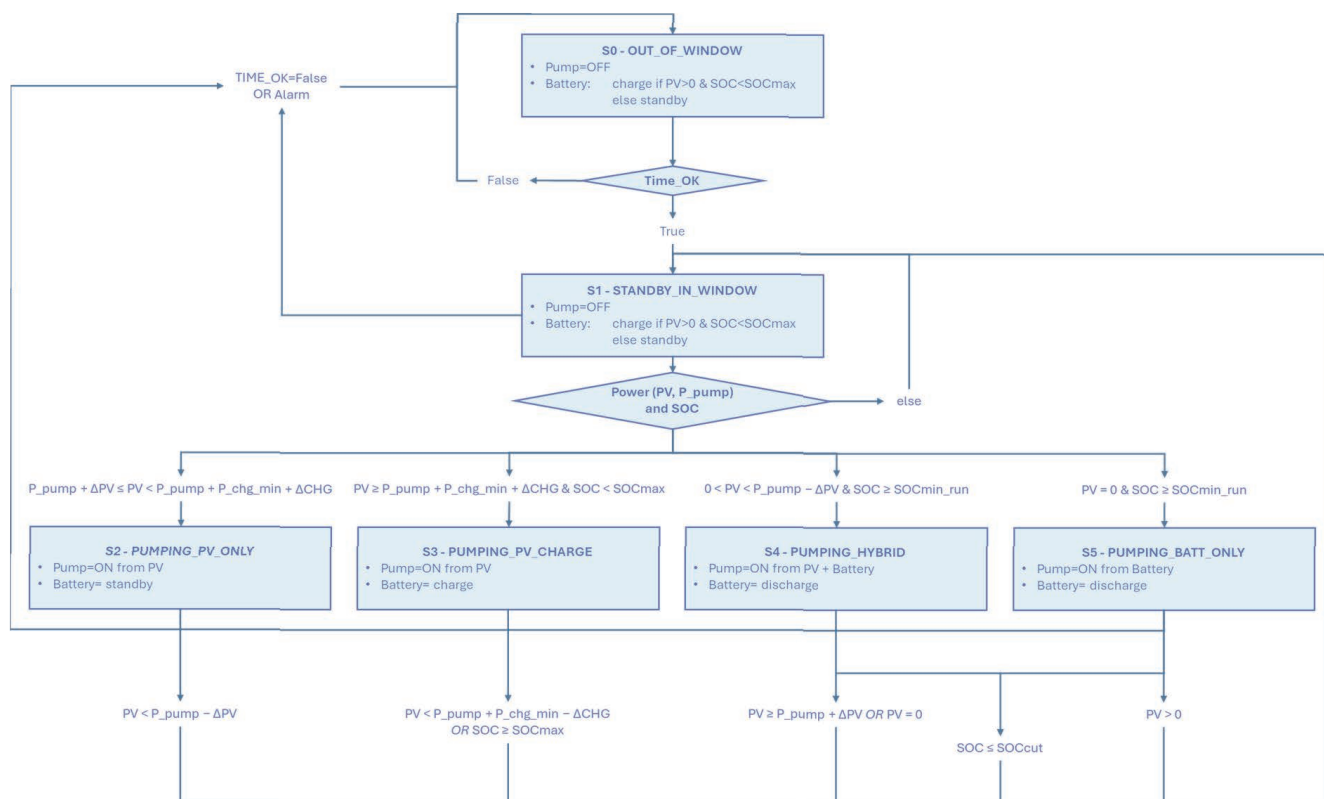


Figure 4. Control logic diagram of the system.

thresholds. State S3 (PUMPING_PV_CHARGE) is selected when there is a true and persistent surplus over demand, defined as $PV \geq P_{\text{pump}} + P_{\text{chg_min}} + \Delta\text{CHG}$ with $\text{SOC} < \text{SOCmax}$, so the pump is fed entirely from PV and the surplus charges the battery. State S2 (PUMPING_PV_ONLY) is selected when PV safely covers the pump but is insufficient to charge, defined by $P_{\text{pump}} + \Delta PV \leq PV < P_{\text{pump}} + P_{\text{chg_min}} + \Delta\text{CHG}$, leaving the battery on standby. State S4 (PUMPING_HYBRID) is selected when PV is insufficient but non-zero, defined by $0 < PV < P_{\text{pump}} - \Delta PV$, and $\text{SOC} \geq \text{SOCmin_run}$, in which case PV provides what it can and the battery injects the deficit. State S5 (PUMPING_BATT_ONLY) is selected when $PV=0$ (cloud or night condition) and $\text{SOC} \geq \text{SOCmin_run}$, operating solely from the battery. If none of the pumping conditions is met, the selector stays in S1, with standby charging when applicable. Each operating state has a condition to return to S1. State S2 returns to S1 when PV drops below the safe threshold, that is $PV < P_{\text{pump}} - \Delta PV$. State S3 returns when the surplus is no longer sufficient to sustain charging, that is $PV < P_{\text{pump}} + P_{\text{chg_min}} - \Delta\text{CHG}$, or when the battery reaches $\text{SOC} \geq \text{SOCmax}$. State S4 returns when PV regains sufficiency up to $PV \geq P_{\text{pump}} + \Delta PV$, or when PV collapses to zero, or when the battery hits the protection threshold $\text{SOC} \leq \text{SOCcut}$. State S5 returns when irradiance reappears, that is $PV > 0$, or by battery protection if $\text{SOC} \leq \text{SOCcut}$. From any state, a change of TIME_OK to false or an active Alarm immediately forces S0. In practice the PLC filters PV and P_{pump} with a short moving average inside t_{scan} to align the dynamic response with ΔPV and ΔCHG and to minimize flicker; $P_{\text{chg_min}}$ is set from the charger and target charging power and can be expressed as a fraction of P_{pump} for consistency across setpoints. This logic guarantees PV priority, hybrid operation when required, battery-only operation when there is no irradiance, and off-schedule charging whenever power is available.

Sizing of the photovoltaic system

Based on the required power of the irrigation system (3,740 W), a 6,000 W photovoltaic system has been sized to supply this power with a sufficient margin for the most unfavorable conditions. The photovoltaic system, installed on the roof of the container, is designed to provide the necessary energy for the autonomous and sustainable operation of the irrigation system.

Twelve monocrystalline solar panels with 21% efficiency and a maximum power output of 500 Wp per module have been selected, ensuring high energy performance even under variable radiation conditions. The arrangement of the panels on the container roof has been optimized to maximize solar capture and minimize losses due to shading or incorrect tilt.

The photovoltaic array consists of two strings of six panels connected in series, allowing the system to reach an optimal DC input voltage for the inverter. The panel tilt angle, once deployed, is 30°, which is suitable for the regions considered in the case study. Additionally, the photovoltaic system is housed on the upper part of the container with a foldable design for transportation, considering its dimensions in relation to the container during this design validation phase.

As shown in Figure 5, the left side presents the top view of the container, where the dimensions of the photovoltaic system can be observed, while the right side shows a profile view of the irrigation container, illustrating the tilt of the photovoltaic panels.

The photovoltaic system is complemented by:

- An inverter with an integrated regulator, which converts direct current (DC) into alternating current (AC) and manages battery charging.
- A battery bank, designed to store sufficient energy to meet system needs under low solar radiation conditions.
- A control system, which optimizes the system's operation, ensuring energy supply stability.

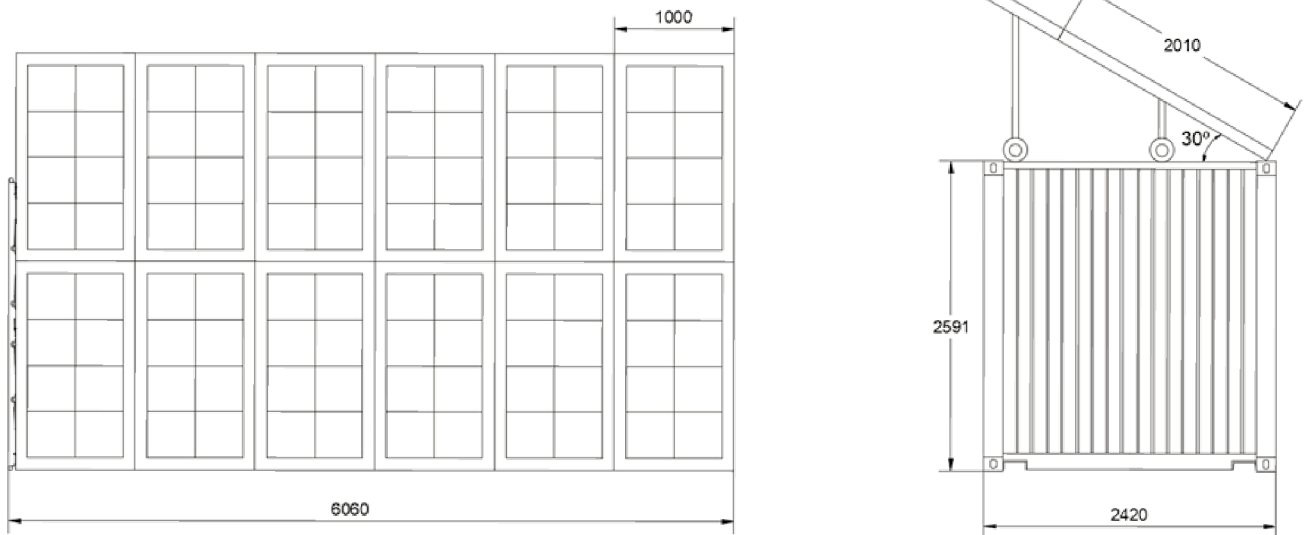


Figure 5. Layout of the solar panels on the container roof (mm).

This design enables the installation to operate efficiently and stably, guaranteeing the continuous supply of energy for the irrigation pump and other auxiliary consumptions. The total installation cost, including the foldable metallic structure, is approximately 0.74€/W. Therefore, the complete photovoltaic installation for the container amounts to €4,460.

Table 1 presents the main technical specifications of the system along with the corresponding cost for each component. For the energy storage system, lithium-ion (LiFePO₄) batteries were selected due to their high energy density, long cycle life (>4,000 cycles at 80% DoD), and reduced maintenance requirements compared to lead-acid alternatives such as AGM or GEL. The battery bank was sized to guarantee one day of autonomy under average irrigation demand conditions.

The total daily energy consumption of the system is:

$$E_{\text{demand}} = P_{\text{system}} \cdot t = 3470 \text{ W} \cdot 8\text{h} = 27.8 \text{ kWh / day} \quad (\text{Eq. 3})$$

Considering an inverter efficiency of 95% and additional system losses ($\approx 10\%$), the effective required storage rises to 30 kWh. With a maximum depth of discharge of 80% for LiFePO₄ batteries. Thus, a nominal battery capacity of 37 kWh is required. This sizing was considered adequate since irrigation generally occurs during daytime hours when solar production contributes directly to the load.

Experimental validation

During the study period, the irrigation system operated in two locations with different climatic conditions: Pulpí during the autumn and winter months and La Calahorra in spring and summer. Analyzing the average temperatures in both locations is essential to assess the impact of climate on system performance, particularly in terms of irrigation demand and photovoltaic system efficiency.

In Pulpí, from October to March, recorded average temperatures ranged from 20.1°C in October to 10.2°C in January, with intermediate values of 16.3°C in November, 15.1°C in December, 11.0°C in February, and 13.7°C in March. These mild temperatures, characteristic of the semi-arid Mediterranean climate, result in lower evapotranspiration rates and reduced irrigation requirements compared to warmer months. Additionally, solar radiation during winter averages 3.5 to 5 kWh/m²/day, which results in lower energy generation, making battery storage essential to ensure irrigation autonomy on days with lower sunlight exposure.

In contrast, La Calahorra, where the system operates from May to October, experiences significantly higher temperatures due to its higher altitude and continental climate, leading to a greater need for irrigation. During this period, average temperatures range from 15.0°C in May and October to a peak of 24.3°C in July, with values of 20.0°C in June and September and 24.0°C in August. These higher temperatures, combined with increased solar radiation levels of 5.5 to 7 kWh/m²/day, lead to greater water demand for crops to compensate for higher evapotranspiration rates. While energy generation is higher in this region, the elevated temperatures negatively impact the efficiency of solar panels, reducing their power output by approximately 0.4% per degree Celsius above 25°C. On the hottest days, when panel temperatures exceed 50°C, this efficiency loss can reach 10% or more, affecting total energy availability. These climate differences directly influence irrigation demand, with La Calahorra requiring a significantly greater water supply compared to Pulpí. In Pulpí, lower evaporation rates and mild temperatures allow for more efficient water use, whereas in La

Calahorra, the higher temperatures and increased evapotranspiration drive a greater irrigation demand, requiring higher water and energy availability to maintain crop health. This highlights the importance of the modular system design, allowing it to efficiently adapt to different water and energy needs depending on seasonal conditions. To assess the feasibility of the photovoltaic system and its ability to meet the irrigation system's energy demands, an analysis was conducted under three different climatic scenarios: sunny day, cloudy day, and rainy day. In all cases, it was assumed that the battery starts at 50% charge capacity, representing an intermediate situation between a partial discharge cycle and a full recharge. To ensure that these scenarios were representative of real conditions, an extensive evaluation of historical meteorological records from the studied areas was carried out. Daily global solar irradiation and ambient temperature data from recent years were collected from official databases (AEMET and PVGIS) and subjected to a preliminary quality control to remove incomplete or anomalous entries. Subsequently, the dataset was statistically analysed to characterise the distribution of daily irradiation values throughout the year. Based on this distribution, three representative weather categories were defined. For each category, the average daily profiles of solar irradiation and temperature were calculated, and these aggregated values were adopted as the boundary conditions for the energy balance evaluation. This procedure ensured that the considered scenarios are not arbitrary but derived from actual long-term climatic patterns observed in the study areas, providing a realistic framework to assess the system's evaluation to meet the irrigation demands.

Case 1 - sunny day

This scenario represents optimal solar radiation conditions, allowing the solar panels to operate at maximum capacity. As shown in Figure 6, photovoltaic production exceeds the irrigation system's consumption for most of the day, enabling full battery charging and ensuring an uninterrupted power supply. At night, the energy stored in the batteries is sufficient to cover consumption without the risk of depletion.

Case 2 - cloudy day

In this scenario, solar radiation decreases, affecting the energy production of the panels. However, as shown in Figure 7, photovoltaic generation is still sufficient to supply the irrigation pump's consumption during the day, although with a lower margin for fully recharging the batteries. The initial storage capacity of 50% is crucial to ensure that the system can continue operating in the early morning hours and at night without relying on external energy sources.

Case 3 - rainy day

Adverse weather conditions in this case drastically reduce solar production, creating a critical scenario for the system's autonomy. As shown in Figure 8, photovoltaic generation is insufficient to fully cover the system's total consumption. However, thanks to the initial 50% battery charge, the system can continue operating for several hours before reaching critical discharge levels. This analysis highlights the importance of optimizing storage capacity and improving energy management efficiency.

Overall, the results of the experimental validation demonstrate that the photovoltaic system is capable of sustaining irrigation system operation under different weather conditions. However, in scenarios of prolonged low solar radiation, it is recommended to

explore complementary strategies, such as increasing the battery bank capacity or implementing more efficient energy management systems.

Final distribution of the irrigation container

The irrigation container has been designed to efficiently integrate all the necessary components for the autonomous supply of water in agricultural operations. Its structural design optimizes the arrangement of key elements, ensuring easy access for maintenance and guaranteeing efficient and safe operation.

The container includes the following functional areas:

- Energy storage area: contains the battery bank and the inverter
- with an integrated regulator, responsible for storing and managing the energy generated by the solar panels.
- Pumping and filtration system: houses the irrigation pump, sand filters, and the pipe network that distributes water to the agricultural installation.
- Fertigation space: includes three fertilizer tanks, allowing for controlled mixing and dosing of nutrients in the irrigation water.
- Control panel: contains the irrigation controller, which regulates irrigation schedules and the amount of water supplied, ensuring efficient water management.
- Exterior structure: equipped with photovoltaic solar panels on

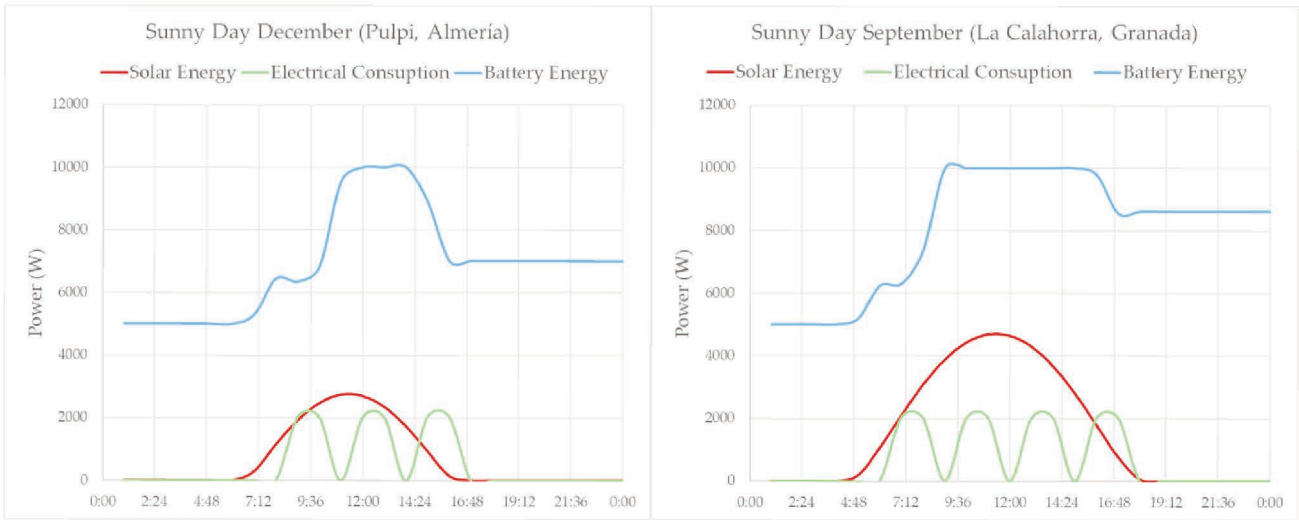


Figure 6. Photovoltaic production and energy consumption on a sunny day.

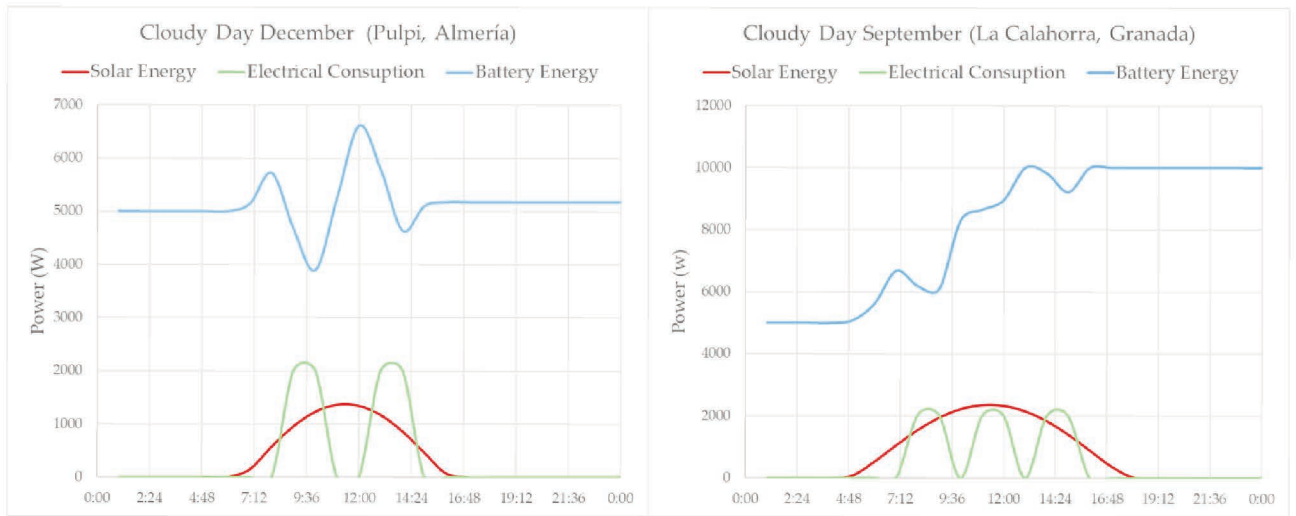


Figure 7. Photovoltaic production and energy consumption on a cloudy day.

the container roof, maximizing energy capture without affecting internal storage space.

Figure 9 presents the 2D schematic view of the irrigation container, detailing the distribution of components and their interconnection within the system.

3D model of the irrigation container

To complement the system design and anticipate potential improvements before implementation, a 3D model of the irrigation container has been developed. This digital representation allows

for the precise visualization of component locations, optimization of available space, and facilitation of the assembly process. Additionally, it helps identify possible interferences between elements, ensuring an efficient and functional distribution within the structure. The model illustrates how the photovoltaic solar panels are arranged on the container roof, maximizing the available surface without affecting the system’s mobility. Inside, the storage batteries, inverter, and irrigation controller are strategically positioned to ensure accessibility for maintenance. Likewise, the pumping and filtration system is arranged to optimize water flow

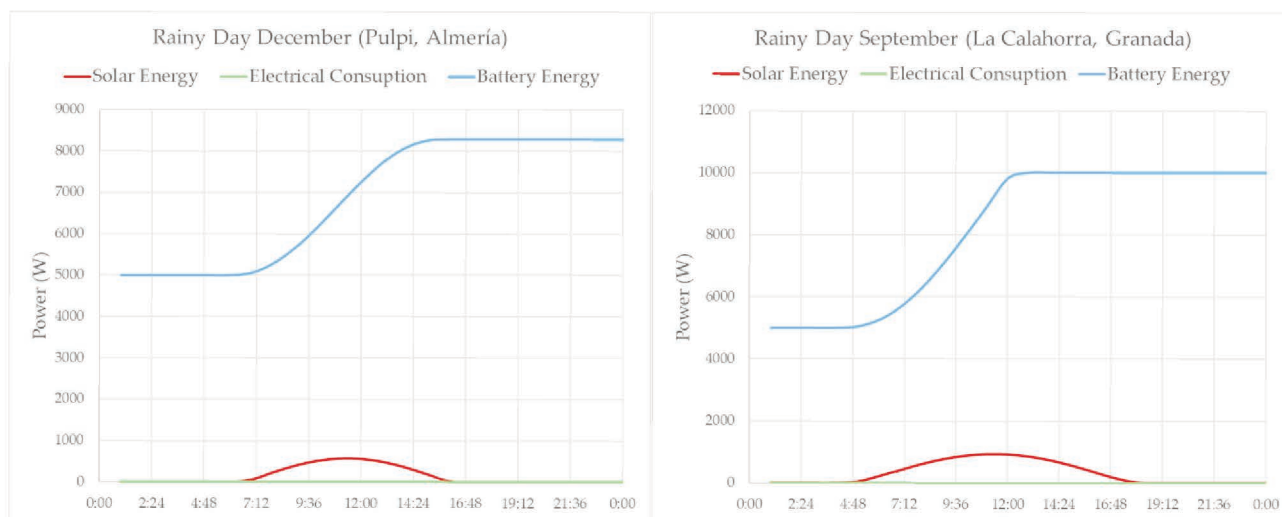


Figure 8. Photovoltaic production and energy consumption on a rainy day.

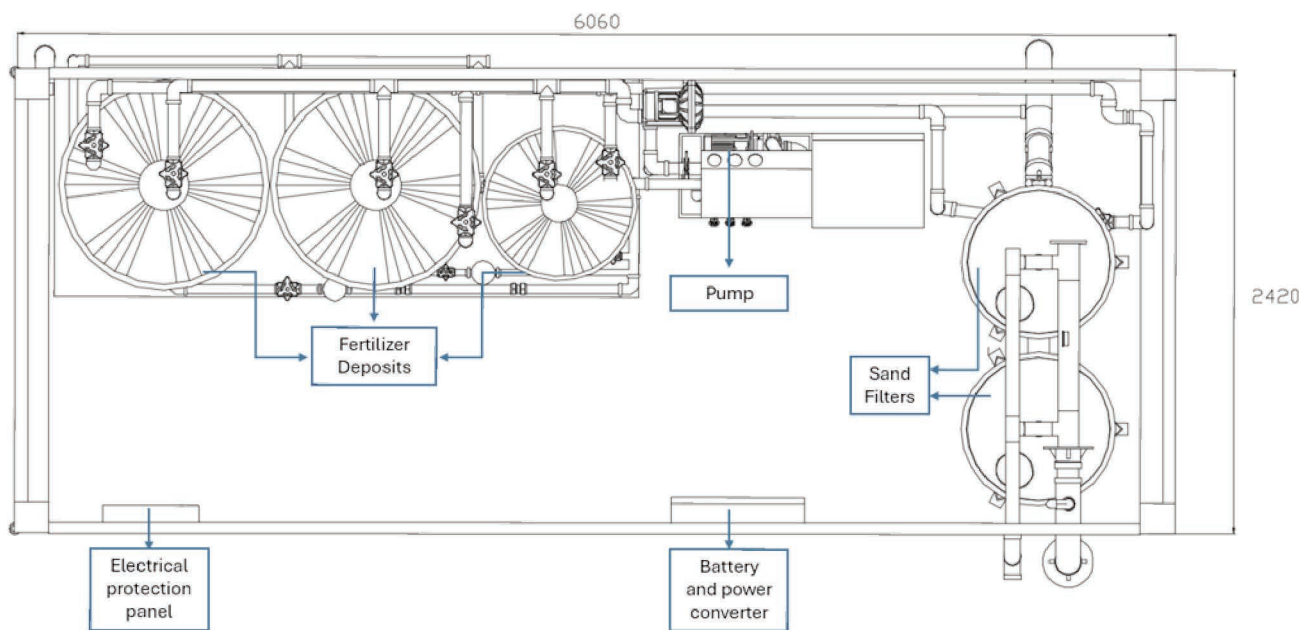


Figure 9. Schematic of the irrigation system inside the container.

and facilitate connection with the distribution network. Thanks to this three-dimensional design, it is possible to analyze the structural and operational feasibility of the container before fabrication. Additionally, it serves as a valuable tool for on-site assembly, minimizing installation errors and allowing for adjustments in component configuration if necessary. Figure 10 displays the 3D model of the irrigation container, showing the internal and external distribution of its main elements.

Based on the sizing results obtained in this study, several areas for further optimization of the transportable irrigation system based on shipping containers have been identified. One of the main proposed improvements is increasing the battery bank capacity, which would extend the system's autonomy during prolonged periods of low solar radiation, ensuring a continuous energy supply for irrigation. Another potential enhancement is the implementation of a hybrid system, combining solar energy with other renewable sources, such as small wind turbines or hydrogen-based backup systems. This would provide greater energy stability in adverse weather conditions and expand the applicability of the system to various agricultural regions.

Economic validation

The proposed alternative of the mobile irrigation container presents a very different cost structure compared to the traditional model of fixed concrete irrigation sheds. Its main advantage lies in the fact that a single container can be moved between two agricultural holdings and serve both during the same annual season, thereby avoiding the need to duplicate infrastructure. In terms of initial investment (CAPEX), the container only requires the container adaptation (€1400), the photovoltaic installation (€4460), and the irrigation system (€1600), reaching a total cost of €7460. In contrast, concrete sheds involve a much higher outlay: for each one it is necessary to invest in civil works (€15,000), photovoltaics (€4460), irrigation system (€1600), and construction permits (€1200), which amounts to €22,260 per shed. Since two sheds are

needed to cover both holdings, the initial investment rises to €44,520, that is, almost six times more than the mobile solution. Regarding recurring costs (OPEX), the situation is partially reversed. In the case of the container, the main expense comes from transport between holdings, which, with two trips per year at €1000 each, amounts to €2000/year. In contrast, fixed sheds only generate recurrent tax costs, estimated at €110/year per shed, totaling €220/year for both facilities. When analyzing a 10-year horizon, the container proves to be significantly more advantageous: the accumulated cost amounts to €27,460, compared to €46,720 for the sheds, resulting in a saving in favor of the container of €19,260. This difference is explained by the strong contrast in the initial investment, which more than compensates for the higher annual transport costs. In addition to the direct savings in investment and operation, the mobile solution avoids the indirect costs associated with the construction of fixed sheds, such as taxes, building permits, and environmental authorizations. These procedures not only entail additional financial outlays (in fees and technical project approvals) but also delay system commissioning. Since it is a reused and transportable container, it can be categorized as a mobile installation or work equipment, which carries no significant administrative burden and facilitates its deployment across different farms without the need for complex permits. This aspect represents an additional advantage that further improves the cost-benefit ratio of the system compared with permanent civil works alternatives.

Discussion

The results obtained in the experimental validation allow for evaluating the performance of the transportable irrigation system under different climatic conditions and its ability to operate autonomously using solar energy. It has been observed that location and time of year significantly influence photovoltaic energy

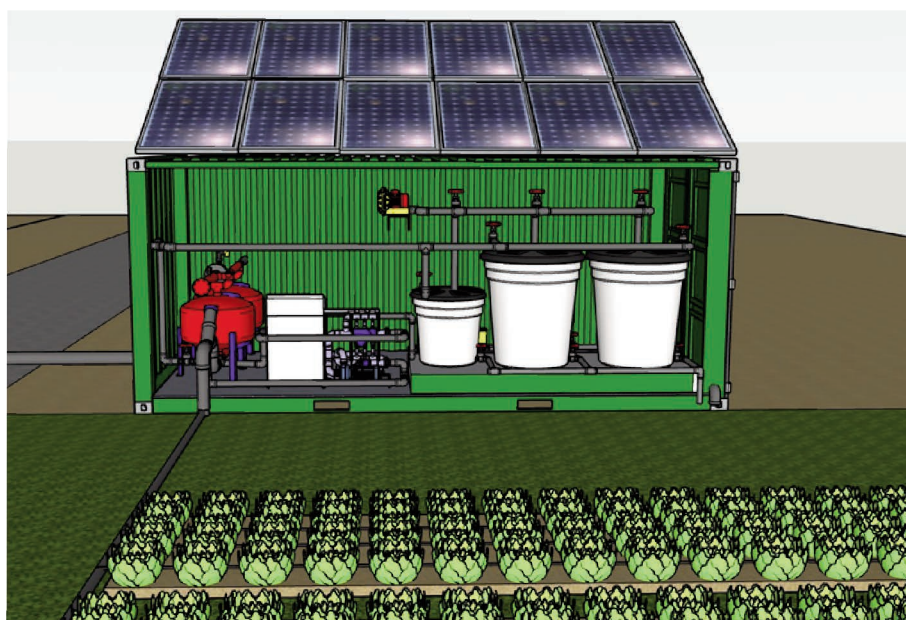


Figure 10. 3D model of the irrigation container.

production and the system’s energy demand. In Pulpí, where the system operates in autumn and winter, lower solar irradiation limits its energy production, increasing dependence on battery storage to ensure system operation. However, milder temperatures contribute to better solar panel efficiency and lower water consumption due to reduced evaporation.

On the other hand, in La Calahorra, during spring and summer, energy production is higher due to greater solar irradiation. However, the increase in temperature negatively affects panel efficiency, reducing energy output on the hottest days. In addition, the higher water demand of crops during this period results in increased energy consumption, requiring efficient management of energy storage and distribution.

The analysis of operating scenarios confirms that the system is capable of meeting irrigation demands under favorable conditions, especially on sunny days when photovoltaic production far exceeds system consumption and allows for full battery bank charging. On cloudy days, reduced solar radiation decreases energy generation, but the system maintains its operation thanks to previously stored energy. However, on rainy days, when photovoltaic production is minimal, the system’s autonomy depends largely on the previous battery charge state, which may compromise its operation if the period of low generation is prolonged.

Table 2 presents the environmental and economic comparison between the proposed solar container and a conventional diesel-based system. The solar solution eliminates the direct consumption of approximately 1300-1500 L of diesel per year, which translates into a reduction of about 3.5-4.0 tons of CO₂ annually. Economically, although the initial investment of the solar system is higher, its very low operating costs result in a payback period of 5-9 years, whereas the diesel option entails continuous annual fuel and maintenance expenses with no possibility of recovery. In terms of lifetime, the solar container also offers longer durability of its core components, reinforcing its suitability as a sustainable alternative for irrigation in off-grid agricultural areas.

Regarding the scalability of the system, the necessary adaptations would be as follows. For smaller irrigation areas, the current system increases resilience, or alternatively, costs could be reduced by downsizing its components. In the case of larger cultivation areas requiring higher irrigation volumes, the first adaptation would be to ensure sufficient pumping capacity by installing a larger pump, which does not pose a problem given the container dimensions. The increased water flow may, however, be limited by the available electrical supply and storage capacity. Therefore, it would be necessary to increase battery capacity, feasible due to the ample space available inside the container, and to enhance power generation, either by installing higher-power solar panels or by increasing the number of panels, which would require an alterna-

tive supporting structure. Finally, it should be noted that the current model is oversized for this case study, making it suitable for most typical plantations. From a safety perspective, the main risks associated with the use of the irrigation container occur during loading and unloading operations with the crane truck, where collisions or accidental falls may pose a hazard. In addition, as the unit combines both irrigation equipment and an electrical installation, special care must be taken during operation to avoid electric shocks. To mitigate these risks, the container is equipped with a fire extinguisher in case of emergencies, as well as ventilation grilles that help maintain adequate battery cooling and reduce the likelihood of overheating incidents.

Despite the positive results, the study presents certain limitations. The system’s autonomy during extended periods of low irradiation still depends on the battery bank’s capacity, which may require adjustments based on the specific consumption of each agricultural operation. The impact of temperature on panel efficiency suggests the need to explore mitigation strategies, such as materials with better thermal dissipation or passive cooling systems. In addition to the environmental and economic aspects, some practical challenges of field deployment must also be considered. Routine maintenance is limited to periodic cleaning of the photovoltaic panels, cleaning of sand filters, pump checking, inspection of battery status, and verification of electrical connections, which can be integrated into standard maintenance schedules. Regarding extreme weather resilience, the container structure provides robust protection against wind, dust, and precipitation, although severe conditions such as hailstorms or high ambient temperatures may affect photovoltaic efficiency. The mobility of the irrigation container offers an additional advantage, as it can be installed only during the cropping season, thereby avoiding long periods of inactivity in remote rural areas when the system would otherwise remain unprotected. Future research proposes conducting tests in other locations with different climatic conditions, evaluating integration with other renewable energy sources, and optimizing the energy management system to improve storage and distribution efficiency based on irrigation demand. Another research avenue to consider is the incorporation of hydraulic turbines in the irrigation system to regulate pressure and generate additional energy. In certain irrigation systems, height differences or variations in flow can generate overpressures that, instead of being dissipated through relief valves, could be harnessed using micro-hydraulic turbines to produce electricity (Rodríguez-Pérez *et al.*, 2024). This energy could be used to charge the system’s batteries and improve autonomy during periods of low solar radiation. Implementing this solution would optimize the system’s energy balance and reduce exclusive dependence on photovoltaic energy, providing a complementary and sustainable alternative for irrigation energy supply.

Table 2. Environmental and economic comparison between the solar irrigation container and a diesel-powered alternative.

Parameters	Solar system	Diesel-powered system
Emissions and fuel	Avoided ≈3.5-4.0 t CO ₂ /year	Diesel ≈1,300-1,500 L/year
Initial investment	11,000-21,000 € (PV, inverter, batteries, integration in 20 ft container)	3000-6000 € (10–15 kVA generator)
Annual operating cost	Low (cleaning, filters, periodic checks)	1800-2500 € (fuel + routine maintenance)
Payback period	5-9 years (vs diesel OPEX above)	-
Expected lifetime	20-25 years (PV); 8-12 years (inverter/batteries, with replacements as needed)	5-7 years (generator replacement)

Conclusions

The design and development of a transportable irrigation system based on a shipping container has proven to be a viable, sustainable, and efficient solution for optimizing water and energy use in agricultural operations without access to the electrical grid. The integration of photovoltaic solar panels, battery storage, and an automated irrigation system ensures a stable water supply without relying on conventional energy sources, reducing operational costs and minimizing environmental impact.

The results obtained from the experimental validation have confirmed the system's ability to operate autonomously under different weather conditions. On sunny days, photovoltaic production far exceeds consumption, allowing for full battery recharge. On cloudy days, the system maintains its operation thanks to prior energy storage, while on rainy days, system autonomy depends on the initial battery charge, highlighting the importance of proper energy storage management.

This study demonstrates that repurposing shipping containers as transportable irrigation stations not only contributes to the circular economy but also provides an adaptable and scalable alternative for the agricultural sector. The system was intentionally oversized for the case study conditions, ensuring reliability under demanding scenarios and making it suitable for most typical plantations. This oversizing also facilitates system scalability, since for smaller irrigation areas the installation can be downsized to reduce costs, while for larger cultivation areas the design allows straightforward adaptations, such as increasing pump capacity, expanding the photovoltaic array, or reinforcing the battery storage system. In this way, the proposed solution not only meets the needs of the present study but also offers flexibility for a wide range of agricultural contexts. As potential improvements, it is recommended to assess the feasibility of increasing the battery bank capacity or implementing a hybrid system with additional backup in cases of prolonged low solar radiation. Future research could involve testing the system with different crop types and in various climatic zones to evaluate its performance under different agricultural conditions.

References

- Al-Smairan M, Khawaldeh HA, Shboul B, Almomani F, 2024. Techno-enviro-economic analysis of grid-connected solar powered floating PV water pumping system for farmland applications: A numerical design model. *Heliyon* 10:e37888.
- Augustyn G, Mikulik J, Rumin R, Szyba M, 2021. Energy self-sufficient livestock farm as the example of agricultural hybrid off-grid system. *Energies* 14:7041.
- Aziz G, Sarwar S, Waheed R, Khan MS, 2024. The significance of renewable energy, globalization, and agriculture on sustainable economic growth and green environment: Metaphorically, a two-sided blade. *Nat Resour Forum* 48:763-783.
- Beerge R, Sachin D, 2024. Diesel-powered engine and agriculture. In: H. Koten, editor. *Diesel engines – Current challenges and future perspectives*. IntechOpen.
- Bhattacharjee J, Subhasis R, 2024. Significance of renewable energy in water management and irrigation. In: S. Suriyanarayanan, H.P. Shivaraju and D. Jenkins, editors. *Water management in developing countries and sustainable development*. Singapore, Springer. pp. 235-252.
- El Mezouari A, El Fazziki A, Sadgal M. 2022. Smart irrigation system. *IFAC-PapersOnLine* 55:3298-3303.
- Emezirinwune MU, Adejumbi IA, Adebisi OI, Akinboro FG, 2024. Off-grid PV/biomass/DG/battery hybrid renewable energy as a source of electricity for a farm facility. *e-Prime-Adv Electr Eng Electron Energy* 10:100808.
- Fernández García I, Lecina S, Ruiz-Sánchez MC, Vera J, Conejero W, Conesa MR, Montesinos P, 2020. Trends and challenges in irrigation scheduling in the semi-arid area of Spain. *Water* 12:785.
- García AM, Gallagher J, Díaz JAR, McNabola A, 2024. An economic and environmental optimization model for sizing a hybrid renewable energy and battery storage system in off-grid farms. *Renew Energy* 220:119588.
- García AM, Gallagher J, Díaz JAR, McNabola A, 2024. An economic and environmental optimization model for sizing a hybrid renewable energy and battery storage system in off-grid farms. *Renew Energy* 220:119588.
- Ghareeb AY, Gharghan SK, Mutlag AH, Nordin R, 2023. Wireless sensor network-based artificial intelligent irrigation system: challenges and limitations. *J Techn* 5:26-41.
- Ibrahim WI, Mohamed MR, Ismail RMTR, Leung PK, Xing WW, Shah AA, 2021. Hydrokinetic energy harnessing technologies: A review. *Energy Rep* 7:2021-2042.
- İnada AA, Arman S, Safaei B, 2022. A novel review on the efficiency of nanomaterials for solar energy storage systems. *J Energy Storage* 55:105661.
- Irshad AS, Ludin GA, Masrur H, Ahmadi M, Yona A, Mikhaylov A, Senjyu T, 2023. Optimization of grid-photovoltaic and battery hybrid system with most technically efficient PV technology after the performance analysis. *Ren Energy* 207:714-730.
- Mainuddin M, Kirby M, Chowdhury RAR, Shah-Newaz SM, 2015. Spatial and temporal variations of, and the impact of climate change on, the dry season crop irrigation requirements in Bangladesh. *Irrig Sci* 33:107-120.
- Ndunagu JN, Ukhurebor KE, Akaaza M, Onyancha RB, 2022. Development of a wireless sensor network and IoT-based smart irrigation system. *Appl Environ Soil Sci* 2022:7678570.
- Neethirasu A, Perumalsamy I, Kannan K, Mani R, Rajaram RS, Victor K, 2024. Examining agrovoltaic system: impacts on energy yield and crop productivity. In: P. Pathak, S. Ilyas, R.R. Srivastava, J. Dar and S. Kothandaraman, editors. *Cham*, Springer. pp. 373-390
- Obaideen K, Yousef BA, AlMallahi MN, Tan YC, Mahmoud M, Jaber H, Ramadan M, 2022. An overview of smart irrigation systems using IoT. *Energy Nexus* 7:100124.
- Obalalu AM, Bajaj M, Salalwu SO, Singh AR, Vishnuram P, Abbas A, Adeshola AD, 2025. Optimizing solar water pumps for irrigation: the impact of aluminum–titanium hybrid nanofluid on thermal efficiency and performance. *Multiscale Multidiscip Model Exp Des* 8:53.
- Olivkar PR, Katekar VP, Deshmukh SS, Palatkar SV, 2022. Effect of sensible heat storage materials on the thermal performance of solar air heaters: State-of-the-art review. *Renew Sustain Energy Rev* 157:112085.
- Pacesila M, Burcea SG, Colesca SE, 2016. Analysis of renewable energies in European Union. *Renew Sustain Energy Rev* 56:156-170.
- Poddar A, Kumar N, Shankar V, 2021a. Evaluation of two irrigation scheduling methodologies for potato (*Solanum tuberosum* L.) in north-western mid-hills of India. *ISH J Hydraul Eng* 27:90-99.
- Poddar A, Kumar N, Kumar R, Shankar V, 2022. Application of

- regression modeling for the prediction of field crop coefficients in a humid sub-tropical agro-climate: a study in Hamirpur district of Himachal Pradesh (India). *Model Earth Syst Environ* 8:2369-2381.
- Poddar A, Kumar N, Kumar R, Shankar V, Jat MK, 2020. Evaluation of non-linear root water uptake model under different agro-climates. *Curr Sci* 119:485-496.
- Poddar A, Shankar V, Kumar N, 2021b. Estimating crop water requirements for irrigation scheduling in different crops in humid subtropical agro-climate of Western Himalayas. *J Agrometeorol* 23:356-359.
- Rana MM, Uddin M, Sarkar MR, Shafiullah GM, Mo H, Atef M, 2022. A review on hybrid photovoltaic - Battery energy storage system: Current status, challenges, and future directions. *J Energy Storage* 51:104597.
- Rekioua D, 2023. Energy storage systems for photovoltaic and wind systems: A review. *Energies* 16:3893.
- Rodríguez-Pérez ÁM, García-Chica A, Caparros-Mancera JJ, Rodríguez CA, 2024. Turbine-based generation in greenhouse irrigation systems. *Hydrology* 11:149.
- Singla MK, Gupta J, Gupta A, Safaraliev M, Zeinoddini-Meymand H, Kumar R, 2025. Empowering rural farming: agrovoltaic applications for sustainable agriculture. *Energy Sci Eng* 13:35-59.
- Wang T, Ng AK, Wang J, Chen Q, Pang J, Tang J, 2024. Adaptation planning of container ports in the context of typhoon risks: The case of Ningbo-Zhoushan port in China. *Ocean Coast Manage* 257:107303.

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