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# Energy and environmental performances of hybrid photovoltaic irrigation systems in Mediterranean intensive and super-intensive olive orchards

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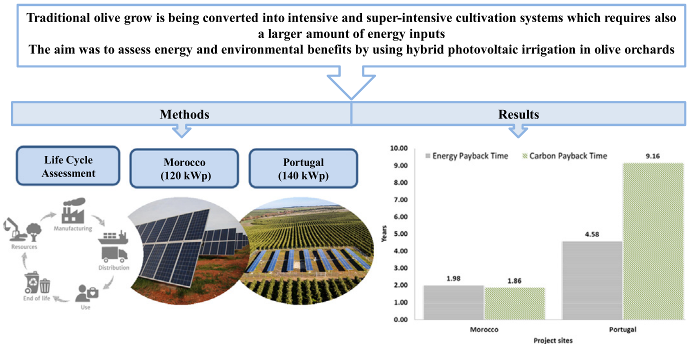
## HIGHLIGHTS

- Life cycle assessment approach was used to evaluate hybrid PV irrigation systems.
- PV plants were exclusively devoted to supply energy to Mediterranean olive orchards.
- The HPVIS $CO_2$ emissions rates were 48 and 103 $gCO_2e$ per kWh.
- The PV plants allowed to save among 41 and 67% of the energy previously consumed.

## GRAPHICAL ABSTRACT


Traditional olive grow is being converted into intensive and super-intensive cultivation systems which requires also a larger amount of energy inputs
The aim was to assess energy and environmental benefits by using hybrid photovoltaic irrigation in olive orchards

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## ABSTRACT

Over the last decades, traditional olive production has been converted to intensive and super-intensive cultivation systems, characterized by high plant density and irrigation. Although this conversion improves product quality and quantity, it requires a larger amount of energy input. The new contributions in this paper are, first, an analysis of the energy and environmental performance of two commercial-scale high peak-power hybrid photovoltaic irrigation systems (HPVIS) installed at intensive and super-intensive Mediterranean olive orchards; second, an analysis of PV hybrid solutions, comparing PV hybridization with the electric power grid and with diesel generators; and finally, a comparison of the environmental benefits of HPVIS with conventional power sources. Energy and environmental performances were assessed through energy and carbon payback times (EPBT and CPBT). The results show EPBT of 1.98 and 4.58 years and CPBT of 1.86 and 9.16 years for HPVIS in Morocco and Portugal, respectively. Moreover, the HPVIS were able to achieve low emission rates, corresponding to 48 and 103 g $CO_2e$ per kWh generated.

The EPBT and CPBT obtained in this study were directly linked with the irrigation schedules of the olive orchards; therefore, weather conditions and irrigation management may modify the energy and environmental performances of HPVIS.

The consumption of grid electricity and diesel fuel, before and after the implementation of HPVIS, was also analyzed. The results obtained show fossil energy savings of 67% for the Moroccan farm and 41% for the Portuguese

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installation. These savings suggest that the energy produced by HPVIS in olive orchards will avoid the emissions of a large amount of greenhouse gas and the exploitation of natural resources associated with fossil fuel production.

## 1. Introduction

The cultivation of olives in semi-arid regions represents a key sector for the rural economy in the southern Mediterranean area, also providing an important source of employment. In 2016, over 19 million tonnes of olives were produced worldwide, 80% of which were harvested in the Mediterranean basin, with Spain, Greece and Italy being the main producing countries (FAOSTAT, 2018).

Olive orchards are traditionally grown with low planting density, under rainfed conditions, and with low level of mechanization. However, several studies reveal how climate change, particularly irregular precipitation, extreme rainfall events, long periods of drought and extreme temperatures, is influencing olive production (Chebbi et al., 2018; Lorite et al., 2018; Santos et al., 2017; Gabaldón Leal et al., 2017; Rosenzweig et al., 2001). Over the last decades, the cultivation of olives has been improved by more competitive management practices. Recent studies have shown that irrigating olive orchards results in a remarkable increase in product quality and yield (Ahumada Orellana et al., 2018; Martorana et al., 2017; Zeleke and Ayton, 2014; Fernandes-Silva et al., 2013; Psarras et al., 2011; Moriana et al., 2003; Melgar et al., 2008). In fact, traditional olive orchards are being converted to intensive and super-intensive cultivation systems, characterized by high plant density, drip irrigation and mechanical harvesting (Bernardi et al., 2018; Stillitano et al., 2017; Arbonés and Pascual, 2014; El Mouhtadi et al., 2014; Lodolini et al., 2014; Gómez del Campo, 2013; Martín Vertedor et al., 2011; Tous et al., 2010; Orgaz et al., 2006). Although this conversion is improving product quality and quantity and sector profitability, it requires a larger amount of energy input which generates corresponding environmental impacts. Cappelletti et al. (2014) found that the agricultural phase uses more than 90% of the total energy demand for the production of virgin olive oil, with irrigation as one of the main energy-demand activities. Kaltsas et al. (2007) reported that irrigation energy demand accounted for approximately 21% of the total energy consumption in conventional Greek olive orchards, while Guzmán and Alonso (2008) found that irrigation technology represented the greatest energy demand in olive cultivation.

The environmental impact of crop irrigation has been studied by several authors who found that achievement of sustainable food production included improvements in irrigation water use and pumping efficiency (Benbi, 2018; Deligios et al., 2019). Xu et al. (2015) found that energy input for irrigation was the major contributor to $CO_2$ emissions in wheat production. Similarly, intensive and super intensive olive orchards are responsible for high environmental impacts (48% and 43% in the ecotoxicity category, respectively) due to the electricity consumed during irrigation (Romero-Gamez et al., 2017).

Different approaches have been explored with the aim to improve irrigation energy efficiency in agriculture. Several studies proposed irrigation network sectoring to reduce energy requirements by organizing farms into irrigation turns according to their water-flow and pressure requirements (Rodriguez Diaz et al., 2009; Jiménez Bello et al., 2010; Moreno et al., 2010; Jiménez Bello et al., 2011; Carrillo Cobo et al., 2011). Irrigation network sectoring was also applied to an irrigation district devoted to olive production in Andalusia (Spain) and resulted in an approximately 30% reduction in energy consumption (Navarro Navajas et al., 2012).

The need to promote more sustainable agricultural production with respect to natural resources and human health is leading farmers and stakeholders to invest in renewable energy systems. Recently, several renewable energy technologies have been implemented in pressurized irrigation systems to reduce energy requirements while also reducing the related greenhouse gas emissions. In particular, Merida García et al. (2018) developed a real-time model (Smart Photovoltaic Irrigation Manager) to synchronize PV power availability with the energy required by an irrigation system for different sectors of an irrigation network of olive orchards in Southern Spain. Other studies have been performed to determine the optimal sizing of photovoltaic systems for irrigation electricity requirements of olive cultivation in the Mediterranean basin (Ahmed et al., 2017; Taousanidis and Gavros, 2016; López Luque et al., 2015; Moral et al., 2009; Cuadros et al., 2004). Carroquino et al. (2015) studied six farming facilities of Mediterranean crops to find the optimal electric generation technology using a simulation and optimization tool. The tool identified hybrid PV-diesel systems as the optimal solution, with energy costs from 0.13 to 1.08 €/kWh.

These previous studies all report on either modelled scenarios or PV irrigation systems that had low peak power demand (<50 kWp) (Li et al., 2017; Chandel et al., 2017; Wazed et al., 2018). However, some recent studies report that high peak-power PV irrigation systems are even more economically feasible (Lorenzo et al., 2018).

Other authors report that hybridization with pre-existing diesel sources can be also an interesting option (IRENA, 2016; Bakelli et al., 2016; Carroquino et al., 2015; Ammar et al., 2015). The door to increase the power of PV irrigation systems was opened with the use of standard frequency converters (Abella et al., 2003; Brito and Zilles, 2006; Fernández-Ramos et al., 2010; Valler et al., 2016) and the possibility of avoiding the problems associated to PV power intermittences (EIP Water, 2012). These problems have been solved and demonstrated by a recent European H2020 project called MASLOWATEN (Maslowaten Project, 2018) developing control algorithms to avoid instabilities in the frequency converter of the PV irrigation systems when clouds are passing over the generator(Narvarte et al., 2018).

The new contributions in this paper focus on analysis of the environmental benefit of high peak-power hybrid PV irrigation systems (HPVIS) for intensive and super-intensive olive orchards. There are three novel aspects: first, the analysis of high peak-power HPVIS shows the energy and environmental benefits of these systems. To the authors' knowledge, only results related to small PV systems have been previously reported in the literature. We have monitored the performances of two commercial-scale high peak-power HPVIS that were designed, installed, operated and evaluated in Morocco (120 kWp) and Portugal (140 kWp). Second, this paper analyses hybrid PV irrigation systems with the grid (Morocco) and with diesel generators (Portugal). Hybridization is a remarkable issue in agricultural applications due to the variety and complexity of existing irrigation networks. Hybridization is the only profitable alternative for PV applications when a farm requires a number of hours of irrigation beyond daylight hours. Therefore, analyzing and comparing the environmental impact of PV-diesel and PV-grid hybridization can be very useful for the design and improvement of this type of farm. Finally, the application of HPVIS to olive orchards and comparison of the environmental benefits to other conventional power sources and irrigation techniques also represents a new valuable contribution to the literature.

In spite of the aforementioned large number of studies conducted on renewable energy technologies applied to the irrigation systems of olive orchards, there is a lack of knowledge on assessing the energy and environmental impacts of such systems (e.g., energy and carbon payback time, energy return on energy investment, etc.). Whereas technical issues and optimal sizing of PV irrigation systems have been deeply analyzed in olive orchards, less attention has been given to energy and environmental aspects.

The objectives of this study were to assess and evaluate the primary energy demand and the potential environmental benefits of producing electricity with ground-mounted hybrid (solar+grid/diesel) photovoltaic irrigation systems (HPVIS) equipped with solar trackers for intensive and super-intensive Mediterranean olive orchards.

## 2. Materials and methods

### 2.1. Goal and scope

The goal and scope of this study were to assess the inputs-outputs and potential energy-related environmental impact of HPVIS for olive orchards located in Morocco and Portugal using a life cycle assessment (LCA) methodology (ISO 14064-1, 2012; ISO/TS 14067, 2013; ISO 14040, 2006; ISO 14044, 2006). The phases of the LCA included goal and scope definition, inventory analysis (LCI), impact assessment (LCIA) and interpretation of results.

This LCA analysis allows comparison of three main aspects:

- the energy and environmental benefits of high peak-power HPVIS compared with the current state-of-the-art for small-capacity power generation solutions;
- the energy and environmental impacts of a PV-grid hybrid irrigation system compared with a PV-diesel hybrid system; and
- the energy and environmental benefits of using HPVIS for irrigation of olive orchards compared with the use of other conventional power sources.

This analysis also accounts for the influence of other external factors such as the water needs of super-intensive olive orchards, the lack of adequate water sources, and the effective use of the HPVIS by farmers.

### 2.2. Hybrid PV technology description and data source

The LCA analysis of HPVIS used the performance monitoring of two commercial-scale HPVIS that were designed, implemented, operated and evaluated in the framework of the European Union Horizon 2020 Program's MASLOWATEN Project (Maslowaten Project, 2018) to supply water for productive agriculture irrigation.

HPVIS configuration is the only possibility when the daily irrigation schedule exceeds the number of daylight hours due to, for example, the distribution tube diameter that limits the maximum water-flow, obliging to irrigate not only during the day but also during the night. As an example, the Fig. 1 shows an example of the irrigation scheduling for a typical year in the Portuguese farm that will be later described. The figure also shows the length of the daytime, which is sometimes shorter than the irrigation schedule that reaches 17 h per day in the peak period.

It is true that another alternative to solve this problem would be to include batteries in the design of the large-power PV irrigation systems but electrochemical accumulation devices have been disregarded due to reliability and economic reasons. It is worth to note that these demonstrators were designed and installed in the framework of the H2020 project MASLOWATEN, whose main objective was the market uptake of large-power PV solutions for irrigation. So, to enter into the market, it was necessary to design HPVIS economically feasible, and the current battery market prices and the battery size required, endangered the HPVIS feasibility. Furthermore, the reliability of batteries, when they are brought under to deep discharges, is low and the project had the target of system lifetimes of 25 years to have business plans attractive to invest on.

The electricity produced by HPVIS is directly conveyed to the irrigation pumps. In fact, the HPVIS were designed to maximize the exploitation of electricity generated in the PV plant and use as little fossil fuel energy as possible (from either diesel fuel or the electric grid). Moreover, HPVIS do not allow any electricity exchange to the grid what means that the design does not consider the injection into the grid of the possible excess of PV electricity. The reason for this decision is that the sale of PV electricity to the grid is being regulated by the different governments with continuous changes in the law that lead to uncertainties in the investments. So we decided to prove the feasibility of the systems even when this excess is lost. Moreover, the payment of this excess varies from one country to other. For example, in Spain, the sale of the excess of PV electricity implies the obligation of paying taxes not only for the PV electricity injected into the grid but also for the self-consumed one (RD 900/2015, 2015). This diversity made difficult to extract general conclusions about the economic and environmental feasibility of the HPVIS, so we decided not to consider the sale of the excess in this analysis. In case this sale of the excess, the figures

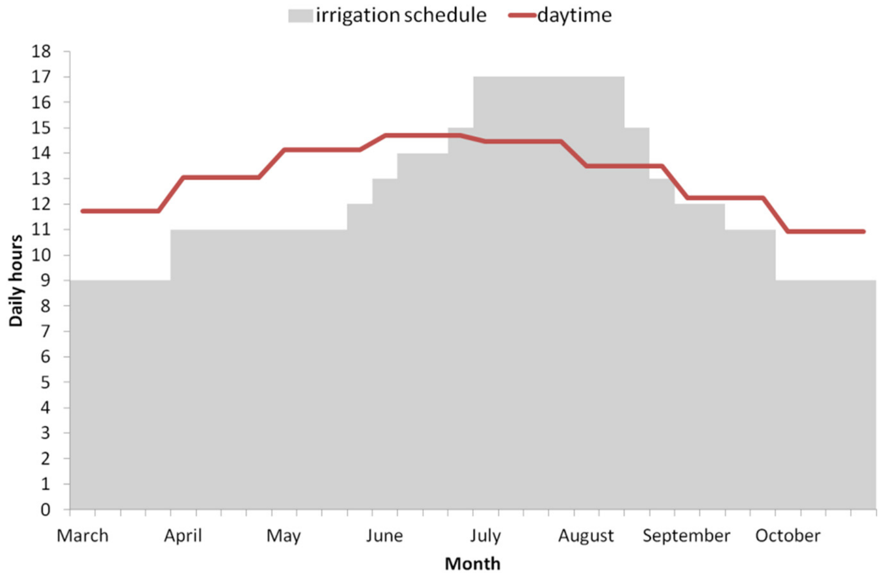

**Fig. 1.** Hours per day of a) Irrigation scheduling, b) Daytime.

of this analysis would be even better and, therefore, this assumption can be understood as a “worst case”.

The HPVIS developed are able to pump at constant flow and pressure and to interact with the irrigation automation to realize a complete integration with the existing drip-system irrigation network.

The HPVIS have three operational modes for managing energy supply:

(Abella et al., 2003) PV Mode, the irrigation pumps are powered only by the electricity generated from the PV plant. Operations were in this mode most of the time;

(Ahmed et al., 2017) Hybrid Mode, on cloudy days, the pumps use all the available PV power and the additional power needed to reach the required water flow and pressure is taken from the grid or diesel generator. This avoids power fluctuation at sunrise and sunset and with passing clouds; and (Ahumada Orellana et al., 2018) Grid/Diesel Mode, the pumps are powered only with electricity from the grid (Morocco HPVIS) or the diesel generator (Portugal HPVIS). This mode is only used during the night, when solar energy is not available.

Both HPVIS were developed and assembled using the same modularity and technologies. The crystalline PV modules were placed on a north-south horizontal axis solar tracking system. This system is able to control multiple rows of PV arrays and to rotate the plant frame based on solar position. The advantage of this tracker for irrigation applications is double: in the one hand, it has hourly profiles quasi-constant, that matches with the requirement of constant power for the irrigation with constant pressure devices, and in the other hand, it has an important production gain during the summer months. Some authors (Almeida et al., 2018) have reported that the use of this tracker increases a 42.8% the yearly volume of water pumped.

### 2.3. Farm descriptions

The first HPVIS, a hydraulic hybridization of PV and diesel generators, was installed in Alter do Chao (Alentejo, Portugal). The farm has 215 ha of super-intensive olive orchards, irrigated by a drip system. The farm is divided into 14 irrigation sectors, served at constant flow and pressure (5.7 bar). The peak utilization of the irrigation system occurs during the summer season, when the pumps need to work approximately 17 h per day. The pumps move water from a water tank that is, in turn, filled from a lake located 3 km away (Table 1).

The HPVIS is composed of a 140 kWp PV generator, three 55 kW frequency converters, one soft-starter and three 45 kW centrifugal pumps that deliver water to the same distribution pipe (Fig. 2). One pump is powered only by the PV generator, another is power only by the diesel generator (15 kVA), and the third can be powered by either the PV or diesel generator depending on the available PV power. Although there are three pumps, only two are necessary to reach the required water flow and pressure, allowing operation in the three operation modes described in Section 2.2.

**Table 1**
Characteristics of the photovoltaic (PV) hybrid irrigation systems in this study.

| HPVIS | Morocco (Tamellalt) | Portugal (Alter do Chao) |
|---|---|---|
| Longitude | 7° 31′ 12″ W | 7° 41′ 35″ W |
| Latitude | 31° 46′ 48″ N | 39° 10′ 0,03″ N |
| Altitude (m) | 584 | 208 |
| Day annual insolation (kWh/m$^2$) | 5.61 | 4.93 |
| Crop system | Olives | Olives |
| Water need (m$^3$/y) | 694,000 | 334,000 |
| Water source | Borehole | Borehole |
| Well depth (m) | 60 + 60 | 70 + 70 |
| Well flow (L/s) | 53 + 53 | 34 + 34 |
| Pumps (n) | 2 | 3 |
| Pump power (kW) | 45 + 45 | 45 + 45 + 45 |
| Photovoltaic power (kWp) | 120 | 140 |
| System type | Hybrid (PV + grid) | Hybrid (PV + diesel) |
| Inverters (n x power) | 2 × 55 kW | 3 × 55 kW |
| Photovoltaic tracker system (n × type) | 1× H1250 multi-row tracker (6 axes) | 1× H1250 multi-row tracker (7 axes) |
| Area occupied (m$^2$) | 3500 | 4290 |

The procedure to size the PV generator is based on assuring that the PV generator suffices for powering all the irrigation system at midday on the equinox days, which are roughly the limits of the irrigation period. Fig. 3 shows the solar irradiance, $G$, in Alter do Chao during the summer solstice and the equinox. The power delivered by a PV generator is:

$$P_{AC} = P^* \frac{G}{G^*} \times \eta_{\mathrm{P}} \times \eta_{\mathrm{T}} \times \eta_{\mathrm{DC/AC}} \qquad (1)$$

where P* is the nominal power of the PV generator, $\eta_{\mathrm{P}}$ is the ratio real power versus nominal power of the PV generator which includes the losses due to dirtiness and ageing of the PV generator, $\eta_{\mathrm{T}} = 1 + \gamma(\mathrm{T_C} - \mathrm{T_C}^*)]$ is the thermal efficiency of the PV generator ($\gamma$ is the power temperature coefficient of the PV modules) and $\eta_{\mathrm{DC/AC}}$ is the efficiency of the frequency converter. Assuming that $P_{\mathrm{AC}}$ must be at least 80 kW to run the pumps at the desired constant pressure and that reasonable values for the rest of variables are $\eta_P = 0.96$, $\eta_T = 0.9$ and $\eta_{DC/AC} = 0.95$, Eq. (1) leads to $P^* \geq 125$ kW. Due to the solar tracker obliges to units of PV generator of 20 kWp, the final power of the PV generator was established in $P^* = 140$ kWp.

It is worth noting that the threshold for changing from the “Only PV” to “Hybrid” modes is slightly higher than the required $P_{\mathrm{AC}} = 80$ kW to allow a stable performance, being finally established in 95 kW. The transition from “hybrid” to “Diesel2 mode is done at $P_{\mathrm{AC}} = 45$ kW. In terms of solar irradiance, and considering an approximation of solar cell temperature equal to the one corresponding to standard test conditions, these thresholds would be 744 W/m$^2$ and 352 W/m$^2$, respectively. It must be underlined that the solar irradiance of 352 W/m$^2$ corresponds to a dark cloudy day.

The second HPVIS was installed in Tamellalt, Morocco, on a farm with 230 ha of intensive olive cultivation, divided into 8 irrigation sectors. Two boreholes provide approximately 53 L/s of water each, and the water is conveyed to the orchard by a drip irrigation system at 4.3 bar pressure.

The HPVIS is composed of a 120 kWp PV generator (calculated with the same procedure than explained above), two 55 kW frequency converters and two 45 kW centrifugal pumps. The frequency converters can also take power from the grid. The PV generator, with 120 kW peak power, is mounted on a north-south horizontal axis solar tracker with 80 PV panels per row. In this case, when the PV power provides less than $P_{\mathrm{AC}} = 90$ kW, grid power is automatically absorbed by the frequency converter. This threshold corresponds to a solar irradiance of 823 W/m$^2$. As solar irradiance and PV power are practically proportional, the proportion of conventional energy increases linearly when the solar irradiance decreases from this limit.

At both farms, irrigation water is applied according to traditional practices based on fixed water volumes supplied at fixed intervals of time from the beginning of growing season to harvest and irrespective of phenological stages and pedoclimatic conditions.

### 2.4. Functional units and system boundaries

The selected functional units of this study were 1 kWp of HPVIS installed and 1 kWh of PV electricity supplied to the irrigation pumps.

The assessment of the energy and environmental impacts, from raw material extraction, manufacturing process, transportation and utilization of the HPVIS, to end-of-life treatment was analyzed in this study (Fig. 4). Thus, the system boundary was from cradle-to-grave, including the end-of-life recycling treatment. The values used to assess the energy

**Fig. 2.** Hybrid (photovoltaic + diesel) irrigation system installed in Alter do Chao (Alentejo, Portugal).

and emission loads from the dismantlement of the PV system through the recycling treatment were 2780 MJ and 370 kg $CO_2e$ per tonne of PV waste, respectively (Latunussa et al., 2016).

### 2.5. Life cycle inventory (LCI)

The data used in the life cycle inventory were collected from direct measurements at the farm sites, farm manager interviews, and from the inventory list of the Maslowaten project. The LCI includes an extended set of inputs and outputs such us the overall HPVIS components, amenities, and supplied electricity to the pumps. Analyses of the inventoried data were conducted by splitting the overall HPVIS components into several groups including: PV modules; frequency converters; steel PV plant frame (including solar tracker); diesel generator (when applicable); other items (wiring, cables, electrical components, etc.); civil works (digging, excavation, foundation, etc.); pumps; transportation (road and sea transport); fencing; and maintenance (weed control, PV panel cleaning, etc.).

In regard to energy and emissions associated with transportation of the HPVIS components, distances from the manufacturer to the HPVIS sites were accounted for assuming 16–32 t Euro 5 trucks for road transportation, and sea transport via ship was assessed for the HPVIS components sent to Morocco.

Electricity generated by the HPVIS were recorded for the years 2016 and 2017 in order to quantify the energy and the environmental benefits recovered by the use of HPVIS. While 2016 was a standard year from a climatological point of view, 2017 was characterized by a severe drought with a lack of adequate water sources.

### 2.6. Impact assessment

The impact categories considered to quantify the energy and the environmental impact of HPVIS were cumulative energy demand (CED) and climate change. The first category was largely used to analyze the primary energy (MJ) requirements of a given system, while the second category quantifies the greenhouse gases (GHG) emitted by the production system. Both categories include the full working life of the system (from cradle-to-grave).

As defined by the Intergovernmental Panel on Climate Change (IPCC, 2014), the impact on climate change of each GHG emitted during the life cycle of a product was calculated by multiplying the mass of a given gas by its Global Warming Potential (GWP) using a 100-year time horizon.

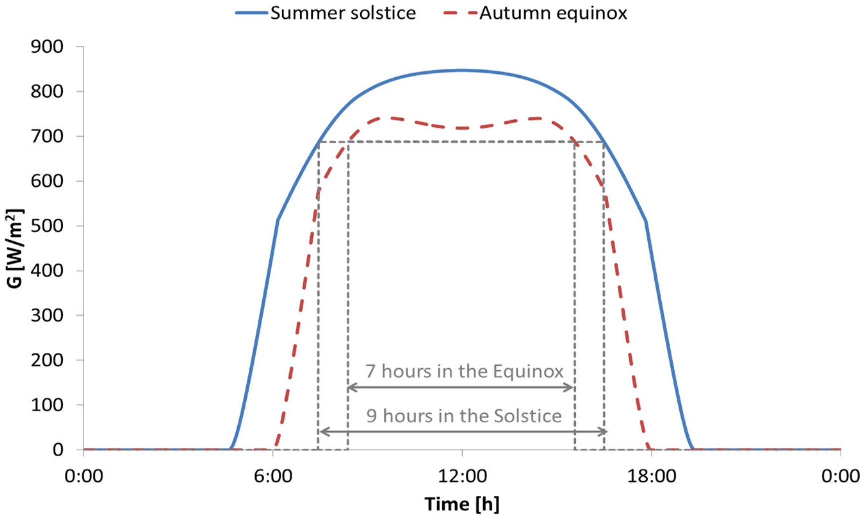

**Fig. 3.** Incident irradiance profile on the tracker during the autumn equinox and the summer solstice.

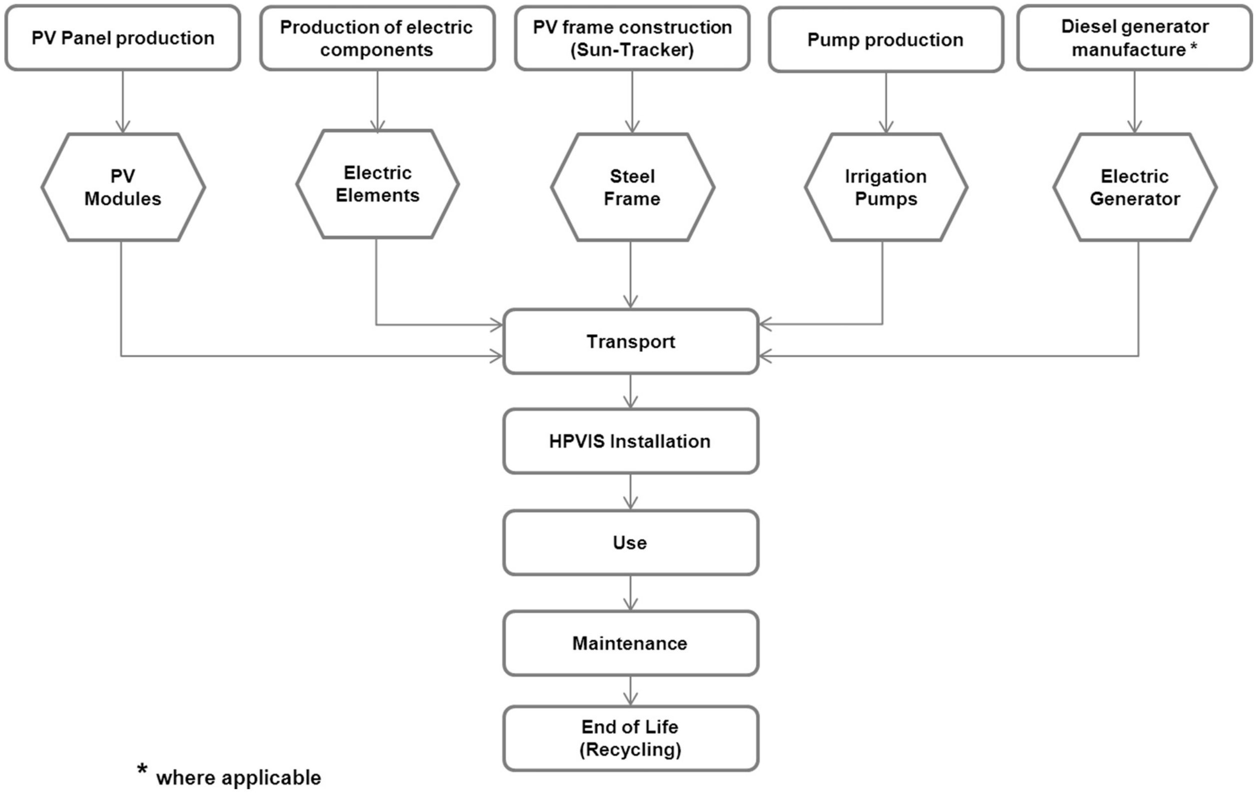

**Fig. 4.** The life cycle of hybrid PV irrigation systems.

The GWP represents the contribution of a GHG to the greenhouse effect, and it is represented in units of kg of carbon dioxide equivalent ($CO_2e$). The energy equivalents and missions factors used in this study are listed in Table 2.

In addition, the energy and carbon payback times (EPBT and CPBT) and the energy return on investment (EROI) were assessed for HPVIS. EPBT and CPBT are considered the most suitable measurements to evaluate the energy and environmental benefit obtained from the use of renewable systems (Luo et al., 2018; Chen et al., 2016; Hou et al., 2016; Leccisi et al., 2016; Mann et al., 2014).

The EPBT, expressed in years, represents a ratio between the primary energy (MJ) spent by the HPVIS during its entire lifetime and the annual primary energy saved in terms of MJ. In other words, the EPBT expresses the time necessary for the HPVIS to save the same amount of primary energy consumed throughout its full life.

The CPBT is a ratio between the amount (kg) of carbon dioxide emitted during the full life of the HPVIS and the yearly amount (kg) of carbon dioxide avoided. The result is expressed in years and represents the time required for the HPVIS to avoid the same quantity of $CO_2e$ emitted during its life cycle.

The EROI, a dimensionless ratio, represents the long-term viability of an energy generating system considering the energy (MJ) gathered from a renewable system and the amount of energy invested in that system throughout its full working life (Bhandari et al., 2015).

In order to assess the energy and environmental benefit of HPVIS, energy and emission factors of the electricity generation mix were accounted. Specifically, 36.8 MJ/L of diesel fuel and 9.19 MJ/kWh were used, respectively, for the systems in Morocco and Portugal, while the emissions rates accounted for 644.8 and 280 g $CO_2e$ per kWh, respectively (Itten et al., 2014; IEA, 2015; ENEA, 2018).

When evaluating the primary energy (MJ) produced and/or saved and the related GHG emissions (kg $CO_2e$), realistic scenarios for the Moroccan and Portuguese HPVIS were developed. These scenarios estimated the electricity produced by each PV generator and included one

**Table 2**
Energy equivalents and emission factors applied in the LCA of hybrid PV irrigation systems.

| Item | Energy equivalent | | Emission factor | | References | Lifetime (y) |
|---|---|---|---|---|---|---|
| Photovoltaic panels | 3640 | MJ/m$^2$ | 213 | kgCO$_2$e/m$^2$ | Wernet et al., 2016 | 25 |
| Frequency converter | 1085 | MJ/kW | 71 | kgCO$_2$e/kW | Wernet et al., 2016 | 15 |
| PV recycling | 2780 | MJ/t | 370 | kgCO$_2$e/t | Latunussa et al., 2016 | 25 |
| Wiring | 183 | MJ/m | 4.473 | kgCO$_2$e/m | Wernet et al., 2016 | 20 |
| Pumps | 64.8 | MJ/kg | 3.54 | kgCO$_2$e/kg | Nassiri and Singh, 2009<br>Rotz et al., 2010 | 20 |
| Other components | 992 | MJ/kg | 65 | kgCO$_2$e/kg | [Wernet et al., 2016 | 20 |
| Steel | 24.2 | MJ/kg | 1.76 | kgCO$_2$e/kg | Our Calculation | 20 |
| Reinforced concrete | 1.56 | MJ/kg | 0.18 | kgCO$_2$e/kg | Our Calculation | 20 |
| Excavation digger | 8.41 | MJ/m$^3$ | 0.552 | kgCO$_2$e/m$^3$ | [Wernet et al., 2016 | 25 |
| Road transport | 2.76 | MJ/tkm | 0.17 | kgCO$_2$e/tkm | [Wernet et al., 2016 | 20 |
| Sea transport | 0.179 | MJ/tkm | 0.0116 | kgCO$_2$e/tkm | [Wernet et al., 2016 | 20 |
| Electricity (Morocco) | 9.91* | MJ/kWh | 0.6448 | kgCO$_2$e/kWh | [Itten et al., 2014; IEA, 2015 | – |
| Diesel fuel | 36.8 | MJ/L | 0.280 | kgCO$_2$e/kWh | ENEA, 2018 | |

*Total cumulative energy demand per 1 kWh of the electricity mix at the plant based on the country average (Itten et al., 2014).

critical year (such as 2017) for every five favorable years (such as 2016). The scenarios were also utilized to determine EPBT, EROI, CPBT and the emissions rate (g $CO_2e$/kWh) of electricity produced by the PV systems.

Additionally, the consumption of diesel fuel or grid electricity before and after the PV plant installation was measured, as well as the environmental benefit achieved by the use of HPVIS.

## 3. Results and discussion

The implementation of each component in the HPVIS for irrigating intensive and super-intensive olive orchards was considered in order to express energy and environmental impacts as indexes. The overall results were divided by the nominal power (kWp) of the HPVIS and then by each individual life span, as reported in Table 2. The yearly distribution of the primary energy (MJ) and the GHG emissions (kg $CO_2e$) of each item installed in HPVIS is shown in Table 3. The results are expressed in reference to the nominal power of the HPVIS and highlight the PV-module proportion of the main quota (from 71% to 76%) of the embodied primary energy and the GHG emitted from the HPVIS. The remaining installed components represented a smaller portion of the energy and environmental impact. In fact, the frequency converters, the PV plant frame and other items were collectively responsible for approximately 15% of these impacts. Negligible values were found for maintenance, fence, and transport. However, the transport phase was much higher for the Moroccan HPVIS due to the longer distance from the manufacturer sites to the HPVIS site.

The total annual primary energy for from the HPVIS was 1284 and 1317 MJ per nominal power installed (kWp), respectively, in Morocco and Portugal. One of the main differences between the two HPVIS was related to the diesel generator. The diesel generator at the Portuguese installation annually contributed 77 MJ of primary energy and 5.5 kg $CO_2e$ per kWp. The annual environmental emissions from the HPVIS throughout its lifetime per nominal power installed was 78.8 kg $CO_2e$ for the Moroccan HPVIS and 81.6 kg $CO_2e$ for the Portuguese system.

### 3.1. Energy and environmental performance

The energy and carbon payback times were strictly related to a multitude of direct and indirect factors that influenced the quantity of electric generation. These factors, including local irradiation, weather conditions, PV cells and HPVIS efficiencies, and effective use of the HPVIS by the user, significantly affected the magnitude of EPBT, CPBT and EROI. Accordingly, Conceição et al. (2018) evaluated the impact of Saharan dust transported to southern Portuguese PV plants, resulting particle accumulation on PV surfaces, and associated reductions in the cell's incoming radiation.

The Moroccan HPVIS had an EPBT and CPBT of 1.98 and 1.86 years, while the same parameters for the Portuguese system were 4.58 and 9.16 years, respectively (Fig. 5). Considering the long working life of a PV plant, these results surely underline the energy and environmental benefits of the use of HPVIS. The energy produced by these technologies can avoid a large amount of GHG emissions and exploitation of natural resources. However, the energy and carbon payback times were considerably distinct between the two HPVIS. One of the main reasons of these differences, as reported in Table 4, is related to the higher use of the HPVIS installed in Morocco (4931 vs 2757 MWh). Expressing these results in terms of annual electricity harvested per PV system size, the Portuguese installation produced approximately 788 kWh per kWp, which represents less than 52% of the generation by the Moroccan HPVIS. This difference is mainly due to the lower need for pumped water for the Portuguese crop, which shows the importance of external factors in the performance of HPVIS.

To the authors' knowledge, there has been no scientific study focusing on EPBT and CPBT of hybrid PV irrigation systems. For comparison of the results of this study with other similar findings of stand-alone PV plant performance, the following EPBT values have been reported: 1.94 to 5.25 years for high peak-power PV irrigation systems installed in Spain and Italy (Todde et al., 2018); 9.08 years for a 4.2 kWp photovoltaic system installed in Spain (Garcıa Valverde et al., 2009); from 3.5 to 6 years for a multi-crystalline PV system installed in Greece equipped with battery storage (Kaldellis et al., 2010); and from 3 to 3.96 years for a hybrid (PV/thermal) module under outdoor conditions in New Delhi (Tiwari et al., 2009).

The estimated EROI in this study was 12.6 and 5.5 for the Moroccan and Portuguese HPVIS, respectively. Ten studies related to silicon multicrystalline PV systems reported a harmonized EROI of 11.6 (±5.2) (Bhandari et al., 2015), while Hall et al. (2009) suggested a minimum EROI (3:1) that a society must achieve from its energy exploitation to support economic activity and social functions.

Furthermore, dividing the total amount of the embodied primary energy (GJ from cradle to grave) by the total forecasted electricity (MWh) produced throughout the entire working life of the HPVIS, a cumulative energy demand of 0.787 and 1.68 GJ/MWh was calculated for the Moroccan and Portuguese sites, respectively. In spite of the similar embodied energy content of both HPVIS, the cumulative energy demand was much lower for the Moroccan installation mainly due to the high forecast for electricity production.

Another important aspect to consider is the amount of GHG embodied from cradle to grave in the HPVIS. The Moroccan installation represented approximately 236 t of $CO_2e$, while the Portuguese system represented approximately 285 t of $CO_2e$. These results were divided by the forecasted electric production throughout the 25 years of expected working life to obtain emission rates of 48 and 103.5 g $CO_2e$ per kWh generated for the Moroccan and Portuguese HPVIS, respectively. The higher emissions rate of the Portuguese HPVIS is mainly due to under-use of the irrigation system (adverse weather conditions, crop management, etc.) and the need to irrigate with the diesel generator during the night and at other critical periods. Regardless, the emission rates obtained in this study were much lower (approximately 13 and 3 times less emissions) than those from the conventional energy used before HPVIS installation (see Table 2). This allowed avoidance of a remarkable quantity of GHG emissions, as was also found in other studies. In fact, Todde et al. (2018) reported emissions rates ranging from 46 to 124 g $CO_2e$/kWh for installed stand-alone PV systems exclusively devoted to irrigation in Spain and Italy. An emissions rate of 37.1 g $CO_2e$ per kWh was found by Masakazu et al. (2016) for a simulated commercial-scale multi-crystalline silicon PV system installed in Morocco. The environmental benefits of three different roof-integrated multi-crystalline PV systems were studied in Singapore, and emission rates ranging from 20.9 to 30.2 g $CO_2e$ per kWh were found (Luo et al., 2018).

The operational performances and the emissions data recorded during 2016 and 2017 are summarized in Table 5, which shows the consumption of grid electricity and diesel fuel before and after the HPVIS implementation. These results show savings of 110 MWh of electricity

**Table 3**
Distribution of the annual primary energy and the carbon dioxide equivalents of each item in the HPVIS from cradle to grave, expressed per nominal power of HPVIS.

| Item | Morocco (120 kWp) | | Portugal (140 kWp) | |
|---|---|---|---|---|
| | kg $CO_2e$/kWp | MJ/kWp | kg $CO_2e$/kWp | MJ/kWp |
| PV modules | 58.1 | 982 | 58.1 | 982 |
| Frequency converter | 4.3 | 66 | 3.7 | 57 |
| PV plant frame | 4.9 | 67 | 4.9 | 68 |
| Diesel generator | – | – | 5.5 | 77 |
| Other items | 2.7 | 65 | 2.3 | 59 |
| Civil works | 4.1 | 37 | 4.1 | 37 |
| Irrigation pumps | 1.9 | 34 | 0.9 | 17 |
| Transport | 1.4 | 22 | 0.6 | 10 |
| Fence | 1.1 | 15 | 1.0 | 14 |
| Maintenance | 0.4 | 5 | 0.2 | 5 |
| Total HPVIS | 78.8 | 1284 | 81.6 | 1317 |

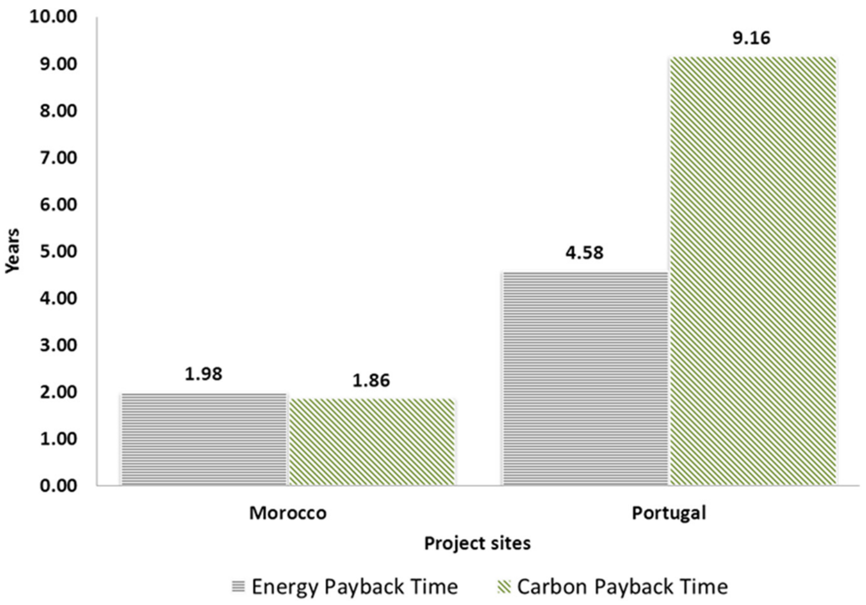

**Fig. 5.** Energy and carbon payback times (from cradle to grave) per HPVIS.

(67%) at the Moroccan farm and approximately 11,000 l of diesel fuel (41%) at the Portuguese installation. The large amount of fossil fuels saved allowed avoidance of a large amount of GHG, corresponding to approximately 70,700 and 19,700 kg $CO_2e$ for the Moroccan and Portuguese HPVIS, respectively.

The results presented underline the environmental advantages achieved using HPVIS in intensive and super intensive olive orchards. Moreover, a simulation study conducted by Deriu (2016) on the Alter do Chao site was aimed at developing irrigation management options to increase water savings, and found that the previous water management strategy, with water applied at fixed timing (weekly interval) without considering soil spatial variability, phenological phases and evapotranspiration demand, the available soil water content fell to the wilting point with evidence of water stress in August and at the beginning of September which is, according to Sanz-Cortés et al. (2002), the most critical stage for reproduction activity. Moreover, the output of the simulation study revealed that the most watering effective strategy is to supply water at the right time and at the right amount. This means that, notwithstanding an increase in the recommended total irrigation water volume (a 99% increase compared to the standard water management) and with an equal the number of irrigation periods, there would be a positive effect on both the trees' water status and the HPVIS efficiency.

**Table 4**
Energy produced, EROI and emission rate of the HPVIS per farm.

| Items | Morocco (120 kWp) | Portugal (140 kWp) |
|---|---|---|
| Electricity produced in 25 years (MWh) | 4931 | 2757 |
| Energy produced in 25 years* (GJ) | 48,870 | 25,341 |
| Yearly electricity produced per PV system size (kWh/kWp) | 1644 | 788 |
| Yearly electricity produced per PV surface area (kWh/m$^2$) | 246 | 118 |
| Cradle-to-grave primary energy per HPVIS (GJ) | 3879 | 4641 |
| Energy return on investment (EROI) | 12.6 | 5.5 |
| Cradle-to-grave GHG per HPVIS (t $CO_2e$) | 236.5 | 285.5 |
| HPVIS emissions rate (g$CO_2e$/kWh) | 48.0 | 103.5 |

*Based on a cumulative energy demand of 1 kWh (ENEA, 2018; Itten et al., 2014).

## 4. Conclusions

The energy and environmental benefits were assessed for hybrid PV irrigation systems implemented in Mediterranean intensive and super-intensive olive orchards, from which the main findings were as follows:

- The primary energy embodied in the HPVIS accounted for 1284 and 1317 MJ per kWp, while the related embodied GHG emissions were 78.8 and 81.6 kg $CO_2e$ per kWp for the Moroccan and Portuguese installations, respectively. The most critical stage was the manufacture of PV modules, which contributed approximately 75% of total embodied energy.
- The energy and environmental performances resulted in an EPBT of 1.98 and 4.58 years and a CPBT of 1.86 and 9.16 years for the Moroccan and Portuguese HPVIS, respectively. The variation in EPBT among the two sites was mainly due to the higher solar radiation and better HPVIS management at the Moroccan site. The CPBT performed in the Moroccan olive orchard was remarkably low due to the high emissions rate of grid electric generation in that country. The use of renewable energy technologies, such as HPVIS, can allow a drastic reduction in the exploitation of natural resources over the next decades.

**Table 5**
Direct operational fossil energy consumption and GHG emissions before and after installation of the HPVIS, 2016–2017.

| | Items | Morocco (120 kWp) | Portugal (140 kWp) |
|---|---|---|---|
| Before HPVIS | Diesel (L) | 0 | 27,761 |
| | Electricity (MWh) | 163 | 0 |
| | Diesel (GJ) | 0 | 1072 |
| | Electricity (GJ) | 1616 | 0 |
| | Diesel (t $CO_2e$) | 0 | 73.0 |
| | Electricity (t $CO_2e$) | 105 | 0 |
| After HPVIS | Diesel (L) | 0 | 16,469 |
| | Electricity (MWh) | 53.4 | 0 |
| | Diesel (GJ) | 0 | 636 |
| | Electricity (GJ) | 529 | 0 |
| | Diesel (t $CO_2e$) | 0 | 43.3 |
| | Electricity (t $CO_2e$) | 34.4 | 0 |
| Fossil fuel saved (MWh or L) | | 109.7 | 11,292 |
| Energy saved (GJ) | | 1087 | 436 |
| Energy saved (%) | | 67 | 41 |
| Emissions avoided (kg $CO_2e$) | | 70,749 | 19,701 |

- In this study EPBT, CPBT and EROI were directly linked with the irrigation schedules of the olive orchards (no battery storage and nor exchange with an electric grid). Therefore, water availability, weather conditions and irrigation management may modify the energy and environmental performances of HPVIS.
- The implementation of HPVIS for existent irrigation systems allowed unaltered irrigation schedules and practices, providing energy savings of approximately 41 and 67% in Morocco and Portugal, respectively, and avoiding the exploitation of natural resources and the emission of large amounts of GHG to the environment.
- The shift from traditional irrigation water management to automatic and precision water management combined with HPVIS is recommended to improve the environmental and economic sustainability of intensive and super-intensive olive cropping systems.

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## Conflicts of interest

The authors declare no conflicts of interest.

## Author contributions

GT conceived and designed the experiments, wrote the manuscript, collected and analyzed the data. LM and AP conceived and designed the experiments. RH, IC collected the data. MM provided data on irrigation water scheduling. PAD and LL curate the irrigation aspects and revised the manuscript. LN revised the manuscript. All authors read and approved the final manuscript.

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