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The environmental and economic benefits of a hybrid hydropower energy recovery and solar energy system (PAT-PV), under varying energy demands in the agricultural sector

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ABSTRACT

A comparative environmental and economic impact analysis between a hybrid pump-as-turbine/solar pilot system (PAT-PV) and a traditional diesel generator, with the innovation of the seasonal energy supply preconditions in an off-grid farm in Southern Spain was conducted. The results show lower climate change, fossil fuels, and dissipated water burdens over a 20-year lifespan, for the hybrid PAT-PV system, especially for fossil fuels (40-times lower). However, there was an increased demand for minerals and metals compared with the diesel generator, mostly due to the batteries and electronic components contribution, representing between 66% and 87% of the burdens. The hybrid PAT-PV system presented a lower total cost, but a higher investment, with an 8-year payback period. The low energy demand of the farm represented only 2.2% of the energy potential generation of the hybrid PAT-PV system, with a higher impact per kWh of energy than expected. The total use of the energy generated was proven to be essential, decreasing the environmental impacts up to 45 times, which provide a way to further reduce fossil energy consumption at farm level, as surplus energy could be used to power electric vehicles or tools, contributing to the reduction of GHG emissions, for a more sustainable agriculture.

1. Introduction

Sustainable solutions are required to combat climate change and the continuous degradation of the planet, through resource exploitation, waste and pollution generation. In this context, the total greenhouse gas (GHG) emissions in 2018 were around 76.8% compared to 1990 levels (Eurostat, 2020). The 2019 Climate Action Summit outlined the need for a 45% reduction target in carbon dioxide emissions by 2030, to reach net zero in 2050 (CAS, 2019). To achieve this goal, countries must propose measures to reduce emissions across all the different sectors, from transport to industry, energy to agriculture. Consequently, the European Union established, as a key renewable energy (RE) target for 2030, that at least 32% of final energy consumption comes from RE sources (EC, 2018).

A sustainable agriculture sector needs to consider the complexities of the water-energy-food nexus (Albrecht et al., 2018), in particular the water and energy demands of food production using irrigation (Daccache et al., 2014). The adoption of RE technologies to replace fossil fuel (diesel) consuming generators for pumping in the irrigation sector is one key strategy to reduce emissions and improve the sustainability of the agriculture sector (MAPA, 2001; Carrillo-Cobo et al., 2014). In some European regions, stakeholders are working together to make irrigation more sustainable (Velasco-Muñoz et al., 2019), which has led to the integration of RE technologies and development of RE communities within the agricultural sector (Lowitzsch et al., 2020). Solar photovoltaics (PV) can be effectively integrated into irrigation systems to offset primary energy demands for pumping (Mérida García et al., 2018; Todde et al., 2019). Furthermore, the combination of solar PV technology with other RE sources, such as wind turbines, has been shown to increase the autonomy of irrigation systems (Vick and Almas, 2011). Nevertheless, sustainable agriculture and irrigation require the optimal design of the entire system to reduce the total investment cost, the operation of the system and optimise water and energy consumption (Reca-Cardeña and López-Luque, 2018; Mérida García et al., 2020).

Within the irrigation sector, previous energy efficiency studies have focused on developing operational tools for network

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Abbreviations and nomenclatures

B	environmental burden per unit
C_{inst}	installation cost
C_{ope}	operation cost
e	process or material
E	total number of different materials and processes
EB	environmental burden
ESS	energy supply system
GHG	greenhouse gas
i	impact category
LCA	life cycle assessment
LCC	life cycle cost
MHP	micro-hydropower
PAT	pump as turbine
PV	photovoltaic
RE	renewable energy
U	total units of each material/process

optimisation through an exploration of the advantages of controlling critical pressure points (Rodríguez Díaz et al., 2012; González Perea et al., 2014); and turn-based irrigation organisation and sectoring (Fernández García et al., 2013). Despite this, excess pressure remains at specific control locations within these networks, which is typically dissipated using pressure reducing valves to avoid pipe bursts and leakage (García et al., 2018; Fernández Garcia and Mc Nabola, 2020). Recent research has explored energy recovery opportunities at locations of excess energy with the installation of micro-hydropower (MHP) turbines or Pumps-As-Turbines (PATs) (Pérez-Sánchez et al., 2017; Crespo Chacón et al., 2020a). In particular, PATs have been shown to be a cost-effective option for energy recovery in water distribution systems (Crespo Chacón et al., 2019, 2020b). This energy can be used to reduce the total energy demands of pumping, or for complementary activities and equipment, to further enhance the sustainable performance of agriculture.

Despite the renewable nature of these energy sources, there is an inherent investment of resources to manufacture, construct and operate an energy recovery system or RE technologies (Gallagher et al., 2019). The adoption of life cycle assessment (LCA) has provided a suitable methodology to provide a balanced analysis of the environmental impacts associated with RE (Luo et al., 2018; Mérida García et al., 2019) and energy recovery technologies i.e. MHP systems (Gallagher et al., 2019), implemented in different water distribution networks (Ueda et al., 2019). Nevertheless, environmental impact assessments show large variations in results between different studies even for a same technology and scale (Raadal et al., 2011; Ueda et al., 2019). The design and operation of energy recovery installations present complexities relating to variations in pressure and flow characteristics in water networks (McNabola et al., 2014; Fernández García et al., 2019). Despite this, Gallagher et al. (2015) estimated that MHP installed in water networks can achieve a reduction of more than 98% in global warming emissions and fossil fuel consumption. However, these previous studies estimate the impact burdens per energy unit considering that all energy potential generated by the system is used, which may not always the case, as some activities and sectors have a considerable variation between renewable energy supplies and local energy demand across the year. This variation between supply and demand is very prevalent in the agriculture sector for example, where irrigation activity occurs intensively in the summer months. Moreover, the installation of these RE energy systems has led to a higher depletion of material resources than traditional energy sources providing grid electricity. Therefore, it is important to consider the environmental and economic paybacks when installing RE and energy recovery technologies, under different boundary conditions, in water networks (Gallagher et al., 2015).

The objective of this work was to assess the environmental and economic impacts of a hybrid energy recovery (PAT) and RE (solar PV) system installed at farm-level in an irrigation network, with the operation preconditions established by a seasonal energy demand, not assessed in previous LCA studies of this nature. This seasonality results in low percentages of energy utilization in PVs, for example, in which used energy for irrigation related to the total energy generated, can fall below 20% (Mérida García et al., 2019). These long periods of inactivity make the environmental impact of the RE installations (MHP in this case) more significant for each kWh of energy used, compared to MHP installations in run-off-river systems or drinking water networks where activity and energy demand is less variable. In this case, this hybrid PAT-PV system will replace the existing energy demands (fertigation, filtration, electrovalves and compressor) at this off-grid location, which were supported by a diesel generator energy supply. The PAT installation presents unique conditions in the irrigation network as compared to previous studies, due to the seasonal and variable energy demands, and operational requirements of the system. Due to the very intermittent nature of irrigation activity across the year and to guarantee the system's greater stability, the hybrid installation also required a battery system to store the energy generated by the PAT and PV panels. Thus, the LCA conducted here encompassed the environmental burdens associated with the installation of PATs and solar PV technologies, combined with energy storage systems in off-grid locations, whose generated energy is only partially used, due to the very seasonal energy demands of irrigation. The results of this study will help assess the feasibility of a hybrid PAT-PV system, as an innovative energy supply technology alternative to the traditional diesel generators in off-grid farms, showing the importance of the particularities derived from a partial use of the energy generated. Moreover, this study deepens the analysis of the potential positive contribution, not only of installing this type of system, but also in optimizing the maximum use of the energy production, thus promoting the transition towards a more sustainable agricultural sector and the reduction of pollutant emissions.

2. Methodology

2.1. Goal and scope

This study will evaluate the life cycle environmental and economic impacts of a hybrid energy recovery and RE system installed on a farm in Córdoba in Southern Spain, in the form of a MHP installation (a PAT) supplemented by a small solar PV and battery storage system. This system was installed in 2019 and has replaced a diesel generator power supply to support the energy demands coming from the fertigation system, a compressor, some electrovalves and the filtration station. This PAT system was installed in the main irrigation network, which feeds a number of farms in the Comunidad de Regantes del Margen Izquierdo del Canal del Genil (Left Bank of the Genil River Channel Irrigation District) in Palma del Río. The installation was designed to recover energy from a hydrant presenting excess pressure and replace the energy generated by the diesel generator (Crespo Chacón et al., 2021).

The small solar PV (0.66 kW) and battery storage system was included to supplement small energy demands outside of the irrigation season, where no power can be recovered by the PAT due to a lack of water flow from October to March (approx.). The energy from the diesel generator was required intermittently throughout the day and irrigation season, therefore the associated environmental impacts and economic viability of this system was to be compared to the new hybrid PAT-PV system.

To conduct this LCA study, all materials and processes involved in the manufacturing, transport, installation and operation of the different technologies and their components (diesel generator & hybrid PAT-PV system) were included in the assessment. A cradle-to-grave life cycle was considered to account for the installation and operational impacts of the project; however, the associated end-of-life impacts for this infrastructure was excluded. This represents a limitation to the work scope, but undoubtedly, the end of life and recycling of these technologies often represents a great uncertainty, and therefore, as in many other works, it has not been included in this study. The project lifespan considered for this study was based on the technical information for the different technologies included in the hybrid PAT-PV system. Specifically, the two technologies used for energy generation, PAT and PV panels, have a minimum useful life of 20 years. So an average useful life of the project of 20 years was estimated. The functional unit selected was 1 kWh of energy used, was adopted to express and compare the environmental burden associated with the different impact categories for each technology.

The impact calculations were based on the use of the International Reference Life Cycle Data System 2018 midpoint model, and the Ecoinvent 3.6 database (Ecoinvent, 2019). Four impact categories were selected as they represented the most relevant burdens for this water-energy-food nexus study: climate change (expressed as kg CO_2 eq.), representative of greenhouse gas emissions; fossil (expressed as MJ), representative of fossil fuels; minerals and metals (expressed as kg Sb eq.), representative of material resources, and dissipated water (expressed as m^3 water eq.), representative of water footprint. Climate change is the most widely studied impact category in this kind of assessment, directly related to energy consumption and, of course, to global warming. Similarly, the consumption of fossil and mineral resources represents, in general terms, the high demand for resources by solutions based, on combustion engines and renewable energies, respectively. Finally, the use of water was added as a complementary category due to the relevance of this natural resource and its importance in the agricultural sector and, specifically, in irrigation projects. An overview of the life cycle methodology is presented in Fig. 1.

2.2. Case study

The selected case study was located in the Guadalquivir region of Palma del Río, in Cordoba, Southern Spain. The 170-ha walnut farm is part of the Left Bank of the Genil River Channel Irrigation District (Fig. 2). This off-grid farm was equipped with an automatic fertigation system, together with other complementary loads (compressor, electro-valves and filtration station) and these were originally powered by a 6 kVA (4.8 kW) diesel generator (Fig. 3).

In 2019, the hybrid PAT-PV system was installed to replace the diesel generator and provide all the necessary power requirements on the farm. This included: 2 injection pumps (1.5 CV each), 1 compressor (1.6 CV), 18 solenoid valves for water filtration equipment (5.5 W each), and 60 solenoid valves of the irrigation network (0.5 W each). The energy supplied was used at farm level only and not for the distribution of water in the irrigation network, which originates from a centralised source at irrigation district level. This assessment determined that the maximum power requirement of the system was 3.6 kW, and as such the previous diesel generator was oversized (Crespo Chacón et al., 2021).

2.3. Effects of seasonality on the system

The irrigation season for the walnut trees in Spain is typically between March/April and September/October, varying depending on the meteorological conditions of the hydrological year. The mean annual rainfall and evapotranspiration at the case study location over the last ten years (2009–2018) amounted to 641.8 mm and 1328.6 mm respectively, with an annual daily average irradiance of 5.14 kWm^{-2}, with maximum values from 9:30 h to 15:30 h (local time). In any case, the annual distribution of the rainy period only results in the start and end date of the irrigation season being later/earlier, but the total count of irrigation hours remains practically invariable, as it is adjusted to the annual water allocation for each crop. Thus, the annual operation time of the installation was defined as approximately 3199 h of irrigation for 2019 (Crespo Chacón et al., 2021), based on the total irrigation allocation for the crop, as cubic meters per hectare per year ($m^3 \cdot ha^{-1} \cdot year^{-1}$).

2.4. Inventory analysis

A breakdown of the energy system components, as well as all materials and processes involved from its manufacturing and maintenance, was collated and included in the assessment (see Table S1 in the supplementary information (S.I.) supporting this paper). The Ecoinvent 3.6 database provided all life cycle impact assessment) data relating to materials used in the system, with the allocation, cut-off by classification system model selected (Ecoinvent, 2019). The total environmental burdens for the four impact categories (climate change, fossil, minerals and metals, and dissipated water) was calculated (Eq. (1)) using the inventory data and LCA database. This impact linked to all flows and materials included in the installation, transport and operation stages, for each energy supply option (Mérida García et al., 2019), following Eq. (1):

$$EB_{ESS,i=}\sum_{e=1}^{E} B_{e,i}\cdot U_e \tag{1}$$

where EB is the environmental burden associated to each energy supply system ESS and impact category i; B is the environmental burden associated to one unit of each material or process e; E is the total number of different materials and processes; and U is the total units of each material or process.

2.4.1. Hybrid PAT-PV system

The PAT(4 kW) was installed on a by-pass to the main water intake system (Ø400 mm pipe) that feeds the farm irrigation network. This 150 mm diameter by-pass pipe consists of a cast iron pipe in the turbine insertion section, including 2 cut-off valves, one before and one after the PAT. The PAT was installed on a by-pass to ensure continued operation of the irrigation network downstream during PAT repairs or maintenance. This irrigation network is composed of a branched set of pipes fed by a single hydrant. The turbine operates with the head pressure of the incoming water, so its maximum operation time, and thus the maximum energy generation time, equals the duration of downstream irrigation in the network. A hydraulic regulation system ensures that the turbine always operates at pre-determined flow and pressure values, thus ensuring its correct operation.

The hybrid PAT-PV system was installed in an extension to the existing valve house on the farm. It also includes several electrical devices, such as inverters, rectifiers, and charge controllers. All equipment in the hybrid PAT-PV system, with the exception of the batteries, was estimated to have a 20-year lifespan, based on

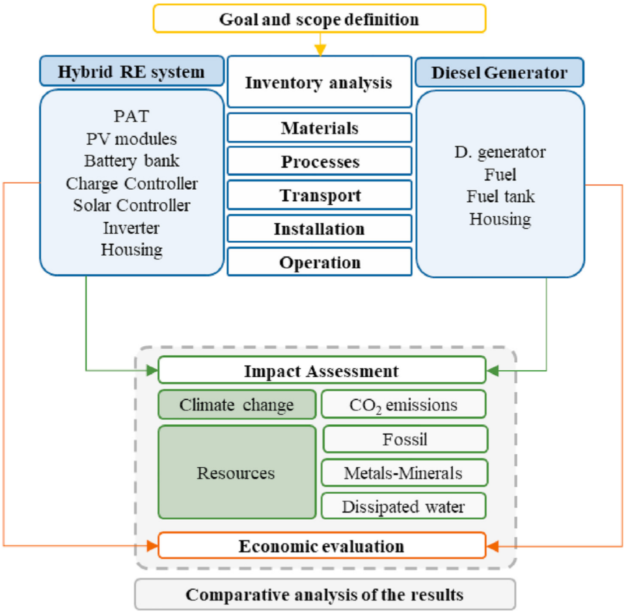

Fig. 1. Simplified scheme of the methodology applied.

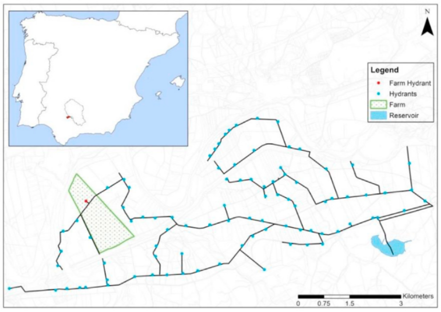

Fig. 2. Location and distribution of the Genil River Channel Irrigation District network (Southern Spain) and the farm where the hybrid PAT-PV system is operating (Crespo Chacón et al., 2021).

individual technical information for the different devices. A more conservative lifespan of the batteries was taken as it is strongly influenced by their operating pattern i.e. discharge and recharge. As such, a lifespan of 10 years was considered, and therefore required to be changed once during the 20 years being assessed. It was assumed that the batteries are fully charged using the solar PV panels outside the irrigation season (when the PAT is not in operation), with the only loss of charge due to self-discharging at night.

The technical details of the main elements integrated in the hybrid PAT-PV system (Fig. 4) are summarized in Table 1.

2.4.2. Diesel generator

The diesel generator in this case study was the Ayerbe AY-1500 6-TX model, with 6 kVA (4.8 kW) of power, and a total weight of 300 kg. It had an average fuel consumption of 1.2 l h^{-1}. The diesel generator worked at an almost unchanged rate of fuel consumption, regardless of the energy demand downstream. Due to the complexity of the materials decomposition of a diesel generator, the environmental assessment was simplified to that corresponding to the most representative materials, including the energy requirements for the manufacturing process, as it was made in previous works (Benton et al., 2017; Mérida García et al., 2019).

In addition to the environmental impact estimations corresponding to the diesel generator, and its replacement after the first 10 years of the project, the accumulated fuel consumption throughout the irrigation seasons, for the 20 operation years, was also accounted for. This was quantified based on the technical description of the generator and the average fuel consumption data for the 2018 irrigation season. The transport for the installation of the generator in the farm, as well as for the annual supply of fuel, and the tank storing the fuel in the farm, were also considered. Finally, a small metal structure which housed the generator on the farm was accounted for, composed of wire mesh, posts, and sandwich panel as roof cover.

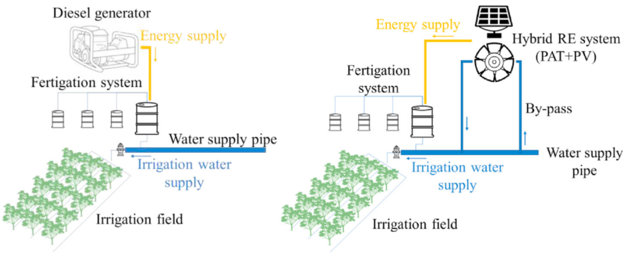

Fig. 3. Schematic representation of the case study configuration of the energy and water supply systems with the (a) diesel generator and (b) the hybrid PAT-PV system.

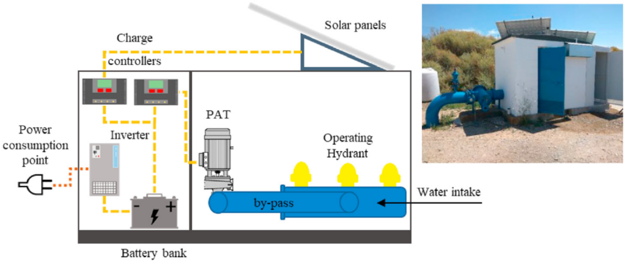

Fig. 4. Schematic representation of the hybrid PAT-PV system including the main elements and connections.

Table 1
Main components of the hybrid PAT-PV system and their principal characteristics.

Component	Model	Description
Turbine-generator	INLINE 080-B	57 kg cast iron, 20 m pressure head and 30 l s^{-1} flow rate
Cut-off valves and pipe	-	Cast iron
Charge controller	MPPT (Schneider- electric)	Capacity of up to 80 amps
Panel with rectifier and solar charge controller	PWM 48-20 (Victron)	Installed inside a metal frame (60x60 × 21 cm)
Battery bank	AGM monobloc	Total capacity 10.56 kW. Self-discharge rate 2% per month (20 °C)
Three phase inverter panel	3 Victron single-phase inverters (model 48/3000)	18 kW peak power
Solar panels	AMERISOLAR	2 × 330 W. Polycrystalline (1956x992 × 40 mm). Fixed to the roof with a metallic structure.
Extension of the house	-	Sandwich panels, metallic frames, door, and reinforced concrete.

2.5. Seasonal energy balance

The operation of the fertigation system, compressor, filtration station, and electro-valves on the farm during the irrigation season were previously powered by the diesel generator. The hybrid PAT-PV system now provided this energy supply, with the batteries providing storage for energy generated by the PAT that is in excess of the energy demands of the fertigation system. When irrigation is not taking place, the solar PV system supplements the batteries to ensure they remain fully charged.

In terms of providing an efficient and balanced energy supply, the PAT was designed to provide enough energy to supply local demands throughout the year, with the solar PV panels working intermittently to supplement the demand. Considering the two sources of energy supply (PAT and PV panels), the self-discharge rate of the batteries and the energy consumption by the loads (fertigation equipment, filtration station, compressor, and electro-valves), a seasonal energy balance was estimated.

2.6. Scenario analysis

The first scenario aims to further improve the environmental performance of the hybrid PAT-PV system by evaluating the opportunity to account for and consume the maximum potential energy generation from the system. This scenario accounted for all the energy generation potential from the PAT throughout the irrigation season and the solar PV panels during all the sunlight hours each year.

A second scenario evaluated the environmental impacts of an equivalent solar PV plant, to compare the environmental impacts of this technology as an alternative to the system installed. In this case, the solar PV plant was sized to equal potential energy production, the energy generated by the hybrid system, which resulted in a higher installed peak power.

2.7. Life cycle cost and payback period

The life cycle costs of both energy supply systems were considered. This accounted for the costs of all equipment and consumables required to install and operate these systems over the 20-year lifespan, as it is expressed in Eq. (2):

$$LCC_{ESS} = C_{inst,ESS} + C_{ope,ESS} \tag{2}$$

where LCC represents the Life Cycle Cost of the Energy Supply System ESS; and C_{inst} and C_{ope} the total costs associated to the installation and operation stages, respectively. For the hybrid PAT-PV system, the majority of the total cost was associated with the installation, covering the investment of the turbine, batteries, and solar PV panels. Operational costs were also incurred with the replacement of batteries after a 10-year period.

The initial costs for the diesel generator was associated with the generator itself and fuel tank, however the predominant ongoing cost was attributed to fuel consumption during operation and the replacement of the generator, after 10 years.

The lifecycle costs allowed for the payback period for the hybrid PAT-PV system to be calculated. This can allow for a comparison of the economic and environmental life cycle impacts of the diesel generator and hybrid PAT-PV system.

3. Results and discussion

3.1. Energy balance

The energy balance (Table 2) accounted for all battery energy inputs and outputs, corresponding to the energy produced by the PAT and PV panels, and that demanded by the fertigation system, filtration station, compressor, and electro-valves, respectively.

The data from one representative irrigation season i.e. 2019 showed that the total energy demand (222 kWh) represented approximately 41% of the total energy generated (Table 2), even when the operating time of the turbine and panels was restricted (not all the irrigation time and year working). The excess energy, which existed even though the turbine was working only for one-third of the total irrigation time, was dissipated. From the total energy generated, 78% (429 kWh) of the input power to the batteries was provided by the PAT, while the PV panels produced the remaining 22% (118 kWh). This was recorded by the control system installed in the pilot plant for research purposes.

The maximum potential energy generated by the hybrid PAT-PV system was estimated based on the assumptions that the PAT operates during the total irrigation hours at an operating efficiency of 68%, and the PV panels generates energy during sunlight hours throughout the year. PAT efficiency was directly measured from the telemetry system of the pilot plant monitoring flow, pressure, and power generation. This estimate was carried out to check the percentage of energy that was actually being used, and compared with the total potential of the system.

The current energy input to the batteries from the PAT and PV panels represented only 5% and 10% of their maximum energy generation potential, respectively. The total energy demand on the farm represented only 2.2% of the total energy production potential of the hybrid PAT-PV system. As such, there is significant potential for additional energy from these sources to be consumed on the farm and offset other processes or systems which utilise non-renewable energy.

3.2. Contribution analysis

The results obtained from the LCA of the hybrid PAT-PV system and the diesel generator (see Table S2 in the supplementary information (S.I.) supporting this paper). are represented as the environmental burdens per kWh of electricity consumed by the farm over a 20-year lifespan and summarized in Table 3.

The cumulative energy demands on the farm during this period equalled 4.4 MWh. In comparison to a previous investigation of energy demands and associated environmental burdens from renewable and fossil sourced energy for irrigation by Mérida García et al. (2019), these results in this study were significantly higher for all the impact categories analysed.

The diesel generator presented a higher environmental burden for three impact categories (climate change, fossils, and dissipated water) with fossil fuel consumption in particular having a burden 40 times higher than the corresponding hybrid PAT-PV system. However, for the minerals and metals category, the hybrid PAT-PV system was almost double that of the diesel generator. This was due to the larger material demands for constructing the three key components of this system: turbine, solar PV panels and batteries.

The climate change burden shown by the hybrid PAT-PV system reached a total of $2.6 \cdot 10^3$ g CO_2 eq.$\cdot$kWh^{-1}, almost 30 times lower than the burden shown by the diesel generator-based option ($7.3 \cdot 10^4$ g CO_2 eq.$\cdot$kWh^{-1}). The difference between the hybrid RE system and previous works highlight the environmental impact of plants with seasonal activity. This seasonal activity and the variability on energy demand results in a partial use of the energy generated, which is very common in irrigation energy supply systems based on renewable energies. Therefore, for short operating hours, the environmental burdens are greater proportionally per kilowatt of electricity generated and final energy consumed. This case remains higher compared to a similar seasonal energy demand for irrigation provided by solar PV undertaken by Mérida García et al. (2019), as the global warming impact for PV technology was around 120 g CO_2 eq.$\cdot$kWh^{-1}. In the case of the minerals and metals, and fossils, the hybrid PAT-PV system option showed a total burden of $3.1 \cdot 10^{-1}$ g Sb eq.$\cdot$kWh^{-1} and $3.8 \cdot 10^4$ kJ$\cdot$kWh^{-1}, respectively. Finally, for dissipated water, the hybrid PAT-PV system burden was approximately half of that associated to the diesel generator, with $1.4 \cdot 10^3$ and $2.8 \cdot 10^3$ m^3 water eq., respectively.

The large environmental burdens obtained for this case study, in comparison to results from previous works, could be explained by

Table 2
Current and potential energy generation from the PAT and solar PV panels and current energy demanded by the farm.

	Period	Energy (kWh)
Current power input to the batteries by the PAT	1 irrigation season	429
PAT potential energy generation	1 irrigation season	8701
Current power input to the batteries by the PV panels	1 irrigation season	118
PV potential energy generation	1 year	1236
Current energy demand	1 irrigation season	222

Table 3
Environmental burdens per kWh of energy consumed for the hybrid PAT-PV system and diesel generator over the 20-year project lifespan.

System	Climate Change (g. CO_2 eq.$\cdot$kWh^{-1})	Resources		
		Fossils (kJ$\cdot$kWh^{-1})	Minerals and metals (g Sb eq.$\cdot$kWh^{-1})	Dissipated water (m^3 water eq.$\cdot$kWh^{-1})
Hybrid PAT-PV system	$2.6\cdot10^3$	$3.9\cdot10^4$	$3.1\cdot10^{-1}$	$1.4\cdot10^3$
Diesel generator	$7.3\cdot10^4$	$1.6\cdot10^6$	$1.8\cdot10^{-1}$	$2.8\cdot10^3$

the differences in the boundary conditions. The extension of the useful life of the project, as well as the system's operational hours, and thus the energy produced and finally used, was found to have a strong impact on the results. Most LCA studies include the manufacturing and installation of the MHP system and the building construction in their calculations, however an energy storage system and additional electronic devices or inverters are typically omitted. As such the significant environmental burdens presented in these results are partially attributed to these additional components. Fig. 5 provide a breakdown of component contributions with the percentage distribution of the total burdens for the four impact categories, disaggregated in the main components for each technology.

The burden distribution between the different components pointed out the importance on the total environmental impact of the inclusion of the batteries and electronic components, in the hybrid PAT-PV system, representing between 66% and 71% of the total burden for climate change, fossils, and dissipated water, respectively. It contributed towards 87% of the associated impact relating to mineral and metals, similar to that results obtained in previous studies evaluating hybrid RE supply systems involving batteries (Jhud Mikhail et al., 2020). By contrast, the PAT installation (turbine, by-pass and valves), together with the extension of the housing, only accounted for a maximum of 8% of the burden across the four impact categories. The PV panels contributed with less than 8% of the total impact for all categories except for dissipated water, for which the solar PV technology represented 22% of the burden.

In the case of the diesel generator, most of the environmental burden was associated with fuel consumption over the 20-year operational lifespan of the project, representing approximately 95% of the total climate change and fossils burdens, with 42% and 70% of the minerals and metals, and dissipated water impacts, respectively.

These distributions between components for both technologies composed the breakdown between stages (installation and operation) shown in Fig. 6.

The installation stage included the manufacture, transport and installation of the elements that compose each system, while the operation stage included the operational consumables for the different technologies and the replacement of such devices at the end of their useful life. Thus, the operation of the hybrid PAT-PV system involved the replacement of batteries after a 10-year period, including its transport. For the diesel generator, this included the replacement of the generator at a similar 10-year period, the fuel consumed by the generator throughout the life of the project, and associated transport for both the generator and fuel.

Most of the burden associated to the diesel generator option, as it was previously mentioned, was related to the operation period, due to the production, transport and combustion of the diesel, required for the operation of the system thought the 20-years of life of the project. In the case of the climate change and fossils, only 1–2% of the burden was associated with its installation, while in the case of the minerals and metals, and dissipated water, the manufacturing of the generator increased the burden associated with the installation phase, reaching a 25% and 15% of the total, respectively. By contrast, the hybrid PAT-PV system presented the larger environmental impacts relating to the installation, with results ranging from 65 to 72% of the total burdens for the four impact categories examined. In this case, most of the burden was

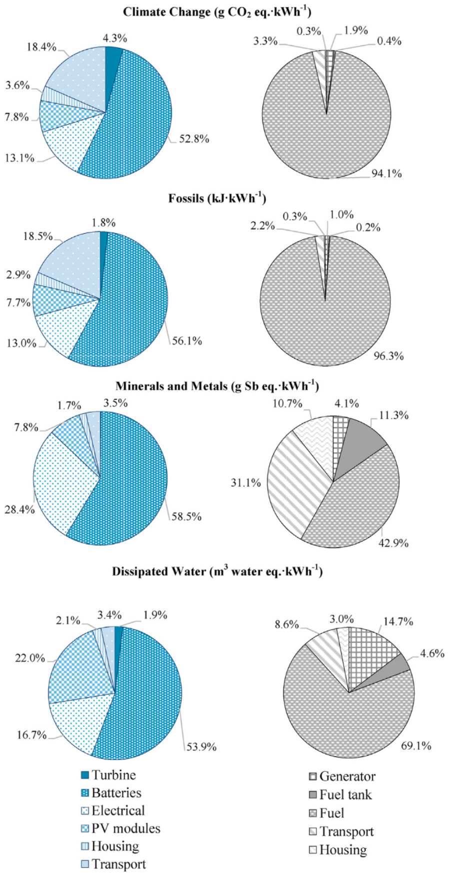

Fig. 5. Percentual contribution of the components for the four impact categories for (a) the hybrid PAT-PV system and (b) the diesel generator options.

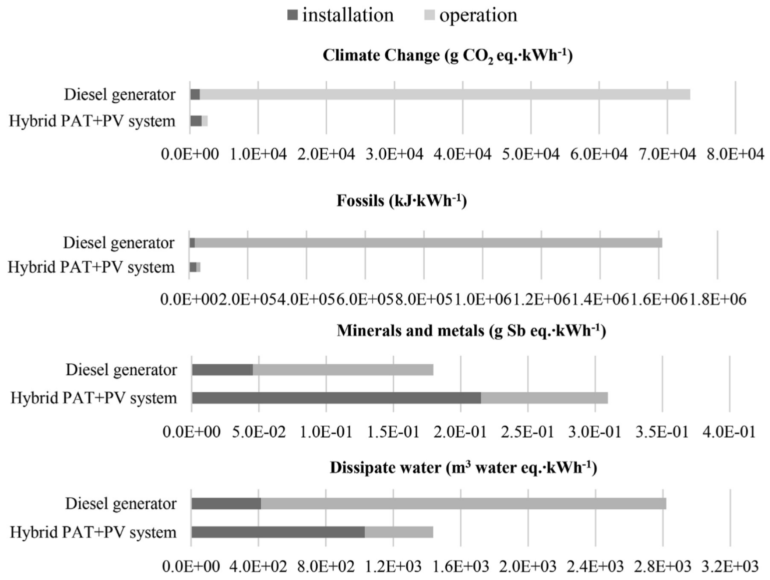

Fig. 6. Environmental burdens per kWh of energy associated with the installation and operation of the diesel generator and hybrid PAT-PV system.

associated to the installation stage, except that corresponding to the replacement of the batteries (including the manufacture and transport-installation) after the end of their useful life (approximated to 10 years), which was accounted in the operational phase.

Typically, the greatest environmental impacts for RE projects are linked to the installation stage, due to the manufacture of the equipment, with a virtually emission-free operating period. However, in these cases in which electronic and storage components (with a shorter useful life than the project) are included, their replacement increases the burden associated with the operation stage of the system.

The impacts of the installation phase of the hybrid PAT-PV system exceeded that corresponding to the diesel generator option in all impact categories analysed. This presents a case in relation to the importance of considering the useful life of a project, as it affects the life cycle environmental outcomes of this hybrid PAT-PV system in comparison with a diesel generator. As such, considering the operational lifespan of these technologies for a minimum horizon of 20 years, the hybrid PAT-PV system provides clear environmental advantages.

3.3. Scenario analysis

Once the LCA was performed, considering the impact of seasonality of irrigation, and the low energy demands on the farm, a scenario analysis considered alternative scenarios.

Firstly, a scenario in which all the maximum energy generation potential of both RE technologies (PAT and PV) was considered. This maximum potential energy generation would be achieved when the turbine operated throughout all active irrigation hours and the small auxiliary solar PV plant operated for all sunlight hours throughout the year. In this scenario, the remaining excess energy, which is equivalent to 194.6 MWh over the 20-year lifespan of the project (97.8% of the total energy potential generation), could power complementary activities at the farm, such as electric vehicles (quads, currently used in the farm) or other types of agricultural equipment, as brush-cutters and branch shakers. This would replace diesel consumption by farming equipment and reduce the environmental impact of activities in the farm by 192 tons CO_2 eq., or offset an equivalent 27 tons CO_2 eq. in grid electricity. This estimation of the reduction on the environmental impact was based on the excess of energy generated by the hybrid PAT-PV system (97.8%), and considering the nominal fuel consumption of the generator (1.2 l h^{-1}) and an average rate of 40.5 MJ l^{-1} for the diesel. These results have a significant impact on reducing the economic payback of such a hybrid PAT-PV system.

The second scenario considered the environmental performance of an equivalent solar PV plant (in terms of energy generation potential) as an alternative to the hybrid PAT-PV system. The inventory for this solar PV plant included the corresponding inverter and battery bank, so that this installation allows to maintain the irrigation during the night hours, keeping the same current irrigation pattern in the farm. In this case, the theoretical PV plant had 5.3 kW of peak power, to be equivalent, in terms of energy production, to the hybrid system, in the 20-year lifespan of the project. Table 4 summarizes the comparative results for both systems in terms of environmental burdens per kWh of energy.

In the case of the solar PV plant, all environmental burdens exceeded that of the hybrid PAT-PV system, especially in the case of the dissipated water category, for which the burden was more than

Table 4
Environmental burdens per kWh of energy for the hybrid PAT-PV system and equivalent solar PV plant, over the 20-year project lifespan considering the maximum potential energy generation of the system.

System	Climate Change ($g\ CO_2\ eq.\cdot kWh^{-1}$)	Resources		
		Fossils ($kJ\cdot kWh^{-1}$)	Minerals and metals ($g\ Sb\ eq.\cdot kWh^{-1}$)	Dissipated water (m^3 water eq.$\cdot kWh^{-1}$)
Hybrid PAT-PV system	57.6	860.4	$6.9\cdot 10^{-3}$	32.1
Solar PV plant	92.0	1402.8	$1.1\cdot 10^{-2}$	86.6

double. For climate change, fossils and minerals and metals impact categories, the burden associated to the hybrid PAT-PV system approximated to two thirds of that of the equivalent PV plant.

Based on the scenario analysis results, the importance of consuming all the potential energy generated and the capacity for energy storage from these renewable systems is evident as it impacts upon the system performance and associated economic and environmental payback. In particular, in the case of environmental impact, the burdens would be reduced by up to 45 times. It also highlights the value in comparing the environmental impacts of different RE systems to determine the suitability of individual or hybrid systems in different settings.

Even considering the total energy generation potential of the hybrid PAT-PV system, the results were higher than those shown by previous studies. In the case of climate change and MHP technology, as an example, previous studies showed results in the range of 2.14–15 g CO_2 eq.$\cdot kWh^{-1}$ (Rule et al., 2009; Gallagher et al., 2015). These figures are provided in the supplementary information (S.I.) supporting this paper (Table S3). Nevertheless, considering a PAT installed on an irrigation network, the operation time is restricted to the irrigation time, so its energy production remains seasonal. Therefore, the particularities of these kind of systems, continue to make the comparison of them with previous environmental assessments focused on RE technologies difficult. These usually consider a 24/7 operation regime (approximately 60% higher than the operation time of the analysed PAT, in annual terms).

3.4. Life cycle cost and payback period

The economic analysis was conducted by accounting for investment and operating costs for the diesel generator and the hybrid PAT-PV system (Table 5). A breakdown of the cost of the main components is presented in Table S4 in the supplementary information (S.I.) supporting this paper.

The initial investment for the hybrid PAT-PV system amounted to a total of € 24049, corresponding to the acquisition of all the equipment, with the only operating cost of replacing the batteries (€ 1699). The diesel generator showed a lower initial investment of € 5918, corresponding to the purchase of the generator (€ 4062.5) and the fuel tank (€ 1855). However, this option had an important operating cost, which amounted to a total of € 57425, corresponding to the cumulative annual diesel demand, to which the replacement of the generator was also added. The fuel cost was approximated using the average cost of diesel (€ 0.695 per litre) used for agricultural equipment, in Spain.

Based on these results, and despite the majority of energy available but not being consumed, a payback period of 8 years was estimated for the hybrid PAT-PV system. This could be further reduced if the excess energy potential could be consumed on the farm with the use of electrically powered transport and equipment.

Table 5
Total, investment and operating cost for the hybrid PAT-PV system and diesel generator.

System	Investment	Operating	Total cost
Hybrid PAT+PV system	€ 22350	€ 1699	€ 24049
Diesel generator	€ 5918	€ 57425	€ 63342

4. Conclusions and future prospects

This paper provides a comparative study of the environmental impacts of a hybrid RE system based on MHP and solar PV technologies, to replace the use of a diesel generator, under the particularities of a seasonal energy supply on an off-grid farm in Southern Spain. The total environmental burdens for the hybrid PAT-PV system were considerably lower than the diesel generator for most impact categories (climate change, fossils and dissipated water) analysed, with the exception of minerals and metals. The greatest burden attributed to the hybrid PAT-PV system was associated with its installation, with the replacement of batteries representing the only operational impact for this system. Despite the lower installation burdens for the diesel generator itself, the high fuel demands to operate the generator represented significant environmental impacts. The batteries and other electronic components in the hybrid PAT-PV system contributed between 66% and 87% of the total environmental impacts, as the installation of the PAT only accounted for a maximum of 8% of the total environmental burdens. The PV panels contributed with less than 8% of the total burden for all categories except for dissipated water, with 22% of the total burden associated to the hybrid system. Undoubtedly, the results obtained for both energy supply options, the hybrid PAT-PV system and diesel generator, were considerably higher than previous studies, due to the seasonality of irrigation and, therefore, low annual energy demands on the farm. As only 2.2% of the total energy production potential of the hybrid PAT-PV system was consumed, there is a huge capacity for the farm to exploit this energy and electrify other energy demands (transport and equipment). A scenario analysis determined that this would result in a 45-time reduction of the environmental burdens of the hybrid PAT-PV system per kWh of energy used, which presents a huge potential to further reduce pollutant emissions at farm level, if the excess energy generated can be used by complementary activities. Although these results have been obtained for a specific case study, the partial consumption of the energy generated is a common phenomenon in seasonal activities across the world, such as irrigation. Therefore, the conclusions obtained from this study can be extrapolated to other similar cases. The scenario analysis also identified that this hybrid system has a lower environmental impact than an equivalent solar PV plant, highlighting the importance of this kind of studies to find the most eco-friendly RE supply system solution. An economic analysis showed that despite a high initial investment cost, the hybrid PAT-PV system has a payback period of 8 years. These results show a huge potential of hybrid systems based on MHP and solar PV technologies, which together can fully replace fossil-fuels at farm scale, with positive environmental and economic outcomes to support achieving a more sustainable agriculture.

These results reveal new opportunities for the development of integrated models for the optimal sizing of hybrid RE systems. In these integrated systems account must be taken of economic and environmental aspects, and also the maximization of the use of energy to achieve a total green-energy supply at farm level. In this way, the configuration of the proportion of different energy sources as well as the storage devices will condition the final impact results. However, the search for the use of surplus renewable energy available in irrigation settings will require new management strategies at a global scale, allowing the synchronisation of energy demand and generation on the farm as a whole. In addition, a deeper knowledge about the end of life of the technologies involved would favourably complement the analysis of the results. Therefore, future work should address the development of optimal sizing models for an integral energy management at farm level, considering combined renewable energy technologies, energy storage and support systems (diesel generators and electricity grid).

Authorship contributions

The specific contributions made by each author are listed below:
Conceptualization: A.M., J.G. and A.M.G.
Methodology: A.M.G., A.M. and J.G.
Investigation: A.M.G., M.C.C., J.G. and A.M.
Resources: M.C.C., J.G. and A.M.
Data curation: A.M.G., J.G.
Writing—original draft preparation: A.M.G., J.G. and A.M.
Writing—review and editing: A.M.G., M.C.C., J.G. and A.M.
Visualization: A.M.G., M.C.C., J.G. and A.M.
Supervision: A.M., J.G.

Declaration of competing interest

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

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Appendix A. Supplementary data

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