



## Life cycle assessment of large-scale solar photovoltaic irrigation

J.A. Flores Cayuela<sup>a,\*</sup>, A. Mérida García<sup>b</sup>, I. Fernández García<sup>c</sup>, J.A. Rodríguez Díaz<sup>a</sup>

<sup>a</sup> Department of Agronomy, University of Córdoba, Campus Rabanales, Edif. Da Vinci, 14071 Córdoba, Spain

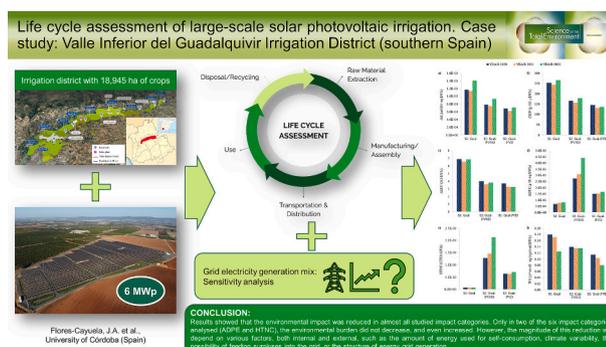
<sup>b</sup> Department of Engineering, University of Almería, Rd. Sacramento s/n, La Cañada de San Urbano, 04120 Almería, Spain

<sup>c</sup> Department of Electrical Engineering and Automatic Control, University of Córdoba, Campus Rabanales, Edif. Da Vinci, 14071 Córdoba, Spain

### HIGHLIGHTS

- Life cycle assessment was used to evaluate a large PV system in an irrigation district.
- All PV energy generated was utilized since the surplus energy was fed into the grid.
- PV system allowed savings around 50 % of primary energy and 46 % of greenhouse gases.
- Even with 50 % renewables in the grid mix, PV system is still environmentally viable.

### GRAPHICAL ABSTRACT



### ARTICLE INFO

Editor: Jacopo Bacenetti

#### Keywords:

Electricity grid  
Climate change  
Environmental burden  
Renewable energy  
On-grid photovoltaics

### ABSTRACT

In the last years, concerns about climate change have led to the search for cleaner and cheaper energy sources. For some years now, photovoltaic solar energy has been implemented in small pumping installations, with low peak installed power systems. However, irrigation districts with high pumping power are currently using this kind of energy thanks to large solar plants. Although these large solar plants do not have a significant environmental impact during their operational phase, their environmental impact becomes evident during the manufacturing of their components and construction. In this work, the life cycle assessment (LCA) of a large solar photovoltaic plant of 6 MWp of an irrigation district, located in southern Spain, has been carried out. From the analysis of the data provided, energy payback time (EPBT) between 3.51 and 3.81 years, and carbon payback time (CPBT) between 3.39 and 3.67 years were determined. The influence on the reduction of environmental impact was also analysed revealing that even with partial energy consumption from the grid, greenhouse gas emissions (GHG) and fossil fuel energy consumption have been reduced by nearly 50 %.

### 1. Introduction

To tackle global warming, major challenges need to be addressed such as the reduction in GHG emissions and promote increased use of

renewable energies solutions (Jennings, 2009). The Paris Agreement, adopted by 196 parties in 2015, aimed to limit global warming to 1.5 °C compared to the pre-industrial level, setting a net-zero emissions target by 2050 (UNFCCC, 2018). This goal aligns with two of the 17 Sustainable Development Goals (SDGs) of the United Nations: SDG 7 Affordable

\* Corresponding author.

E-mail address: [g12fcaj@uco.es](mailto:g12fcaj@uco.es) (J.A.F. Cayuela).

<https://doi.org/10.1016/j.scitotenv.2024.176813>

Received 22 May 2024; Received in revised form 14 September 2024; Accepted 6 October 2024

Available online 10 October 2024

0048-9697/© 2024 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

Nomenclature			
ADPE	Abiotic Depletion Potential: Elements	GWP	Global Warming Potential
ADPF	Abiotic Depletion Potential: Fossil Fuels	GWP <sub>GRID</sub>	Grid Electricity's Global Warming Potential
AE	Accumulated Exceedance	HTNC	Human Toxicity Non-Carcinogenic
CPBT	carbon payback time	ID	Irrigation District
EB	environmental burden	LCA	life cycle assessment
EF	environmental footprint	LCC	life cycle cost
E <sub>GRID</sub>	grid electricity consumed	LI	lifetime impact
E <sub>PV-C</sub>	photovoltaic energy consumed	PE	primary energy
E <sub>PV-G</sub>	photovoltaic energy generated	PV	photovoltaic
E <sub>T</sub>	total electricity consumed	PVS	photovoltaic system
EPBT	energy payback time	RE	renewable Energy
EROI	energy return of investment	SDG	Sustainable Development Goal
GHG	greenhouse gases	S.I.	supplementary information
		VIGID	Valle Inferior del Guadalquivir Irrigation District
		WU	water use

and Clean Energy, and SDG 13 Climate Action (United Nations, 2015). Agriculture is estimated to account for about 12 % of global GHG emissions, a figure that increases up to 18.4 % with land use and forestry (Ritchie et al., 2020). When considering the whole food system, including refrigeration, food processing, packaging, and transportation, it accounts for about 26 % of global GHG emissions (Poore and Nemecek, 2018). One of the GHG emissions sources in agriculture comes from irrigation, due to the intensive use of fossil fuels and electricity for energy supply, particularly important in pumping systems of large pressurized irrigation networks (García-Valverde et al., 2009). Thus, the incorporation of renewable energies in irrigated agriculture could contribute to reduce GHG emissions.

In addition, energy costs have increased considerably in the last years. As an example, in Spain, from 1998 to 2023, annual grid energy price has increased by 350 %, from 25.05 €/MWh to 87.43 €/MWh. In that period, there are some years with even higher energy prices, such as 2022, with an annual average price of 209.69 €/MWh on the wholesale market (OMI-POLO ESPAÑOL S.A., n.d.). This fact represents a limitation for farmers since their production costs have significantly increased. In contrast, photovoltaic (PV) energy has become considerably cheaper in recent years, mainly due to the continuing decline in the price of PV panels. Between December 2009 and December 2022, crystalline silicon module prices declined by 88–94 % (International Renewable Energy Agency, 2024). This has made solar PV one of the cheapest and most accessible renewable energy sources for farmers.

PVs is a low-carbon energy source, in which the annual production pattern matches the water demand of the main crops (Reca-Cardena and López-Luque, 2018). The integration of PV technology to the agri-food sector has been the subject of numerous studies over the years (Hamidinasab et al., 2023), with the aim of reducing the economic and environmental impacts of energy consumption. Despite the variable nature of PV energy production, due to the dependence on climatic variables (López-Luque et al., 2015), several models have shown the environmental and economic effectiveness of this technology for a total or partial energy supply in irrigation (Mérida García et al., 2018). Although PV energy is free of CO<sub>2</sub> emissions during its operational phase, there is an environmental burden mainly associated with the production, transport, and installation of the components that make up a PV system (PVS) (PV panels, inverters, metal structures, cables, etc.) (Desideri et al., 2012). Life Cycle Assessment (LCA) has traditionally evaluated the environmental advantages of PVSs in different applications (Fthenakis et al., 2008; Peng et al., 2013; Sumper et al., 2011), some dating back to the 1990s and 2000s (Alsema, 2000; Palz and Zibetta, 1991). Reductions between 54 % and 77 % of the environmental impact have been found in small (Mérida García et al., 2019) and medium-sized off-grid PVSs for irrigation (Todde et al., 2018; Wettstein et al., 2017), when compared to the use of diesel generators or the grid

electricity. However, the seasonality of irrigation results in higher environmental burdens per kWh of energy used when the PVS is evaluated as off-grid, since the generated energy is not entirely consumed (Merida García et al., 2021).

Solar energy has been used for years to irrigate small farms, but it is only recently that it has been introduced into large-scale irrigation systems due to their complexity. Large irrigation districts (ID) typically provide water on demand, ensuring it is continuously available to farmers both day and night. Thus, all farmers have available a continuous supply of water (24 h per day) with adequate pressure and flow-rate. Also, the power required is much higher since the water is supplied to large areas and it is supplied with big high-power pumps usually connected in parallel. The problem of providing continuous service (24 h) when solar energy is only available during the day adds a major technical problem, which requires the hybridization of the system with several energy sources to ensure quality of the service.

In 2019, the Valle Inferior del Guadalquivir Irrigation District (VIGID) (southern Spain) became one of the first districts to combine solar power with grid electricity to manage energy costs. Since then, other IDs have followed suit, incorporating large PVSs into their irrigation operations (van de Loo et al., 2024). Hybridisation of PV energy with other energy sources enables the widespread use of solar technology in more water demanding crops and large irrigation installations, in which irrigation time generally extends beyond sunshine hours. However, the hybridisation type (with other renewables or traditional energy sources) will condition the environmental burden associated to the resulting energy. Todde et al. (2019) studied the environmental impact of two hybrid PVSs for existent irrigation installations, in which solar energy was complemented with non-renewable energy sources: grid electricity, and a diesel generator. Both systems, with similar peak capacities, led to a reduction in energy use by 41 % to 67 %, respectively, preventing the emission of large amounts of GHG without changing irrigation scheduling and practices. In the case of PVSs hybridised with other Renewable Energy (RE) sources, Mérida García et al. (2024) developed an economic and environmental optimization model based on small hydro and PVS, with potential reductions in the total cost of up to 69 %, when compared to the use of traditional energy sources. However, the reduction of the environmental burden associated with climate change, water use, energy resources and land use impact categories, linked to renewable energy solutions, generally entailed a significant increase in mineral resources consumption, due to materials requirements.

Up to this point, most of the research of LCA in PVSs in irrigation networks have focused on small scale off grid projects at farm level, sometimes combined with other energy sources, mainly non-renewable, such as diesel generators. The new contribution in this study focuses on the analysis of the environmental benefits of large commercial PVSs.

These PVSs, supplying water to big collective pressurized irrigation networks organised on-demand, are commonly designed to feed large areas devoted to different crops in the Mediterranean region. This analysis, with real data from a large-scale PVS ground mounted and equipped with solar trackers, will enable to evaluate the environmental and economic performance of grid hybridised PVSs, under on-demand energy consumption pattern. In addition, the possibility of the injection into the grid and sale of surplus energy and the varying composition of the grid power, which directly affects the LCA results, will also be analysed.

## 2. Methodology

### 2.1. Case study: Valle Inferior del Guadalquivir Irrigation District

An actual case study was selected to quantify the environmental and economic effects of large-scale PV irrigation. The analysed case study was the solar PV plant of the VIGID, located in Seville (southern Spain) (Fig. 1). This area is characterized by high irradiance levels and temperatures, especially during the summer period (June–September). The annual average temperature in this area is 17.88 °C, with 25.06 °C and 11.27 °C as average maximum and minimum temperatures, respectively. The average annual precipitation is 507.86 mm, and the average irradiation is approximately 6500 MJ/m<sup>2</sup> (1800 kWh/m<sup>2</sup>).

VIGID is organised in 10 sectors and takes water from the Guadalquivir River through a small diversion reservoir located at the headwater. From there, one canal runs through the different irrigation sectors of the district. Water from this canal is pumped to reservoirs located in each sector, each one with a pump station to supply the irrigation water to the farms throughout pressurized irrigation networks (one network per sector). The irrigation network has about 465,474 m of pipes with diameters ranging from 110 to 1800 mm, and about 2962 irrigation hydrants. More information about the irrigation network can be found in the supplementary information (S.I.) (Tables S1 and S2). The design flow rate is 1.2 L/s/ha and the minimum pressure at hydrant 35 m. Currently, irrigation is organised on demand, so farmers can irrigate whenever and for as long as they want, without exceeding the maximum water allocation established for the irrigation season. This ID covers a total area of 18,945 ha, with both annual (wheat (7 %), potato (8 %), cotton (9 %), etc.) and woody crops (citrus (42 %), fruit trees (6 %),

etc.).

The energy demand, mainly originated from the pumping stations for irrigation, is partially supplied by a 6 MWp-PVS, which was installed in 2019, and comprises a total of 17,880 PV monocrystalline panels (335Wp/panel). The panels, model CS6U-335 M, with 22.4 kg of weigh, and an efficiency of 17.23 %, are mounted on metal structures on the ground, with single-axis trackers (north-south orientation). Each tracker, with an individual small PV panel for self-power, mounts 60 panels, with a total number of trackers of 298. Energy is transformed into AC current by 2 × 3000 kVA inverters, with an approximate weight of 8000 kg (5640 × 2,340 × 2,235 mm). This PVS covers a total area of 14.37 ha, surrounded by a metallic fence. The maximum power demand amounts to 12.76 MW (including hydraulic pumps and other loads such as computers, lights, heating, air conditioners, etc.), more than twice the peak power of the PVS.

The PVS is grid-connected, which allows any surplus energy generated not consumed, to be discharged into the grid. Simultaneously, VIGID can draw energy from the grid when the generated energy by the PVS is not enough to meet the demand. It should be noted that the last three irrigation seasons have been heavily affected by a severe drought situation, leading to significant reductions in water allocations for irrigation. Consequently, energy consumption during these periods has been lower compared to standard years without water allocation restrictions.

### 2.2. Goal and scope definition

This study evaluates the environmental and economic impacts of a large PVS which supplies energy to an ID in southern Spain, through the Life Cycle Assessment (LCA) methodology (Heath et al., 2016). This methodology was applied to: (i) determine the environmental impact of large-scale PVS applied to the irrigation sector; (ii) estimate the reduction of the ID environmental impact by reducing/suppressing the energy consumption from the grid electricity; (iii) evaluate the differences in the environmental impact in both cases: with and without discharging the surplus PV energy generated to the grid.

The application of the LCA methodology involved the evaluation of the different components, materials and processes implied in the manufacturing, installation, and operation phases for the exploitation of this technology. Impacts associated with plant maintenance were not



Fig. 1. Location and distribution of the Valle Inferior del Guadalquivir Irrigation District (Comunidad de Regantes del Valle Inferior del Guadalquivir, n.d.).

considered in this study, as they were estimated negligible. Due to the different useful life of the PVS components, a system lifetime of 25 years was considered. The average lifetime of PV panels generally ranges between 25 and 30 years (Muteri et al., 2020). The cables used in PV systems must comply with the IEC 60216-2 standard (IEC, 2005), which establishes a minimum lifetime of 30 years. The lifetime of the metal support structures for PV panels is 60 years (Mason et al., 2006). In the case of inverters and transformers, their estimated lifetime is 15 years for small-scale plants (residential use) and 30 years for large PV systems, with partial components replacement every 10 years, accounting for 10 % of their mass (Fthenakis and Raugei, 2017). The functional units of 1 kWh of energy produced or consumed, and 1 m<sup>3</sup> of water for irrigation, were considered in this study for comparative analysis of the results.

The EF 3.0 (Environmental Footprint) method, with a wide range of categories to assess the environmental impact of a material or process (European Parliament; Council of the European Union, 2021), has been used. Six different impact categories were selected as the most representative and suitable for this study (Table 1). Climate change (GWP), evaluated as equivalent GHG emissions, and the use of non-renewable resources through the impact category Abiotic Depletion Potential Fossils (ADPF), are the most widely impact categories assessed in previous studies. The Abiotic Resources Depletion Potential (metals and minerals) (ADPE) is especially interesting to be evaluated when renewable energies are considered, as its environmental burden is usually high, due to material consumption for the generator (PV panels, in this case) (Boulard et al., 2011; Gallagher et al., 2015; Katsigiannis et al., 2010). Additionally, the impact on ecosystems and people, by the inclusion of the Accumulated Exceedance (acidifying impact) (AE) and human toxicity (HTNC) were also considered. Finally, the impact category water use (WU) was included due to the relevance of this resource in irrigated agriculture.

### 2.3. Energy supply scenarios

For comparative analysis of the PVS effects on the 6 impact categories analysed in different possible configurations, 3 possible energy supply scenarios combining grid energy and PV energy have been evaluated.

- Scenario 1 (S1: Grid): 100 % energy provided by the grid.
- Scenario 2 (S2: Grid-PV<sub>ND</sub>): combined energy supply grid-PV without surplus discharge.
- Scenario 3 (S3: Grid-PV<sub>D</sub>): combined energy supply grid-PV with surplus discharge.

S1 (Grid) corresponded to the initial situation of the case study ID, where there was no PVS, and all the energy consumed was taken from

**Table 1**  
Description of the impact categories selection.

	Impact category	Description
AE	Accumulated Exceedance (mol H+ eq.)	Impact of acidifying substances on soil, water, organisms, ecosystems, and materials.
GWP	Global Warming Potential (kg CO <sub>2</sub> eq.)	Related to GHG emissions contributing to climate change.
ADPF	Abiotic Depletion Potential: fossil Fuels (MJ)	Energy resources (non-renewable) depletion used to generate electricity.
ADPE	Abiotic Depletion Potential: elements (kg Sb eq.)	Related to the extraction of material resources (minerals and fossil fuels), from global reserves.
HTNC	Human Toxicity Non-Carcinogenic (CTUh)	Effects of toxic substances on the human environment, excluding risks due to workplace exposure.
WU	Water Use (m <sup>3</sup> world eq. Deprived)	Indicator of the relative amount of water used, based on regionalized water scarcity factors.

the grid. S2 (Grid-PV<sub>ND</sub>) and S3 (Grid-PV<sub>D</sub>) considered PV energy covering part of the demand, but without/with the possibility of selling or feeding the excess of energy back into the grid, respectively. Since it is not possible to supply all the energy required only with the solar plant, a scenario with 100 % of the energy supplied by the PVS has not been considered.

Due to the differences in the total energy consumption of the VIGID in the last three years (in which the PVS was operating), originated by water consumption restrictions, the environmental impact per energy unit was estimated under the constraints of each year.

### 2.4. Inventory analysis

The data used in the inventory analysis was obtained from the execution project of the PV solar plant and other documents provided by VIGID. This inventory analysis included a breakdown of all components of the PVS (panels, cables, trackers, plastics, inverters, etc.), civil works required for the construction, transportation of different elements, and fencing. Transportation of the components of the solar plant was assumed to be carried out by road, from the manufacturing sites of the different elements to the ID location using EURO 5 trucks (Todde et al., 2019).

The total environmental burden associated with each studied impact category has been calculated as the sum of all processes and materials involved, multiplied by the corresponding unit environmental burden attributed to each impact category, as expressed in Eq. (1) (Mérica García et al., 2019):

$$EB_{s,i} = \sum_{x=1}^X K_{x,i} \cdot U_x \tag{1}$$

where EB is the total environmental burden associated to each supply scenario analysed and the impact category i, K is the environmental burden associated with each unit of process or material x; X is the total number of different processes and materials; and U is the total number of units for the process or material considered. All life cycle impact data related to materials and processes were sourced from the Ecoinvent v3.9.1 database, with allocation, cut-off by classification system model selected (Wernet et al., 2016). In this study, the impact assessment considered the period known as cradle to grave, in which the environmental burden is estimated from the raw material extraction to the end of the useful life of the installation.

### 2.5. Economic and environmental payback times

To carry out the LCA of the PVS of the VIGID, data related to PV energy generated, PV energy auto-consumed, PV energy discharged into grid, and grid energy consumed by de VIGID were collected and analysed for the operating years, on a daily and annual basis.

Energy payback time (EPBT), energy return on investment (EROI) and carbon payback time (CPBT) where evaluated to complement the analysis of on-grid PVS (Mohd Nordin et al., 2022; Raugei et al., 2012). These indicators provide quick and easy-to-use information for comparison with other studies on solar PV or other renewable technologies for electricity generation. These data have been used to quantify the energy balance pattern, which allows evaluating the economic and environmental benefits from the PVS.

The EPBT (Eq. (2)) expresses the time in years required for the PVS to save the same amount of primary energy consumed during its lifetime (manufacture, construction, and operation).

$$EPBT = \frac{PE_{mat} + PE_{manuf} + PE_{transp} + PE_{ins}}{PE_{saved}} \tag{2}$$

where PE<sub>mat</sub>, PE<sub>manuf</sub>, PE<sub>transp</sub>, and PE<sub>ins</sub> are the primary energy required for PVS materials production, manufacturing, transport, and

installation, expressed in total MJ during its entire lifetime.  $PE_{saved}$  is the primary energy saved annually, expressed as MJ per year. This indicator can be evaluated from a local perspective ( $EPBT_{LOCAL}$ ), when considering  $PE_{saved}$  as the PV energy consumed by the ID, or globally,  $EPBT_{GLOBAL}$ , if  $PE_{saved}$  is equal to all the energy generated by the PVS.

EROI (Eq. (3)) is a dimensionless ratio that represents the long-term viability of an energy generation system. This ratio considers the energy production of the PVS versus the energy invested in its manufacturing process (Bhandari et al., 2015). This ratio can also be calculated as the ratio between the lifetime of the installation, and the EPBT of the PVS.

$$EROI = \frac{EG_{lifetime}}{PE_{mat} + PE_{manuf} + PE_{transp} + PE_{ins}} = \frac{t}{EPBT} \quad (3)$$

where  $EG_{lifetime}$  is the energy generated by the PVS (MJ) over its lifetime  $t$  (years).

The CPBT (Eq. (4)) (Chen et al., 2016; Luo et al., 2018) represents the operation time (years) of the PVS required to save the amount of  $CO_2$  emitted during its manufacturing.

$$CPBT = \frac{GWP_{PVS}}{GWP_{grid} \cdot PE_{saved}} \quad (4)$$

where GWP is the Global Warming Potential (kg  $CO_2$  eq.) corresponding to the PVS ( $GWP_{PVS}$ ) during its entire lifetime, and to each kWh of the grid electricity ( $GWP_{grid}$ ). As with CPBT, this indicator could be considered at local scale ( $CPBT_{LOCAL}$ ) or global scale ( $CPBT_{GLOBAL}$ ).

The economic benefits were evaluated by the Life Cycle Cost (LCC) (Eq. (5)), following the methodology described by Wu et al. (2018), and applied by Mérida García et al. (2019) to evaluate a small irrigation PVS. This methodology accounted for the LCC as the sum of the equipment, consumables and maintenance costs. This study calculated the LCC for the three different supply scenarios previously described (S1 to S3):

$$LCC = LCC_{inst} + LCC_{ope} + LCC_{s-p} \quad (5)$$

where LCC represents the life cycle cost of the supply scenarios, associated to the installation (inst) and operational (ope) stages, and the life cycle cost associated with the sale and purchase (s-p) of energy in S3.

Additionally, to show the impact of installing a PVS for large scale irrigation, a GHG emissions and energy balances were included in the results section to compare both the previous and current energy supply solutions.

## 2.6. Sensitivity analysis

The generation mix of grid electricity is significantly influenced by the increasing share of RE sources in the last years in many regions, as it is the case of Spain. Fig. 2 shows this trend for Spain in the period 2007 to 2023, with a significant increase in wind and PV energies, with RE as a whole doubling their share in 2023 (50.75 %) compared to 2007 (20.44 %) (Redeia, 2023).

As the composition of the grid's electricity generation mix changes over time, a sensitivity analysis has been included to understand how these changes condition the environmental results. Three possible future scenarios projecting five years into the future were established, based on past trends, representing Fut. S1, Fut. S2, and Fut. S3, the trend over the last 17, 10 and 6 years, respectively. The analytical least squares method has been used to calculate these future scenarios. This mathematical method is applied to fit a trend line to historical power generation data, based on different time periods to project how the power generation mix might change in the future. The selection of the different time periods was based on the analysis of the trend changes observed, except the Fut. S1, which includes all the available data.

The contribution of nuclear power has been considered constant, given the role it plays in stabilizing energy supply. On the other hand, coal energy has not been included due to a strong downward trend in recent years. These simplified hypothetical future scenarios do not consider external factors as changes in energy policies. Actual results may vary depending on the complexity of the system.

## 3. Results and discussion

### 3.1. Energy balance

In Mediterranean areas, summer months (June, July, and August) usually represent the highest energy consumption for IDs, matching with the highest crops irrigation requirements. But also these months represent the highest PV energy production, as shown in S.I. (Fig. S1). However, on-demand irrigation implies energy consumption at night, which must be supplied by the grid. At the same time, a portion of the solar energy generated by the PV system is not utilized directly by the irrigation district during daytime, as shown in the S.I. (Fig. S2).

The evaluation of the operating pattern of the VIDID over the last three years showed that, in an on-demand ID, the share of PV energy and grid electricity for the annual energy supply was similar, with slight changes depending on the availability of water for irrigation (Table 2).

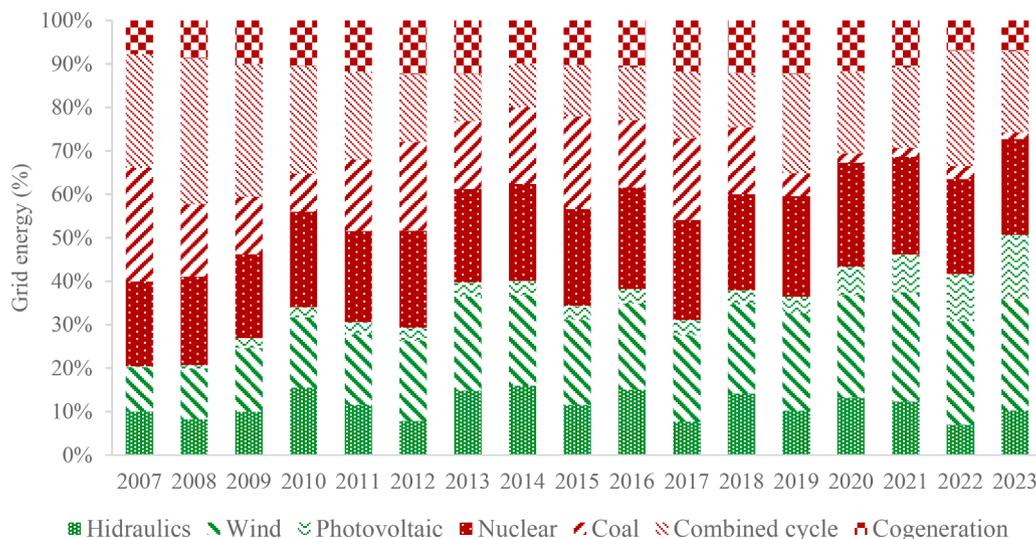


Fig. 2. Evolution of the main energy sources that make up the structure of electricity generation in the Spanish electricity grid. Source: Red Eléctrica Española - REE.

**Table 2**  
VIGID energy data.

	2020	2021	2022
Irrigation allocation (m <sup>3</sup> /ha)	3000	2500	1500
PV energy produced (MWh)	10,607	11,533	10,867
PV energy discharged (MWh) (% Produced)	5467 (51.54 %)	6656 (57.71 %)	7356 (67.69 %)
PV energy self-consumed (MWh) (% Supply)	5140 (49.67 %)	4877 (53.71 %)	3511 (56.86 %)
Grid energy consumption (MWh) (% Supply)	5209 (50.33 %)	4204 (46.29 %)	2664 (43.14 %)
Total energy consumption (MWh)	10,349	9081	6175

Lower water allocations led to an increase in the PV energy discharged into the grid, while the proportion of the energy demand supplied by the PVS also increased. This could suggest that a reduction in the water allocation resulted in a reduction in the irrigation events operated during night hours or months with lower PV production (when crop evapotranspiration is also lower), which meant a reduction in the energy consumed from the grid.

### 3.2. PVS environmental burden

Table 3 summarizes the LCA results of the PVS of the VIGID for the six impact categories analysed. The GWP value obtained per unit of installed power (LI/kWp) was 15 % lower than those reported in previous studies (Todde et al., 2018, 2019), in which smaller PVSs (40 to 360 kWp) were analysed. The ADPF value obtained was also lower, between 28 and 55 %, than those calculated for smaller PVSs. However, the type of PV panel installed plays an important role when comparing different installations, since the environmental impact is closely linked to the energy requirements of the production process (Kittner et al., 2013). Additionally, the annual energy production per unit of installed power capacity in the VIGID PVS, ranging from 1767 to 1921 kWh/kWp, was higher (12–22 %) than that obtained in the studies mentioned above. Consequently, the specific PV technology (panel type and use of trackers) and the allocation of the PVS could explain the differences between these impact results (Serrano-Luján et al., 2017). Furthermore, the results corresponding to the impact per unit of self-consumed (LI/kWh<sub>s,c</sub>) and total generated energy (LI/kWh<sub>G</sub>) (Table 3) evidence how the partial consumption of the energy generated resulted in an increase of up to >100 % of the impact per unit of energy.

Fig. 3 shows the environmental burden comparison between the electricity generated by the PVS (LI/kWh<sub>G</sub>) and grid electricity (Spain in 2022). In this case, RE represented 41.67 % of the grid energy generation mix. According to the results, the environmental burden of PVS electricity was between 3 and 14 times lower than that obtained for the grid electricity for the impact categories WU, AE, GWP and ADPF. However, PVS electricity had higher environmental burdens for ADPE and HTNC impact categories, due to the large amount of material resources required for the PVS manufacturing (metals, plastics, minerals...). ADPE impact category was around three times higher for PVS

**Table 3**  
LCA results for the different impact categories expressed as lifetime impact (LI), and lifetime impact per kWp (LI/kWp), kWh generated (LI/kWh<sub>G</sub>), and kWh self-consumed (LI/kWh<sub>s,c</sub>).

	LI	LI/kWp	LI/kWh <sub>G</sub>	LI/kWh <sub>s,c</sub>
AE (mol H+ eq.)	50,323.85	8.38	1.83E-04	3.92E-04
GWP (kg CO <sub>2</sub> eq.)	9,825,449.36	1636.70	3.57E-02	7.65E-02
ADPF (MJ)	130,445,894.65	21,729.39	4.74E-01	1.02
ADPE (kg Sb eq.)	623.74	1.04E-01	2.27E-06	4.85E-06
HTNC (CTUh)	0.32	5.38E-05	1.17E-09	2.51E-09
WU (m <sup>3</sup> world eq. deprived)	12,549,871.81	2090.53	4.56E-02	9.77E-02

electricity than grid electricity, and HTNC was 17 times higher. Several studies have investigated the importance of end-of-life of PVS and how PV modules recycling could reduce the environmental impact due to the use of large amount of material resources (Ansanelli et al., 2021; Lim et al., 2022; Muteri et al., 2020).

### 3.3. Components contribution analysis

The impact burden associated to the different categories, for a useful lifetime of the project of 25 years, was summarized, by components contribution, in Figure. As expected, in large-scale PVS, solar panels represented the highest contribution (ranging from 72 to 95 %) for all impact categories, as they were the main and most abundant elements, according to previous studies results (Szilágyi and Gróf, 2020).

PV panels were followed by solar trackers, which contributed with 2 to 14 % of the impact in the different categories. This component included the metal structure to fix the panels to the ground, the tracker system and the small solar panels required to move the structure. Mason et al. (2006) concluded that inverters were the second component with the highest impact load in a fixed and field-mounted PVS. This difference could be explained by the type of support structure and the incorporation of the tracking system, which added 3.5 times more kg/MWp of materials than other fixed structures analysed.

Inverters were, in this case, the third component with highest contribution, representing between 1 and 15 % of the total impact, depending on the category. The combined contribution of the remaining components, such as cables, fencing, etc., accounted for <6.5 % of the total impact results. “Other elements” included small components such as junction boxes, conduits and fittings, or utility poles to grid connection (Fig. 4).

### 3.4. PVS economic analysis

The LCC considered the real investment cost of the PVS and an estimated cost for inverters replacement after 15 years, operation and maintenance activities, based on the detailed PVS implementation project. According to that project and data collected, an average annual consumption of 10,500 MWh and PV energy generation of 11,000 MWh were considered. 55 % of the PV energy generated was discharged to the electricity grid, being the remaining 45 % consumed by VIGID. That 45 % of PV self-consumed energy supposed the 52 % of the total energy consumed by the VIGID. The remaining 48 % of energy required not covered by the PV production was supplied by the electricity grid. These assumptions were considered for “standard” years, with no water restrictions, and were considered enough to make the comparison between the different scenarios. Finally, for the grid energy, the fixed monthly cost per unit of contracted power and the average energy prices for the last five years (IDAE, 2023; MINETUR, 2023) in Spain were considered. Surpluses sale price was estimated as 70 % of grid energy purchase price, according to data provided by VIGID.

Figure shows the costs comparison between different scenarios of energy consumption over the PVS lifespan (25 years). In S1 (Grid), energy sale-purchase represented the cost of the grid energy consumed, and operation cost is a fix cost that depends on the contracted power of electricity grid. In S2 (Grid-PV<sub>ND</sub>) and S3 (Grid-PV<sub>D</sub>), installation and operation costs were constant, as installation cost represented the investment cost of the PVS, and operation cost was the fix cost per contracted power of electricity grid plus the PVS operation and maintenance activities costs (panels cleaning, inverters renovation, etc.).

The contracted power of electricity grid was lower in S2 and S3 due to the PVS, which resulted in a lower operation cost for both scenarios compared with S1. In these scenarios, PVS covered most of the power and energy demand during the central hours of the day, when grid energy and power grid prices were more expensive. The main difference between S2 and S3 was related to energy sale-purchase. The possibility of selling the surplus of PV energy in S3 reduced the LCC by 49 %, when

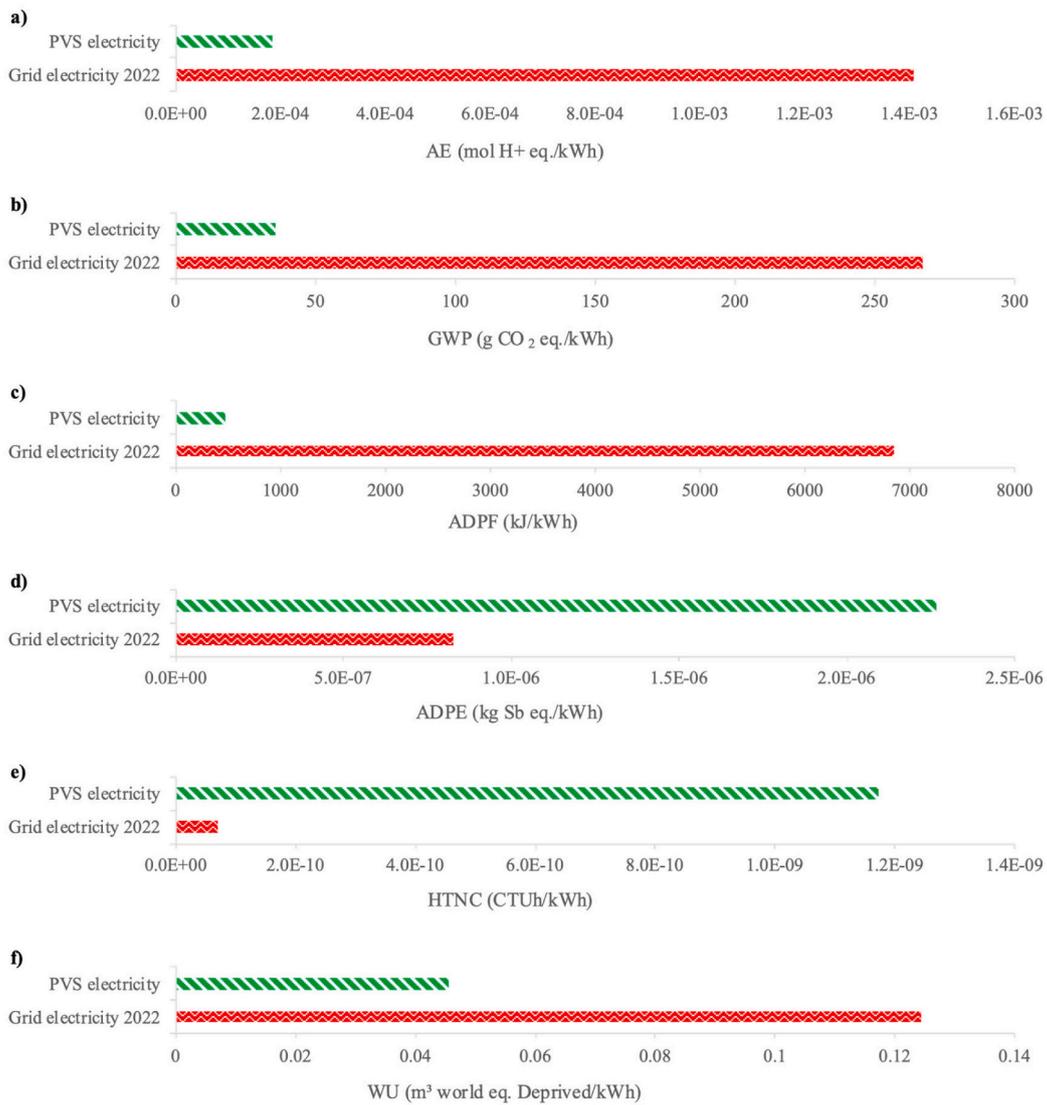


Fig. 3. Comparison between PV and grid electricity environmental burdens per unit of energy.

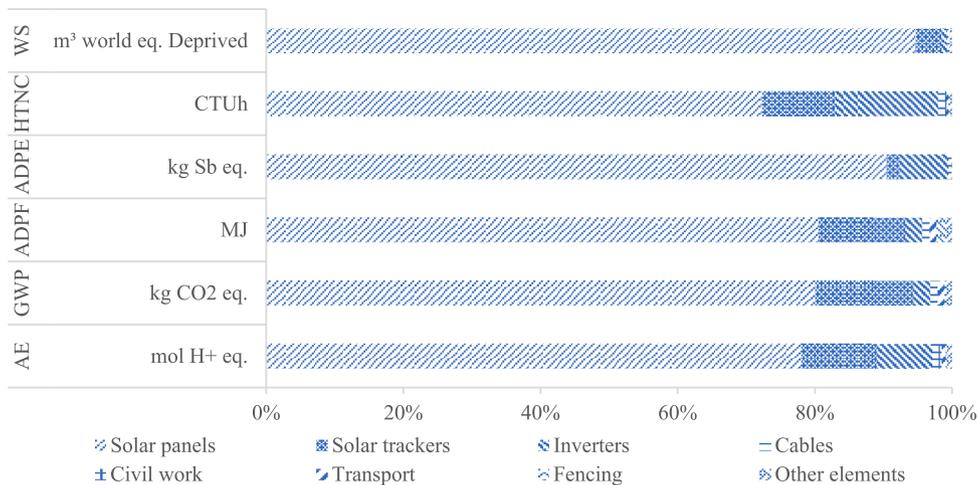


Fig. 4. Component contribution to the impact categories of the VIGID PVS.

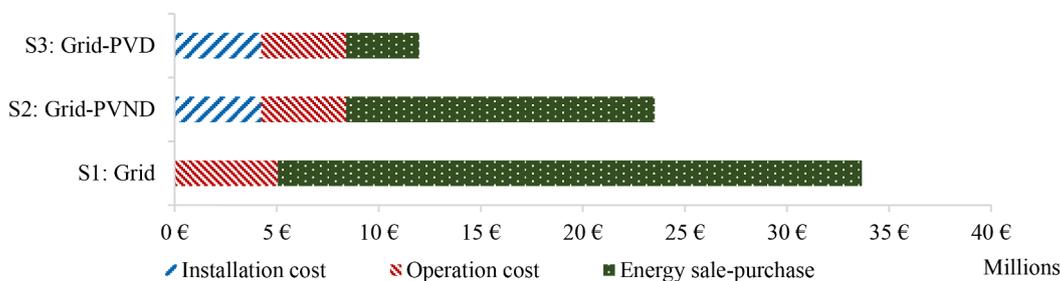


Fig. 5. LCC comparison (in million Euros) between different supply scenarios for a PVS 25 years lifespan.

compared with S2 (Fig. 5).

Despite the higher installation costs associated with large-scale PVS, results showed a lower total LCC for those scenarios with PV energy consumption, even without the possibility of feeding surplus energy into the grid (S2: Grid-PV<sub>ND</sub>). When this last is possible, the LCC can be reduced up to 64 %, compared to S1 (Grid). These results demonstrate the economic advantages of integrating RE sources, such as PVs, particularly in large-scale applications where the potential for surplus power generation and the opportunity to offset installation costs through the sale of energy is considerable.

### 3.5. EPBT, CPBT and EROI

The results of the EPBT and EROI indicators were significantly affected by the energy generation capacity of the system, which in term was conditioned by the PV module efficiency and solar radiation. For CPBT, external factors, such as the structure of the grid energy generation, conditioned the results. Table 4 shows the results of these indicators for each year of operation of the VIGID PVS, as well as the average value. EPBT was primarily influenced by the energy generated by the PV system, while CPBT was affected by the energy generated, the fraction that was consumed and the energy generation mix of grid electricity.

GWP<sub>grid</sub> was required to determine the CPBT indicator. This GWP showed small differences between years, due to the variable share of the different energy resources in the electricity mix. EPBT and CPBT results were similar to those obtained in other LCA of PVS. Todde et al. (2018), who analysed three smaller PVSs for irrigation (360 kW<sub>p</sub>, 160 kW<sub>p</sub> and 40 kW<sub>p</sub>) in southern Europe (two in Spain and one in Italy), obtained EPBT values ranging from 1.94 to 5.25 years and CPBT values ranging from 4.62 to 9.38 years. They found that these indicators were related to

Table 4  
Energy and carbon indicators results obtained for the three years of operation of the PVS of the VIGID.

	2020	2021	2022	Average
EPV-G (MWh) <sup>a</sup>	10,607	11,533	10,867	11,002
EPV-C (MWh) <sup>b</sup>	5140	4877	3511	4509
E <sub>GRID</sub> (MWh) <sup>c</sup>	5209	4204	2664	4026
E <sub>T</sub> (MWh) <sup>d</sup>	10,349	9081	6175	8535
GWP <sub>grid</sub> (kg CO <sub>2</sub> eq./kWh)	0.2526	0.2438	0.2668	0.2544
EPBT <sub>LOCAL</sub> (years)	7.87	8.29	11.52	8.97
EPBT <sub>GLOBAL</sub> (years)	3.81	3.51	3.72	3.68
EROI	6.56	7.13	6.72	6.80
CPBT <sub>LOCAL</sub> (years)	7.57	8.26	10.49	8.56
CPBT <sub>GLOBAL</sub> (years)	3.67	3.49	3.39	3.51

<sup>a</sup> Photovoltaic energy generated.  
<sup>b</sup> Photovoltaic energy consumed.  
<sup>c</sup> Grid electricity consumed.  
<sup>d</sup> Total electricity consumed.

the size of the PVS, as larger systems had lower EPBT and CPBT values. However, the size of the PV system is not the only factor influencing the CPBT and EPBT values, as other studies (Mohd Nordin et al., 2022) obtained similar results to those reported by Todde et al. (2018) even for PVSs larger than the one of VIGID. This suggests that while the size of the system may influence the results, it is the power generation capacity of the system and the structure of a country's electricity generation mix that ultimately determine, by comparison, the environmental performance of a PVS.

According to Hall et al. (2009), the EROI value should maintain a ratio between the generated energy during PVS lifetime and the consumed energy for manufacturing of at least 3:1 to be considered as a viable energy source for society. This ratio would equal an EROI value of 7.5, based on the energy production of the case study, slightly higher than the values obtained in this study. This difference, could be associated, as mentioned above, to the repercussion of so many factors (type of PV panel, structures, inclusion or not of solar trackers, etc.) with significant impact on the results.

As shown in Table 4, two analyses (Local and Global) were carried out for the calculation of EPBT and CPBT. The first one considered only the self-consumed PV energy, i.e., the energy no longer consumed from the grid. In this case, there was a wide variation in EPBT, ranging from 7.87 to 11.52 years, and CPBT, ranging from 7.57 to 10.49 years, due to the differences in the amount of energy consumed by the ID. The lower the PV energy consumed, the longer period for the energy and carbon emissions of manufacturing compensation results. However, when the analysis was conducted globally, considering all the energy generated by the PVS (both self-consumed and discharged to the grid), both EPBT and CPBT were reduced to approximately 3.5–3.6 years, with no significant variations between the studied years. This would mean that a large portion of the energy generated by the PVS (corresponding to an 88 % of its useful life), would be free of these impacts, which highlights the benefits of large grid-connected PV installations.

The GWP of the VIGID PVS was 35.59 g CO<sub>2</sub> eq./kWh generated, 7 times lower than the GWP associated to the Spanish electricity grid (254.41 g CO<sub>2</sub> eq./kWh). The results are in line with previous estimations, as values between 20.9 and 30.2 g CO<sub>2</sub> eq./kWh were estimated for various rooftop-integrated polycrystalline PV systems in Singapore (Luo et al., 2018) or values ranging between 19 and 29 g CO<sub>2</sub> eq./kWh for a small PV plant of thin-modules in Spain (Mérida García et al., 2019).

### 3.6. Energy and GHG emissions balance

An energy and GHG emissions balance was included to easily compare the environmental impact of the ID in its current (S3: Grid-PV<sub>D</sub>) and previous (S1: Grid) situation. The recorded and available data for the three years (2020 to 2022) and the corresponding electricity generation mix of the Spanish grid were considered for this balance. GWP and ADPF were selected as the most representative impact categories, widely used to analyse the environmental performance of RE production systems (Beylot et al., 2014; Kommalapati et al., 2017; Todde et al., 2019). Moreover, these impact categories are ones of the most important

**Table 5**  
ADPF and GWP with and without the PVS and net CO<sub>2</sub> balance of the system.

		2020	2021	2022
S1: Grid	Grid energy consumption (MWh)	10,349	9081	6175
	PV energy consumption (MWh)	0	0	0
	GWP (t CO <sub>2</sub> eq.)	2614	2214	1648
	ADPF (MJ)	71,371,320	59,571,212	42,236,393
S3: Grid-PV <sub>D</sub>	Grid energy consumption (MWh)	5209	4204	2664
	PV energy consumption (MWh)	5140	4877	3511
	GWP (t CO <sub>2</sub> eq.)	1506	1191	838
	ADPF (MJ)	38,452,686	29,784,511	19,907,035
ADPF saved (MJ)	32,918,634	29,786,701	22,329,357	
ADPF saved (%)	46.12	50.00	52.87	
GWP avoided (t CO <sub>2</sub> eq.)	1108	1023	810	
GWP avoided (%)	42.38	46.20	49.15	
Net CO <sub>2</sub> balance of the system		328	-205	-859

in EF 3.0, with weighting factors of 21.06 and 8.32 %, respectively (Sala et al., 2018). Table 5 shows the GWP and ADPF impacts associated to the annual energy consumption, as well as the reduction achieved using PV solar energy. In the three years of the VIGID PVS study, the APDF of grid energy ranged between 6.56 and 6.90 MJ/kWh, while GWP ranged between 0.2438 and 0.2668 kg CO<sub>2</sub> eq./kWh (Redeia, 2023). GWP and ADPF values in S3 (Grid-PV<sub>D</sub>) were calculated as the annual impact of the PVS plus the impact of grid consumption in each year.

With self-consumption rates of between 50 and 57 %, a large-scale PVS can significantly reduce the environmental impact in the main categories analysed and can even halve it. However, when the net balance of CO<sub>2</sub> emissions was calculated, considering the energy fed into the grid, the positive impact of the PVS (with lower CO<sub>2</sub> emissions than grid electricity) became even more significant. In situations where energy consumption is lower and a large amount of energy is feed back to the grid, the CO<sub>2</sub> balance can turn negative. A negative CO<sub>2</sub> balance indicates that emissions are offset by contributing a substantial amount of RE to the grid, which can help replace energy that would otherwise come from non-renewable sources, typically associated with higher emissions per unit of energy compared to PVS.

Furthermore, to assess the impact of large-scale PVSs, the different impact categories were calculated per kWh of energy consumed for the three years of operation, under the three different energy supply scenarios. From the analysis of these scenarios (Fig. 6), it was concluded that the use of PV energy results in a significant reduction in most of the calculated impact categories. Only for the impact categories of ADPE and HTNC, PV energy did not lead to an impact decrease, as previously mentioned. This was because PV cells and metals, which are the main components of any solar PVS, have a high environmental burden associated with these impact categories.

As PV energy increases its proportion in the total energy consumed, to that supplied by the grid, the unit impact for AE, GWP, ADPF and WS categories decreases (Figure). S3 (Grid-PV<sub>D</sub>) showed lower environmental impact compared to S2 (Grid-PV<sub>ND</sub>) due to the use of 100 % of the generated energy (consumed and sold). Considering ADPE and HTNC impact categories, the result was the opposite. More PV energy use meant higher environmental burdens. In each scenario the environmental load value for each year was different since the proportion of energy consumed by the VIGID (from PVS and from the grid) and generated by the PVS varied annually.

Focusing on the impact categories considered the most important or relevant, GWP and ADPF, a combination of self-consumption, grid consumption and dumping of surpluses, led to a reduction between 43 and 50 % in GHG emissions and between 46 and 53 % in the use of fossil fuels.

### 3.7. Sensitivity analysis

In recent years, the generation mix in Spain has changed with an increasing share of RE sources. Therefore, the current environmental

burden of the electricity grid is lower compared to previous years, with GWP having decreased from 0.7652 kg CO<sub>2</sub> eq./kWh in 2007 to 0.2135 kg CO<sub>2</sub> eq./kWh in 2023, and APDF reductions from 12.18 MJ/kWh in 2007 to 6.07 MJ/kWh in 2023. This sensitivity analysis examined the value of CPBT, both locally and globally, in future scenarios in which the current trend of increasing RE versus non-RE was considered for the generation mix structure. For comparative purposes, the CPBT for years 2010 and 2015, with a percentage share of RE almost 10 % below the current level, was included. Furthermore, results for 2020 were examined in this comparative analysis as it represented the operation year with the least irrigation restrictions, in which the self-consumed energy represented 5140 MWh.

Table 6 shows the future scenarios examined. Looking at the percentage of RE, Fut. S1 and Fut. S2 appear quite similar. However, despite Fut. S2 has a lower RE percentage than Fut. S1, the GWP is also lower. This difference arises because PV and hydropower energies have a higher GWP/kWh than, for instance, wind energy. Consequently, despite the lower contribution of RE in Fut. S2 compared to Fut. S1, the overall impact decreases. Naturally, this reduced impact implies a longer CPBT, both local and global. In Fut. S3, the share of RE surpasses that of the other scenarios, with a notably significant increase in PV energy to the detriment of co-generation energy, which is non-RE, but also of hydropower, which is a RE source.

Results show how as the percentage of RE increases, the GWP impact of the grid decreases and, therefore, the time required to offset the carbon emissions from the installation phase of a large-scale PVS also increases. In all future scenarios analysed, with a percentage over 50 % of RE in the generation mix, CPBT<sub>LOCAL</sub> increased to 12–17 years. Considering all energy generated, CPBT<sub>GLOBAL</sub> increased in the same proportion and reached values from 6 to 8 years. Thus, increasing the CPBT of a PV generation system can significantly affect the environmental viability of the system. If the compensation time is extended too long, the environmental effectiveness of PV power compared to energy from electricity grid can be questioned. Therefore, is important to carefully consider the CPBT of PV power generation systems and take steps to minimise the carbon emissions associated with the manufacture, installation and operation of these systems.

## 4. Conclusions

The integration of solar photovoltaic (PV) energy into irrigation systems has shown significant potential to reduce both environmental and economic impacts in the agriculture sector. Through life cycle assessment (LCA) and life cycle cost (LCC), these impacts have been analysed across a wide spectrum of indicators. While many irrigation systems continue to rely wholly or partially on grid power, the incorporation of solar PV has generally resulted in substantial reductions in the environmental burdens in various regions and system configurations. However, this trend is not observed for all impact categories, as it is the case of resources depletion and human toxicity, due to the

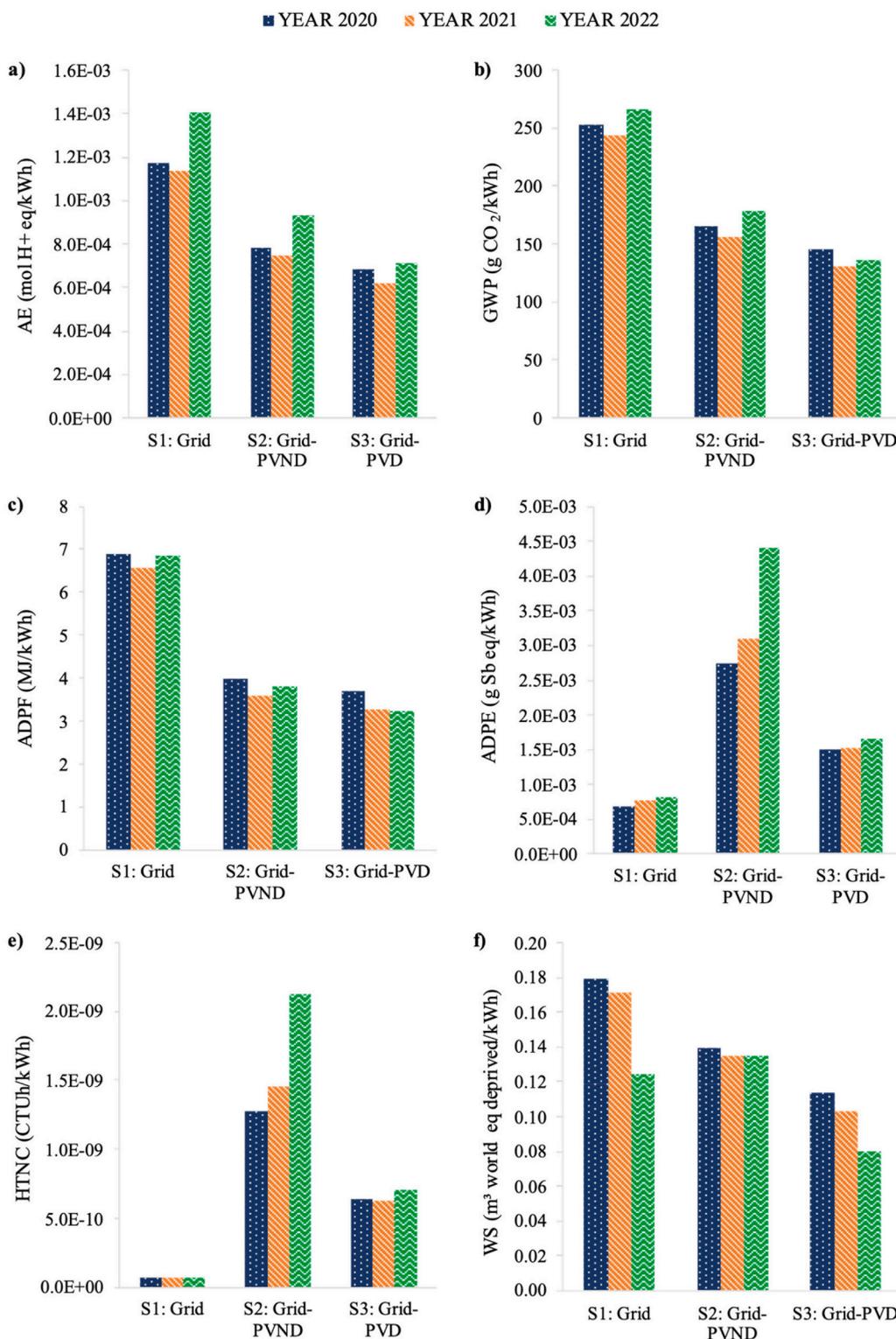


Fig. 6. Environmental impact associated to (a) AE, (b) GWP, (c) ADPF, (d) ADPE, (e) HTNC and (f) WS burden categories per kWh consumed for each energy supply scenario and for every operation year.

extensive use of materials such as metals and minerals for PV systems manufacturing. This highlights a global challenge related to the deployment of renewable energies, which could be mitigated by improving recycling efforts and promoting the reuse of materials at the end of a system's life cycle.

The influence of climate variability is a common factor in irrigation operations worldwide. Variations in water availability, influenced by

drought or other climatic conditions, affect both energy consumption patterns and the economic payback period of large-scale PV irrigation systems. Despite these fluctuations, the environmental benefits in terms of reduced carbon emissions tend to remain constant, especially when surplus PV energy can be fed into the grid. Grid-connected solar PV systems tend to shorten both environmental and economic payback periods and can even contribute to a negative carbon balance by

**Table 6**

Results of the sensitivity analysis of CPBT with different power generation mix from the grid.

Year	2010	2015	2020	Fut. S1	Fut. S2	Fut. S3
Hydropower	15.51 %	11.53 %	13.17 %	10.18 %	7.10 %	5.37 %
Wind energy	16.15 %	19.54 %	23.60 %	28.47 %	29.88 %	31.81 %
PV Solar Energy	2.38 %	3.35 %	6.58 %	19.16 %	18.37 %	26.79 %
Nuclear energy	21.97 %	22.20 %	23.96 %	22.13 %	23.37 %	23.11 %
Coal energy	8.79 %	21.37 %	2.16 %	0.00 %	0.00 %	0.00 %
Combined cycle power	24.77 %	11.79 %	18.92 %	10.84 %	11.52 %	11.22 %
Co-generation energy	10.42 %	10.23 %	11.62 %	9.22 %	9.76 %	1.70 %
Total energy	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %	100.00 %
RE grid (%)	34.04 %	34.41 %	43.34 %	57.81 %	55.35 %	63.97 %
Non-RE grid (%)	65.96 %	65.59 %	56.66 %	42.19 %	44.65 %	36.03 %
GWP <sub>GRID</sub> (kg CO <sub>2</sub> eq./ kWh)	0.4208	0.6151	0.2526	0.1564	0.1511	0.1120
CPBT <sub>LOCAL</sub> (years)	4.54	3.11	7.57	12.22	12.65	17.06
CPBT <sub>GLOBAL</sub> (years)	2.20	1.51	3.67	5.92	6.13	8.27

supplying low-carbon energy to the grid, offsetting emissions from the overall energy system.

One of the main economic advantages of large-scale PV irrigation systems is the possibility to sell surplus energy to the grid, a strategy already established in several countries that significantly reduces the life-cycle costs. However, to achieve full energy independence, the integration of additional renewable sources or energy storage solutions would be necessary to ensure a continuous electricity supply to match the irrigation requirements. This presents an opportunity for future studies to further analyse the life-cycle costs and benefits of these hybrid solutions in different regional contexts.

The specific composition of national energy grids - in particular the share of renewables - affects both the environmental and economic performance of solar PV systems. Even in countries with an increasing share of renewables in their grids, solar PV installations have favourable carbon payback times, leading to positive environmental benefits over the lifetime of the system. However, when surplus energy cannot be sold to the grid, payback periods may increase, depending on local energy consumption patterns and regulatory frameworks.

In summary, the use of solar PV energy in irrigation systems worldwide offers considerable environmental and economic benefits compared to conventional energy sources, especially for large-scale operations. The extent of these benefits, however, depends on factors such as the proportion of self-consumed energy, local climatic conditions, the level of integration with national energy grids and the structure of national energy policies. Future research should focus on the effects of maintenance, recycling and material reuse, as these factors could further improve the sustainability of solar PV systems in irrigation.

#### CRedit authorship contribution statement

**J.A. Flores Cayuela:** Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **A. Mérida García:** Conceptualization, Formal analysis, Methodology, Resources, Supervision, Writing – review & editing. **I. Fernández García:** Conceptualization, Formal analysis,

Methodology, Supervision, Writing – review & editing. **J.A. Rodríguez Díaz:** Conceptualization, Funding acquisition, Project administration, Methodology, Supervision, Writing – review & editing.

#### 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.

#### Acknowledgements

This research has been supported by the Spanish Ministry of Science and Innovation, through the HOPE Project (PID2020-115998RB-C21). The authors express their gratitude to Dr. John Gallagher, from Trinity College Dublin (Ireland), for his support.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2024.176813>.

#### Data availability

The data that has been used is confidential.

#### References

- Alsema, E.A., 2000. Energy pay-back time and CO<sub>2</sub> emissions of PV systems. *Prog. Photovolt. Res. Appl.* 8, 17–25. [https://doi.org/10.1002/\(SICI\)1099-159X\(200001/02\)8:1<17::AID-PIP295>3.0.CO;2-C](https://doi.org/10.1002/(SICI)1099-159X(200001/02)8:1<17::AID-PIP295>3.0.CO;2-C).
- Ansanelli, G., Fiorentino, G., Tammara, M., Zucaro, A., 2021. A life cycle assessment of a recovery process from end-of-life photovoltaic panels. *Appl. Energy* 290. <https://doi.org/10.1016/j.apenergy.2021.116727>.
- Beylot, A., Payet, J.O., Puech, C., Adra, N., Jacquin, P., Blanc, I., Beloin-Saint-Pierre, D., 2014. Environmental impacts of large-scale grid-connected ground-mounted PV installations. *Renew. Energy* 61, 2–6. <https://doi.org/10.1016/j.renene.2012.04.051>.
- Bhandari, K.P., Collier, J.M., Ellingson, R.J., Apul, D.S., 2015. Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: a systematic review and meta-analysis. *Renew. Sust. Energ. Rev.* <https://doi.org/10.1016/j.rser.2015.02.057>.
- Boulard, T., Raepffel, C., Brun, R., Lecompte, F., Hayer, F., Carmassi, G., Gaillard, G., 2011. Environmental impact of greenhouse tomato production in France. *Agron. Sustain. Dev.* 31, 757–777. <https://doi.org/10.1007/s13593-011-0031-3>.
- Chen, W., Hong, J., Yuan, X., Liu, J., 2016. Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: a case study in China. *J. Clean. Prod.* 112, 1025–1032. <https://doi.org/10.1016/j.jclepro.2015.08.024>.
- Comunidad de Regantes del Valle Inferior del Guadalquivir, n.d. Comunidad de Regantes del Valle Inferior del Guadalquivir [WWW Document]. URL <https://valleinferior.es/> (accessed October 19, 2022).
- Desideri, U., Proietti, S., Zepparelli, F., Sdringola, P., Bini, S., 2012. Life Cycle Assessment of a ground-mounted 1778kWp photovoltaic plant and comparison with traditional energy production systems. *Appl. Energy* 97, 930–943. <https://doi.org/10.1016/j.apenergy.2012.01.055>.
- European Parliament; Council of the European Union, 2021. Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. *Off. J. Eur. Union* 471, 1–593 (L series 64).
- Fthenakis, V., Raugei, M., 2017. Environmental life-cycle assessment of photovoltaic systems. In: *The Performance of Photovoltaic (PV) Systems: Modelling, Measurement and Assessment*. Elsevier Inc., pp. 209–232. <https://doi.org/10.1016/B978-1-78242-336-2.00007-0>.
- Fthenakis, V.M., Hyung, C.K., Alsema, E., 2008. Emissions from photovoltaic life cycles. *Environ. Sci. Technol.* 42, 2168–2174. <https://doi.org/10.1021/es071763q>.
- Gallagher, J., Styles, D., McNabola, A., Williams, A.P., 2015. Life cycle environmental balance and greenhouse gas mitigation potential of micro-hydropower energy recovery in the water industry. *J. Clean. Prod.* 99, 152–159. <https://doi.org/10.1016/j.jclepro.2015.03.011>.
- García-Valverde, R., Miguel, C., Martínez-Béjar, R., Urbina, A., 2009. Life cycle assessment study of a 4.2 kWp stand-alone photovoltaic system. *Sol. Energy* 83, 1434–1445. <https://doi.org/10.1016/j.solener.2009.03.012>.
- Hall, C.A.S., Balogh, S., Murphy, D.J.R., 2009. What is the minimum EROI that a sustainable society must have? *Energies (Basel)* 2, 25–47. <https://doi.org/10.3390/en2010025>.

- Hamidinabas, B., Javadikia, H., Hosseini-Fashami, F., Kouchaki-Penchah, H., Nabavi-Pelesaraei, A., 2023. Illuminating sustainability: a comprehensive review of the environmental life cycle and exergetic impacts of solar systems on the agri-food sector. *Sol. Energy*. <https://doi.org/10.1016/j.solener.2023.111830>.
- Heath, G., Frischknecht, R., Raugi, M., Sinha, P., de Wild-Scholten, M., Fthenakis, V., Chul Kim, H., Alsema, E., Held, M., Anctil, A., Beloin-Saint-Pierre, D., Flury, K., Fraile, D., Ito, M., Pölz, W., Vanbuggenhout, P., 2016. *Methodology Guidelines on Life Cycle Assessment of Photovoltaic Electricity 3rd Edition IEA PVPS Task 12, Subtask 2.0, LCA*.
- IDAE, 2023. Instituto para la Diversificación y Ahorro de la Energía, Informe de precios energéticos regulados [WWW Document]. URL: <https://www.idae.es/>. (Accessed 5 February 2024).
- IEC, 2005. 60216-2:2005, *Electrical Insulating Materials - Thermal Endurance Properties - Part 2: Determination of Thermal Endurance Properties of Electrical Insulating Materials - Choice of Test Criteria* (Geneva, Switzerland).
- International Renewable Energy Agency, 2024. IRENA. Statistical profiles [WWW Document]. URL: <https://www.irena.org/Data/Energy-Profiles>. (Accessed 10 September 2024).
- Jennings, P., 2009. New directions in renewable energy education. *Renew. Energy* 34, 435–439. <https://doi.org/10.1016/j.renene.2008.05.005>.
- Katsigiannis, Y.A., Georgilakis, P.S., Karapidakis, E.S., 2010. Multiobjective genetic algorithm solution to the optimum economic and environmental performance problem of small autonomous hybrid power systems with renewables. *IET Renew. Power Gener.* 4, 404–419. <https://doi.org/10.1049/iet-rpg.2009.0076>.
- Kittner, N., Gheewala, S.H., Kamens, R.M., 2013. An environmental life cycle comparison of single-crystalline and amorphous-silicon thin-film photovoltaic systems in Thailand. *Energy Sustain. Dev.* 17, 605–614. <https://doi.org/10.1016/j.esd.2013.09.003>.
- Kommalapati, R., Kadiyala, A., Shahriar, M.T., Huque, Z., 2017. Review of the life cycle greenhouse gas emissions from different photovoltaic and concentrating solar power electricity generation systems. *Energies* (Basel). <https://doi.org/10.3390/en10030350>.
- Lim, M.S.W., He, D., Tiong, J.S.M., Hanson, S., Yang, T.C.K., Tiong, T.J., Pan, G.T., Chong, S., 2022. Experimental, economic and life cycle assessments of recycling end-of-life monocrystalline silicon photovoltaic modules. *J. Clean. Prod.* 340. <https://doi.org/10.1016/j.jclepro.2022.130796>.
- López-Luque, R., Reza, J., Martínez, J., 2015. Optimal design of a standalone direct pumping photovoltaic system for deficit irrigation of olive orchards. *Appl. Energy* 149, 13–23. <https://doi.org/10.1016/j.apenergy.2015.03.107>.
- Luo, W., Khoo, Y.S., Kumar, A., Low, J.S.C., Li, Y., Tan, Y.S., Wang, Y., Aberle, A.G., Ramakrishna, S., 2018. A comparative life-cycle assessment of photovoltaic electricity generation in Singapore by multicrystalline silicon technologies. *Sol. Energy Mater. Sol. Cells* 174, 157–162. <https://doi.org/10.1016/j.solmat.2017.08.040>.
- Mason, J.E., Fthenakis, V.M., Hansen, T., Kim, H.C., 2006. Energy payback and life-cycle CO<sub>2</sub> emissions of the BOS in an optimized 3.5MW PV installation. *Prog. Photovolt. Res. Appl.* 14, 179–190. <https://doi.org/10.1002/ppp.652>.
- Mérida García, A., Fernández García, I., Camacho Poyato, E., Montesinos Barrios, P., Rodríguez Díaz, J.A., 2018. Coupling irrigation scheduling with solar energy production in a smart irrigation management system. *J. Clean. Prod.* 175, 670–682. <https://doi.org/10.1016/j.jclepro.2017.12.093>.
- Mérida García, A., Gallagher, J., McNabola, A., Camacho Poyato, E., Montesinos Barrios, P., Rodríguez Díaz, J.A., 2019. Comparing the environmental and economic impacts of on- or off-grid solar photovoltaics with traditional energy sources for rural irrigation systems. *Renew. Energy* 140, 895–904. <https://doi.org/10.1016/j.renene.2019.03.122>.
- Merida García, A., Gallagher, J., Crespo Chacón, M., McNabola, A., 2021. 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. *J. Clean. Prod.* 303. <https://doi.org/10.1016/j.jclepro.2021.127078>.
- Mérida García, A., Gallagher, J., Rodríguez Díaz, J.A., McNabola, A., 2024. An economic and environmental optimization model for sizing a hybrid renewable energy and battery storage system in off-grid farms. *Renew. Energy* 220, 119588. <https://doi.org/10.1016/j.renene.2023.119588>.
- MINETUR, 2023. Ministerio de Industria y Turismo, Precio neto de la electricidad para uso doméstico y uso industrial [WWW Document]. URL: <https://www.mintur.gob.es/es-es/Paginas/index.aspx>. (Accessed 5 February 2024).
- Mohd Nordin, A.H., Sulaiman, S.I., Shaari, S., Mustapa, R.F., 2022. Energy and environmental impacts of a 37.57 MW dc ground-mounted large-scale photovoltaic system in Malaysia: a life-cycle approach. *J. Clean. Prod.* 335. <https://doi.org/10.1016/j.jclepro.2021.130326>.
- Muteri, V., Cellura, M., Curto, D., Franzitta, V., Longo, S., Mistretta, M., Parisi, M.L., 2020. Review on life cycle assessment of solar photovoltaic panels. *Energies* (Basel). <https://doi.org/10.3390/en13010252>.
- OMI-POLO ESPAÑOL S.A., n.d. OMIE [WWW Document]. URL: <https://www.omie.es/> (accessed January 10, 2024).
- Palz, W., Zibetta, H., 1991. Energy pay-back time of photovoltaic modules. *Int. J. Solar Energy* 10, 211–216. <https://doi.org/10.1080/01425919108941464>.
- Peng, J., Lu, L., Yang, H., 2013. Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renew. Sust. Energy. Rev.* <https://doi.org/10.1016/j.rser.2012.11.035>.
- Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. *Science* (1979) 360, 987–992.
- Raugi, M., Fullana-i-Palmer, P., Fthenakis, V., 2012. The energy return on energy investment (EROI) of photovoltaics: methodology and comparisons with fossil fuel life cycles. *Energy Policy* 45, 576–582. <https://doi.org/10.1016/j.enpol.2012.03.008>.
- Reca-Cardena, J., López-Luque, R., 2018. Design principles of photovoltaic irrigation systems. In: *Advances in Renewable Energies and Power Technologies*. Elsevier, pp. 295–333. <https://doi.org/10.1016/B978-0-12-812959-3.00009-5>.
- Redeia, 2023. REE - Red Eléctrica Española [WWW Document]. URL: <https://www.ree.es/es>. (Accessed 27 October 2023).
- Ritchie, H., Roser, M., Rosado, P., 2020. CO<sub>2</sub> and greenhouse gas emissions [WWW Document]. Published online at OurWorldInData.org. URL: <https://ourworldindata.org/co2-and-greenhouse-gas-emissions>. (Accessed 23 May 2023).
- Sala, S., Cerutti, A.K., Pant, R., 2018. Development of a weighting approach for the environmental footprint. In: *Publications Office of the European Union*. <https://doi.org/10.2760/446145>.
- Serrano-Luján, L., Espinosa, N., Abad, J., Urbina, A., 2017. The greenest decision on photovoltaic system allocation. *Renew. Energy* 101, 1348–1356. <https://doi.org/10.1016/j.renene.2016.10.020>.
- Sumper, A., Robledo-García, M., Villafáfila-Robles, R., Bergas-Jané, J., Andrés-Peiró, J., 2011. Life-cycle assessment of a photovoltaic system in Catalonia (Spain). *Renew. Sust. Energy. Rev.* <https://doi.org/10.1016/j.rser.2011.07.023>.
- Szilágyi, A., Gróf, G., 2020. Estimating the environmental footprint of a grid-connected 20 MWp photovoltaic system. *Sol. Energy* 197, 491–497. <https://doi.org/10.1016/j.solener.2020.01.028>.
- Todde, G., Murgia, L., Carrelo, I., Hogan, R., Pazzona, A., Ledda, L., Narvarte, L., 2018. Embodied energy and environmental impact of large-power stand-alone photovoltaic irrigation systems. *Energies* (Basel) 11, 2110. <https://doi.org/10.3390/en11082110>.
- Todde, G., Murgia, L., Deligios, P.A., Hogan, R., Carrelo, I., Moreira, M., Pazzona, A., Ledda, L., Narvarte, L., 2019. Energy and environmental performances of hybrid photovoltaic irrigation systems in Mediterranean intensive and super-intensive olive orchards. *Sci. Total Environ.* 651, 2514–2523. <https://doi.org/10.1016/j.scitotenv.2018.10.175>.
- UNFCCC, 2018. *The Paris Agreement* (Paris).
- United Nations, 2015. Sustainable development goals [WWW Document]. URL: <https://sdgs.un.org/>. (Accessed 20 September 2023).
- van de Loo, M., Camacho Poyato, E., van Halsema, G., Rodríguez Díaz, J.A., 2024. Defining the optimization strategy for solar energy use in large water distribution networks: a case study from the Valle Inferior irrigation system, Spain. *Renew. Energy* 228. <https://doi.org/10.1016/j.renene.2024.120610>.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 21, 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>.
- Wettstein, S., Muir, K., Scharfy, D., Stucki, M., 2017. The environmental mitigation potential of photovoltaic-powered irrigation in the production of South African Maize. *Sustainability* (Switzerland) 9. <https://doi.org/10.3390/su9101772>.
- Wu, B., Maleki, A., Pourfayaz, F., Rosen, M.A., 2018. Optimal design of stand-alone reverse osmosis desalination driven by a photovoltaic and diesel generator hybrid system. *Sol. Energy* 163, 91–103. <https://doi.org/10.1016/j.solener.2018.01.016>.