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Comparison of Environmental Impact Assessment Methods in the Assembly and Operation of Photovoltaic Power Plants: A Systematic Review in the Castilla—La Mancha Region

Marichell Zarzavilla [1], Andrea Quintero [1], Manuela Andrés Abellán [2], Francisco López Serrano [2], Miguel Chen Austin [1,3,4] and Nathalia Tejedor-Flores [1,3,4,5,*]

[1] Grupo de Investigación en Energética y Confort en Edificaciones Bioclimáticas (ECEB), Faculty of Mechanical Engineering, Universidad Tecnológica de Panama, Panama City 0801, Panama; marichell.zarzavilla@utp.ac.pa (M.Z.); andrea.quintero@utp.ac.pa (A.Q.); miguel.chen@utp.ac.pa (M.C.A.)
[2] Escuela Técnica Superior de Ingenieros Agrónomos de Albacete, Universidad Castilla-La Mancha, 02071 Albacete, Spain; manuela.andres@uclm.es (M.A.A.); fco.lopez@uclm.es (F.L.S.)
[3] Centro de Estudios Multidisciplinarios en Ciencias, Ingeniería y Tecnología (CEMCIT-AIP), Panama City 0801, Panama
[4] Sistema Nacional de Investigación (SNI), Panama City 0816, Panama
[5] Centro de Investigaciones Hidráulicas e Hidrotécnicas (CIHH), Universidad Tecnológica de Panamá, Panama City 0801, Panama
* Correspondence: nathalia.tejedor@utp.ac.pa

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Abstract: Solar energy is in high demand due to its environmental benefits and economic potential; however, concerns remain about the total impact it holds. In 2020, for Spain, Castilla-La Mancha was the second autonomous community with the highest photovoltaic energy production. Thus, a systematic review on 15 large-scale PV solar energy projects was carried out to assess the industry impacts, through environmental impact assessment (EIA), within the Autonomous Community of Castilla—La Mancha. An estimation of these impacts from a pre-operational approach is presented, based on primary energy needs and emissions discarded during its life cycle due to the manufacture, operation, and recycling of the photovoltaic modules. Based on both the life cycle assessment (LCA) and EIA, the approaches were compared with the results obtained. The obtained results suggest that determining the actual impacts of power plants in this region could provide justified information for the public administration and technicians in the measures for the installation and operation of PV plants and the future benefits of renewable solar technologies. Furthermore, the results indicate the possibility to recognize the relationship between the size of the plant and a high generation capacity, with a shorter time to pay for emissions from the manufacture and recycling of panels, suggesting that it is around 1.66–2.08 years for the Castilla-La Mancha region.

Keywords: clean energy; environmental impact assessment; greenhouse gas emissions; life cycle analysis; photovoltaic power plant

1. Introduction

Due to the potential threat posed by global climate change, predominantly anthropogenic, there is increasing pressure on traditional energy sources for the rising global energy demand. This has prompted the search for renewable energy (RE) generation sources as a path to combat these concerns.

Within the efforts made during the last decades on climate change, it has been concluded that there has not been enough to avoid the imminent increase of the planet's temperature. By the end of this century, a growth of 3.20 °C is estimated, well above the targets set in the Paris Agreement (limited to 1.50 °C or 2 °C). It is possible to maintain the 2 °C margins if nations commit to reducing their emissions, which are expected to rise globally to a range of 25–41 $GtCO_2e$ by 2030 [1].

Renewable energies continue to be part of the roadmaps developed by nations due to their capacity to diversify the energy matrix and its progressive decarbonization. With their arrival, it is possible to improve the security of supply, thanks to the reduction in fossil fuel imports and dependence on this type of energy.

Currently, the energy obtained by photovoltaic (PV) systems is rapidly expanding, where the accumulated installed capacity globally is estimated at 627 GW (2019), according to the International Energy Agency (IEA). China, the world leader in PV installations, has 30.1 GW, followed by the European Union with 16 GW, Spain and Germany in the top 10, and then the United States with 13.3 GW [2].

For Spain in particular, 62,225 MW of PV systems have been reached in operation, and 3528 MW were installed in 2020 alone, counting between centralized, decentralized, and off-grid systems. In addition, Spain's energy objectives, according to the National Integrated Energy and Climate Plan 2021–2030 (PNIEC), expect to reach 39,181 MW of PV systems by 2030 [3]. Accordingly, photovoltaics has the potential to become one of the largest sources of energy globally, supported by three key elements: falling battery prices, the rapid adoption of electric vehicles, and the emergence of commercial plants for green hydrogen production [4].

Within this frame of reference, the different energy strategies currently in force in Spain can be considered, e.g., those included in the National Energy Plan (PEN-91), which, through the Energy Saving and Efficiency Plan (PAEE), has been promoting the energy sector policy in Spain since 1991. Some of the other plans in force in the country are mentioned below [5]:

- 2008–2012 Action Plan of the Energy Saving and Efficiency Strategy in Spain (PAE4+): it avoids emissions of approximately 238 million tons of CO_2 into the atmosphere through savings in the country's primary energy.
- Spanish National Action Plan for Renewable Energies (PANER) 2011–2020: Considers as its main objective a gross final energy consumption of 20% of the fraction coming from clean energies by 2020.
- Renewable Energy Plan (PER) 2011–2020: Contemplates the different perspectives considered in the expected development of costs and technologies from a sectoral analysis of the factors involved.
- Energy Action Plan "20-20-20" of the European Union: It includes the general objectives of the 27 member nations to reduce by 20% the emissions produced in 2020 in relation to the figures obtained in 1990; as well as that 20% of the energy consumption within the European Union by this year comes from renewable sources.
- Paris Climate Agreement: It is based on establishing as a final objective to be able to maintain below two degrees Celsius the increase of temperatures on the planet, restricting 195 signatory countries not to increase their temperatures to 1.5 degrees Celsius. This will be possible by setting national targets every five years to reduce greenhouse gas emissions [5].

As a brief literature review, it is mentioned in [6] that the different methods applied in the installation of photovoltaic plants in their location can reduce the environmental impact at these sites. The authors in [7] point out that as life cycle assessment is concerned, the system's environmental performance depends heavily on the energy efficiency of the system manufacturing and electricity production. It focuses on the fact that emissions related to the transport of the modules are insignificant compared to those associated with the manufacture, where transport emissions were only 0.1–1% of manufacturing-related emissions. In [8], it is concluded that no manmade project can avoid environmental impacts on solar energy technologies, highlighting that potential environmental burdens depend on the size and the nature of the project.

The study area on which this article focuses is the area of Castilla-La Mancha, the third community with the largest surface area in Spain (15.7% of the total). In 2020, Castilla-La Mancha was the second autonomous community with the highest photovoltaic energy production after Andalusia; for this reason, it is considered ideal for the development of this study. Moreover, this technology has experienced an increase of 56.50% in the community and has reached a maximum contribution to the region's mix at 13.40% of the total [9].

The central government of Castilla-La Mancha aims to achieve 78.60% of electricity production to be renewable by 2030. In this regard, since 2019, a share of over 50% renewables has been achieved [10].

As has always been projected in the literature, the demand for solar energy is high due to its environmental benefits and economic potential. However, concerns remain about the impact of solar module manufacturing, with silicon, aluminum, copper, and silver mining becoming more relevant.

Considering the effects of large-scale photovoltaic installations, studies have been found that evaluate different aspects quantitatively and qualitatively during the manufacturing, installation, and operating phases [8]. Some of them include the following methods:

(a) Indicators

These are numerical values that indicate quantitative measures of the state of a project, according to specific parameters of the environment and human health. They can be monitored over time or across a broad range of geographic scales. The indicators make it possible to evaluate the effectiveness of the implemented mitigation measures [11].

(b) Life Cycle Assessment (LCA)

LCA is considered one of the most comprehensive tools for determining environmental impacts and is recognized by ISO, thanks to its standardized procedure. Within its use to evaluate PV, this method quantifies the extraction of raw materials, manufacturing, transportation, operation, or useful life, up to the final recycling or waste management [12].

The use of LCA has been seen in numerous studies. The most impactful was conducted by the National Renewable Energy Laboratory (NREL), which undertook a literature review of the life cycle GHG emissions of different PV systems. The result was abstracted from 400 studies on PV systems, including crystalline silicon (c-Si), thin-film (TF), and copper indium gallium diselenide (CIGS) [13]. The determination of its life cycle covers the "from the cradle to the grave" concept, which involves analysis in stages: extraction of materials, silicon transformation, panel assembly, photovoltaic installation & operation, and the end of life (disposal or recycling). This information is used to calculate the total emissions intensity, i.e., the total carbon units during its useful life, evaluated in energy units: gCO_2e/kWh. The study estimated this intensity for PV energy at approximately 40 gCO_2/kWh, while for coal, it was much higher due to its operational nature, ranging at 1000 gCO_2/kWh.

(c) Geographical Information System (GIS)

GIS is considered a computer system that can manage spatial information, processing it to estimate territory availability for certain types of uses. The data structure can be represented by georeferenced information layers that allow the user to overlay and view through the map block. They are suitable tools to reflect the physical reality with a spatial component. To do so, they use layers of information that allow existing relationships to be analyzed. In this way, new layers of information can be created, which in turn can be visualized and printed in the form of a map at the most appropriate scale [14].

(d) Environmental Impact Assessment (EIA)

According to [14], an environmental assessment is "*the process by which the significant effects that plans or projects may have on the environment are analyzed prior to their adaptation, including effects on factors such as: population, health, flora, fauna, biodiversity, geodiversity, soil, air, water, landscape, climate change, as well as the cultural heritage of an area*". Its main objective is to provide a preliminary assessment in the most objective manner possible of the socioeconomic and biogeographic impacts of a series of specific planned projects [11].

In general, as noted by [8], the negatively recognized impacts, depending on the size and scope of the project, are:

- The loss of visual amenity;

- The loss of arable land and other economically valuable land uses;
- The impact on ecosystems; The accidental release of chemicals into the local environment; and occupational hazards during construction and operation.

Regarding the benefits generated by PV power plants, the most prominent ones are mentioned as:

- Reduction in greenhouse gas emissions (mainly CO_2, NO_x) and prevention of toxic gas emissions (SO_2, particulate matter).
- Recovery of degraded land;
- Reduction in necessary transmission lines of electrical grids;
- Increased regional/national energy independence;
- Provision of job opportunities;
- Diversification and security of energy supply;
- Support for deregulation of energy markets;
- Acceleration of rural electrification in developing countries.

According to these methods, this work aims to carry out a thorough review and comparison of different large-scale photovoltaic solar energy projects and their respective environmental impact assessment, i.e., the effects on soil, air, water, fauna, landscape, population, and economy, within the Autonomous Community of Castilla—La Mancha. In addition, we also seek to determine these impacts from a pre-operational approach, knowing the primary energy and emissions discarded due to the manufacture, transport, operation, and recycling of the photovoltaic modules intended to generate clean and non-polluting energy in the Spanish community.

2. Methodology

For the development of this paper, we aim to define an objective criterion for screening the projects that best represent the final effects of PV power plants and then discuss the results abstracted from this information to reduce its most predominant impacts.

An investigation of 15 photovoltaic power plants selected from different provinces within the Castilla-La Mancha region is required for this comparison. First, we will calculate the break-even point for the emissions embedded in the production, operation, and discard. This means, with the emissions from manufacturing and recycling of PV modules and their elements, and the avoided emissions from electricity production, we aim to identify when these emissions will become net. Knowing this value, the time needed for the plants to start generating emission-free energy is found. Furthermore, a similar calculation in terms of primary energy used during the PV system's life cycle was performed, in order to estimate the necessary years of operation to entirely return this energy.

Subsequently, it is expected to collect information within different environmental impact studies (EIA) from the selected areas to recognize the impacts and factors that are mostly affected by implementing of this type of project.

In Figure 1, the approach of this work is presented. It intends to cover the aspects involved in the life cycle of a solar plant (upper part of the picture) and an environmental impact assessment (lower part of the picture). Both processes coincide through a time scale, represented by an arrow, having their respective phases (bold arrows) and sections (dotted arrows). Each phase of the process in the section above takes place at the same time as the process in the section below, without interfering with each other. As a result, the different environmental studies that take place at every phase of the PV plant and its components are shown.

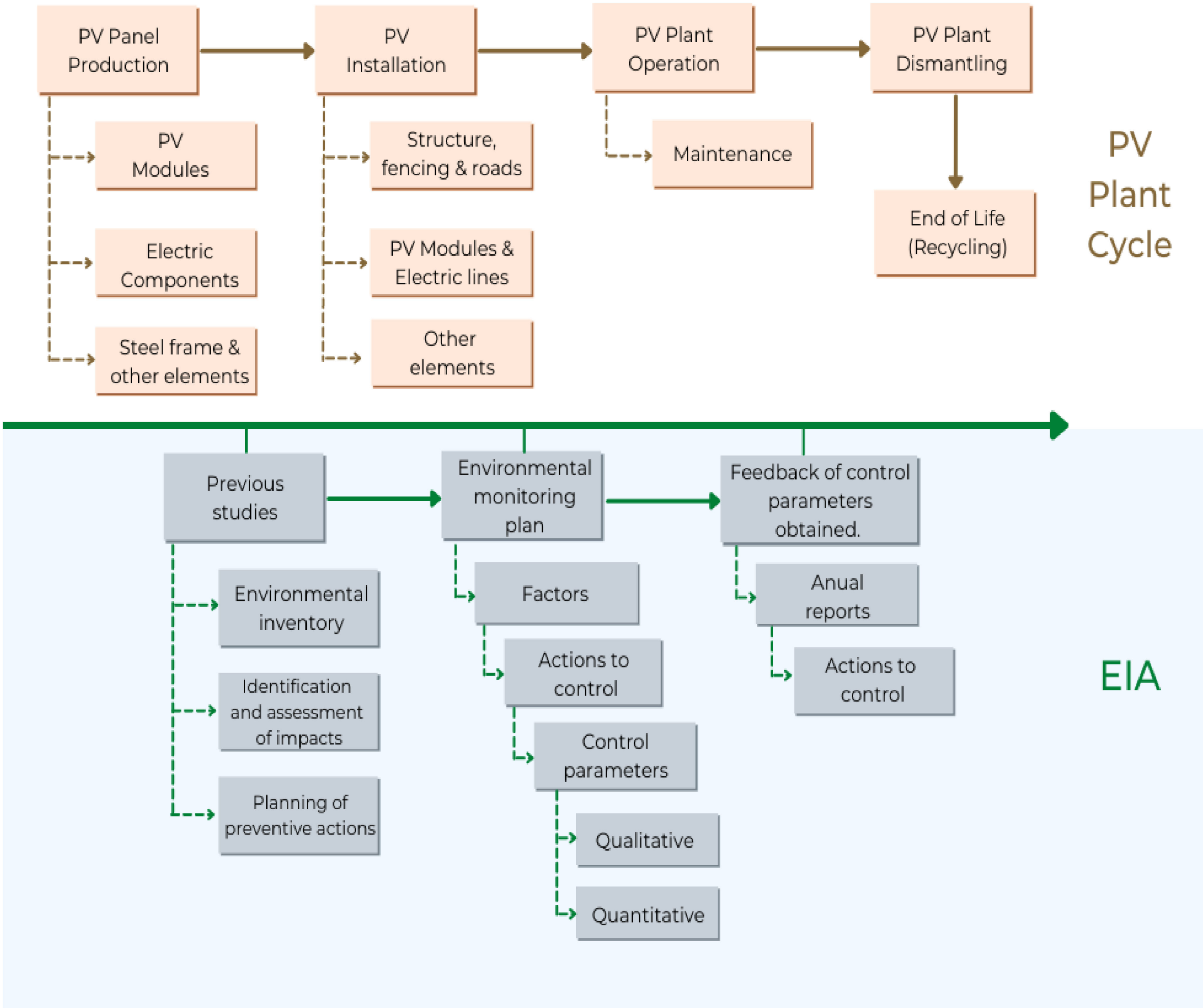

Figure 1. Schematic of the approach proposed for this paper. Own elaboration.

2.1. Addressed Concepts

Some key concepts regarding this investigation are addressed below.

2.1.1. PV Modules Production

In today's market, there are several innovative solar panel technologies; just a decade ago, the average efficiency of 16% per solar cell was obtained. However, with new technologies, such as passivated emitter rear contact (PERC) cells, efficiencies of up to 25% can be achieved [15].

The first generation of solar modules was the crystalline silicon, which still dominates the PV market share. These modules currently have an efficiency of 16–22% [16], and the two types that exist are:

- Monocrystalline silicon (mono c-Si): The cells used to manufacture the c-Si module consist of porous p-n junction sheets. Mono c-Si is homogeneous, which means its composition is a continuous crystal without a grain boundary, and the orientation of silicon atoms and lattice parameters remain constant throughout the material [17,18]. Further, in a warm environment, monocrystalline solar modules can deliver higher efficiency than Poly c-Si because of their high-temperature coefficient.

- Polycrystalline silicon (poly c-Si): This type of module has a lower market share than mono c-Si, and it is produced by melting multiple silicon fragments together to produce the wafers. They also have an additional layer to reduce light reflection. Poly c-Si has the advantage of a lower price; however, their efficiency is also lower (14–16%) due to their reduced silicon purity (the electrons in each cell have less space to move because of the many crystals) [19].

Table 1 describes the main features and differences between Mono c-Si and Poly c-Si technologies.

Table 1. Monocrystalline vs polycrystalline solar panels. Adapted from [19].

Parameters	Monocrystalline	Polycrystalline
Cost	High	Low
Efficiency	High	Low
Appearance	Black color panels	Bluish color panels
Temperature Coeff.	High	Low
Key Manufacturers	SunPower, LG	SolarWorld, Trina

The technology of thin-film PVs is the second generation of solar systems. This type of module uses several absorbing layers, i.e., a much smaller quantity than the conventional first-generation (c-Si), thus obtaining a considerable reduction in the production cost of c-Si technologies. These thin films have lower power and durability than their competitors but have a low-temperature coefficient. Some of them are the well-known: cadmium telluride (CdTe), opper indium gallium selenide (CIGS), amorphous Si (a-Si:H), gallium arsenide (GaAs) [15].

For the first and second generation, efficiency has a limit for single absorber material devices, where they cannot exceed a maximum efficiency of 30% at 1.1 eV. This is known as the Shockley–Queisser limit [20].

The increase of efficiency for mass-manufactured PV modules can be observed in Figure 2, where Figure 2a presents the continuous development of efficiency for top products on the market, dependent on the material of the cell. Figure 2b then shows the average efficiency of these crystalline silicon modules through the years.

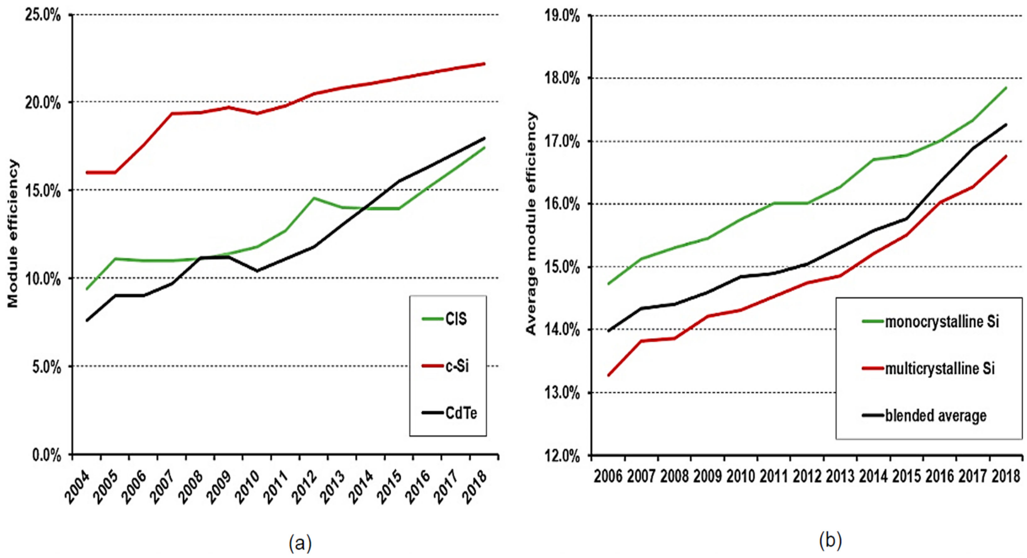

Figure 2. (**a**) Development in efficiency for the top products on the market. (**b**) Development of average efficiency in crystalline silicon modules [16].

The factors that significantly impact the module's efficiency in real-world use are irradiance, shading, orientation, and temperature. Because of this limitation, there is currently a growing interest in changing from BSF cells to PERC cells for higher efficiency, and from multi-crystalline to monocrystalline starting wafer [16]. Based on the market, Figure 3 shows a comparison of total PV module production by type of technology.

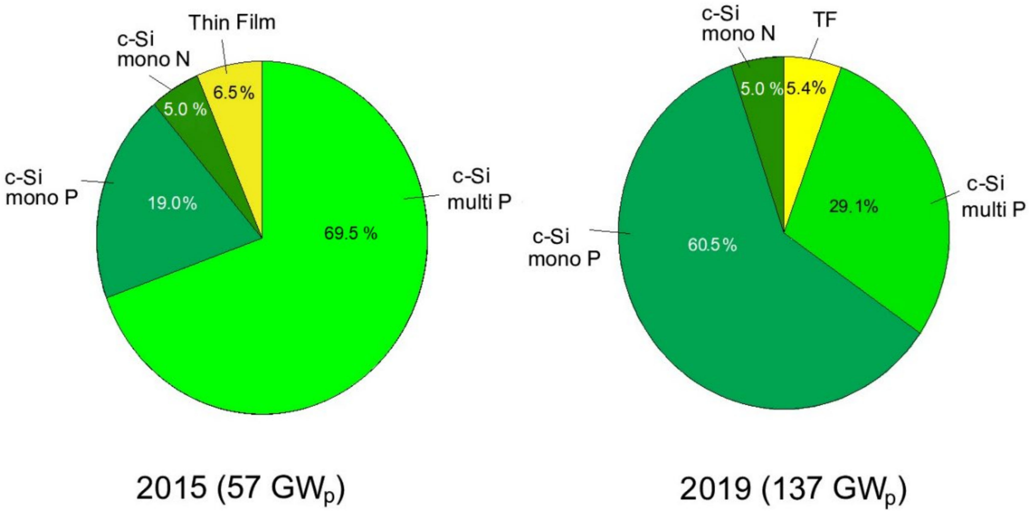

Figure 3. Global comparison of PV technologies in their total production [21].

2.1.2. Emissions from the PV Industry

The PV industry is currently in high demand, with global growth in electricity generation from 27% in 2019 to 29% in 2020, the highest annual increase on record. The increase in renewables in the power sector has clearly impacted emissions from this industry, where carbon emissions are avoided by a ratio of 10% each year on average [22].

Nevertheless, the equivalent carbon emissions from the manufacturing and deployment, called the embodied emissions of a project, must be considered. The avoided emissions rate can be seen as a way to measure the benefits of a PV power plant displacing others in operation (from conventional sources).

It is important to recognize that the installation site of a PV project will have different avoided emissions rates. For instance, comparing a project in North Carolina, it will displace almost fifteen times more emissions than any project located in France, where there are low carbon plants to displace. Furthermore, silicon technologies, especially monocrystalline, include greater emissions due to the material and manufacturing requirements, while thin-film technologies cause lower emissions [23].

For this paper, the equivalent for carbon dioxide emissions that are obtained from the creation of PV modules is calculated by multiplying a coefficient of emission for both manufacturing and the recycling of the module at the end of its life, and the inverters used in the installation, these factors are listed in Table 2.

Table 2. Emissions factors. Adapted from [12].

Panel Average Weight	PV Modules Production	PV Modules Recycling	Inverter
24 kg	213 $kgCO_2e/m^2$	370 $kgCO_2e/ton$	29.6 $kgCO_2e/kW$

According to [24], the carbon dioxide payback time (CPBT) can clearly express the time it takes for a project to avoid the same amount of CO_2e that emits during its life cycle (Equation (1)):

$$\text{CPBT (years)} = \frac{\text{kg } CO_2\text{e emitted during its life}}{\text{kg } CO_2\text{e avoided per year}} \quad (1)$$

The ratio used to measure the energy produced in relation to the energy needed to create it is known as the energy return on investment or EROI (Equation (2)). For a power plant, the long-term viability of the generation system can be assessed with this dimensional ratio.

$$\text{EROI} = \frac{\text{MJ of energy generated by the PV system (25 years)}}{\text{MJ of primary energy used in the creation of PV systems}} \quad (2)$$

This is the amount of energy obtained from a generation system during its lifetime, divided by the amount of energy invested in that system from the cradle to the grave. PV modules represent the main portion (about 80%) of the primary energy used in a power PV plant. For this reason, the calculations will denote only the energy spent to create these. Table 3 shows the energy coefficients used for this calculation.

Table 3. Energy factors. Adapted from [12].

Item	PV Modules Production	PV Modules Recycling	Inverter Large
Energy	3640 MJ/m^2	2780 MJ/t	492 MJ/kW

2.1.3. Ecological Principles

The reception capacity is considered as the existing relationship between the environment and the different human activities, considering the best use that can be made of the environment in terms of its fragility and potential. Figure 4 shows the concertation from the exclusive point of view of the environment, primarily in terms of impact (conservationists) and the suitability or potential of the territory (promoters) [14].

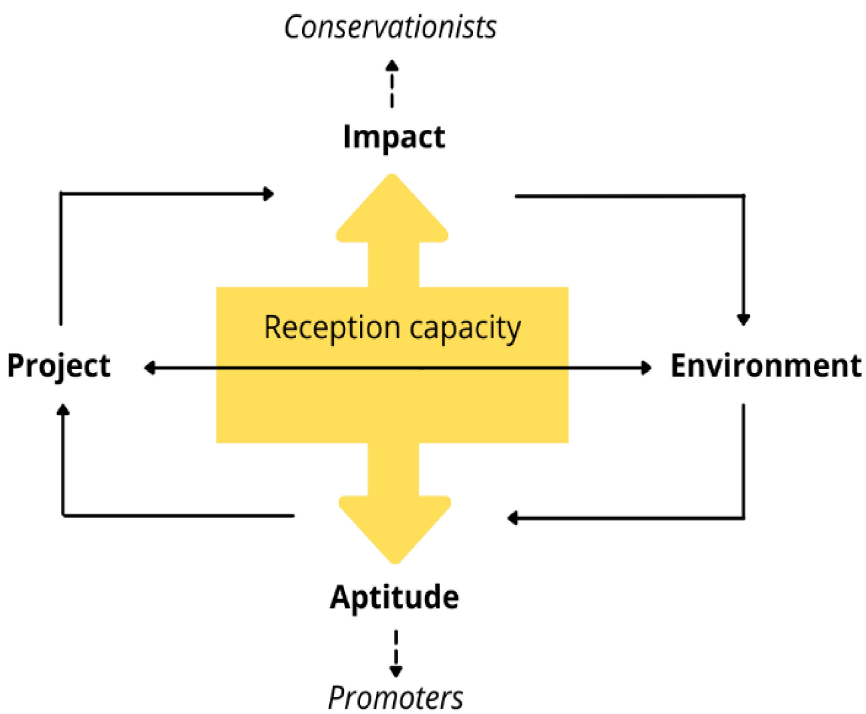

Figure 4. Relationship between the project and the environment, considering the existing reception capacity. Adapted from [14].

In the evaluation of any type of project that may generate a significant impact or effect on the environment, two basic concepts must be considered:

- Environmental factor: Any element or aspect of the environment susceptible to interact with the actions associated with the project to be executed, whose change in quality generates an environmental impact.
- Environmental impact: Alteration introduced by human activity in the environment; this last concept identifies the part of the environment that interacts with it.

Both are considered in the "Importance Matrix", which seeks to define whether the action of a project will generate a negative or positive impact over time or of considerable magnitude. Table 4 shows some of the aspects considered along with their nomenclature, description, and different weightings.

Table 4. Aspects considered in the calculation of the importance of actions performed. Adapted from [21].

Aspects	Nomenclature	Description	Weighting
Sign	+/−	Indicates the nature of the impact.	Beneficial: + Detrimental: −
Intensity	IN	Refers to the degree of incidence of the action.	Low: 1; Medium: 2 High: 4; Very high: 8 Total: 12
Extension	EX	It is the area of influence of the impact on the project environment.	Punctual: 1 Partial: 2 Extensive: 4 Total: 8
Moment	MO	It is the time that elapses between the occurrence of the action and the onset of the effect.	Long: 1 Medium: 2 Immediate: 4
Persistence	PE	It refers to the time that the effect would remain from its appearance until the environment returns to the initial conditions.	Fleeting: 1 Temporary: 2 Permanent: 4
Reversibility	RV	It refers to the possibility of reconstruction of the affected environmental factor.	Short-term: 1 Medium: 2 Irreversible: 4
Synergy	SI	It indicates that the manifestation of the single effects acting simultaneously is greater than that of both effects separately.	No synergy: 1 If there is synergy: 2 Very synergistic: 4
Accumulation	AC	It gives an idea of the progressive increase in the manifestation of the effect when the action that generates it persists continuously.	Simple: 1 Cumulative: 4
Effect	EF	It refers to the form of manifestation of the effect on the factor.	Indirect: 1 Direct: 4
Periodicity	PR	Given by the regularity of the manifestation of the effect.	Unpredictable or irregular: 1 Regular or periodic: 2 Continuous: 4
Recoverability	MC	Possibility of total or partial reconstruction of the affected factor as a consequence of the project.	Immediate: 1 Medium-term: 2 Mitigable: 4 Irrecoverable: 8

The equation described below determines the level of importance of an action in respect to the environmental factor impacted:

$$\text{Importance (I)} = \pm\, 3\text{IN} + 2\text{EX} + \text{MO} + \text{PE} + \text{RV} + \text{SI} + \text{AC} + \text{EF} + \text{PR} + \text{MC} \quad (3)$$

2.2. Study Scenario

The autonomous community of Castilla-La Mancha is made up of five provinces: Albacete, Ciudad Real, Cuenca, Guadalajara, and Toledo. It has a surface area of 79,463 km^2 and a population of 2,045,221 inhabitants.

According to [25], the provinces of Albacete, Ciudad Real, and Toledo are considered among the provinces with the most hours of sunshine in Spain, topping the list, with an average of approximately 3000 h of sunshine per year.

It has a subtropical continental climate characterized by relatively cool winters and very warm summers. In most of its territory, rainfall ranges from moderate to scarce. Rainfall is highly variable over time, with periods of drought as well as high levels of precipitation. Figure 5 shows the different types of climates, according to the Köppen classification, existing in Castilla-La Mancha.

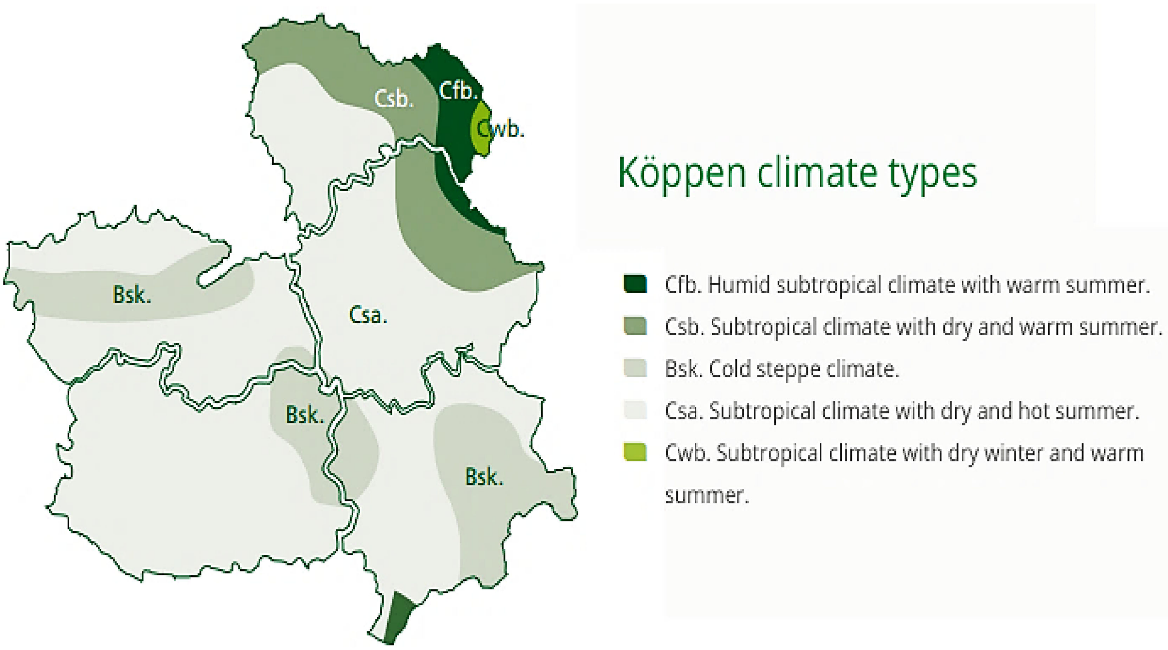

Figure 5. Climatic regionalization based on Köppen's classification (adapted from [5]).

There is a trend towards large-scale solar energy within the different renewable projects carried out in Castilla-La Mancha, where PV plants have been added more frequently in recent years.

By 2022, it is expected to reach 7503 MW of solar energy. This is thanks to the 11,578 PV plants currently in operation and the other 336 in the pipeline [26].

Around this, PV infrastructures of around 49.9 MW on more than 85 hectares were recently approved for Albarreal de Tajo; another 35 MW with 8.70 hectares of Barcience, and 3 MW on 7.50 hectares in Pepino.

For this paper, the main characteristics of 15 photovoltaic plants belonging to the five provinces of Castilla-La Mancha were considered: province, project area, installed capacity, type and quantity of modules, unit power, dimensions, and the area occupied by the modules. Among the selected plants, the most powerful is the Solar PV ALMANSOL I, with an installed power of 50 MW and assembled with 147,030 panels. For the detailed description, refer to Table A1 in Appendix A.

2.3. E.I.A framework in Castilla—La Mancha

The current framework of environmental impact assessment is regulated at the state level by Law 21/2013, of 9 December which regulates the administrative procedures of environmental assessment, whose character is basic; on the other hand, concerning the time limits of the procedure, the application of Law 4/2007, of 8 March 2007, on Environmental Assessment in Castilla-La Mancha, which is autonomous, is made. More recently, there is the National law 9/2018. This one is transposed by Law 2/2020, of 7 February on Environmental Assessment, in addition to other policies such as: Decree 178/2002, and Law 3/2008, of 12 June on Forestry and Sustainable Forest Management of Castilla-La Mancha. An environmental impact assessment must present the following information for the project executed in this region [14]. Figure 6 shows a synthesized description of the procedure.

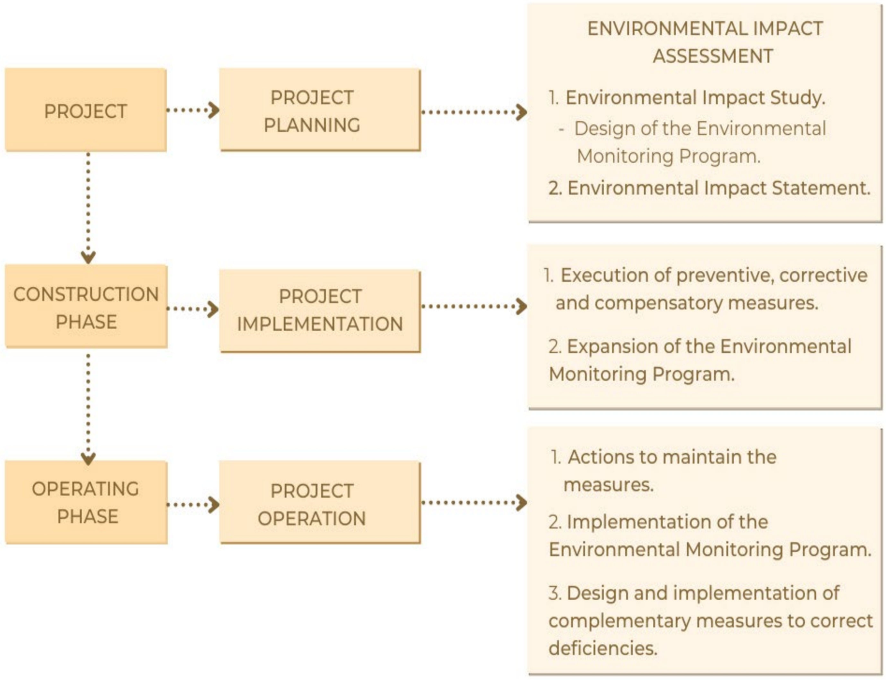

Figure 6. Project phases and procedures to mitigate the environmental impact. Adapted from [11].

3. Results Analysis and Discussion

3.1. CPBT and EROI Calculation

Total emissions per plant were determined for the photovoltaic elements, i.e., the sum of emissions from production and operation components, recycling of PV panels, and their different parts. In addition, for the estimation of avoided emission values, a comparison was considered for each plant with a plant of the same size and generation if it were a natural gas combined cycle plant with a useful life of 25 years. A factor of 0.39 kgCO_2e/kWh was used as the average of the emissions generated by the natural gas combined cycle at the national level in Spain during the year 2021 (until October), according to data abstracted from REE (Red Eléctrica de España) [27].

For better understanding, Table A2 in Appendix A presents the total carbon-dioxide payback time (CPBT) results for the different plants selected.

These results show that only three of the 15 plants (two from Guadalajara) are close to the 2-year margin, and the rest have relatively low values for the time it takes to balance their emissions from manufacturing and recycling. These data are estimates only for solar panels and inverters, being the technology with the highest emissions rooted in the PV plant (about 78% overall). Figure 7 details the result for each solar plant, three of them for each province of the community: Albacete (ALB), Ciudad Real (CR), Cuenca (CU), Guadalajara (GJ), and Toledo (TD).

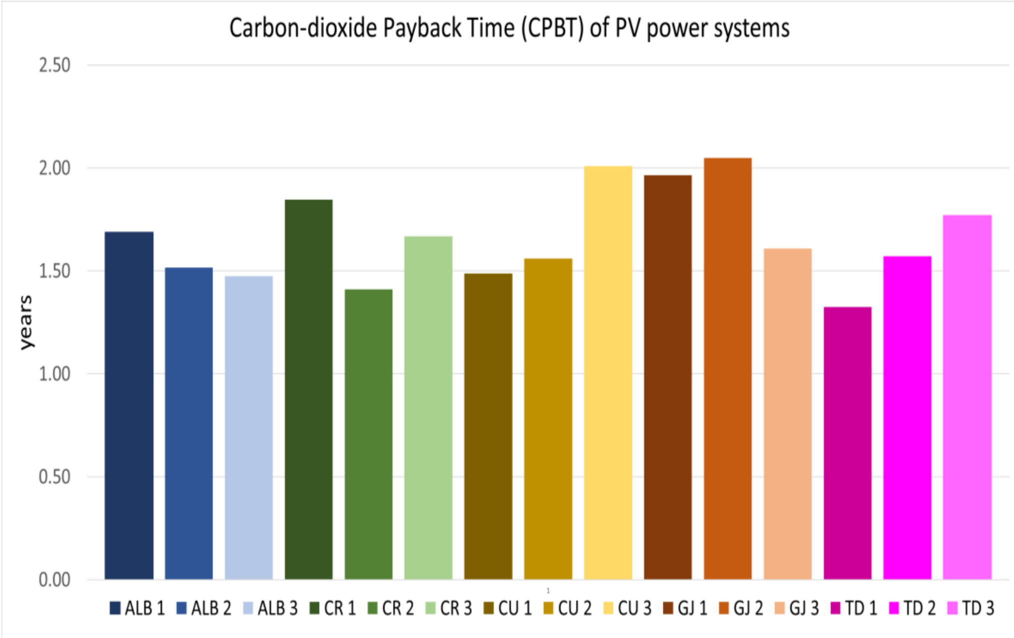

Figure 7. Carbon-dioxide Payback Time for the different PV power centrals in Castilla—La Mancha.

It can then be seen that in most of the photovoltaic installations in Castilla La Mancha, they would be producing emission-free electricity (from the PV elements carbon footprint) at the margin of 1.66 years as an average. Considering that 78–80% of embodied emissions of a PV plant [12] come from PV modules alone, this calculation covers most of it. However, if we estimate by adding the remaining 20% that comes from civil works, plant steel frame, and other components (solar tracking, wiring, and conduits), we obtain an average of 2.08 years for the emissions recovery. Therefore, for a useful life of 25 years for each plant, carbon-free energy would be produced during at least 90% to 93.40% of its operation life if the maximum and minimum CPBT values from the plants are subtracted.

Further, it could be observed how the CPBT behaved in responding to the plant size, e.g., the more MWh per year generated by large facilities, the shorter the payback time, with some of the lowest CPBTs corresponding to CR2 (Perseus Photon III) with 1.41 years and 36.10 MW of installed power, and to ALB3 (Almansol I) with 1.47 years and 50 MW. On the contrary, the highest CPBT was observed in the 5 MW PV plant of Cañamares (GD2) with 2.05 years.

For the calculation of MJ generated by the PV plant during its lifetime, the value of MWh per year was used as a reference, and degradation of its efficiency by 0.50% each year was added [28] (average value for solar panels in the market), resulting in that the energy provided at its 25th year of operation will only be 88.67% of the original one. With the amount of MWh and MJ generated and using the primary energy factors mentioned in Table 2, the EROI was calculated for each plant. These estimates are presented in Table A3 in Appendix A.

A high EROI means that energy production from that source is relatively easy to obtain and cost-effective. On the contrary, if a deficient number is acquired, it is concluded that obtaining energy from that generation system is very expensive and challenging. For instance, a ratio of 1.0 means no return on the energy expended at all. Corresponding to these valuations, it is determined by the World Nuclear Association that the break-even number is 7.0 for large-scale plants [29].

According to calculations for the selected plants, the EROI ranged from 6.23 to 9.51 years, where the trend of this value is linked to the size of the PV plant and its generation capacity per year. Figure 8 shows the final values obtained from every PV central, where only four were below the 7.00 mark.

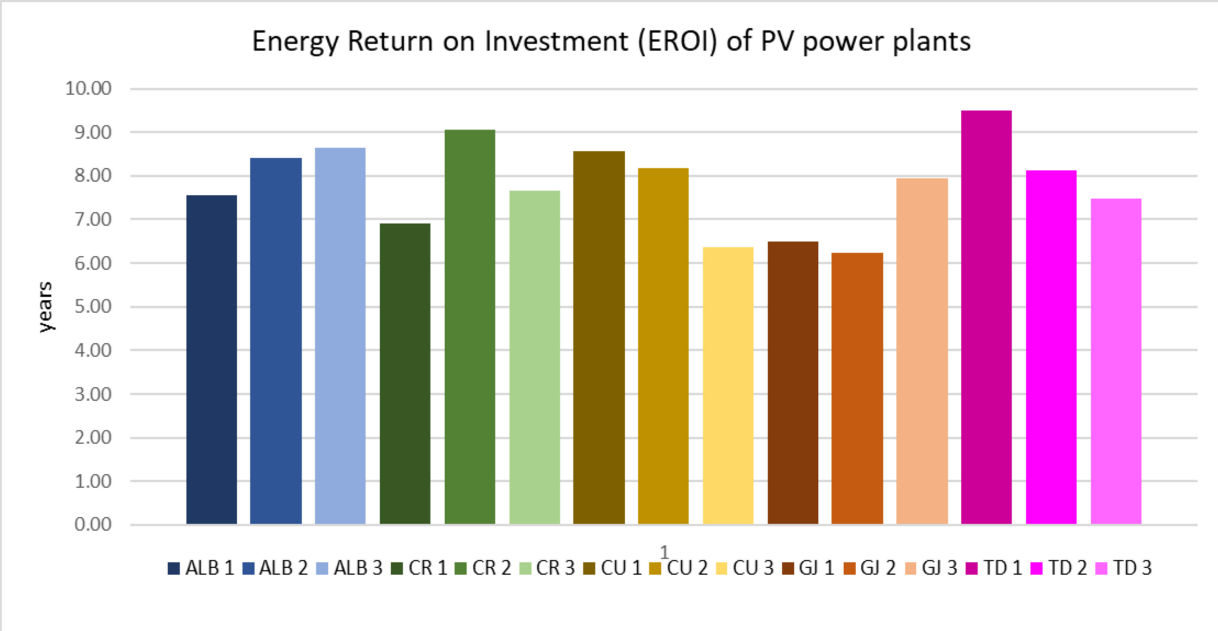

Figure 8. Representation of the calculated EROI values.

In Table 5, we can see the different EROI numbers for the Solar PV industry, where most of the PV modules technologies obtain a small number in comparison to other technologies. However, the rooftop industry provides a great potential for returning the energy, with an average of 10–12 EROI. For the ground systems, as the evaluated solar PV plants, an average EROI number would be 7.5, but a mean value of 7.81 was obtained for this study.

Table 5. Values of EROI for the PV industry. Adapted from [29].

Solar PV	Rooftop (crystalline Si)	Alsema 2003 [30]	10–12
	Ground (crystalline Si)	Alsema 2003 [30]	7.50
	Polycrystalline Si (field)	Weissbach 2013 [31]	3.80
	Amorphous Si (field)	Weissbach 2013 [31]	2.10
	Amorphous silicon (field)	Kivisto 2000 [32]	3.70

In most of the PV plants with low generation and few panels installed (lower energy needed for production & recycling), an EROI higher than 7.00 was observed, even obtaining a value as high as 9.50 with only 10 GWh per year (TD1, PV El Pensamiento, in Toledo). Likewise, high generation plants tended to have a high EROI, almost all of them exceeding the 8.00 mark thanks to their constant contribution to the grid (between 95 GWh-107 GWh per year). However, those of medium generation, between 33 GWh and 81 GWh per year, obtained ranges below the 7.00 break-even, achieving between 6.35 and 6.90 because of the large number of panels they have, and low energy production delivered.

3.2. E.I.A Findings and Analysis

Other methods used for evaluating a PV power central consider the final effects related to the environmental aspects involved in the construction and operation phases of the 15 plants studied. The NEVA platform [33] was used to obtain official information from the different plants. This includes the files of each approved project, from the beginning to the completion of the structure, within the five provinces in Castilla-La Mancha. Based on the Environmental Impact Assessment reports, some of the effects considered, along with the significance value of each action, are summarized in Table 6. The values in this table represent the average result from all PV plants, categorized by the actions involved in the project, according to the direct effect on different environmental factors (air, soil, water, vegetation, fauna, landscape) and economic factors. Both values were calculated separately for the construction and operation phase for each plant (See Appendix A section, Tables A4 and A5, for complete data).

Table 6. Environmental factors with its actions and average importance at different stages of the solar plants studied. Adapted from [33].

	Environmental Factors	Actions	Average Importance (Construction)	Average Importance (Operation)
Natural environment	Effects on the atmosphere	Air quality and climate change	−82.78	34.00
		Noise	−35.78	−18.25
	Effects on soil	Occupation and compaction	−124.33	−26.00
		Soil and subsoil contamination	−64.89	−22.00
		Geomorphological and relief alteration	−58.56	0.00
		Erosion and loss of fertile soil	−91.56	3.83
	Effects on water	Surface and groundwater quality	−53.63	2.57
		Change of use and consumption	0.00	21.00
	Effects on vegetation	Elimination of vegetation cover	−90.67	0.00
		Impact on habitats of community interest	−15.00	0.00
	Effects on fauna	Alteration and elimination of wildlife habitats	−44.33	−41.00
		Disturbance	−33.86	−21.00
		Mortality	−21.43	−38.89
	Effects on the landscape	Visual intrusion and effects on landscape quality	−55.00	−42.56
Economic environment	Effects on the population	Increased traffic	−26.50	−2.13
		Disturbance to the population	−18.13	−5.56
	Effects on the economy	Economic development	51.22	35.67
		Soil productivity	−23.71	−22.38
		Energy resources	0.00	36.11
	Effects on the territory	Impact on property	−31.57	−22.86
		Impact on hunting resources	−27.57	0.00
		Impact on protected areas	−4.43	0.00
	Effects on cultural heritage	Impact on B.I.C. and archaeological remains	−12.78	−2.75
Vulnerability	Risks	Flood risk	0.00	−21.00
		Seismic risk	0.00	−20.00
		Meteorological risks	0.00	−20.00
		Forest fire risk	0.00	−24.00

The following table has a weighting where environmental factors will be positive (beneficial factors) or negative (harmful factors).

The scale will consider values lower than 25 as non-significant impacts, greater than 25 and less than 50 will be moderate impacts, greater than 50 and less than 75 as severe impacts, while greater than 75 will be of critical impact [34].

With the average level of importance obtained for each action, Figure 9 shows the most worrisome actions for the natural environment, generally, by activities such as: removal of vegetation cover, occupation, and compaction, use of machinery, which have effects in loss of fertile soil, erosion, and affectation to air quality. On the other hand, the economic environment aspect obtained positive values in terms of economic development, with a value of 51.22; other actions in this section caused non-significant or low impact effects.

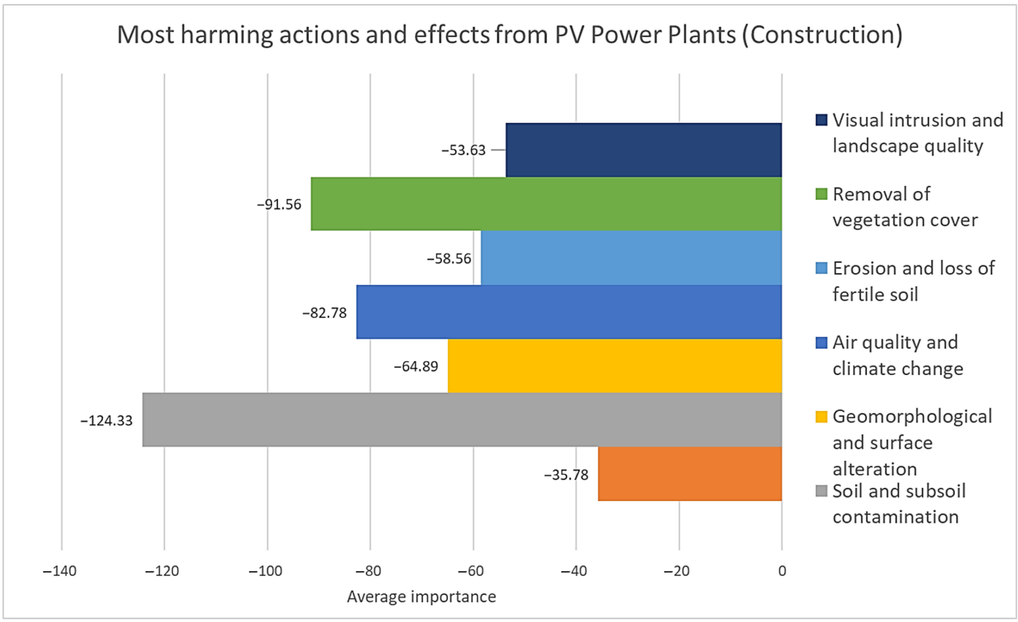

Figure 9. Average importance values of the most harming actions during installation of PV centrals.

Performing the same evaluation for the years of operation of the different plants, the following actions were determined as the most relevant. Values lower than 25 are considered compatible or not significant; therefore, Figure 10 only shows the moderate values or those with a significant impact on the natural environment during operation that cannot be avoided after preventive and corrective measures. In addition, the positive impacts that exist after the start-up of the PV plant are observed, such as: energy resources, economic development, job positions, change of use and consumption; and with power generation, the impact of avoided emissions that contribute to air quality and climate change.

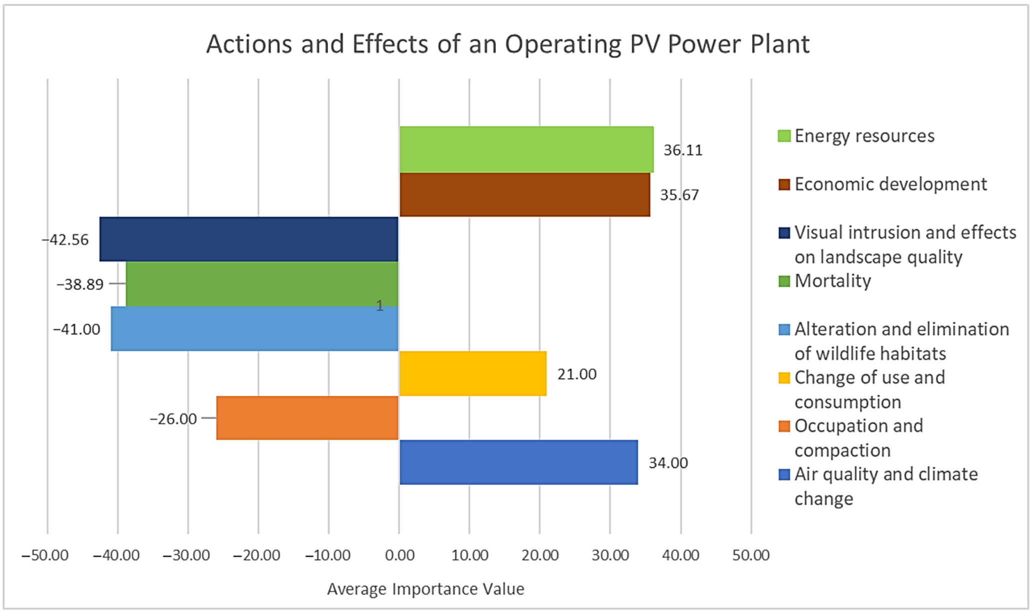

Figure 10. Average importance values of the actions regarding the operational phase of PV centrals.

As an analysis of the different impacts obtained, the following discussion for each factor is presented:

- Effects on the atmosphere: Within the construction phase (earthmoving, dust raising, removal of vegetation cover) it is noted that a PV plant is "compatible and moderate" where these effects are immediate, direct, and continuous during the initial phase, but are reversible, recoverable, and not very persistent.
- Effects on soil and subsoil: Due to earthworks and contamination by pile-driving or foundations, a high rating was observed in different reports, especially for occupation and compaction, including incorporating of exterior materials, soil mixing, etc. The average importance of the erosion factor was tolerable and moderate, derived from temporary actions. However, this is susceptible to the initial state of the soil for the project, where 0–12 tha/yr is a low value, 12–25 tha/yr is medium, and >25 tha/yr is considered high.
- Effects on water: In terms of possible contamination of surface and groundwater, PV power plants that include preventive measures do not have a predominant impact, since this contamination can only occur due to construction actions, such as: earth movements (possible dragging of material) and the presence of machinery (accidental spills), and not due to any polluting compound related to energy generation and necessary for its operation, as occurs in fossil fuel power plants.
- Effects on fauna: The temporary absence of vegetation on some plants means a loss of space that provides shelter and food for numerous fauna species, which leads to the displacement or reduction of species in that space. In terms of disturbances caused by noise, there is an immediate flight reaction in vertebrates, and certain birds move away.
- During the operation phase, due to the plant's operability and the reduced availability of space due to the intrusion of foreign elements (fencing and photovoltaic solar panels), a barrier effect and habitat alteration maybe be created, impacting the fauna. This matter should be studied in detail to verify its real scope. These impacts can be contained if prior environmental monitoring of the populations is carried out to avoid affecting them and consider carrying out the work outside the breeding, nesting, and rearing seasons (March–July). During the operation stage, the risk of collision presented by the solar panels for birds and bats is low, although not impossible.
- Effects on the landscape: In the construction phase, the previous analysis in the environmental inventory is considered, i.e., concerning the previous state of the landscape unit where the project is installed, a minor or major effect on the different landscapes will be obtained. In this phase, this effect was considered compatible or not significant. However, in the operation phase, with the view of the solar panels, inverters, roads, and enclosures, the visual impact will be greater according to the surface area of the photovoltaic projects and the larger it is, and is considered permanent for the 25–30 years of its life cycle. It is concluded that there may be an accumulation with other nearby solar plants or other existing power lines, and in general, there is a moderate impact.
- Effects or nuisances on the population: They are considered compatible or not significant.
- Effects on the economy: There is a contribution of the project works and its operation or maintenance to economic development, where there is a great impact on the rural economy and a significant positive impact of this value. On the other hand, the loss of soil productivity can be related to the paralysis or hindrance of the normal development of agricultural activities on land near the PV plant. This effect can be moderate in certain facilities. The section of new energy resource is also considered, where its installation means using an autochthonous and inexhaustible resource, thus avoiding the burning of fossil fuels.
- Effects on the territory: In the case of property, hunting, or agricultural areas, it is considered that since the land is not used due to the occupation of the solar plant, there is a moderate impact due to the permanent, irreversible, and continuous effects.

- Effects on cultural heritage: Due to possible architectural findings during earthworks, this effect is considered; however, it is considered insignificant in most studies and is not predominant in the impacts of PV power plants.

Figure 11 shows the performance in terms of the total absolute environmental impact of nine selected plants, using the existing data of environmental impact studies in the autonomous community. This important value considers the sum of the effects on the atmosphere, soil, water, vegetation, fauna, landscape, population, economy, territory, heritage, and risks.

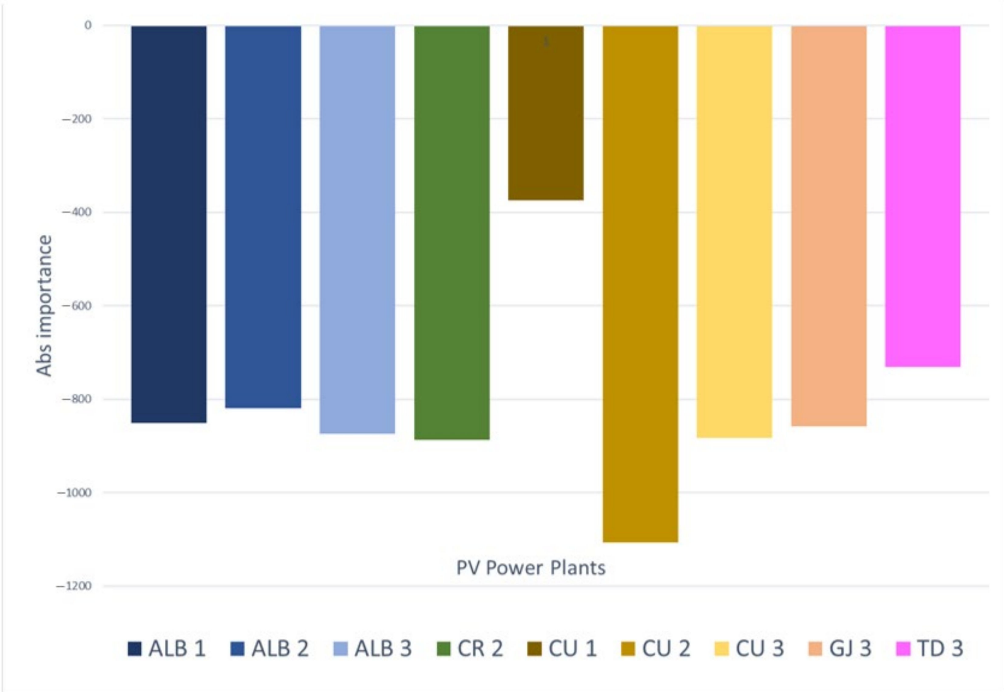

Figure 11. Representation of total absolute importance for different PV solar power plants in the construction phase.

Considering the absolute importance obtained through the different photovoltaic plants studied in the construction phase, it can be observed that the PV plant Escuderos I in Torrejoncillo del Rey (CU2) was the one with the highest value. In contrast, the one with the lowest value is the Bañuela Photovoltaic Plant in Altarejos (CU1), both located in the province of Cuenca.

Abstracting this information, it can be noted that both plants have the same installed capacity. However, the natural environment was highly affected in the Escuderos I during the construction phase. It is also relevant to mention that the actions related to the economic environment were very few evaluated. In contrast, in the case of the Bañuela Photovoltaic Plant, impacts related to the human environment, such as vulnerability and economic environment, were not evaluated or were considered null, which could influence in the few impacts overall.

For the operation stage, as can be seen in Figure 12, the Virgen de Belén Photovoltaic Solar Plant (ALB2), located in Albacete, is the one that most affects the surrounding environment, while the Romeral Solar Plant (CU3) and Puerta del Sol (GJ3), are the ones that least affected the environment. Because of their similarities in both technical and physical capacities, these two present the same values.

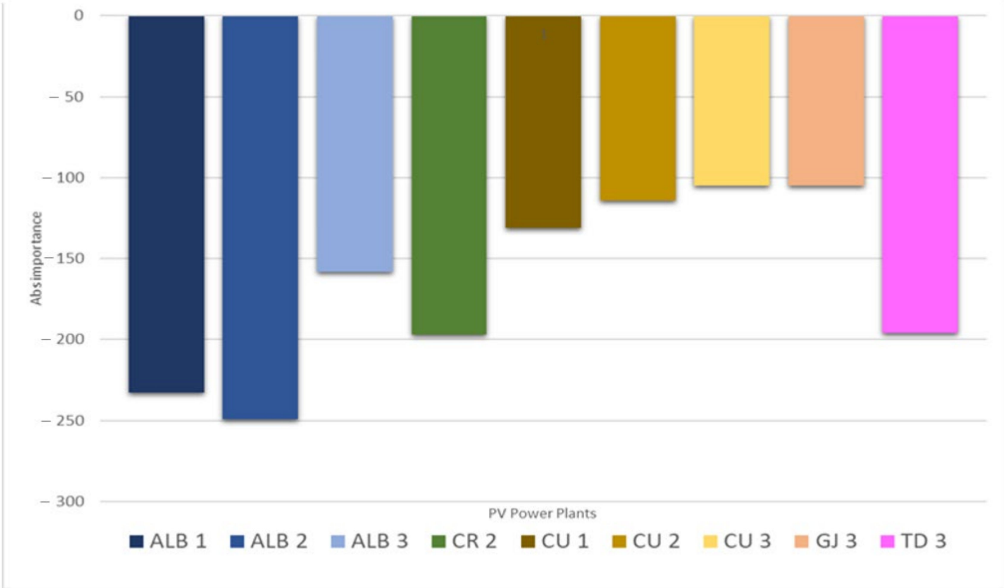

Figure 12. Representation of total absolute importance for different PV solar power plants in the operation phase.

The ALB2 Photovoltaic Plant has considerably less capacity; therefore, it presents values with a marked difference. For the evaluation, actions on the effects on cultural heritage are considered, while they were null for the two previous plants (CU3 and GJ3). Furthermore, for ALB2, there were values assigned to actions that may cause risks, while the other two do not consider them relevant.

It is remarkable how seven out of nine plants exceed the margin of 800 points in the construction phase. In operation, this value is already much lower, suggesting that the impacts are caused mostly by the civil works and not by the generation of solar PV energy in the operation phase, which does not happen with fossil fuel plants, whose effects are even more prolonged in generation and operation.

For the final disposal of these projects (dismantling phase), waste must be identified according to types, where most of the civil works would be non-hazardous, such as concrete, bricks, earth, and different stones; and metals like iron and steel. In the case of photovoltaic panels, there are numerous emissions and major energy use during the thermic recycling and mechanic recycling of these modules. Therefore, there must be a high capacity for recycling, handling in landfills, and valuation of metals at the site of interest or in areas near the project. In the case of hazardous waste, storage will be carried out following specific regulations; silicon solar panels are managed as Waste Electrical and Electronic Equipment (WEEE). For instance, according to a regulation inside the EU, since 2012, solar panel producers have been obliged to recycle their panels that are no longer in use.

4. Conclusions

A systematic review on 15 large-scale PV solar energy projects was conducted to assess the industry impacts, using an estimation of simplified LCA and environmental impact assessment (EIA), within the Autonomous Community of Castilla—La Mancha. The industry impact was addressed in terms of the effects and importance on the natural environment, economic environment, and vulnerability in each PV plant's construction and operation phases.

According to the methods evaluated, in the calculation of the payback time (CPBT) needed for the plant to be a net generator of emissions, it was possible to recognize the relationship between the size of the plant and a high generation capacity, with a lower time to pay for these emissions from the manufacture and recycling of panels. This is around

1.66–2.05 years for the Castilla-La Mancha region. This value is susceptible to change according to the avoided emissions factor of a site and the type of energy displaced.

With the primary energy required for the creation of a panel and the amount of energy generated from it, it can be said that PV technology has a low EROI compared to other conventional types of energy, so it is necessary to improve the manufacturing methods and efficiency in the production of these or increase its efficiency of solar energy transformation for a greater contribution to the grid with recent innovations.

According to the results in the case of EIA, the most aggressive actions were the operation and presence of machinery, earthworks, and vehicle traffic during construction, towards factors such as: atmosphere, soils, hydrology, and heritage, while the most affected environmental factor was fauna.

Together with the landscape, the fauna will be the factors most likely to be affected by the alteration of their habitat and the visual impact of the facilities. However, the solar plant does not have the impacts associated with other types of conventional energy, such as the formation of ozone, the emission of acid rain precursors, or the depletion of resources.

For the operation stage, the factors most affected by the operation of the plant, at a moderate level, were alteration and elimination of wildlife habitats, visual intrusion, and effects on the quality of the landscape. For this reason, integration actions such as vegetation screening and decompaction are used to reduce these impacts. With the proper application of an environmental monitoring plan, solar plants can implement the correct preventive and corrective measures that make them one of the least polluting energies for large-scale installation after wind power.

For future works, it is recommended to test different methods as a comparison in the evaluation of plants, e.g., indicators, GIS, or other types of field evaluations, for the same plants in this investigation or other installations outside the Castilla-La Mancha region.

Further evaluations can be extended to comparing neighboring countries, which are more developed in terms of renewable energy plants, such as countries with less installation and generation than Spain, considering the possible change in CPBT and EROI times. It is recommended to compare different types of energy such as wind, hydro, and conventional for a life cycle analysis within the same region.

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Appendix A

Table A1. Description of the selected Photovoltaics Power Plants from the Castilla—La Mancha region.

Province	Name of Project	Project ID	Installed Power (MW)	Project Area (hectare)	Location	Modules Quantity	Module Type	Power (Wp)	Dimensions Lenght × Width (mm)	
Albacete	Planta solar Fotovoltaica Los crespos	ALB 1	20.00	50.2	Almansa, Albacete	51.298	Monocrystalline	340	1956	992
	Planta solar fotovoltaica "Virgen de Belén"	ALB 2	4.90	15.27	Almansa, Albacete	13,338	Monocrystalline	450	2205	1032
	Planta solar fotovoltaica Almansol i	ALB 3	49.99	99.31	Bonete, Albacete	147,030	Polycrystalline	450	1956	992
Ciudad Real	Planta solar Fotovoltaica de 19.99 MW	CR 1	19.99	41.78	Ciudad Real, Ciudad Real	57,120	Polycrystalline	350	1956	992
	Planta solar Fotovoltaica "Perseo fotón III"	CR 2	36.10	80.79	Manzanares, Ciudad Real	91,408	Monocrystalline	395	2015	996
	Planta solar Fotovoltaica 50 MW Antilia Solar	CR 3	49.90	26.51	Puertollano, Ciudad Real	133,272	Monocrystalline	375	1755	1038
Cuenca	Planta fotovoltaica Bañuela 49.98 MWp	CU 1	49.98	85.00	Altarejos, Cuenca	135,090	Monocrystalline	370	1977	996
	Planta fotovoltaica Escuderos I	CU 2	49.99	98.50	Torrejoncillo del Rey, Cuenca	131,544	Monocrystalline	380	2010	992
	Planta solar Fotovoltaica "Romeral"	CU 3	50.00	76.64	Alarcón, Cuenca	149,234	Monocrystalline	335	1960	992
Guadalajara	Planta solar Fotovoltaica Canredondo	GJ 1	22.00	64.60	Canredondo, Guadalajara	66,640	Polycrystalline	330	1956	992
	Planta solar Fotovoltaica Cañamares	GJ 2	5.00	11.80	Fontanar, Guadalajara	15,150	Polycrystalline	330	1960	990
	Planta solar Fotovoltaica Puerta del sol	GJ 3	49.98	78.73	Galapagos, Guadalajara	142,800	Monocrystalline	350	1956	992
Toledo	Planta solar Fotovoltaica El Pensamiento	TD 1	5.00	9.44	Cebolla, Toledo	10,846	Monocrystalline	460	2182	1029
	Parque solar "Escalonilla este"	TD 2	3.63	21.96	Escalonilla, Toledo	12,330	Polycrystalline	340	2000	992
	Planta FV AR Recas Solar 2 MW	TD 3	2.20	5.04	Recas, Toledo	6400	Polycrystalline	345	1300	790

Table A2. Data and calculation for the Carbon-dioxide Payback Time (CPBT) of the 15 selected PV centrals in the Castilla-La Mancha region.

Province	Project ID	PV Panels Ocuppied Area (m^2)	Emissions from Panels Production ($ktCO_2eq$)	Emissions from Panels Recycling ($kgCO_2eq$)	Inverters Quantity	Inverters Power (kW)	Inverters Emissions ($kgCO_2e$)	Energy Generated (MWh/Year)	Emissions Avoided ($ktCO_2e$/Year)	Carbon Dioxide Payback Time (Years)
Albacete	ALB 1	99,739	21.24	455,526	112	19,600	580,160	33,480	13.20	1.69
	ALB 2	30,351	6.46	118,441	28	5180	153,328	11,280	4.45	1.51
	ALB 3	285,289	60.77	1,305,626	30	3672	108,691	107,000	42.19	1.47
Ciudad Real	CR 1	114,300	24.35	507,225	7	17,200	509,120	34,834	13.74	1.85
	CR 2	183,450	39.07	811,703	12	24,240	717,504	73,078	28.81	1.41
	CR 3	242,780	51.71	1,183,455	8	22,760	673,696	81,441	32.11	1.67
Cuenca	CU 1	266,004	56.66	1,199,599	30	1351	39,995	98,807	38.96	1.49
	CU 2	262,288	55.87	1,168,110	14	46,200	1,367,520	95,000	37.46	1.56
	CU 3	290,158	61.80	1,325,197	12	42,000	1,243,200	81,312	32.06	2.01
Guadalajara	GJ 1	129,305	27.54	591,763	12	14,746	436,469	36,866	14.54	1.97
	GJ 2	29,397	6.26	134,532	2	5000	148,000	8101	3.19	2.05
	GJ 3	277,082	59.02	1,268,064	20	27,006	799,377	96,380	38.00	1.61
Toledo	TD 1	24,352	5.19	96,312	4	5332	157,827	10,301	4.11	1.32
	TD 2	24,462	5.21	109,490	25	3300	97,680	8753	3.45	1.57
	TD 3	6572	1.40	56,832	20	2200	65,120	2244	0.86	1.77

Table A3. Calculation of the Energy Return of Investment for the 15 selected PV power plants in Castilla-La Mancha.

Province	Name of Project	Energy from Panels Production (MJ)	Energy from Panels Recycling (MJ)	Inverters Power (kW)	Energy from Inverters (MJ)	Generated Energy in MWh/Year	Generated Energy for 25 Years (MWh)	MJ of Energy Produced from PV Systems (25 Years)	MJ from Craddle to Grave	EROI
Albacete	ALB 1	3.63×10^8	3.42×10^6	1.96×10^4	9.64×10^6	3.35×10^4	7.90×10^5	2.84×10^9	1.53×10^9	7.56
	ALB 2	1.10×10^8	8.90×10^5	5.18×10^3	2.55×10^6	1.13×10^4	2.66×10^5	9.58×10^8	1.14×10^8	8.41
	ALB 3	1.04×10^9	9.81×10^6	3.67×10^3	1.81×10^6	1.07×10^5	2.52×10^6	9.08×10^9	1.05×10^9	8.65
Ciudad Real	CR 1	4.16×10^8	3.81×10^6	1.72×10^4	8.46×10^6	3.48×10^4	8.22×10^5	2.96×10^9	4.28×10^8	6.9
	CR 2	6.68×10^8	6.10×10^6	2.42×10^4	1.19×10^7	7.31×10^4	1.72×10^6	6.20×10^9	6.86×10^8	9.05
	CR 3	8.84×10^8	8.89×10^6	2.28×10^4	1.12×10^7	8.14×10^4	1.92×10^6	6.91×10^9	9.04×10^8	7.65
Cuenca	CU 1	9.68×10^8	9.01×10^6	1.35×10^3	6.65×10^5	9.88×10^4	2.33×10^6	8.39×10^9	9.78×10^8	8.58
	CU 2	9.55×10^8	8.78×10^6	4.62×10^4	2.27×10^7	9.50×10^4	2.24×10^6	8.07×10^9	9.86×10^8	8.18
	CU 3	1.06×10^9	9.96×10^6	4.20×10^4	2.07×10^7	8.13×10^4	1.92×10^6	6.90×10^9	1.09×10^9	6.35
Guadalajara	GJ 1	4.71×10^8	4.45×10^6	1.47×10^4	7.25×10^6	3.69×10^4	8.69×10^5	3.13×10^9	4.82×10^8	6.49
	GJ 2	1.07×10^8	1.01×10^6	5.00×10^3	2.46×10^6	8.10×10^3	1.91×10^5	6.88×10^8	1.10×10^8	6.23
	GJ 3	1.01×10^9	9.53×10^6	2.70×10^4	1.33×10^7	9.64×10^4	2.27×10^6	8.18×10^9	1.03×10^9	7.93
Toledo	TD 1	8.86×10^7	7.24×10^5	5.33×10^3	2.62×10^6	1.03×10^4	2.43×10^5	8.75×10^8	9.20×10^7	9.51
	TD 2	8.90×10^7	8.23×10^5	3.30×10^3	1.62×10^6	8.75×10^3	2.06×10^5	7.43×10^8	9.15×10^7	8.12
	TD 3	3.63×10^8	3.42×10^6	1.96×10^4	9.64×10^6	3.35×10^4	7.90×10^5	2.84×10^9	1.53×10^9	7.56

Table A4. Synthesis of the different importance matrix conducted in the selected PV plants (construction phase).

	Environmental Factors	Actions	Planta Solar Fotovoltaica Los Crespos (ALB1) [35]	Planta Solar Fotovoltaica PF Virgen de Belén (ALB2) [36]	Planta Solar Fotovoltaica Almansol I (ALB3) [37]	Planta de Energía Solar Perseo Fotón (CR2) [38]	Planta FV Bañuela (CU1) [39]	Planta FV Escuderos I (CU2) [40]	Planta Solar Romeral (CU3) [41]	Planta Puerta del Sol (GJ3) [42]	Planta FV AR Recas Solar (TD3) [43]	Average Importance (I)
Natural environment	Effects on the atmosphere	Air quality and climate change	−74	−74	−79	−205	−24	−87	−78	−75	−49	−82.78
		Noise	−19	−19	−53	−77	−31	−57	−22	−22	−22	−35.78
	Effects on soil	Occupation and compaction	−126	−126	−138	−68	−138	−135	−132	−132	−124	−124.33
		Soil and subsoil contamination	−48	−48	−64	−150	−40	−70	−55	−55	−54	−64.89
		Geomorphological and relief alteration	−65	−65	−61	−40	−36	−67	−69	−63	−61	−58.56
		Erosion and loss of fertile soil	−98	−98	−118	-	−39	−133	−115	−112	−111	−91.56
	Effects on water	Surface and groundwater quality	−43	−43	−40	−137	−40	−46	−40	−40	-	−53.63
		Change of use and consumption	0	0	-	-	-	-	0	0	-	0.00
	Effects on vegetation	Elimination of vegetation cover	−95	−95	−93	−123	−29	−102	−97	−94	−88	−90.67
		Impact on habitats of community interest	0	0	0	-	0	−120	0	0	0	−15.00
	Effects on fauna	Alteration and elimination of wildlife habitats	− 31	−31	0	−108	−38	−80	−40	−37	−34	−44.33
		Disturbance	−32	−32	−38	-	-	−38	−38	−35	−24	−33.86
		Mortality	−26	−26	0	-	-	−23	−23	−23	−29	−21.43
	Effects on the landscape	Visual intrusion and effects on landscape quality	−62	−62	−67	−33	0	−73	−66	−63	−69	−55.00
Economic environment	Effects on the population	Increased traffic	−24	−24	−24	−44	-	−24	−24	−24	−24	−26.50
		Disturbance to the population	−18	−18	−21	0	-	−24	−21	−21	−22	−18.13
	Effects on the economy	Economic development	28	28	40	147	40	40	52	49	37	51.22
		Soil productivity	−32	−32	−35	-	-	0	−35	−32	0	−23.71
		Energy resources	0	0	0	0	-	0	0	0	0	0.00
	Effects on the territory	Impact on property	−31	−31	−31	-	-	−34	−31	−31	−32	−31.57
		Impact on hunting resources	−24	−24	−31	-	-	−34	−27	−27	−26	−27.57
		Impact on protected areas	−31	0	0	-	-	0	0	0	0	−4.43
	Effects on cultural heritage	Impact on B.I.C. and archaeological remains	0	0	−22	−49	0	0	−22	−22	0	−12.78
Vulnerability	Risks	Flood risk	0	0	-	-	0	-	-	-	-	0.00
		Seismic risk	0	0	-	-	0	-	-	-	-	0.00
		Meteorological risks	0	0	-	-	0	-	-	-	-	0.00
		Forest fire risk	0	0	-	-	0	-	-	-	-	0.00
Absolute value of importance			−851	−820	−875	−887	−375	−1107	−883	−859	−732	−821

Table A5. Synthesis of the different importance matrix conducted in the selected PV plants (operation phase).

	Environmental Factors	Actions	Planta Solar Fotovoltaica Los Crespos (ALB1) [35]	Planta Solar Fotovoltaica PF Virgen de Belén (ALB2) [36]	Planta Solar Fotovoltaica Almansol I (ALB3) [37]	Planta de Energía Solar Perseo Fotón (CR2) [38]	Planta FV Bañuela (CU1) [39]	Planta FV Escuderos I (CU2) [40]	Planta Solar Romeral (CU3) [41]	Planta Puerta del Sol (GJ3) [42]	Planta FV AR Recas Solar (TD3) [43]	Average Importance (I)
Natural environment	Effects on the atmosphere	Air quality and climate change	35	35	32	0	32	35	35	35	33	34.00
		Noise	−18	−18	−23	0	-	−20	−23	−23	−21	−18.25
	Effects on soil	Occupation and compaction	−22	−22	−23	−48	−23	−26	−24	−24	−22	−26.00
		Soil and subsoil contamination	−21	−21	−21	−26	−21	−24	−21	−21	−22	−22.00
		Geomorphological and relief alteration	0	0	0	0	-	0	0	0	0	0.00
		Erosion and loss of fertile soil	0	0	0	-	-	0	0	0	23	3.83
	Effects on water	Surface and groundwater quality	0	0	0	−24	-	42	0	0	-	2.57
		Change of use and consumption	0	0	-	-	-	-	42	42	-	21.00
	Effects on vegetation	Elimination of vegetation cover	0	0	0	0	-	0	0	0	0	0.00
		Impact on habitats of community interest	0	0	0	-	-	0	0	0	0	0.00
	Effects on fauna	Alteration and elimination of wildlife habitats	−46	−40	−47	−24	−48	−44	−44	−44	−32	−41.00
		Disturbance	−21	−21	−21	-	−21	−21	−21	−21	−21	−21.00
		Mortality	−34	−34	−62	-	−45	−68	−36	−36	−35	−38.89
	Effects on the landscape	Visual intrusion and effects on landscape	−40	−40	−46	−35	−58	−44	−40	−40	−40	−42.56
Economic environment	Effects on the population	Increased traffic	0	0	0	−17	-	0	0	0	0	−2.13
		Disturbance to the population	0	0	0	−50	-	0	0	0	0	−5.56
	Effects on the economy	Economic development	34	34	40	0	40	43	43	43	44	35.67
		Soil productivity	−21	−21	−22	-	−22	−25	−22	−22	−24	−22.38
		Energy resources	38	38	35	27	35	38	38	38	38	36.11
	Effects on the territory	Impact on property	−32	−32	0	-	-	0	−32	−32	−32	−22.86
		Impact on hunting resources	0	0	0	-	-	0	0	0	0	0.00
		Impact on protected areas	0	0	0	-	0	0	0	0	0	0.00
	Effects on cultural heritage	Impact on B.I.C. and archaeological remains	0	−22	0	0	-	0	0	0	0	−2.75
Vulnerability	Risks	Flood risk	−22	−22	-	-	-	-	-	-	−19	−21.00
		Seismic risk	−19	−19	-	-	-	-	-	-	−22	−20.00
		Meteorological risks	−20	−20	-	-	-	-	-	-	−20	−20.00
		Forest fire risk	−24	−24	-	-	-	-	-	-	−24	−24.00
Absolute value of importance			−233	−249	−158	−197	−131	−114	−105	−105	−196	−165.33

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