Energy

http://www.aimspress.com/journal/energy

AIMS Energy, 5(1): 77-95.
DOI: 10.3934/energy.2017.1.77
Received: 22 October 2016
Accepted: 02 January 2017
Published: 09 January 2017

Research article

Real Energy Payback Time and Carbon Footprint of a GCPVS

Miguel de Simón-Martín[1,2,*], **Montserrat Díez-Mediavilla**[2] **, and Cristina Alonso-Tristán**[2]

[1] Energy Resources' Smart Management (ERESMA) Research Group, Department of Electric, Systems and Automatics Eng., University of León, Campus de Vegazana s/n, León, 24071, Spain.

[2] Solar and Wind Feasibility Technologies (SWIFT) Research Group, Department of Electromecanics Engineering, University of Burgos, Campus de Río Vena s/n, Burgos 09001, Spain.

[*] **Correspondence:** Email: miguel.simon@unileon.es; Tel: +34-987-291-000-5391.

Abstract: Grid connected PV systems, or GCPVS, produce clean and renewable energy through the photovoltaic effect in the operation stage of the power plant. However, this is the penultimate stage of the facilities before its dismantlement. Before starting generating electricity with zero CO_2 emissions, a negative energy balance exists mainly because of the embodied energy costs of the PV components manufacturing, transport and late dismantlement.
First, a review of existing studies about energy life cycle assessment (LCA) and Carbon Footprint of PV systems has been carried out in this paper. Then, a new method to evaluate the Real Energy Payback Time (REPBT), which includes power looses due to PV panels degradation is proposed and differences with traditional Energy Payback Time are analysed. Finally, a typical PV grid connected plant (100 kW nominal power) located in Northern Spain is studied in these sustainability terms. This facility has been firstly completely modelled, including PV modules, inverters, structures and wiring. It has been also considerated the energy involved in the replacement of those components with shorter lifespan. The PV panels degradation has been analysed through the comparison of normalised flash test reports on a significant sample of the installed modules before and 5 years after installation.
Results show that real PV degradation affect significantly to the Energy Payback Time of the installation increasing slightly a 4.2% more the EPBT value for the case study. However, along a lifespan of 30 years, the GCPVS under analysis will return only 5.6 times the inverted energy on components manufacturing, transport and installation, rather than the expected 9.1 times with the classical estimation.

Keywords: Grid connected PV systems; Real Energy Payback Time; Life Cycle Assessment; PV degradation; Carbon Footprint; clean energy

1. Introduction

All manufactured products embody energy consumption because of the manufacturing process itself, transport and installation. In the case of energy generators, this energy can be recovered in the operation stage. Moreover, the so-called Renewable Energy generators, such as the Grid Connected Photovoltaic systems (GCPVS) generate back this energy in a sustainable way. To analyse this energy balance and when this sort of energy generation plants are really renewable and sustainable systems the Life Cycle Assessment (LCA) and the Energy Payback Time (EPBT) must be considered [1].

On the one hand, the LCA analyses the environmental impacts made by a manufactured product or construction along its lifespan. On the other hand, the EPBT calculates the needed time to recover the energy involved in the manufacturing, transport and installation processes.

In the case of GCPVS, three variables must be studied to evaluate the energy balance [1, 2, 3, 4, 5]:

- The global irradiation at the facilities location to estimate the energy production.
- The technical characteristics of the power plant parts.
- The Life Cycle Inventories (LCIs) of each component and involved operation.

In the related literature several approaches to evaluate the environmental impact of a PV system can be found. Some authors, like [2, 6, 7], just focus on the photovoltaic module and consider the impact of the other power plant components not significant. They consider that the manufacturing process represents between the 70% to 85% of the whole plant embodied energy, independently of the tracking devices (dual-axis, horizontal-axis or fixed systems) [1, 8]. Therefore, the PV panels' LCA analysis results mandatory. To calculate the LCA of a PV module the silicon purification process, the crystals growth, the transformation of silicon wafers into solar cells and, finally, the module construction is evaluated [4].

In [9, 10] the authors prefer to evaluate the impact of all the power plant components. The volume of the materials involved in the power plant construction is calculated first and then, the energetic cost of the manufacturing process, transport to the site location, start-up and replacement or dismantlement is estimated. This deep analysis results far more complex and requires the collaboration with the components' manufacturers which, sometimes, is not affordable.

Finally, the generated energy must be estimated. For this purpose, hystorical data from the installation or similar facilites can be used. In case these data is not available, PV production can be estimated through the measurement (or modelling) of the solar global radiation at the facilities' site and technical parameters of the generators (peak power and efficiency). Solar global radiation estimation can be conducted almost worldwide by data from private or open databases, such as HelioClim-3 [11] or PVGIS from the European Commission [12].

Unfortunately, PV energy production does not remain constant along the whole lifespan of the GCPVS. PV cells and encapsulation degradation and soiling effects on PV panels make modules' efficiency decrease significantly. There exist several studies on PV modules degradation, but effects under real operation conditions on field are still under study and thus, no general agreement has been found in this issue. Moreover, they depend on the PV technology (mono-Si, amorphous Si, thin-film...), installation conditions (on fixed structures or on sun-trackers), climatological conditions on site, etc [13, 14]. Most manufacturers estimate power looses for degradation in a 10% of the nominal power at the end of the PV modules' lifespan. On the other hand, reference [15] estimates power looses for crystalline sylicon between 0.5%·yr^{-1} and 3.5%·yr^{-1} after reviewing several carried out studies. Moreover, in this report, long-term measurements (more than 20 years exposition) show lower degradation rates than short-term measurements. They also found larger degradation rates for entire systems compared with modules degradation. The rapid initial degradation was attributed to oxygen contamination in the bulk of the Si junction, whereas the slow long-term degradation correlated linearly with ultraviolet exposure. It appeared unlikely that the slow loss was due to EVA browning [16]. High degradation rates are directly correlated with decreasing values for the PV module's fill factor (FF).

All electricity generation technologies generate carbon dioxide (CO_2) and other greenhouse gas emissions. To analyze the impact of a generating technology accurately, the total CO_2 amounts emitted throughout the system's lifespan must be calculated both direct (arising during operation of the power plant) and indirect (arising during other non-operational phases of the life cycle. Solar photovoltaics technology is commonly referred to as *"low carbon"* or *"carbon neutral"* because it does not emit CO_2 during its operation. However it is not really a carbon free generation system since CO_2 emissions arise in other phases of the life cycle such as construction, maintenance or dismantlement.

The carbon footprint is defined as the total amount of CO_2 and other greenhouse gases emitted over the full life cycle of a process or product and, in this case, is expressed as grams of CO_2 equivalent per kilowatt hour of generation which accounts for the different global warming effects of other greenhouse gases [17]. It can be calculated using the LCA method in a *"cradle-to-grave"* approach.

In the case of PV generation systems, the most energy intensive phase (accounting for 60% of the total energy requirement) is the extraction of silicon from quartz sand at high temperatures. Reductions in the carbon footprint of PV technology are expected to be achieved in thin-film PV modules, which use thinner layers of silicon, and with the development of new semi-conducting materials that would be less energy intensive. Life cycle CO_2 emissions are estimated in 35 gCO_2eq·kWh^{-1} for GCPVS operating in Southern Europe [18]. Lower sunlinght hours increase significantly this value.

In this paper, a deep analysis by the LCA method has been applied to a real GCPVS with horizontal axis tracking, which is a typical configuration in Southern Europe PV power plants. Moreover, for the first time, the measurement and evaluation of the PV degradation have been introduced and, thus, the real Energy Payback Time and carbon footprint have been calculated and presented as new parameters to evaluate the evironmental impact of a GCPVS. Then, its influence on the recovered energy by the PV generation along the GCPVS's lifespan is evaluated accurately. Developed methodology can be extended to other energy sources, resulting really worth of interest to compare objectively different power generation systems.

2. Facilities' Description

The Real Energy Payback Time and Carbon Footprint have been evaluated on a real fully-operational GCPVS located at Torquemada, Palencia, at Northern region in Spain (42.308°N latitude, 4.308°W longitude and 740 m.a.s.l.). The facility stands on a gentle, south-facing slope that is conductive to natural air circulation and has been used by the Solar and Wind Feasibility Technologies (SWIFT) Research Group on many previous studies, such as [19], because it represents with high fidelity real operation conditions of GCPVS. The area benefits from very favourable atmospheric conditions. Solar irradiation is estimated at approximately 1 450 kW·h·m^{-2}·yr^{-1} and the ambient temperature range between 4 °C and 20 °C. Moreover, the number of cloudy days is very low along the year. An aerial photograph of the facilities can be seen in figure 1.

In figure 1 it can be observed that few obstacles affect the power plant. The most significant one is a two floors house located next to the south-east corner of the facilities but its shadow only affects some PV panels from one string at the sunrise in winter. Thus, energy production is slightly affected from November to January.

Figure 1. Aerial taken photograph of the facilities. Source [19].

The power plant has installed 101.01 kWp in 546 PV panels model BP-7185S manufactured by BP. They can produce 185 Wp of peak power (2.5% tolerance), have an electric performance in the range 14–15% (manufacturer specifications) and 36.5 V and 5.1 A for the maximum power point. PV modules are arranged in groups of 14 panels in series to work with a voltage of 511 V (within the voltage range of the inverter). The current for each group is 5.1 A. Panels are arranged in 12 rows with three groups in each one and a further two rows with two groups and one group, respectively. This means that the distance between the first and the last row is 60 m and the width is 42 m approx. [19].

A mobile structure was designed which adjusts the position of the panels according to the Sun's declination angle along the year, in order to optimize the energy production. The tracking system consists of a hand-driven device that modifies the slope modules angle between 5° and 50°, allowing an horizontal axis tracking. Figure 2 shows the optimal tilting angles according to [20, 21], both for daily tracking (beta opt. daily) and monthly tracking (beta opt. monthly). As the angular regulation has a 5 degrees step, the hand-driven system requires 20 days at least for changing positions of the whole plant structure, and range is limited between 5° and 50° (due to structural and ground use), PV modules slope must be modified approximately every 26 days in autumn and spring, while in summer and winter their position is fixed at their extremes (beta practical). In figure 3 it can be observed the PV panels in its lowest and highest extreme positions respectively. Finally, the structure was installed in a way that needs no concrete foundations and it is directly driven into the ground.

PV panels generated energy is collected in one 100 kW nominal power inverter manufactured by Ingeteam (model Ingecon Sun 100). It admits an input voltage range of 405–750 V and 187 A of input current. Its harmonic distortion is less than 3% and its efficiency is higher than 96% at nominal operation conditions. In order to prevent unwanted disruptions due to any adverse effects of temperature, a ventilation system to eliminates warm air in summer was installed alongside the inverter in a stall,

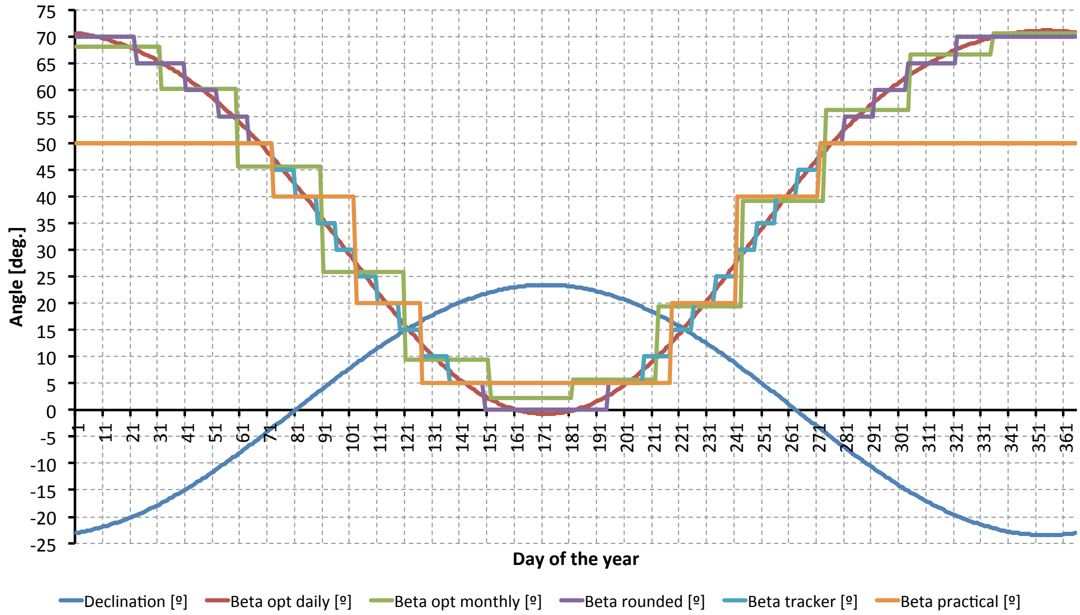

Figure 2. Horizontal axis tracking strategy for the PV power plant.

Figure 3. PV panels structures with hand-driven hor. axis regulation. Source [19].

located 5 m from the front row.

Finally, the protection system is structured in rows. Each PV panels group has a 10 A fuse and a 10 A switch, and the output is added to the previous row. The output wiring section of each protection box was designed to afford the maximum current from the previous rows groups. Thus, the output wiring and the last row protection box closest to the inverter location supports a maximum current of 198.9 A, coming from the 39 groups of PV panels. This output wiring is attached to the DC input inverter, located approximately 5 m from the enclosure of the first row.

3. Materials and Methods

3.1. Energy production estimation

The produced energy by the GCPVS case study has been estimated through real production data and PVGIS estimations for the installation site. It can not be used only real production data because several malfunctions and problems forced to stop and disconnect the power plant and made some production data not representative of the real nominal operation conditions. On the other hand, only PVGIS estimations may differ from the real behaviour of the power plant because of partial shading and real power losses. Thus, a combination with estimations from PVGIS has been used. Real production data has been weighted with a 0.8 factor, which has been considered appropriate for this case according to the reliability of the data. The three final energy estimations can be compared in figure 4. An annual production of 5 238 MJ·kWp^{-1}·yr^{-1} is estimated on average.

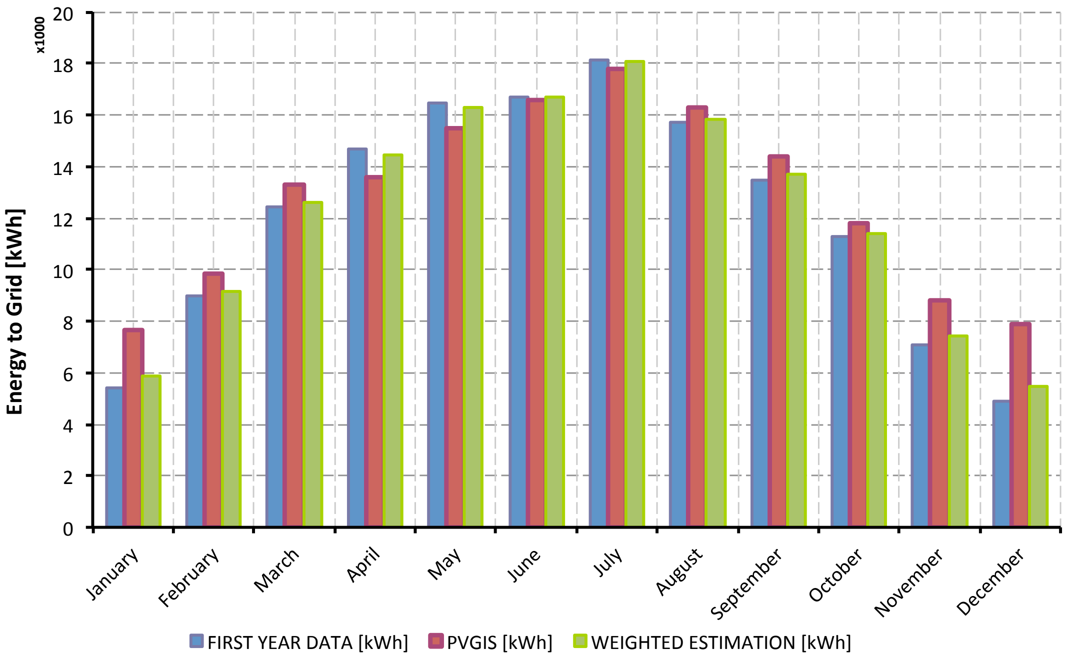

Figure 4. Energy injected to the Grid by the studied GCPVS.

Let's notice that the hand-driven horizontal axis tracking must be considered to estimate the energy production in PVGIS. This web utility does not allow this option by default. Thus, the power plant has been simulated as several fixed GCPVS with different tilting angles.

To compare generated energy and embodied energy, transformation of final electrical energy into primary energy is mandatory. According to the latest report [22], where the National Mix for Spain is considered, this conversion factor is 2.461 $kWh_p \cdot kWh_f^{-1}$, where subindex f refers to final energy and subindex p refers to primary energy. In this case, the contribution of renewable energy sources to the primary energy is just the 13.25%. Thus, conversion efficiency is approx. 0.41, which differs from other studies that consider just 0.35 [23].

In the same way, according to the National Energy Mix, PV generated energy would have associated a negative carbon footprint of 0.399 $kgCO_2eq \cdot kWh_f^{-1}$ [22]. This means that 1 kWh_f generated on a GCPVS is a kWh_f that has not been generated by other sources and, thus, the associated carbon emissions have been avoided. It also could be considered only the non renewable National Energy Mix, with 0.521 $kgCO_2eq \cdot kWh_f^{-1}$ associated emissions [22].

3.2. Degradation analysis

Photovoltaic generators are a relative new technology and they have not been widely tested currently. Although there exist several studies about PV modules performance, more tests along 5, 10, 15, 20 and 25 years are needed to characterize their durability and the properties of the energy production.

For the case study, a sample of 14 PV modules (2.6%) have been randomly selected and monitorized along 5 years since their installation at the power plant. Then, a normalized flash-test for each panel has been conducted and manufacturer specifications and flash-test results have been compared.

The flash test consists on the exposition of a PV module to the Standard Measurement Conditions (1 000 $W \cdot m^{-2}$ incident irradiance, 25°C environmental temperature and 1.5 Air Mass) in a climatic chamber. Through the exposition of a constant radiance flux, the PV module's characteristic I-V curve is obtained and thus, its electrical behaviour and performance. An example of an obtained flash-test report is shown in figure 5. Results for the considered sample can be observed in tables 1, 2 and 3 respectively.

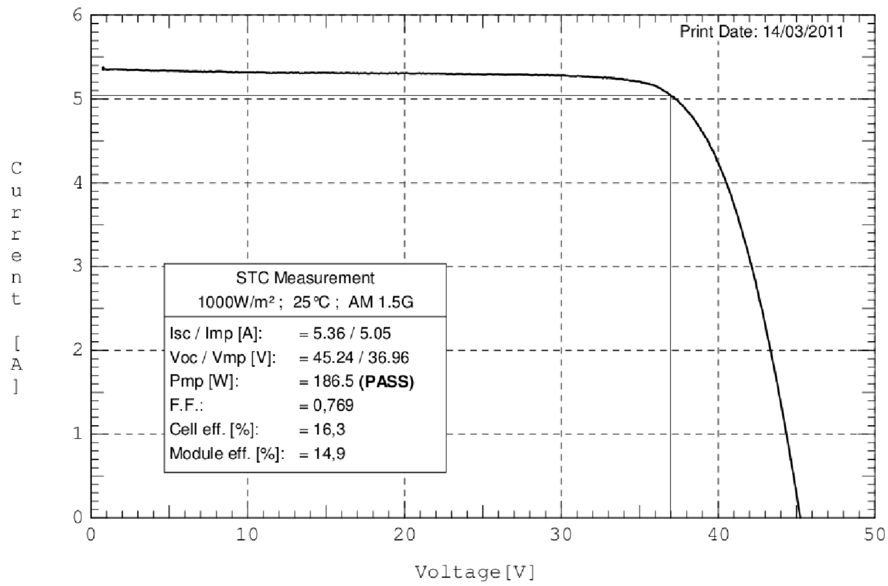

Figure 5. Example of a flash-test report for a PV module.

Table 1. Flash-test results before installation.

Serial No.	P [W]	V_{oc} [V]	I_{sc} [A]	V_{mp} [V]	I_{mp} [A]	FF [-]	Cell [%]	Mod. [%]
4461559	185	43.9	5.6	36.2	5.1	0.751	18.5	17.2
4461573	186	44.2	5.6	36.3	5.1	0.748	18.6	17.2
4462444	189	44.4	5.6	36.7	5.1	0.753	18.9	17.6
4463043	186	44.0	5.6	36.1	5.2	0.762	18.6	17.2
4463077	185	44.0	5.5	36.1	5.1	0.761	18.5	17.1
4463108	185	44.1	5.5	36.4	5.1	0.765	18.5	17.2
4463166	186	44.1	5.6	36.6	5.1	0.756	18.6	17.3
4463167	185	44.1	5.6	36.9	5.0	0.747	18.5	17.1
4465234	189	44.3	5.6	36.5	5.2	0.765	18.9	17.5
4465235	188	44.3	5.6	36.7	5.1	0.754	18.8	17.4
4465283	189	44.2	5.6	36.5	5.2	0.767	18.9	17.5
4465313	188	44.3	5.6	36.4	5.2	0.763	18.8	17.4
4465319	188	44.3	5.6	37.0	5.1	0.761	18.8	17.4
4465942	189	44.4	5.6	36.6	5.2	0.765	18.9	17.5
Mean	187	44.2	5.6	36.5	5.1	0.758	18.7	17.3
Std. dev.	38.0	0.3	0.0	1.0	0.0	0.001	0.4	0.3

Table 2. Flash-test results 5 years after installation.

Serial No.	P_{max} [W]	V_{oc} [V]	I_{sc} [A]	V_{mp} [V]	I_{mp} [A]	FF [-]	Cell [%]	Mod. [%]
4461559	178.0	43.96	5.4	35.37	5.0	0.749	15.5	14.2
4461573	180.0	44.33	5.4	35.85	5.0	0.752	15.7	14.3
4462444	177.8	44.35	5.2	36.22	4.9	0.776	15.5	14.2
4463043	177.6	44.24	5.3	35.88	5.0	0.765	15.5	14.1
4463077	177.3	44.37	5.3	35.93	4.9	0.760	15.5	14.1
4463108	175.6	43.97	5.3	35.69	4.9	0.755	15.3	14.0
4463166	176.4	43.81	5.4	35.68	4.9	0.745	15.4	14.1
4463167	177.3	44.48	5.3	36.42	4.9	0.756	15.5	14.1
4465234	184.8	44.92	5.4	36.52	5.1	0.760	16.1	14.7
4465235	184.1	44.93	5.3	36.56	5.0	0.767	16.1	14.7
4465283	184.5	44.91	5.4	36.64	5.0	0.765	16.1	14.7
4465313	184.0	44.78	5.4	36.44	5.1	0.764	16.1	14.7
4465319	185.2	44.98	5.4	36.70	5.1	0.760	16.2	14.8
4465942	186.5	45.24	5.4	36.96	5.1	0.769	16.3	14.9
Mean	180.7	44.52	5.3	36.20	5.0	0.760	15.8	14.4
Std. dev.	201.0	2.57	0.1	2.88	0.1	0.001	1.6	1.4

Table 3. Annual variation of the PV parameters.

Serial No.	P_{max}	V_{oc}	I_{sc}	V_{mp}	I_{mp}	FF	Cell	Mod.
4461559	-0.76%	0.03%	-0.68%	-0.46%	-0.27%	-0.05%	-3.24%	-3.49%
4461573	-0.65%	0.06%	-0.71%	-0.25%	-0.31%	0.11%	-3.12%	-3.37%
4462444	-1.19%	-0.02%	-1.54%	-0.26%	-0.75%	0.62%	-3.60%	-3.86%
4463043	-0.90%	0.11%	-1.25%	-0.12%	-0.96%	0.08%	-3.33%	-3.60%
4463077	-0.83%	0.17%	-0.87%	-0.09%	-0.67%	-0.02%	-3.24%	-3.51%
4463108	-1.02%	-0.06%	-0.76%	-0.39%	-0.71%	-0.27%	-3.46%	-3.72%
4463166	-1.03%	-0.13%	-0.71%	-0.50%	-0.63%	-0.29%	-3.44%	-3.70%
4463167	-0.83%	0.17%	-1.18%	-0.26%	-0.52%	0.24%	-3.24%	-3.51%
4465234	-0.44%	0.28%	-0.64%	0.01%	-0.54%	-0.13%	-2.96%	-3.20%
4465235	-0.41%	0.28%	-0.93%	-0.08%	-0.27%	0.33%	-2.87%	-3.10%
4465283	-0.48%	0.32%	-0.82%	0.08%	-0.62%	-0.05%	-2.96%	-3.20%
4465313	-0.43%	0.22%	-0.79%	0.02%	-0.58%	0.03%	-2.87%	-3.10%
4465319	-0.30%	0.31%	-0.64%	-0.16%	-0.20%	-0.02%	-2.77%	-2.99%
4465942	-0.26%	0.38%	-0.86%	0.20%	-0.58%	0.09%	-2.75%	-2.97%
Mean	-0.68%	0.15%	-0.88%	-0.16%	-0.54%	0.05%	-3.13%	-3.38%
Std. dev.	0.01%	0.00%	0.01%	0.01%	0.01%	0.01%	0.01%	0.01%

Table 3 shows the annual variation of the PV modules parameters under the hypothesis of a linear variation [24, 25, 26] between the initial conditions (table 1) and 5 years after installation (table 2). Thus, it can be observed that the modules peak power decreases $0.68\%\cdot yr^{-1}$ on average, while the modules fill factor (FF) increases $0.05\%\cdot yr^{-1}$. On the other hand, the cell and module efficiencies decreases more than $3.10\%\cdot yr^{-1}$ and $3.35\%\cdot yr^{-1}$ respectively.

3.3. Life Cycle Analysis

The LCA analysis requires, as first stage, the spatial and temporal limits definition about components and processes [1, 27, 28, 29, 30]. In our study, we have evaluated the energy needed for the manufacturing and transport of the PV modules, wiring, inverter and support structures. On the other hand, we have not considered the impact of the transformation centres, electrical protections, manpower, communication devices and documentation duties because of their impact can be considered almost negligible in the global sum.

To estimate the energy needed by the manufacturing process of a PV module, the methodology exposed in [4, 6, 31, 32, 33, 34] have been applied. The manufacturing process of a PV module can be considered mainly electrical (the 80% of the input primary energy). Therefore, the primary energy quantities depend strongly on the conversion efficiency of the energetic systems which feed the different stages of the whole process. These efficiency values have been estimated through a energy sources mix, which may differ between manufacturing countries and regions [1]. In the case study, the primary energy involved in the manufacturing process of PV mono-crystalline framed modules is $5\,200\ MJ_p\cdot m^{-2}$. As the power plant has 546 panels of 1.593 m x 0.790 m (1.26 m^2), the total amount of energy embodied in the PV panels is $3.573 \times 10^6\ MJ_p$.

On the other hand, the needed energy estimation for the manufacturing of the inverter has been calculated according to Table II in [9] and results from [1]. The embodied energy of the inverter system has been estimated under the hypothesis that the requirement of materials is similar for different manufacturers and proportional to the total weight of the inverter. In [9], a rate of 46.645 $MJ_p{\cdot}kg^{-1}$ is estimated for 150 kW inverters including transformer. Moreover, in [1], the energy involved in an inverter housing for six 100 kW inverters is 162 174 MJ_p (40 m^2 surface and 3 m height). A replacement rate of 10% for the housing components along the life-cycle is also considered. Then, for the inverter in the case study, which has been manufactured by Ingeteam (Spain) and weights 1 250 kg, an embodied energy of 88 402.17 MJ_p has been considered (70.72 $MJ_p{\cdot}kg^{-1}$ or 88.40 $MJ_p{\cdot}kW^{-1}$).

The tracking system and support structure are made of steel, with a weight of 130 $kg{\cdot}kWp^{-1}$. As the structure has no concrete foundations and the tracking system is hand-driven, no other energy needs have been considered for this component. The energy involved in the manufacturing process of the steel has been calculated from [35], which analyse the energy demands of a list of typical construction materials. Thus, for the manufacturing of 1 kg of steel, 35 MJ_p of primary energy have been estimated on average. To consider the energy needed for the installation, a 3% of the manufacturing process needed energy has been added in the estimation.

For the manufacturing of the wiring, which is mainly made of cooper, estimations from [35] have also been considered. Thus, 70 $MJ_p{\cdot}kg^{-1}$ have been estimated as wiring embodied energy. The volume of wiring materials depends on the Ground Cover Ratio (GCR) of the power plant and local technical regulations. In the case study, the total volume of wiring has been estimated taking into account the power plant configuration, described in detail in reference [19]. The electrical scheme of the installation shows 39 groups of 14 PV modules each one (511 V), which are arranged in 12 rows with three groups in each one and a further two rows with two groups and one group, respectively. Each group is connected by a set of 2 wires (positive and negative) which have 4 mm^2 section and total length of 40 m. Groups from rows are connected through protection boxes, which include a 10 A fuse and a 10 A switch per group in a way the section of the wires between protection boxes increases downstream. Thus, power losses remain minimum as total current increases. Distances between rows are 6 m and the wires' section at the inverter input is 95 mm^2. Details can be seen in table 4.

Thus, 6.4×10^{-4} m^3 Cu are involved in the connection of each PV modules group, and 6.48×10^{-3} m^3 Cu link the groupings. Moreover, a 1.5 factor has been added to take into account the ground connections and the communications wiring. Then, total wiring is estimated in 0.046 m^3 Cu.

Finally, along the lifespan of a GCPVS some components shall be substituted in order to guarantee power quality and the system availability. Thus, energetic replacement costs must be also included in the LCA analysis. The failure rates of PV modules, wiring or support structures are often very low -manufacturers must guarantee their products for at least 20 years- and, consequently, their energetic impact may be considered almost negligible. However, inverter devices show higher failure rates, mostly because of the complexity and fragility of their electronic parts. Therefore, according to [1, 36], the energetic impact of the inverters maintenance have been modelled as a replacement of the 10% of the inverter parts every 10 years. An additional 5% of the embodied energy has been added to all components to consider the dismantlement energy costs. Although this energy is not consumed until the end of the installation's life cycle, it has been considered as another energy cost in the manufacturing process.

For the estimation of the carbon footprint of every GCPVS's component, manufacturing origin has

Table 4. Power plant wiring characteristics.

Row	Distance to the inverter [m]	Groups	Nominal current [A]	Section [mm^2]
1	6	3	198.9	95
2	12	3	183.6	70
3	18	3	168.3	70
4	24	3	153.0	70
5	30	3	137.7	70
6	36	3	122.4	35
7	42	3	107.1	35
8	48	3	91.8	35
9	54	3	76.5	16
10	60	3	61.2	16
11	66	3	45.9	16
12	72	3	30.6	4
13	78	2	15.3	4
14	84	1	5.1	4

been taken into account. PV modules and structure were manufactured in Germany, while the Inverter and wiring come from Spain. Thus, primary energy manufacturing requirements have been expressed in final electrical energy terms through the appropriate conversion efficiency. Then, carbon emissions for the industrial sector for each country is applied (45 $gCO_2eq{\cdot}MJ_p^{-1}$ for Spain and 13 $gCO_2eq{\cdot}MJ_p^{-1}$ for Germany) [22, 37].

The energy devoted to the transport of equipment and materials has been calculated from tables in [38]. It has been considered that the transport has been carried out by heavy trucks, with an energetic cost of 2.426 $kJ_p{\cdot}km^{-1}{\cdot}kg^{-1}$. The displacements have been evaluated from the component factories to the installation site, through the main transport routes. Results are sumarized in table 5.

For the transport carbon footprint estimation, heavy trucks transport emission values have been considered. For a diesel 14 tn capacity heavy truck, carbon emissions are estimated in 791.44 $gCO_2eq{\cdot}km^{-1}$ maximum [39, 40, 41]. Thus, specific emissions are 0.0233 $gCO_2eq{\cdot}km^{-1}kg^{-1}$.

3.4. Energy/Carbon Payback Time vs. Real Energy/Carbon Payback Time

The classical evaluation of the EPBT is exposed in [42]:

$$\mathrm{EPBT} = \frac{E_{LCA}}{E_{ac}}, \tag{1}$$

where E_{LCA} is the required energy for the system manufacturing, transport and installation studied in the LCA and E_{ac} stands for the energy produced by the GCPVS along one year on average. Then, the result will be expressed in number of years needed to recover the initial energy consumption.

However, we found that equation 1 does not take into account significant parameters in the real performance of the GCPVS, such as the PV degradation and thus, power looses. Therefore, it results mandatory to rewrite the classical EPBT definition with a most reliable expression.

Table 5. Life Cycle Inventories (LCI) for the components of the GCPVS.

Component	Units [-]	Energy [MJ_p]	Spec. Energy [$MJ_p \cdot kWp^{-1}$]	Contrib. [%]	CO_2 emissions [$kgCO_2eq \cdot kWp^{-1}$]
PV modules	546	3 573 027	35 373	83.96	464.96
Inverter	1	89 293	884	2.10	39.78
Structure	13 131 kg	459 595	4 550	10.80	59.79
Wiring	0.046 m^3	28 687	284	0.67	12.78
Total manuf.	-	4 150 602	41 091	97.53	577.31
Component	**Weight [$kg \cdot kWp^{-1}$]**	**Distance [km]**	**Spec. Energy [$MJ_p \cdot kWp^{-1}$]**	**Contrib. [%]**	**CO_2 emissions [$kgCO_2eq \cdot kWp^{-1}$]**
PV modules	83.24	2 000	404	0.96	3.88
Inverter	12.50	200	6	0.01	0.06
Structure	130.00	2 000	631	1.50	6.05
Wiring	4.05	100	1	0.00	0.01
Total transp.	229.79	-	1 042	2.47	10.00
TOTAL	-	-	42 133	100.00	587.31

Under the hypothesis that the GCPVS degradation is linear through time, it can be considered that the energy injected to grid decreases an annual rate r:

$$E_{ac\,i} = E_{ac\,0} \cdot (1-r)^i, \tag{2}$$

where i is the i-th year and $E_{ac\,0}$ is the initial energy production by the power plant.

As the EPBT occurs when the initial energy is back by the produced energy:

$$E_{LCA} - \sum_{i=1}^{n} E_{ac\,i} = 0, \tag{3}$$

replacing equation 2 on equation 3, a geometric series is obtained:

$$E_{LCA} - \sum_{i=1}^{n} E_{ac\,0} \cdot (1-r)^i = 0,$$

$$E_{LCA} = E_{ac\,0} \cdot \frac{1-(1-r)^n}{1-(1-r)},$$

$$\frac{E_{LCA}}{E_{ac\,0}} = \frac{1-(1-r)^n}{r},$$

$$(1-r)^n = 1 - \frac{r \cdot E_{LCA}}{E_{ac\,0}}.$$

Thus, the Real Energy Payback Time (REPBT) can be evaluated by:

$$\text{REPBT} = n = \frac{\ln(E_{ac\,0} - r \cdot E_{LCA}) - \ln(E_{ac\,0})}{\ln(1-r)}. \tag{4}$$

In the same way, Carbon Emissions Payback Time can be expressed similarly to equation (1):

$$\text{CPBT} = \frac{C_{LCA}}{C_{ac}}, \tag{5}$$

where C_{LCA} are the carbon emissions for the system manufacturing, transport and installation studied in the LCA; and C_{ac} stands for the carbon emissions savings produced by the GCPVS along one year on average. Then, the result will be expressed in number of years needed to retrieve the initial carbon footprint.

While RCPBT refers to the Real Carbon Payback Time and its expression can been deduced as:

$$\text{RCPBT} = n = \frac{\ln(C_{ac\,0} - r \cdot C_{LCA}) - \ln(C_{ac\,0})}{\ln(1-r)}. \tag{6}$$

4. Results and Discussion

Taking into account the LCA analysis sumarized in table 5, the classical Energy Payback Time for the case study is:

$$\text{EPBT} = \frac{42\,133\,\text{MJ}_p\cdot\text{kWp}^{-1}}{12\,776\,\text{MJ}_p\cdot\text{kWp}^{-1}\cdot\text{yr}^{-1}} = 3.30\,\text{yr}.$$

However, the calculated Real Energy Payback Time for the same facilities and conditions, taking into account the 3.38% degradation rate obtained as mean annual variation in table 3, is:

$$\begin{aligned}\text{REPBT} &= \frac{\ln(12\,776\,\text{MJ}_p\cdot\text{kWp}^{-1}\cdot\text{yr}^{-1} - 0.0338\cdot 42\,133\,\text{MJ}_p\cdot\text{kWp}^{-1}) - \ln(12\,776\,\text{MJ}_p\cdot\text{kWp}^{-1}\cdot\text{yr}^{-1})}{\ln(1-0.0338)}\\ &= 3.44\,\text{yr}.\end{aligned}$$

Results for the Carbon Payback Time are:

$$\text{CPBT} = \frac{587.31\,\text{kgCO}_2\text{eq}\cdot\text{kWp}^{-1}}{585.97\,\text{kgCO}_2\text{eq}\cdot\text{kWp}^{-1}\cdot\text{yr}^{-1}} = 1.00\,\text{yr}.$$

$$\begin{aligned}\text{RCPBT} &= \frac{\ln(585.97\,\text{kg}\cdot\text{kWp}^{-1}\cdot\text{yr}^{-1} - 0.0338\cdot 587.31\,\text{kg}\cdot\text{kWp}^{-1}) - \ln(585.97\,\text{kg}\cdot\text{kWp}^{-1}\cdot\text{yr}^{-1})}{\ln(1-0.0338)}\\ &= 1.00\,\text{yr}.\end{aligned}$$

Results show a difference between the REPBT and the EPBT of 4.22 %, which may result not environmentally significant. Figure 6 plots the energy balances between the embodied energy in the GCPVS and the returned energy by PV generation. The classical analysis and the new proposed one taking into account the GCPVS degradation can be easily compared in the graph. At the end of the GCPVS's lifespan, 3.5 times the needed energy for the GCPVS existance is consumed by the system degradation. Long-term more conservative scenarios (0.5% and 1.00% degradation rates) show 3.32 yr and 3.34 yr REPBT respectively, while at the end of the GCPVS's lifespan about 7 times the embodied energy has been generated back in both cases.

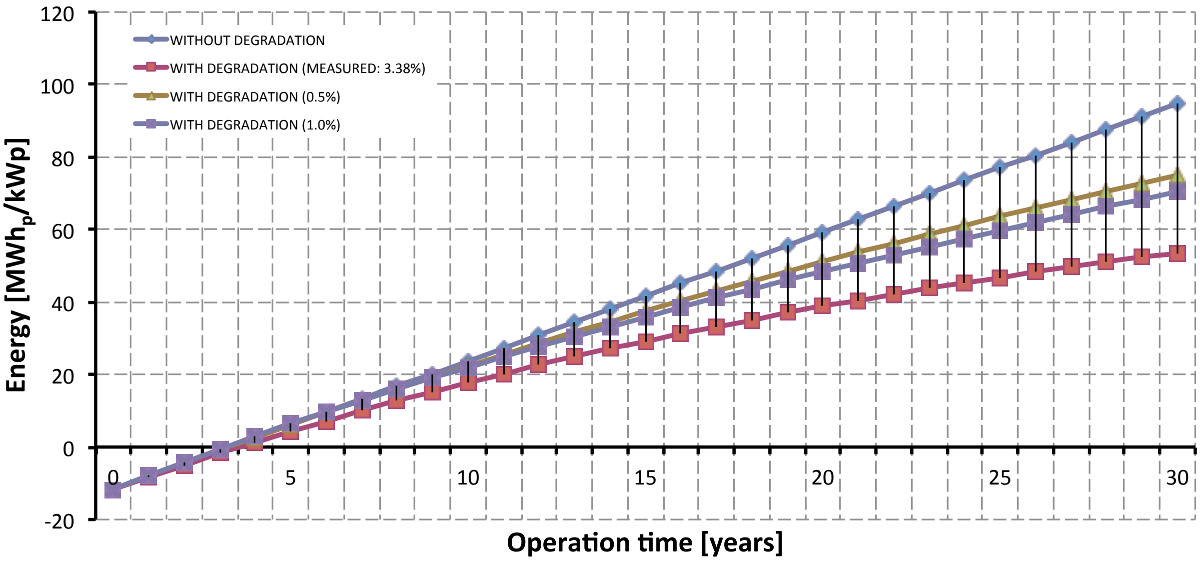

Figure 6. Energetic contribution of a GCPVS for several degradation rates.

On the other hand, manufacturing CO_2eq. emissions are retrieved by the GCPVS clean energy production in just one year under any degradation conditions, as it can be seen in figure 7. From that moment on, the energy produced by the CCPVS is completely free of carbon emissions and thus, it can be considered that every kWh_f has a negative carbon footprint equivalent to the carbon emissions that it would have been produced if that kWh_f would have been generated by other sources (according to the National Energy Mix in Spain: 0.399 $kgCO_2eq{\cdot}kWh_f^{-1}$ [22]). Then, final carbon footprint for the case study is estimated to be (for a 30 years lifespan) of −16 992 $kgCO_2eq{\cdot}kWp^{-1}$ under non degradation hypothesis, but only −10 192 $kgCO_2eq{\cdot}kWp^{-1}$, −15 693 $kgCO_2eq{\cdot}kWp^{-1}$ and −14 513 $kgCO_2eq{\cdot}kWp^{-1}$ under degradation rates of 3.38% (measured in this case study), 0.5% and 1.0% respectively. Nevertheless, in the worst case, the GCPVS is able to retrieve 18.35 times the carbon emissions needed for its components manufacturing, transport, installation and dismantlement.

Table 6 summarizes results from the bibliography and compares them with the obtained values in the current study (last row in the table). Yearly specific production from reference [1] installations have been estimated by PVGIS results according to the location latitude [12], in absence of real data. None of the other studies have considered the degradation effects on the EPBT and carbon footprint balance.

The estimated LCA (42 133 $MJ{\cdot}kWp^{-1}$) is in accordance with other Megawatt GCPVS, as it can be seen in table 6, showing very close results for $MJ{\cdot}kWp^{-1}$ in Spain. Moreover, the obtained EPBT value is in the range of those calculated in [1]. However, results differ significantly from those of [9] and [29].

Let's notice that the described PV plant from [29] has very small size, and it is a rooftop installation. This sort of PV plants reduces significantly the LCA value because of they often do not need foundations, use lighter structures and require less wiring. Thus, results from this reference may not be representative. Moreover, the associated CO_2 eq. amount is extremely low because of the large rate of nuclear energy in the Japanese Energy Mix.

In the case of the PV plant described in [9] and located in Springerville (USA), the LCA value is significantly low because of optimal installation procedures were applied. Nevertheless, obtained

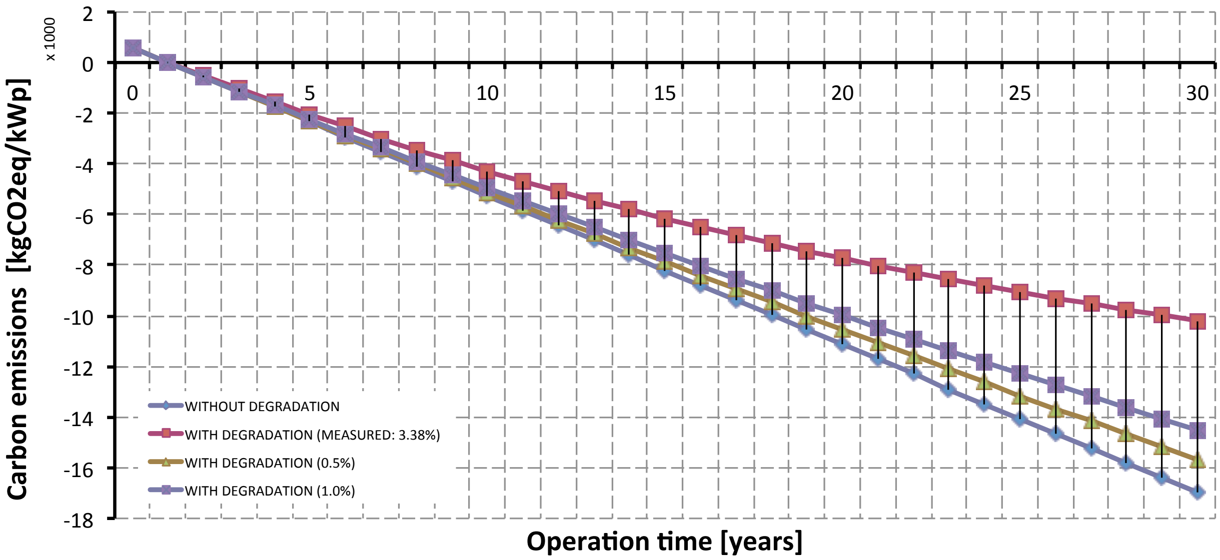

Figure 7. Carbon emissions balance of a GCPVS for several degradation rates.

result values, undoubtely, are out of range in comparison with those from our carried out study. The italian PV plant cited in [9], and described in [43, 44], shows a reduced value for the LCA but closer to the results obtained for several installations in [1].

Alsema carries out an overall study in [23] where he estimates the LCA, EPBT and CO_2 eq. emissions both for central PV power plants and rooftop installed PV plants. In table 6 only the results for central PV power plants are shown. For his present case in 1997, LCA values are in the range between 26 500 and 83 000 $MJ_p{\cdot}kWp^{-1}$, which agrees with our results. Moreover, the EPBT is in accordance with our data. However, Alsema's predictions for 2007 are too low in comparison with our results. Only CO_2 reduction estimation agrees with our calculated value.

From the results seen in [1], a significant scale effect is not observed. Also the EPBT value seems not to be influenced by the tracking system. On the other hand, the ratio EPBT/LCA remains almost constant in all studied cases.

5. Conclusions

Firstly, it has been observed that the LCA of the PV modules contribute, approximately, with the 80% of the embodied energy involved in the GCPVS. The supporting structure is the second highest value, with an 11% contribution.

It has been observed that approximately 3.3 years are needed to produce the energy embodied in the manufacturing, transport, start-up and dismantlement of a GCPVS. Moreover, if real components degradation is taken into account, a 4.5% more is needed. Therefore, under the hypothesis of a useful lifespan of 30 years for a GCPVS, it is able to give back the energy required for its existence 8.1 times at the end of its lifespan with the classical analysis, but only 4.6 times with the accurate study including components degradation.

Finally, the carbon footprint analysis for the case study shows that carbon emissions for the manufacturing, transport, installation and dismantlement of the GCPVS are retrieved in just one year, while

Table 6. Summary of results from the bibliography.

Ref.	Loc.	Traking	Size [kWp]	Production (yr) [kWh·kWp^{-1}]	LCA [MJ$_p$·kWp^{-1}]	EPBT [yr]	CO_2eq. [kg·kWp^{-1}]
[29]	Japan	Fixed	3	1 314	-	-	34.2-69.6
[9]	USA	Fixed	3 500	1 730	4 252-4 381	0.21-0.37	234.44
[9, 43, 44]	Italy	Fixed	2 943	1 160	17 902	1.30	-
[23]	1997	Fixed	-	1 280	26 602-82 816	1.8-8.0	2 304-5 760
[23]	2007	Fixed	-	1 280	16 062	1.0-2.0	768-1 152
[1]	Spain	Fixed	832	≈ 1 700	51 005	3.0-4.8	-
[1]	Spain	Fixed	1 152	≈ 1 620	51 005	3.0-4.8	-
[1]	Spain	Hor.	14 069	≈ 2 820	53 157	2.6-4.9	-
[1]	Spain	2-axes	6 020	≈ 2 150	60 140	2.1-4.3	-
[1]	Spain	2-axes	2 064	≈ 2 220	60 140	2.1-4.3	-
-	Spain	Hor.	101	1 455	42 133	3.44	587.31

degradation of the power plant does not affect this value. At the end of the GCPVS's lifespan, between 10 and 17 tnCO_2eq·kWp^{-1} emissions have been avoided. The better the PV components (with lower degradation rates) and the closer to the installation site they are manufactured, the more environmentally friendly would be the GCPVS. Manufacturing countries also affect significantly to the LCA of the power plant. These aspects may be clearly considered in the promoting of clean energy policies.

Conflict of Interest

All authors declare no conflict of interest in this paper.

References

1. Perpiñán O, Lorenzo E, Castro M A, et al. (2009) Energy payback time of grid connected PV systems: comparison between tracking and fixed systems. *Prog Photovoltaics* 17(2): 137–147.
2. Fthenakis V, Alsema E A, de Wild-Scholten M (2005) Life cycle assessment of photovoltaics: perceptions, needs, and challenges, in: *Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference*, 1655–1658.
3. Keoleian G A, Lewis G M (1997) Application of life-cycle energy analysis to photovoltaic module design. *Prog Photovoltaics* 5(4): 287–300.
4. Sherwani A, Usmani J, Varun (2010) Life cycle assessment of solar PV based electricity generation systems: A review. *Renew Sust Energ Rev* 14(1): 540–544.
5. Tahara K, Kojima T, Inaba A (1997) Estimation of power plants by LCA. *Kagaku Kogaku Ronbun* 23(1): 93–94.
6. de Wild-Scholten M, Alsema E (2004) Towards cleaner solar PV: Environmental and health impacts of crystalline silicon photovoltaics. *Refocus* 5(5): 46–49.

7. Fthenakis V, Alsema E (2006) Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004 – early 2005 status. *Prog Photovoltaics* 14(3): 275–280.
8. Bayod-Rújula A A, Lorente-Lafuente A M, Cirez-Oto F (2011) Environmental assessment of grid connected photovoltaic plants with 2-axis tracking versus fixed modules systems. *Energy* 36(5): 3148–3158.
9. Mason J E, Fthenakis V M, Hansen T, et al. (2006) Energy payback and life-cycle CO2 emissions of the BOS in an optimized 3.5 MW PV installation. *Prog Photovoltaics* 14(2): 179–190.
10. Nawaz I, Tiwari G (2006) Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level. *Energ Policy* 34(17): 3144–3152.
11. SoDa Team SoDa: HelioClim-3, 2016, Available from: `http://www.soda-pro.com/web-services/radiation/helioclim-3-for-free`.
12. Europan Commission: PVGIS- PV Potential Estimation Utility, 2016, Available from: `http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php`.
13. Hacke P, Smith R, Terwilliger K, et al. (2013) Testing and Analysis for Lifetime Prediction of Crystalline Silicon PV Modules Undergoing Degradation by System Voltage Stress. *IEEE J Photovoltaics* 3(1): 246–253.
14. Muñoz M A, Alonso-García M C, Vela N, et al. (2011) Early degradation of silicon PV modules and guaranty conditions. *Sol Energy* 85(9): 2264–2274.
15. Jordan D C, Kurtz S R (2012) Photovoltaic Degradation Rates-An Analytical Review. *NREL/JA-5200-51664* 1(1): 1–32.
16. Osterwald C R, Anderberg A, Rummel S, et al. (2002) Degradation analysis of weathered crystalline-silicon PV modules, in: *Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference*, 1392–1395.
17. University of Manchester: Carbon calculations over the life cycle of industrial activities, 2016, Available from: `http://www.ccalc.org.uk/`.
18. Postnote from the Parliamentary Office of Science and Technology: Carbon footprint of electricity generation, 2006, 268:1–4.
19. Díez-Mediavilla M, Alonso-Tristán C, Rodríguez-Amigo M, et al. (2012) Performance analysis of PV plants: Optimization for improving profitability. *Energ Convers Manage* 54(1): 17–23.
20. Khasawneh Q A, Damra Q A, Salman O H B Determining the Optimum Tilt Angle for Solar Applications in Northern Jordan 9(3): 187–193.
21. Skeiker K Optimum tilt angle and orientation for solar collectors in Syria 50(1): 2439–2448.
22. Government of Spain: Carbon emission factors and primary energy conversion coefficients for the different electrical energy sources in the Building Sector in Spain, 2014, IDAE, 1–32.
23. Alsema E (1998) Energy Requirements and CO2 Mitigation Potential of PV Systems, in: *BNL/NREL Workshop PV and the Environment*, 1–11.
24. Adelstein J, Sekulic B (2005) Performance and reliability of a 1-kW amorphous silicon photovoltaic roofing system, in: *Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference*, 1627–1630.

25. Chamberlin C E, Rocheleau M A, Marshall M W, et al. (2011) Comparison of PV module performance before and after 11 and 20 years of field exposure, in: *2011 37th IEEE Photovoltaic Specialists Conference (PVSC)*, 101–105.

26. Lorenzo E, Zilles R, Moretón R, et al. (2013) Performance analysis of a 7-kW crystalline silicon generator after 17 years of operation in Madrid. *Prog Photovoltaics* 22(12): 1273–1279.

27. Espinosa N, García-Valverde R, Urbina A, et al. (2011) A life cycle analysis of polymer solar cell modules prepared using roll-to-roll methods under ambient conditions. *Sol Energ Mat Sol C* 95(5): 1293–1302.

28. Fthenakis V M, Kim H C (2013) Life cycle assessment of high-concentration photovoltaic systems. *Prog Photovoltaics* 21(3): 379–388.

29. Hondo H (2005) Life cycle GHG emission analysis of power generation systems: Japanese case. *Energy* 30(11-12): 2042–2056.

30. 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 Energ Rev* 19: 255–274.

31. Jiao Y, Salce A, Ben W, et al. (2011) Siemens and siemens-like processes for producing photovoltaics: Energy payback time and lifetime carbon emissions. *JOM* 63(1): 28–31.

32. Mann S A, de Wild-Scholten M J, Fthenakis V M, et al. (2013) The energy payback time of advanced crystalline silicon PV modules in 2020: A prospective study. *Prog Photovoltaics* 22(11): 1180–1194.

33. Mohr N J, Meijer A, Huijbregts M a J, et al. (2013) Environmental life cycle assessment of roof-integrated flexible amorphous silicon/nanocrystalline silicon solar cell laminate. *Prog Photovoltaics* 21(4): 802–815.

34. Yamada K, Komiyama H, Kato K, et al. (1995) Evaluation of photovoltaic energy systems in terms of economics, energy and CO2 emissions. *Energ Convers Manage* 36(6–9): 819–822.

35. Hammond G, Jones C (2008) Embodied energy and carbon in construction materials. *P I Civil Eng Energ* 161(2): 87–98.

36. Pacca S, Sivaraman D, Keoleian G A (2007) Parameters affecting the life cycle performance of PV technologies and systems. *Energ Policy* 35(6): 3316–3326.

37. European Comission: Eurostat database, 2016, Available from: `http://ec.europa.eu/eurostat/data/database`.

38. Davis S C, Diegel S W, Boundy R G (2012) *Transportation Energy Data Book*, volume 1, 31st edition, Oak Laboratory: U.S. Department of Energy.

39. European Environment Agency E U (2016) *Explaining road transport emissions*, volume 1, 1st edition, Luxembourg: Publications Office of the European Union.

40. Oficina Catalana del Canvi Climátic E S (2011) Practical Guide for the Carbon Emissions Calculation. *Oficina Catalana del Canvi Climátic* 1(1): 1–32.

41. Joint Research Centre I E T (Ed.) (2013) *Well-to-wheels analysis of future automotive fuels and powertrains in the European context*, volume 1, 1st edition, Luxembourg: Publications Office of the European Union.

42. Pucker N, Schappacher W (1994) Installation of new energy systems: Energy balances and installation times; application to a photovoltaic system. *Renew Energ* 5(1–4): 212–214.

43. Previ A, Iliceto A, Belli G, et al. The 3.3 MW-peak photovoltaic power station at Serre, in: *Proceedings of 1994 IEEE 1st World Conference on Photovoltaic Energy Conversion - WCPEC (A Joint Conference of PVSC, PVSEC and PSEC)*, volume 1, 750–753.

44. Iliceto A, Vigotti R (1998) The largest PV installation in Europe: Perspectives of multimegawatt PV. *Renew Energ* 15(1): 48–53.