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ESTIMATION OF POWER CONVERSION EFFICIENCY AND IMPACT VARIABLES IN THE PHOTOVOLTAIC TECHNOLOGY FOR GENERATING ELECTRICITY FROM SOLAR ENERGY

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ABSTRACT

Photovoltaic (PV) technology, although an expensive and renewable technology, is the simplest electricity generation technology in terms of design and installation. PV cells are semiconductor materials that convert solar energy directly into electricity. A solar PV system's efficiency is defined as the ratio of the quantity of energy converted to the amount of energy converted. As a result, there are a lot of misunderstandings. The efficiency of a PV cell can be calculated as the ratio of power generated to total solar energy received. Only the electricity generated by the PV cell is taken into account in this definition. Other components and properties of PV cells, including ambient temperature, cell temperature, and the chemical makeup of the PV cell, are not taken into account in this study. PV cells heat up after being turned on and either loss or gain energy depending on how hot or cold the surrounding air is. To put it another way, when calculating the solar panel's collecting efficiency, the heat energy released as a result of the PV cell's heating must also be taken into account. Aside from that, the utilisation of these systems has increased due to the low level of pollution they emit. As a result, the usage of photovoltaic systems is receiving a lot of attention these days, and the deployment of these types of separated systems in Tripoli, Libya's capital, is a possibility.
Keywords: PV Cells, Power conversion efficiency, Case study, impact variables.

1. INTRODUCTION

Photovoltaic (PV) cells are electronic systems that can convert sunlight directly into electricity, have no moving mechanical parts, are easy to maintain and have a long life. PV cells are semiconductor materials that convert solar energy directly into electricity. Working as a semiconductor diode, the PV cell converts the energy carried by sunlight directly into electricity by utilising the internal photoelectric reaction. Solar energy can be converted into electricity with an efficiency of between 5% and 20%, depending on the structure of the PV cell. The surfaces of PV cells are generally square, rectangular and circular. The areas of PV cells also vary between 60-160 cm^2, with an average of 100 cm^2. Their thickness is between 0.2-0.4 mm. Several photovoltaic cells are connected in parallel or series and positioned on a flat surface to maximise the solar panel's power output. This structure is referred to as a PV module. PV modules are joined in series or parallel to form PV arrays ranging in size from a few watts to several megawatts, depending on the power need.

Access to electrical energy is an important factor in the development of humanity [1]. Today, the production of electrical energy depends to a great extent on the fossil resources available and the possibility of access to the electricity grid [2]. For several decades the development of populations has strictly depended on the ability to use fossil fuels to obtain energy, which has caused a great negative impact on the environment with respect to carbon dioxide emissions CO_2 in the atmosphere [3]. Out of this environmental problem has emerged the Green Economy concept, which has gained much prominence among academics and policymakers with regards to energy production issues [4]. The use and production of renewable energy does not exceed 20% in current consumption worldwide [5]. Meanwhile, the demand for energy increases excessively due to the increase in population and industrial development, for this reason, economic, environmental and social policies are promoted aimed at finding new ways to supply the energy needs of the population [5]. This is why there are already several plans led by some countries, such as the EU members, which have the purpose by 2025 of supplying with renewable energy sources more than 20% of the demand for electricity [6]. Some of the renewable energies that have the least impact on the environment are: wind, hydroelectric, bioenergy [7] and solar energy, in which it will be done emphasis to explain its benefits and applications.

Solar energy: Solar energy may be the best option for the future of humanity because it is the most abundant resource of renewable energy. The sun emits about$3.8 \times 10^{23} KW$, of which approximately $1.8 \times 10^{14}\ KW$ are intercepted by our planet [8]; solar energy comes in the form of light and heat. Most of this is lost due to scattering, reflection, and absorption by clouds. Studies have shown that global energy demand can be provided by the sun. Another reason why this is the energy of the future is that its use does not have any detrimental impact on the environment and does not affect the balance of ecosystems, compared to the exploitation of fossil resources that clearly cause a lot of damage. Solar energy harnesses the power of the sun to generate electricity, either directly through photovoltaic (PV) cells or through means of concentrated solar energy (SE). In contrast to solar energy generated by a standard turbine, SE technologies use arrays of mirrors to watch the sun and continuously reflect its rays to the heliostat point, where they are used to heat a working liquid. Concentrated photovoltaic (PV) technology, which is more efficient and of higher quality than prior solar energy technologies, is used in other current solar energy systems. On the other hand, photovoltaic solar panels may be placed on virtually any sunny surface, making them ideal for use in cities and other challenging terrains. PV solar energy refers to the direct conversion of sunlight to electrical energy through the use of either semiconductor devices or the deposition of metals on a substrate called solar cell thin film. Solar photovoltaic systems have recently developed as a feasible form of electricity generation, particularly in places that receive a lot of sunlight. Due to the ease of installation and the cheap ongoing maintenance costs, photovoltaic systems are now being employed more frequently than ever before.

PV system components: Generation block: The generation block is made up of photovoltaic panels. Their number and type of connection between them depends on several factors such as the average value of the insolation of the place, the load, and the load the maximum nominal output power of the panel.

Accumulation block: The accumulation block is the part of the photovoltaic system in charge of storing and controlling the loading and unloading of the system [6]. It is made up of the following components:

1. Battery bank: These are generally deep cycle batteries designed to withstand deep discharge levels during many charge and discharge cycles.
2. Battery bank: Avoid discharging the batteries through the panels at night, when the output voltage of the PV panel is zero.
3. Fuses or protection keys protect the batteries and are incorporated into the system as a safety element.

4. Load meter: Device that allows knowing the bank's state of charge.
5. Load block: The charging block is responsible for supplying the energy produced by the solar panels to the equipment that requires electrical energy [7] and is made up of:
6. Investor: Its function is to convert the direct current from the batteries or directly from the panel into alternating current for its use.
7. Wiring: It is the most basic of the system and its selection plays an important role in reducing energy losses.

MATERIAL AND METHOD

PV system design

The optimal design of PV systems is a very important factor in all PV installations. This optimal design often depends on the solar radiation variable [8]. Several methodologies have been reported in the literature for the sizing of photovoltaic systems, some of these are: intuitive, analytical design and design based on numerical methods. The design by numerical method is the most effective and recommended since it starts from an intuitive design which, through calculations, determines the optimal configuration [9]. Another important point in the selection of the photovoltaic system is the economic factor, since it is very important to select the most economical configuration that satisfies the need for energy to be supplied with the PV system [10]. The great computational development and technology have made it possible to make important advances in the design of photovoltaic systems with the help of the numerical method system, since it iterates many options which are possible solutions to the problem, and allows choosing the most optima [11].

Design for an isolated system

The methodology presented below is the type of isolated photovoltaic system design methodology applied in Tripoli, Libya.

- *Determination of the load profile:* The load profile gives us information on the simultaneity of the consumptions and is used to calculate the power conditioning and distribution systems. To make the consumption profile, it is necessary to take into account the habits of the place, studying for each specific case.
- *Consumption estimation:* It is the daily consumption of electrical energy, which must be supplied by the photovoltaic system, and the energy consumption of DC and AC is taken into account.

$$E_{cc} = \sum \#Eqip \times hours * P_{Eq} \ldots (\text{Eq. }1)$$

Equation 1 refers to the consumption estimate for DC equipment where $\#Eqip$ is the number of equipment with the same characteristics, 'Hours' is the number of hours the equipment is expected to be in operation, and finally, $P_{Eq}$is the nominal power of each connected DC equipment.

$$E_{AC} = \sum \#Equip \times hours * P_{Eq} \ldots (\text{Eq. }2)$$

In equation 2, the variables are exactly the same as in 1, only they apply for AC equipment. The total energy consumed by the load is the sum of the energy consumed by the DC devices and that consumed by the AC devices.

$$E_{Load\ Total} = E_{cc} + E_{AC} \ldots (\text{Eq. }3)$$

- *Loss estimation*: The energy generated by the panels must take into account the anticipated energy losses in the system (wiring, load control, inverter and batteries).

$$\eta_T = \eta_B \times \eta_{inv} \times \eta_R \times \eta_X \ldots (\text{Eq. }4)$$

  - •η_B: efficiency due to battery performance which can typically range from 75% to 90%.
  - •η_{inv}: efficiency due to the performance of the inverter used (if any), that is to say, mainly in 220 V installations. Default values usually range between 85% and 98%.
  - •η_R: efficiency due to the performance of the regulator

used. It usually depends on the technology used, but a default value of 90% is chosen if it is not known.

- •η_X: efficiency that considers the losses not contemplated:
  - Temperature.
  - Losses due to dispersion of parameters and dirt.
  - Losses due to errors in following the maximum powerpoint.
  - Wiring.

Dimensioning of photovoltaic panels: This sizing involves calculating the total energy needed to generate (considering the loss estimate) and based on the local insolation, determining the number of panels and the connection form (series and parallel).

The γ coefficient is a safety factor to deal with the degradation of power and performance of the different photovoltaic system components.

$$E_{gen} = \gamma\left(\frac{E_{AC}}{\eta_{T_{AC}}} + \frac{E_{CC}}{\eta_{T_{CC}}}\right) \dots (\text{Eq. } 5)$$

Where $E_{gen}$is the energy to be generated with the generator block, γ is the safety factor which is usually 1.1, $\eta_{T_{AC}}$ and $\eta_{T_{CC}}$ are the efficiencies of each of the AC and DC systems and, finally, and are the AC and DC daily energy consumption.

Dimensioning of photovoltaic panels: If a regulator with MPPT maximum power point monitoring is not used, whose function is to determine the point of maximum energy efficiency instantly in any situation, it must be taken into account that it will then be the battery that sets the system voltage.

$$E_{panel} = W_{p(T)} \times HSP \times \frac{V_{np}}{V_p} \dots (\text{Eq. } 6)$$

Where E_{panel} the daily energy is generated by the panel, $W_{p(T)}$ is the nominal or peak power of the panel corrected for temperature, HSP is the peak solar time and, finally, V_{np} is the nominal voltage of the panel and V_p is the peak voltage of the panel.

$$W_{p(T)} = W_p \times \left(1 - \Delta T \times \frac{C_d}{100}\right) \dots (\text{Eq. } 7)$$

Where T is the working temperature of the panel in ° C, ΔT = T-25 ° C, which is the increase above 25°C and, finally, $C_d$is the percentage value of the degradation coefficient.

Determination of the nominal voltage of the installation: The operating voltage can be determined from the power of the installation, which is logically related to the energy consumed. The standard voltages are usually used: 12 V, 24 V, 48 V or 120 V.

In general it is recommended:

- 12 V for powers less than 1.5 kW.
- 24 V or 48 V for powers between 1.5 kW and 5 kW.
- 48 V or 120 V for powers greater than 5 kW.

Dimensioning of photovoltaic panels:

1. Total number of panels: The total number of panels will be the number of panels needed to supply the load.

$$N_{TP} = \frac{E_{gen}}{E_{panel}} \dots (\text{Eq. } 8)$$

Where N_{TP} is the total number of panels of the generator block, $E_{gen}$is the daily energy generated by the block and $E_{panel}$is the daily energy generated by the panel.

2. Number of panels in series: The association of panels in series is done to increase the generator block's voltage.

$$N_{PS} = \frac{V_{nom}}{V_{np}} \dots (\text{Eq. } 9)$$

Where V_{enom} is the nominal voltage of the system and $V\ \ pn$ is the nominal voltage of the panel.

3. Number of panels in parallel: The association of panels in parallel is done in order to increase the current capacity of the generator block once the nominal voltage has been reached by the association of panels in series.

$$N_{PP} = \frac{N_{TP}}{N_{PS}} \dots (\text{Eq. } 10)$$

where N_{TP} is the total number of panels of the generator block and N_{PS} is the number of panels in series.

Dimensioning of Battery bank: The battery bank must supply the energy required by the load when there is no sun, or on cloudy days. This must accumulate the necessary energy to power the load during the days without sun and at night. Furthermore, this energy must take into account the losses produced by the various components.

To calculate the capacity of the battery bank, it is necessary to define mainly the following parameters:

- About: days of autonomy with little or no insolation.
- Dmax: maximum depth of discharge of the battery, which would be given by the manufacturer of the batteries; by default a value of 60% or 80% is chosen.
- ηD: discharge efficiency: it must take into account the battery discharge efficiency, the efficiency of the inverter, that of the charge regulator in case it has a DC output, losses in cables, etc. By default, a value of 75% can be used.

$$C_{nb} = \frac{E_{CT} \times (D_{out} + 1)}{V_{nom} \times P_{Dmax} \times \eta_D} \dots (\text{Eq. } 11)$$

Where C_{annab} is the nominal capacity of the battery bank in Ah / day, V_{nom} is the total daily energy consumption of the load, D_{out} is the days of autonomy with low or no insolation, V_{nom} is the nominal voltage of the system, P_{Dmax} is the maximum depth battery discharge and η_D is the discharge efficiency.

Number of batteries:

$$N_{BT} = \frac{V_{nom} \times C_{nom\_Bank}}{V_{nom\_Bat} \times C_{nom\_Bat}} \dots (\text{Eq. } 12)$$

Where N_{BT} is the total number of batteries in the bank, C_{nom_Bank} is the nominal capacity of the bank, V_{nom_Bat} is the nominal capacity of a battery, C_{nom_Bat} is the nominal voltage of the system and is the nominal voltage of a single battery.

Number of batteries in series: $N_{BS} = \frac{V_{nom}}{C_{Bat\_nom}} \dots (\text{Eq. } 13)$

Number of batteries in parallel: $N_{BP} = \frac{N_{BT}}{N_{BS}} \dots (\text{Eq. } 14)$

Charge regulator sizing: The regulator is connected in series with the photovoltaic panels, so their current will flow through it. As a design rule, the nominal current of the regulator is chosen 20% or 25% higher than the short-circuit current ($N_{pp} \times I_{cc}$) delivered by the generator block or the higher value of the DC load current ($I_{car_{cc}}$).

$$I_{reg} = 1.25 \times \max(N_{pp} \times I_{cc} \times I_{car_{cc}}) \dots (\text{Eq. } 15)$$

Where I_{Greg} is the nominal current of the regulator, N_{PP} is the number of solar panels in parallel, (I_{cc}) is the short-circuit current of a photovoltaic panel, $N_{pp} \times I_{cc}$ is the short-circuit current of the generator block and for $N_{pp} \times I_{cc} \times I_{car_{cc}}$ must use the maximum value between the short-circuit current of the generator block and that demanded by the continuous load.

Dimensioning of Inverter: The power of the inverter will be determined based on the power of the AC consumer appliances, the performance of the inverter itself and the simultaneous use of said appliances.

$$S_{inv\_out} = 1.25 \times S_{car_{cA}} \times FS \dots (\text{Eq. } 16)$$

$$S_{inv\_out} = 1.25 \times \frac{P_{car_{cA}}}{Fp} \times FS \dots (\text{Eq. } 17)$$

$$P_{inv\_in} = 1.25 \times \frac{P_{car_{cA}}}{\eta_{inv}} \times FS \dots (\text{Eq. } 18)$$

$$P_{inv\_in} = 1.25 \times \frac{P_{in\_out}}{\eta_{inv}} \times Fp \times FS \dots (\text{Eq. } 19)$$

Where S_{inv_out} is the nominal power of the inverter, P_{inv_in} is the input power of the inverter, $P_{car_{cA}}$ is the power of the loads in AC, Fp is the power factor of the loads in AC, FS is the factor of simultaneity of the consumption in AC and η_{inv} is the inverter yield. To take this fact into account, a simultaneity factor (FS) is applied, which represents the probability of simultaneous use of the AC consumer appliances.

The value of this coefficient results from an estimate due to experience or a regulation.

Case application

The following practical case of application is carried out for a house in Tripoli where the average energy consumption per person is around 1.6 KWh / day; In other words, it is above 6 KWh / day for a family of four according to the per capita electricity consumption indicators of the World Bank. In this case, the photovoltaic system will be dimensioned only for some household appliances in the home, since the idea is not to disconnect the home from the grid, but rather to support its energy consumption with the photovoltaic system.

The appliances are as follows:

1. Five 10W energy-saving light bulbs.
2. A 90 W laptop.
3. Two 10 W cell phones.
4. A 30W digital decoder.
5. A 40 ”100W television.

No DC installation is planned. High system reliability is required for low irradiance (cloudy) days.

Consumption estimation:

Table 1. Estimation of electrical consumption of household appliances in Wh / day.

Device	Quantity	Power(W)	Hours (h)	total Consumption (Wh / day)
Bulbs	5	10	6	300
Portable PC	1	90	3	270
Digital Decoder	1	30	4	120
Cell phones	2	10	2	40
TV	1	10	4	400
Avg. total Consumption (Wh / day)				1130

As can be seen in the table above, the consumption to calculate the system is 1130 Wh / day.

Loss estimation:

- η_B: battery efficiency (80%).
- η_{inv}: inverter efficiency (85%).
- η_R: regulator efficiency (95%).
- η_X: efficiency due to other losses (95%)

Efficiency calculation:

$$\eta_T = 0.8 \times 0.85 \times 0.95 \times 0.95$$

$$\eta_T \approx 0.614$$

The generator block will have to generate 39% more energy to compensate for the losses.

Calculation of the optimal angle of inclination of the panels:

Table 2. Description of the panel.

150W polycrystalline Silicon Solar Panel		
Rated Power	150W	Wp
Intend to PN	18.5	V
Current at PN	8.5	A
Open Circuit Voltage	22.9	V
Short Circuit Current	8.757	A

Using the geographical coordinates of Tripoli, the minimum average insolation data for each month at different inclinations are obtained. Due to its location close to the equator, the angle of inclination can be between 0° and 20° in orientation to the south.

Energy to be generated by the generator block:

$$E_{gen} = 1.1\left(\frac{E_{Cargetotal}}{\eta_T}\right)$$

$$E_{gen} = 1.1\left(\frac{1130\ Wh/day}{0.614}\right)$$

$$E_{gen} \approx 2024.43wh/day$$

Daily energy generated by a 150 Wp panel without MPPT.

For the calculation, it is necessary to know some climatic parameters of the place, the peak solar hours (HSP), the peak power of the panel (Wp) and the peak voltage (Vp). This calculation is carried out by dividing the solar radiation value of the worst time of the year by 1 kW / m2 and in this way the peak solar hours for energy production are obtained.

$$HSP = (4.5\frac{kWh}{m^2}/day)/1\frac{kW}{m^2}) \approx 4.5\ h\ /\ day$$

$$Wp = 150\ W$$

$$Vp = 18.5\ V$$

$$E_{panel} = W_{p(T)} \times HSP = 150W \times \frac{4.5h}{day}$$

$$E_{panel} = 675Wh/day$$

Extra recovery energy:

In this case, it will be considered to generate an extra 20% of energy to prevent the risk of generation on cloudy days.

$$E_{Extra} = 0.2 \times 2024.43\ wh/day$$

$$E_{Extra} = 404.9Wh/day$$

Total number of panels: $N_{TP} = \frac{(2024.43+404.9)Wh/day}{675\ Wh/day}$

$$N_{TP} = |4|$$

$$E_{panel} = 4 \times 150W \times \frac{4.5h}{day} = 2700Wh/day$$

Dimensions of Battery bank: $C_{nb} = \frac{\frac{1130Wh}{day(3+1)}}{24V \times 0.8 \times 0.85 \times 0.9}$

$$= \mathbf{308Ah}$$

12V and 220 Ah nominal maintenance-free batteries will be used for the bank.

Table 3. Battery life time description.

Medium temperature of Operation (°C)	AGM (Years)	Gel (Years)
20	7 to 10	12
30	4	6
40	2	3

Total NUMBER of batteries: $N_{BT} = \frac{24V \times 308Ah}{12V \times 220Ah} = 4$

Number of batteries in series:

$$N_{BS} = \frac{24V}{12V} = 2$$

Number of batteries in parallel:

$$N_{BP} = \frac{4}{2} = 2$$

Maximum bank charge and discharge current:

Next, the maximum charge C_5 and discharge C_{20} current for the calculated battery bank will be calculated.

$$C_{\max\_Car} = N_{BP} \times C_5 = 2\frac{220Ah}{5h}$$

$$C_{\max\_des} = 88A$$

$$C_{\max\_des} = N_{BP} \times C_{20} = 2\frac{220Ah}{20h}$$

$$C_{\max\_des} = 22A$$

MPPT charge controller sizing:

The power of the photovoltaic generator can exceed its maximum input power. In this case, the regulator will limit said power, providing the maximum nominal current specified by the manufacturer, in this way the device will not suffer any damage. One of the characteristics of MPPT regulators is that they have their point of maximum efficiency when working at powers close to the nominal ones. As the cost of regulators increases with their nominal power, sizing a regulator based on the generator's peak power entails unnecessary expense.

For the sizing of the charge regulator, it is necessary to take into account the peak power of the photovoltaic generator and the nominal voltage of the battery bank:

- Nominal voltage of the battery bank: 24 V.
- Peak power of the photovoltaic generator: 600 Wp (4 x 150 Wp).
- Voltage of the open circuit of the photovoltaic panels: 22.9 V.

Table 4. MTTP regulator selection.

Electrical TS-MPPT-45		
Maximum Battery Current	45A	
Nominal Maximum Solar output	12V	600W
	24V	1200W
	48V	2400W
Max Solar Circuit	150W	

A nominal 45A and 1200 Wp nominal power MPPT regulator will be used, operating with a nominal 24 V battery bank.

$$V_{in} = 1.25 \times N_{PS} \times V_{OC}$$

$$V_{in} = 1.25 \times 4 \times 22.9$$

$$V_{in} = 114.5\ V$$

In this case, the maximum input voltage does not exceed the maximum input voltage of the charge controller specified by the manufacturer (150 V).

Maximum charge and discharge current:

The total power consumption of the load will be given by the sum of the (nominal) power of all the electrical components in steady-state and has a value of 290 W.

The maximum charge current can be calculated based on the nominal power of the regulator for a 24 V battery bank.

$$I_{Des\_bat} = 1.25\, {}^{290W}/_{24V \times 0.85} \approx 14.2 < 22A$$

In this case, neither the charging nor the discharge currents exceed the values of C_{20} and C_5 of the battery bank respectively.

$$I_{Carga} = \frac{1200W}{21V} \approx 51.14A < 88A$$

Inverter sizing:

A FP = 0.8 and a FS = 1 will be used because they could all be used simultaneously.

$$S_{inv\_out} = 1.25 \times S_{Car\_CA} \times FS$$
$$= 1.25 \times \frac{P_{Car\_CA}}{Fp} \times FS$$

$$S_{inv\_out} = 1.25 \times \frac{290W}{0.8} \times 1 = 453.2VA$$

$$I_{pico\_carga} = \frac{290W}{220V} \approx 1.4A$$

Table 5. Characteristics of the inverter.

Inverter TGP 24-600 of 600A	
Max Power	11A
Continuous energy	600W
Max Efficiency	90%

Scheme of the system:

- Four 150 W panels.
- A 45 A nominal charge regulator with MPPT.
- 24V and 600 VA inverter.
- Four 220 Ah batteries.

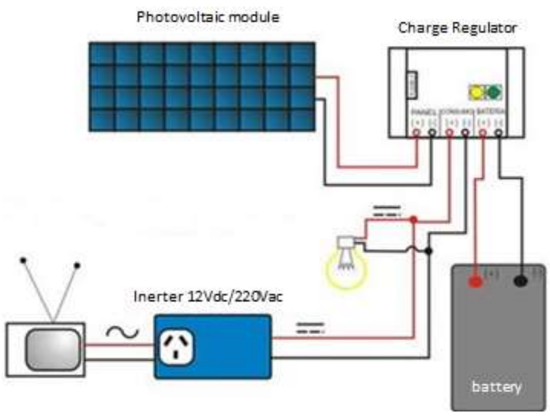

Figure 1. System diagram.

Conclusions.

With the results obtained from the calculations carried out for the sizing of the photovoltaic system, which is designed for a house located in Tripoli, it is possible to observe that it is technically feasible to implement said system. With the data obtained from the radiation of the city it was possible to size a system which, although it is a bit robust due to the fact that the design is based on the worst data of solar radiation that reaches the city (the number of peak hours of sun and the autonomy time of the system), it is a reliable system since it provides the necessary energy for three days and four nights of autonomy without receiving solar radiation during this period. The sizing of the solar system has a large number of variables available to the designer, so the choice of these components must be made taking into account it takes into account the design needs and, additionally, the economic aspect of the project must be taken into account. Since we can have infinite system configurations depending, for example, on the solar panels we choose, since the price of the panels rises considerably as the nominal power value is greater. In addition to this, maintenance of the photovoltaic power production system should be considered. Where we have the solar panels are built to last 25 years and do not need greater care than cleaning dust. On the other hand, there are the batteries, which have an average life time of 10 years, which means that, although the panels last 25 years, the batteries will have to be replaced with new ones after 10 years of use. With the rest of the electrical and electronic systems, it is pertinent to know that they are going to have some type of wear and that due to this degradation of the components, the efficiency that is had at the beginning of the installation is lost.

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