Energy and Buildings (2014): 09/2/2024

DOI: https://doi.org/10.1016/j.enbuild.2014.04.030

DESIGN OF THE BACK-UP SYSTEM IN PATIO 2.12 PHOTOVOLTAIC INSTALLATION

***B. García-Domingo[1], M. Torres-Ramírez[1], J. de la Casa[1], J. Aguilera[1], F.J. Terrados[2]**

[1] *IDEA Research Group, University of Jaén, Campus de Las Lagunillas, 23071*
Jaén (SPAIN)

[2] *Escuela Técnica Superior de Arquitectura, dpto.: Proyectos Arquitectónicos, University of Sevilla, C/ S. Fernando, 4, 41004. Sevilla, (SPAIN).*

*****Corresponding author: Tel.: +34 953 213 306; fax: +34 953 211 967

E-mail address: bgarcia@ujaen.es

ABSTRACT

Andalucía Team presented in the Solar Decathlon Europe 2012 Competition a proposal of a modular, sustainable, self-sufficient housing, Patio 2.12. Inspired by Mediterranean style, Patio 2.12 was composed of four habitable modules around a common space ("patio"). Each habitable module has a photovoltaic system on its roof. Simplicity and modularity determined the design of the photovoltaic system so that, together with a global electrical energy management system, the use of the locally generated electrical energy can be optimized.

Amongst others, a remarkable innovation included in Patio 2.12 was the use of an intelligent controlling device, based on an energetic support system that could manage the flows of electrical energy of all elements of the electrical installation integrated in the house. This system allows adapting the electricity availability to the consumption demand, maximizing the amount of photovoltaic energy locally generated and instantaneously consumed.

This paper implements the use of a simulation software model to analyse the electrical energy balance of the photovoltaic electrical installation. This model estimates the electrical photovoltaic generation and the electrical exchanges with the grid and the battery bank, under a determined load profile, and for a specific period of time, using environmental data as inputs to the model.

Keywords: Self-sufficient housing, Building-Integrated photovoltaic, Solar Decathlon, Photovoltaic system design, electrical energy balance.

1. Introduction

Experts on architecture, photovoltaic (PV[i]) solar energy and Home automation from Universities of Sevilla, Málaga, Granada and Jaén joined to form the Andalucía Team [2, 3]. Andalucía Team presented in the Solar Decathlon Europe (SDE[ii]) 2012 competition, the prototype called Patio 2.12 [4], inspired by Mediterranean life style as show in Fig. 1. This proposal was based on modularity, sustainability and self-sufficiency housing. So, Patio 2.12 was composed of four habitable modules around a common space ("patio") that included a PV system on each roof and a global electrical energy management system. The design of the PV system, together with the implemented management system, allows optimizing the use of the locally generated PV electricity, obtaining a higher autonomy from the electrical grid.

Figure 1. Inside view of the project Patio 2.12.

Members of IDEA[iii] (Investigation and development in solar energy) research group and students of the University of Jaén, designed, developed and implemented the grid connected PV installation and the global electrical energy management system in Patio 2.12.

After the participation of Andalucía Team in SDE 2012, Patio 2.12 got the second award in the general classification on the competition, as well as the first places in contests related to the energy, such as, energy efficiency and energy balance.

This paper describes the design principles of the electrical energy systems installed in Patio 2.12. Furthermore, it introduces a simple simulation model to estimate the real performance of the designed electrical system under determined environmental conditions and a specific load profile. The behavior of this model is evaluated by comparison of the real monitoring data obtained during the competition period with the simulated data by the proposed model. Finally, this model is applied to estimate the annual electrical energy balance of the entire PV system for a Typical Meteorological Year (TMY[iv]) in Madrid.

2. Design of the PV system

2.1. Premises of the design

The participation of the project Patio 2.12 in the SDE competition, made the design to be restricted by a set of rules [5] imposed by the organization of the event. These limitations influenced the PV system design and were referred to the architectural envelope, maximum surface of the housing, maximum AC[v] (Alternating Current) nominal power of the inverter, and maximum capacity of the battery bank. Apart from these restrictions, to carry out the design of the PV system, some principles were taken into account in order to satisfy the project concepts previously mentioned.

- Modular concept.

The modular concept was introduced as one of the main basis of the architectural and PV system design. This modular concept defines the architecture of the house as addition of multiple independent areas that make up a whole space. According to the user requirements at any time, the house may change its setting, increasing the possibility of satisfying the space needs of all kind of families. The adopted solution was based on the use of four habitable modules: kitchen, bedroom, living-room, and technical box, all of them around a common nexus "patio". A PV system was integrated on the roof of each habitable modules. Each PV system was composed of a PV generator, a grid-inverter, and all the necessary security protections.

- Electrical energy autonomy.

In other way, it is remarkable the importance of the electrical energy autonomy in the implemented installation. The main objective of the design of the PV system is supplying the consumption needs of the house, being -as much as possible- grid independent. At the community level, increasing levels of electricity autonomy can deliver social, financial and environmental benefits [6]. To reach this objective, a global electrical energy management system was included as a key element of the electrical installation. At this point, the existence of research works [7,8] with the aim of assessing the energetic, economic and environmental impact of the use of batteries in domestic grid-connected PV systems must be highlighted.

- Optimization of the PV generation use.

To achieve the previous mentioned aim, the PV installation included a global electrical energy management system, in order to maximize the amount of electricity generated by the PV installation and consumed by the local loads in the house [9,10,11].

The incorporation of this global electrical energy management system allows the consecution of two main objectives:

a) To adapt the consumption to the generation, allowing the displacement of the local demand curve, taking into account the PV electricity locally generated, always within the range of load use preferences of the final user. In the particular case of the SDE contest period, some minimum consumption needs were daily imposed by the organization. These consumption needs were used as inputs to the global electrical energy management system, through a self-designed software tool. According to the prediction of available solar resource and the user consumptions preferences, the intelligent management system decided the optimum time interval to activate these load consumptions.

b) To use a backup system, composed of a battery bank and a battery inverter. This backup system allowed that the great majority of the consumption needs were supplied by means of the PV electricity generated in a direct or indirect way (by the use of electric storage). The excess of this PV generated electricity is used to charge the batteries in a first place. After that, and if still having extra electrical energy, this will be injected to the electric grid (only in the case that the battery bank is fully charged). Attending of the State of Charge (SOC[vi]) of the battery, the PV generation, and the instantaneous local load consumption, the global electrical energy management system controlled the interaction between the different components of the system, to follow the strategy previously introduced. Acting this way, we can take advantage of one of the most important characteristics of PV solar energy: it is a distributed electrical energy.

The proposed global electrical energy management system could be applied for residential micro-grids, considering grid tariffs, storage levels and load consumption as system`s control inputs [12].

2.2. PV system description

The house “Patio 2.12” was divided into four independent habitable modules with a “patio” used as nexus of them. Following the modular concept, the installation design consisted of four PV grid-connected systems integrated on the roof of each habitable module. The configuration of each system is shown in Fig. 2. This type of design allows the expansion of the house by simply adding the necessary habitable modules, each one with a fully integrated grid-connected PV system.

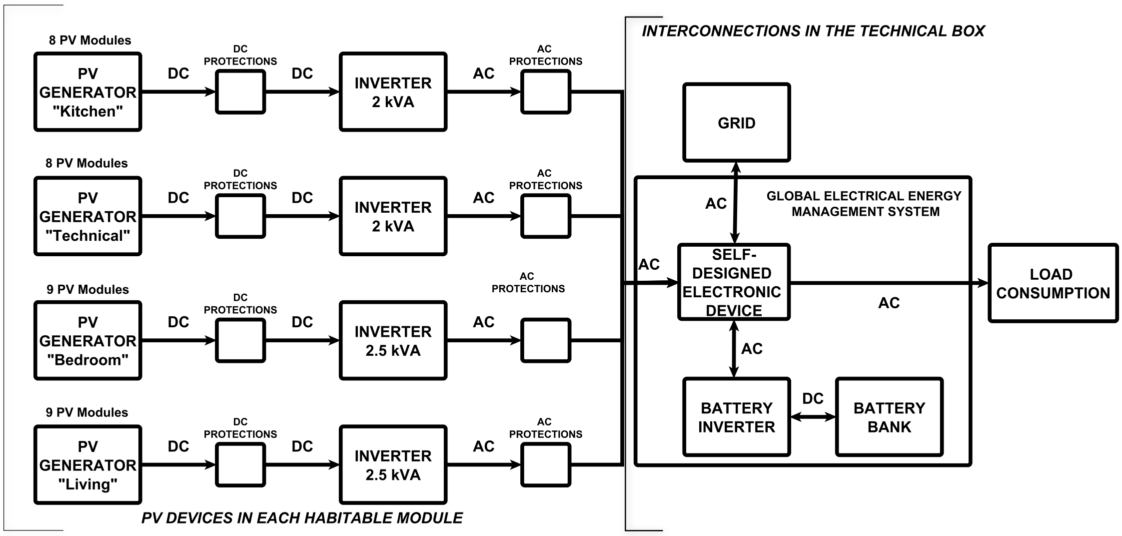

Figure 2. Configuration scheme of each individual PV system. Interconnection in the Technical Box.

- PV Generator and inverters

The PV modules are the most important elements that compose the PV installation. One of the most innovative and efficient PV technologies available in the market was selected for the present installation: Monocrystalline PV modules based on back-contact solar cells-SunPower E20/333 [13]- with 20,4% of efficiency and 333W of maximum peak power. The area occupied by the PV installation was limited by the dimension of the house itself, so that, the election of these PV modules was done due to their high efficiency, which allowed installing the maximum peak power array in the minimum space. The surface requirements of the selected technology were of 4.9m^2 per installed kWp.

The whole installation was formed of 34 PV modules, resulting a PV generator peak power of 11,322 Wp. The PV installation was divided into four PV systems, incorporating one inverter for each PV system. In this way, the PV systems could independently work between them. There were two different PV array configurations in function of the available area on the roof -useful area to the disposal of PV modules. Fig. 3 shows a real overhead view of PV systems’ configuration.

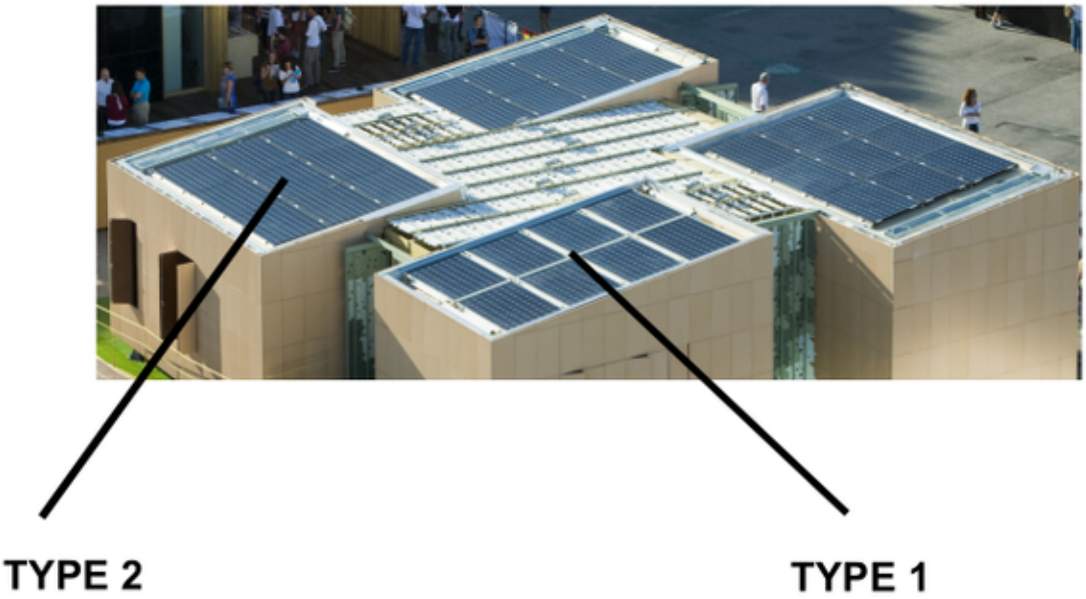

Figure 3. PV installation following the modular concept. Design presented in SDE 2012 competition.

The characteristics of each configuration type are shown in table 1.

Table 1:

Specifications for each configuration considered to the design of the PV systems.

HABITABLE MODULE TYPE	AVAILABLE AREA ON THE ROOF	PV MODULES CONNECETED IN SERIES	INVERTER	TILT ANGLE
TYPE 1	13 m^2	8	2kVA grid inverter - SMA SB 2000 HF-30 [14]	8º
TYPE 2	14.7 m^2	9	2.5 kVA grid inverter -SMA SB 2500 HF-30 [14]	8º

The tilt angle of the PV generator was selected according to the rules related to the solar envelope of each house, imposed the latter limits by the competition organization. Concerning to the modular concept, the use of string-oriented grid connected single-phase inverters [15,16] was justified. In conclusion, the grid-connected PV installation integrated in Patio 2.12 project had 11.32kWp of maximum peak power for the PV generator (2 PV systems TYPE 1 and 2 PV systems TYPE 2), as well as 9kVA of inverter nominal power.

Anyway, in addition to the possibility of incorporating new habitable modules to the house, using the patio as nexus, it is also possible to use the roof of those selected habitable modules (instead of using all of them), to install a PV generator and incorporate it to the system, attending to the consumption needs of each particular user. This possibility allows the customization of the PV installation, through the suitability of obtaining different PV systems, with different final maximum power, in function of the habitable modules in which these PV systems are integrated in.

- Global electrical energy management system

The global electrical energy management system allowed the control of all elements that compose the installation: PV generator, load consumption, grid interconnection and SOC of the batteries. This novel management system was composed of a battery inverter, a battery bank and a self-designed electronic device. The control of this electronic device was made by means of a software tool programmed by researchers of this project. It must be taken into account that this software application did not allow charging the battery from the electrical energy extracted from the conventional grid. In the same way, the electrical energy stored in the battery bank could not be injected to this grid. These limitations were imposed by the rules of the competition and the national electrical codes.

The strategy followed by the global electrical energy management system imposes that if there is an excess of PV generated electrical energy, it must be stored in the batteries or injected to the grid if the batteries are fully charged and the consumption needs are covered. In case of deficit of generated PV energy to cover the electrical energy demanded by the local loads, the discharge of the batteries would start to supply the whole consumption needs. If the electrical energy provided by the batteries is not enough, we would resort to the external electrical grid. Using this strategy, the PV electrical energy is available whenever it is needed, even at nights or at grid faults.

Due to the great interest caused by these strategies for electrical energy use, recent studies and simulations are currently being developed. These studies are related to the behavior of PV systems working under their two main modes: grid-connected and stand-alone [11][17] [18].

3. Theoretical description of the implemented simulation model.

To study and analyze the electrical energy balance of the entire PV system, a simulation model was carried out. This model is based on ambient temperature and irradiance data in a horizontal plane as input data, in the location of SDE 2012 competition: Madrid. The analysis was established for an entire year (TMY) and for the SDE-2012 competition period, which is that between the 17th and the 28th of September, as described in next sections of the paper.

The simulation model implemented in this work is based on the following steps:

STEP1: CALCULATION OF THE IN-PLANE GLOBAL IRRADIANCE: Firstly, it is necessary to transform the horizontal global irradiance (G_{0°) data to real conditions of the implemented PV system [19], in which the PV modules were south-oriented and had a tilt-angle (G_β) of 8º.

STEP 2: CALCULATION OF THE CELL TEMPERATURE: In a second place, it is essential to calculate the cell temperature of the PV generator, from the ambient temperature, knowing the value of NOCT[vii] (Normal Operation Cell Temperature) parameter [20], which is specified in the manufacturer datasheet:

$$T_C(^{\text{o}}C) = T_A(^\circ\text{C}) + G(8^\circ)\left(W/_{m^2}\right) \cdot \frac{NOCT(^\circ\text{C}) - 20(^\circ\text{C})}{1000\, W/_{m^2}} \quad (1)$$

Where:

- $T_C(^\circ\text{C})$ = Cell temperature.
- $T_A(^\circ\text{C})$ = Ambient Temperature.
- $G(8^\circ)\left(\text{W}/_{\text{m}^2}\right)$ = Global irradiance in a plane with 8º of tilt.
- $\text{NOCT}(^\circ\text{C})$ = Nominal operating cell temperature. In this case, the manufacturer gives a value of 45ºC.

Although we know the existence of other more appropriate methods to estimate the cell temperature of building integrated PV modules, the NOCT is the unique parameter given by the manufacturer. Anyway, the estimation of the cell temperature by NOCT method gives very good results with a low associated error in building integration with ventilated roof [21], as is in the present case.

STEP 3: ESTIMATION OF THE MAXIMUM POWER OF THE PV GENERATOR: Once the operating conditions (G_β and T_c) of the photovoltaic system were determined, the P_M (Maximum power) that can be generated by this PV system, working under these determined conditions, was calculated. Studying the performance of PV systems through the calculation and analysis of their P_M, supposing them to be working in the MPP[viii] (Maximum Power Point) most of their operating time, is a habitual practice. This premise is satisfied due to the function of the inverter of searching and making the PV generator to work in this MPP. To obtain the PV generator P_M, the Osterwald method [22] was used. This method allows the determination of the P_M, for a determined incident irradiance and cell temperature, using Eq. 2, and considering a minimum irradiance threshold of 50W/m2:

$$P_M(W) = P_{M,STC}(W) \ * \ \frac{G(8°)\left(W/_{m^2}\right)}{1000\,W/_{m^2}} \cdot \left[1 + \gamma(°\mathrm{C}^{-1}) \cdot \left(T_C(°\mathrm{C}) - 25(°\mathrm{C})\right)\right] \qquad (2)$$

Where:

- $P_{M,STC}(\mathrm{W})$ = Maximum power delivered by the PV generator when working under STC[ix] (Standard Test Conditions). The electric parameters of a PV device under STC are given by the manufacturer.
- $\gamma(°\mathrm{C}^{-1})$ = Temperature coefficient which expresses the dependence of the maximum power with the cell temperature. In this case, the manufacturer gives a value of 0.0038 $°C^{-1}$.

STEP 4: MODELLING OF THE ELECTRICAL ENERGY GENERATED BY THE PV SYSTEM: Finally the DC[x] (Direct Current) electrical energy production of the PV generator ($E_{DC,PVG}$) is calculated through the integration of hourly values of P_M for the particular conditions of in-plane irradiance and cell temperature [23].

$$\mathrm{E_{DC,PVG}\ (kWh)} = \int_{\mathrm{day}} \mathrm{P_M\ dt} \qquad (3)$$

This electrical energy production is decreased when it goes through the different elements of the PV installation due to various losses [24,25,26]. A summary of these losses is shown in Table 2:

Table 2
Summary of considered losses.

	Percentage (%)
Photovoltaic system	
Angular and spectral losses	2.86
DC wiring losses	1.50
Mismatch losses	1.50
Dirt losses	5.00
AC wiring losses	2.00
Inverter	
Maximum power point tracking losses	1.00
DC/AC conversion losses	10.00

It must be taken into account that:

- Dirtiness losses were considered of 5% due to the low tilt-angle of the PV generator.
- DC/AC conversion losses were considered of 10% according to the instantaneous efficiency curve of the inverters, given by the manufacturer.

The final electrical energy injected in the grid, $E_{AC,GRID}$, was obtained using the following expressions, detailed in Fig. 4, in which the losses previously specified are shown in the part of the installation where they appear.

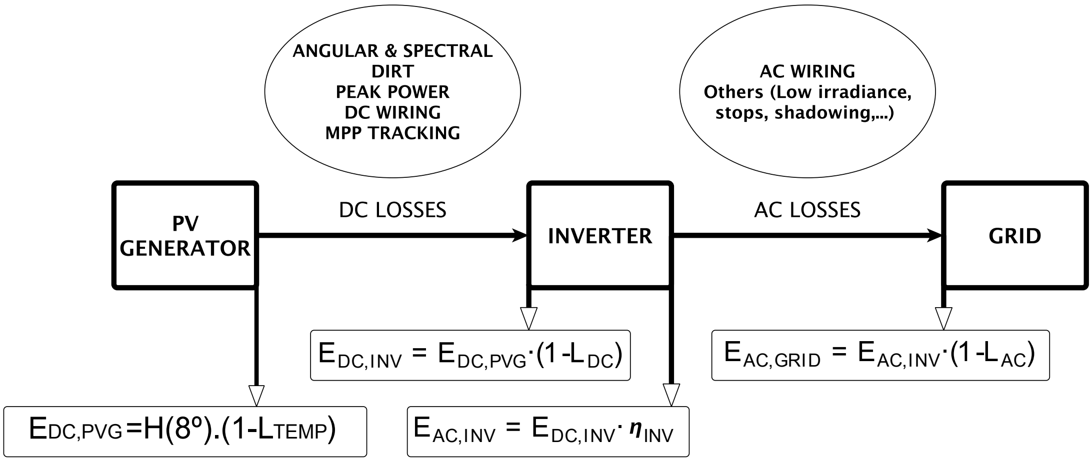

Figure 4. Diagram and equations to obtain the electrical energy production of the PV system.

$$E_{DC,GFV} = H(8^{\underline{o}}) * (1 - L_{TEMP}) \text{ (4)}$$

$$L_{DC} = (1 - L_{AE}) * \left(1 - L_{DC,WIR}\right) * (1 - L_{MM}) * (1 - L_{DIR}) * (1 - L_{MPP}) \text{ (5)}$$

$$E_{DC,INV} = E_{DC,GFV} * (1 - L_{DC}) \text{ (6)}$$

$$E_{AC,INV} = E_{DC,INV} * \eta_{INV} \text{ (7)}$$

$$E_{AC,GRID} = E_{AC,INV} * (1 - L_{AC}) \text{ (8)}$$

Where:

- $E_{DC,PVG}$: DC electrical energy generated by the PV generator
- $H(8°)$: Global Irradiation collected in generator plane:
  $\mathrm{H}(8°) = \int \mathrm{G}(8°)\mathrm{dt}$ (9)
- L_{TEMP}: Losses due to module temperature different to the Standard one (25ºC).
- L_{AE}: Angular and spectral losses.
- $L_{DC,WIR}$: DC wiring losses.
- L_{MM}: Mismatch losses.
- L_{DIR}: Dirt losses
- L_{MPP}: Maximum power point tracking losses.
- $E_{DC,INV}$: DC electrical energy generated at the input of the inverter
- L_{DC}: Losses in DC part of the installation: Angular losses, DC wiring losses, mismatch losses and dirty.
- $E_{AC,INV}$: AC electrical energy provided by the inverter
- η_{INV}: Inverter efficiency: Obtained from the instantaneous efficiency curve.
- $E_{AC,GRID}$: AC electrical energy injected in the electric grid
- L_{AC}: Losses in AC part of the installation: Maximum power point tracking losses and AC wiring losses.

Once the generated PV electricity was calculated, the implemented model estimated the electrical energy balance of the entire PV installation, according to an imposed strategy for the performance operation followed by the system. This strategy was carried out thanks to the use of the global electrical energy management system, previously introduced.

The main aim of the global electrical energy management system is to optimize the use of the generated PV electrical energy. Following this premise, all the electrical energy locally generated by the PV system is used -as much as possible- to cover the electrical energy demanded by the local loads. Once the electrical energy needs are supplied, there are two possible ways of using the spare PV electrical energy. In a first place, this excess of PV electrical energy is employed for charging the battery (when it is not fully charged) and then, if still having available PV electrical energy, this extra electricity is injected to the grid (when the battery is fully charged).

Apart from that, the electrical energy needed for covering the loads consumption at any moment is obtained through two different strategies when the PV generation is not capable of providing this demand. The first strategy consists of using the electrical energy previously stored in the battery (while the battery can cover this consumption). The most disadvantageous situation is to extract the needed electricity from the conventional grid. All this process is graphically represented through Fig. 5.

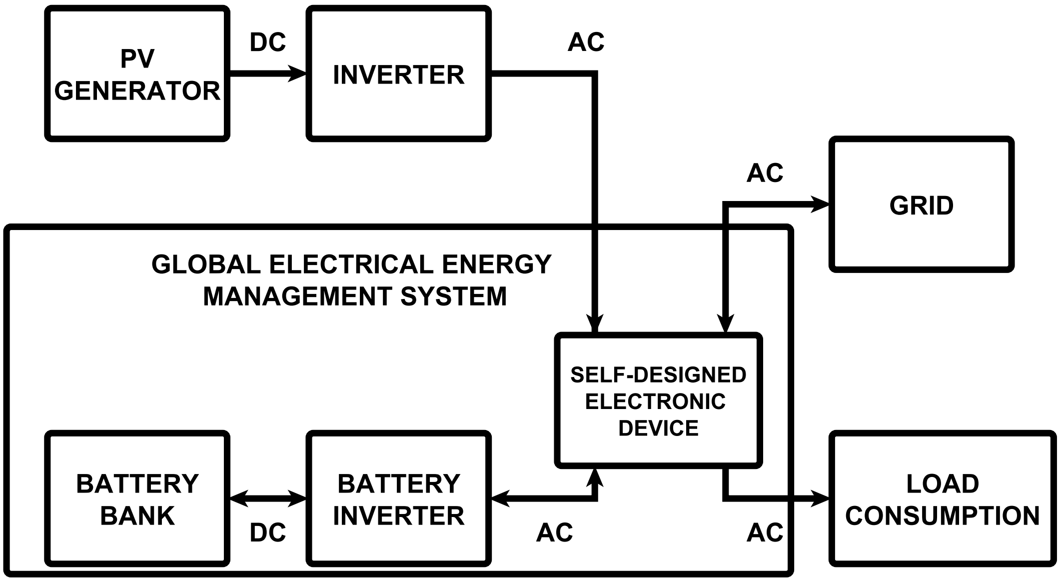

Figure 5. Scheme of the performance strategy of the PV system design. The arrows represent the flow of energy between each component of the installation.

This configuration allows an active demand side, which permits the final user to establish different consumption profiles, making them to be adapted, as much as possible, to the PV generation profile. This objective is fulfilled due to a self-designed electronic device which controls the entire system, through the management strategy previously described, from updated and real time information of all the component elements of the system.

In this way, the designed system tries to be as independent from the conventional electrical grid as possible, looking for the maximization of the self-consumption index. The self-consumption index determines the total amount of electricity consumed in the house, which has been directly supplied by means of PV generated electrical energy, or indirectly covered by means of the electricity stored in the battery bank. This stored electrical energy has equally a PV origin. The latter self-consumption index is calculated, as shown in Eq. 10.

$$\xi = \frac{E_{PV-Consumption}+E_{BAT-Consumption}}{E_{Consumed}} \qquad (10)$$

Where:

- $\mathrm{E}_{\mathrm{PV-Consumption}}$: PV generation used to supply the load consumptions
- $\mathrm{E}_{\mathrm{BAT-Consumption}}$: Electricity extracted from the battery bank to supply the load consumptions
- $\mathrm{E}_{\mathrm{Consumed}}$: Energy consumed by loads

This objective could be implemented in the competition despite having time restrictions of the consumed electrical energy to carry out the “Functioning of the house” and “Comfort Conditions” contests, which affected the final electrical energy balance.

To make the estimation of the electrical energy balance of the system as realistic as possible, two efficiency values related to the backup system, were incorporated to the simulation model:

- 1AC/DC+1DC/AC: Conversion efficiency of battery inverter in both, charge and discharge modes, respectively. This value was considered of 90%.
- Faradaic efficiency of the battery: 90%.

Additionally, as starting point, it was considered that the initial SOC of the battery was 60%.

4. *Comparative analysis between the simulated and the measured electrical energy balance of the system*

To validate the proposed simulation model, a comparative analysis was performed between the electrical energy balance simulated through the use of the model previously described (by means of a software application developed in Matlab^{TM}) and the real electrical energy measurements acquired during the SDE competition. These real data were acquired each minute through a monitoring system integrated in the installation, which registered the information of the electric parameters delivered by all components of the PV system. On the other hand, environmental information from a near-by meteorological station given by the own competition, was used as input to the simulation model, to calculate the modeled data.

In Fig. 6 the evolution of the in-plane irradiance and cell temperature, according to the obtained data from the previous mentioned meteorological station, for the competition period are represented.

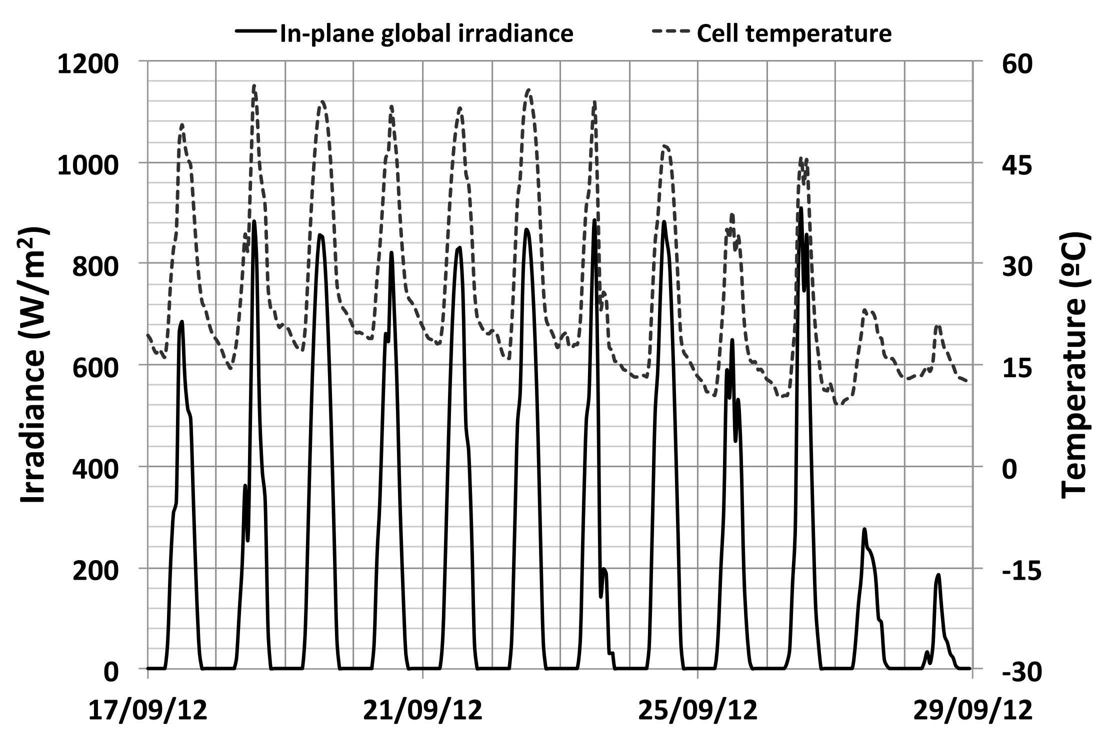

Figure 6. Evolution of the in-plane irradiance and cell temperature during the competition period according to previous simulations.

Using this environmental information represented in Fig. 6, the evolution of the simulated DC power of the entire PV system can be obtained. In Fig.7 the evolution of the simulated DC power is compared with the real corresponding values measured during the competition.

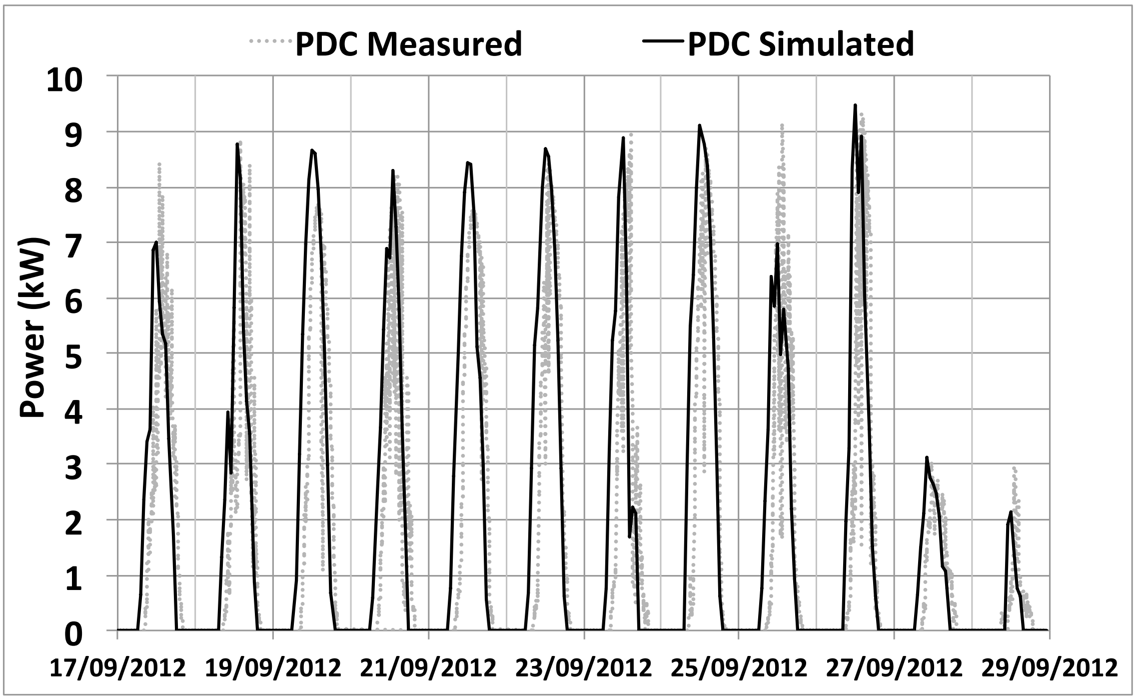

Figure 7. Simulated and measured evolution of the DC power during the competition period.

In the same way, Fig. 8 shows the daily AC electrical energy generated by the PV system for the simulated scenario, in comparison with the real generated electricity registered by the monitoring system during the competition period.

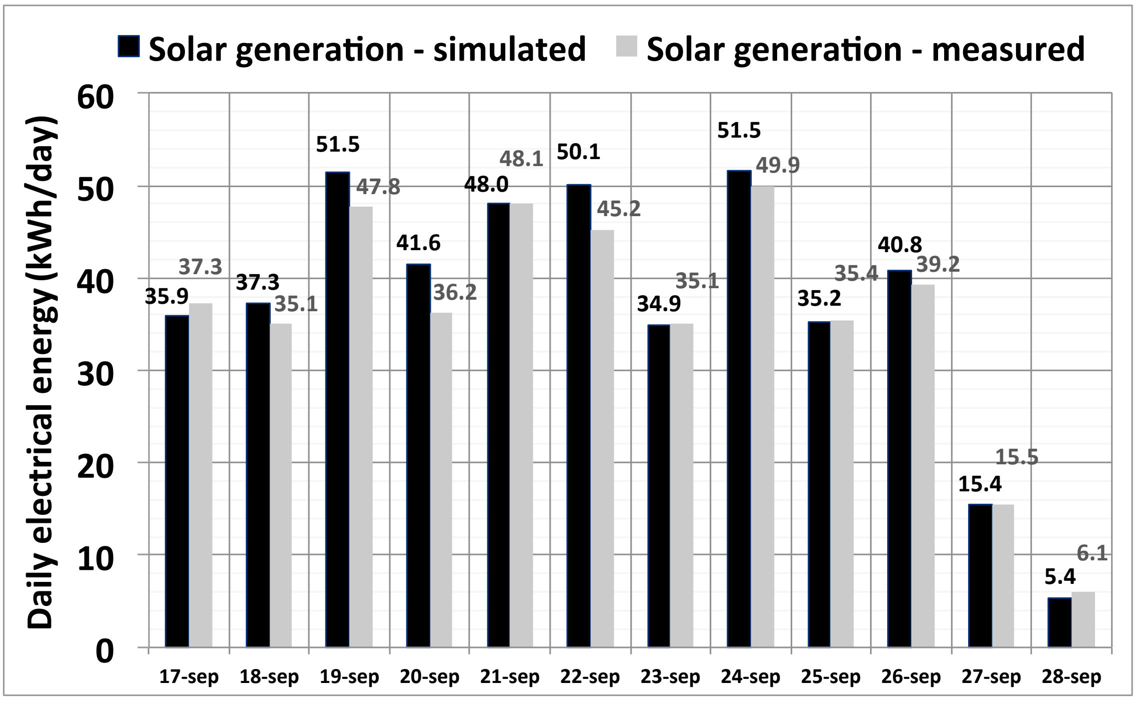

Figure 8. Simulated and measured daily solar generation during the competition period.

As can be appreciated after analyzing the Fig.8, the proposed model gives a very good prediction of the PV system electrical generation.

To perform the electrical energy balance simulation, the real load consumption registered during the competition period was considered. The measured daily load consumption is represented in Fig.9

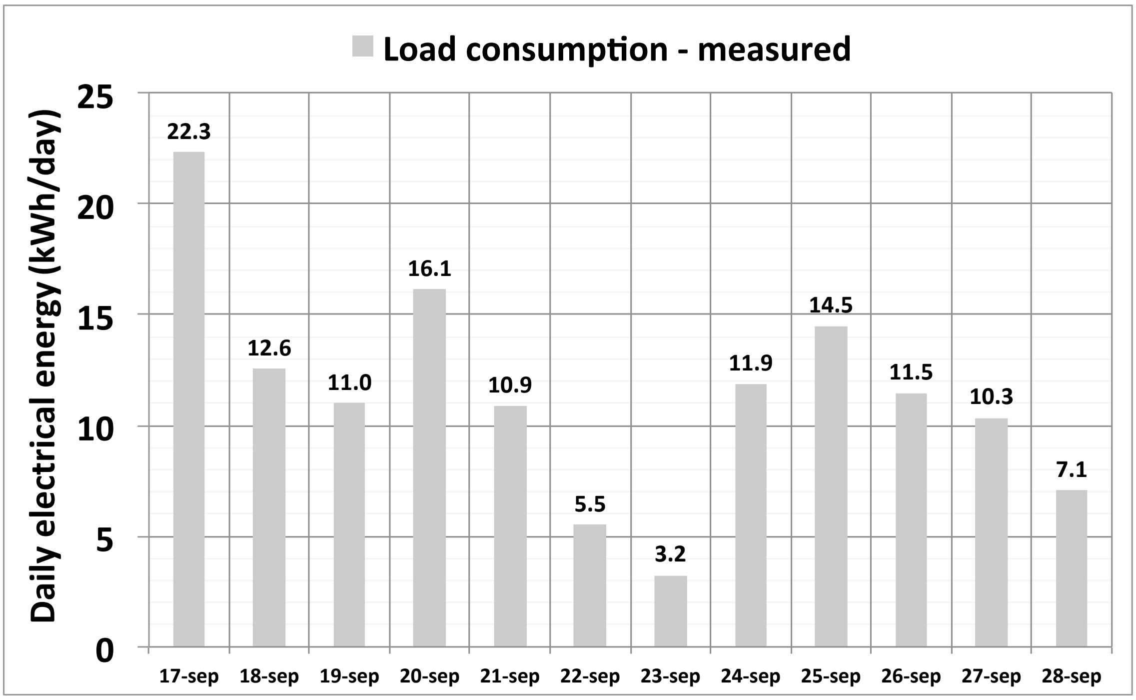

Figure 9. Measured daily load consumption during the competition period.

The study of the electrical energy balance of the PV system consists on analyzing the daily electrical energy exchanged with the battery and with the conventional electrical grid, in comparison with the electrical energy generated by the PV system and the consumption needs.

It must be highlight that the sign criteria for battery exchange and grid exchange used in the model and showed in the hereunder figures, is the following:

- Battery exchange is positive when the global amount of PV electricity injected to the battery is higher than the electricity extracted from it.
- Battery exchange is negative when the global amount of PV electricity injected to the battery is lower than the electricity extracted from it.
- Grid exchange is positive when the global amount of PV electricity injected to the grid is higher than the electricity extracted from it.
- Grid exchange is negative when the global amount of PV electricity injected to the grid is lower than the electricity extracted from it.

Fig. 10 and Fig. 11 respectively show the simulated and measured daily grid exchange and daily battery exchange during the competition period, in order to carry out a fully understood of the global electrical performance of the PV system.

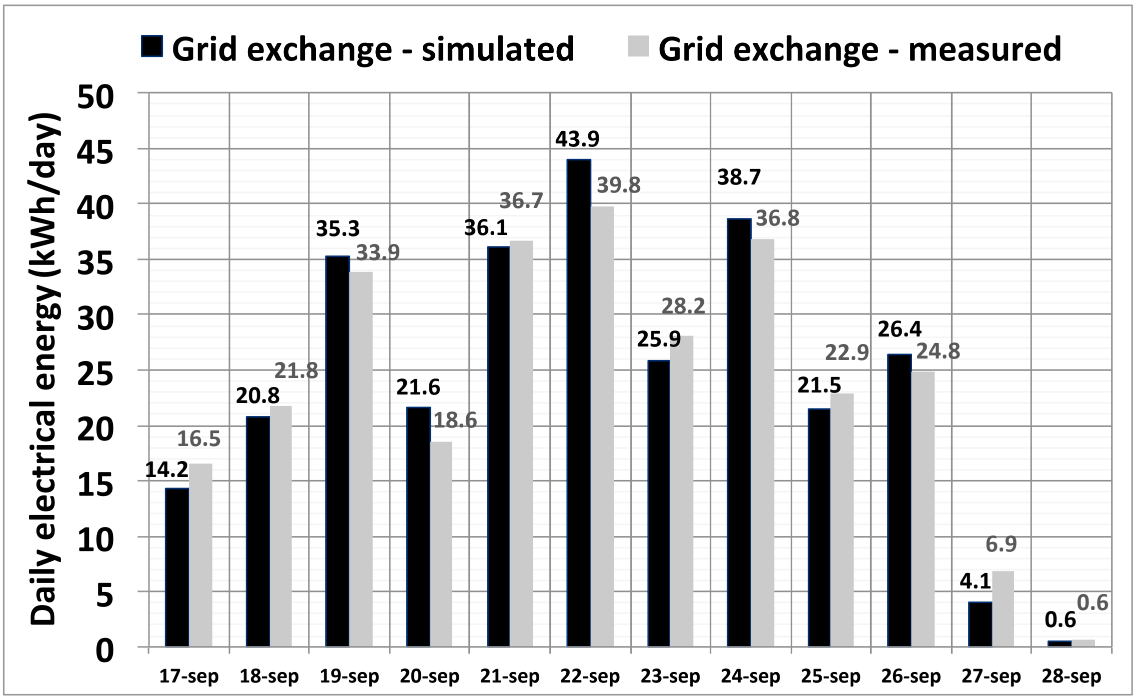

Figure 10. Simulated and measured daily grid exchange during the competition period.

It must be highlighted that there existed a positive daily grid exchange for the whole competition period. This means that, at the end of each day, there was a higher amount of electricity injected to the electric grid, than the one extracted from it. It is important to highlight that this situation was true even at days with low solar resource, as the case of 27th and 28th of September.

Additionally, it is remarkable the fitted predictions of grid-exchange made by the proposed model, with simulated values very similar to the corresponding real measured data.

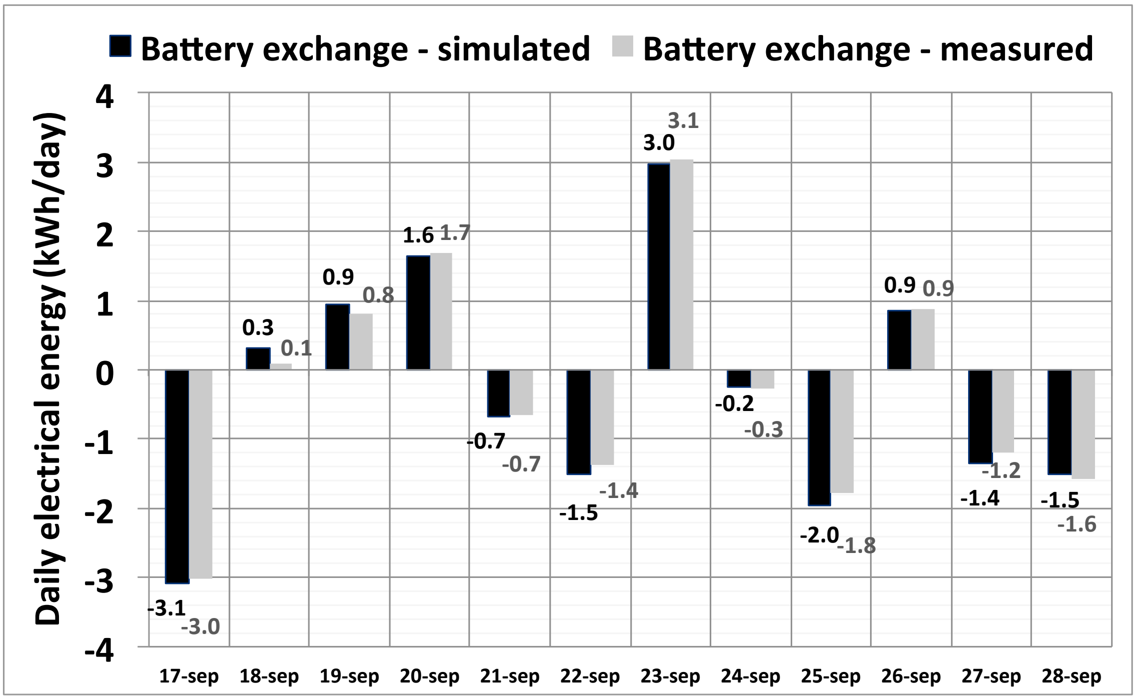

Figure 11. Simulated and measured daily battery exchange during the competition period.

In the case of the battery exchange, there were different situations depending on the considered days of the competition. In this way, a daily negative battery-exchange means that the electricity extracted from the battery exceeded the electricity injected in it. Otherwise, a daily positive battery-exchange means that, at the end of the day, the total amount of PV electricity injected in the battery was higher than the electricity extracted from it to supply the consumption needs in absence of PV generated electricity. As in the case of the battery exchange, very good predictions are obtained by the modelling.

As the main premise of the PV installation consists of being as grid-independent as possible, one of the most important aspects which must be taken into account in this electrical energy balance study, is the self-consumption index. This index, as presented before, is a useful parameter which determines the global electrical performance of the system. Fig. 12 graphically shows the simulated and measured daily self-consumption indexes for the competition period.

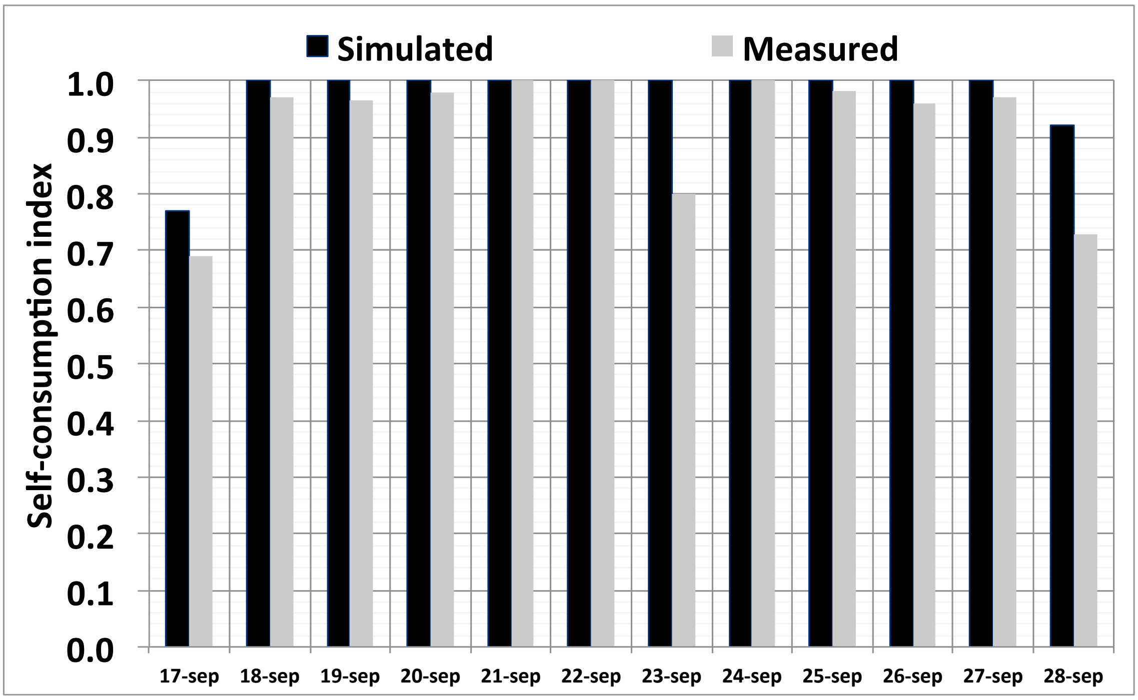

Figure 12. Simulated and measured daily self-consumption index during the competition period.

According to the data registered during the competition period, the global self-consumption index was of 0.92. Regarding the daily values, a daily self-consumption index of 1 was obtained for three days of this period. This means that, for these three days, all the electricity consumed in the house was supplied by PV solar generation. Additionally, the daily self-consumption index value was higher than 0.90 for nine days during the competition.

Fig. 13 shows a comparative analysis of the electrical energy generated and consumed, as well as exchange of electrical energy in batteries and with the electrical grid, for simulated and real measured scenarios, during the competition period.

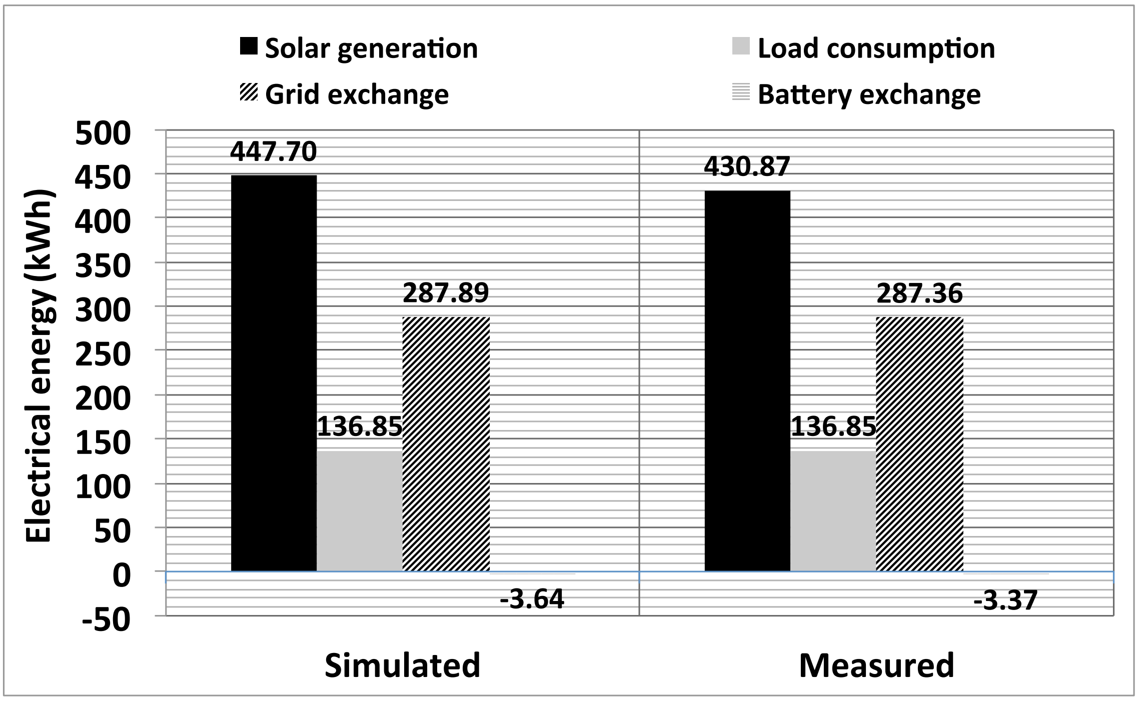

Figure 13. Final results at the end of the competition period.

Attending to Fig. 13, electricity generated by the PV installation was notably higher than the load consumption of the house. Additionally, the grid exchanges were positive in both measured and simulated cases, what means that more electrical energy was injected to the grid than extracted from it. Apart from that, both battery exchanges (measured and modeled) showed a negative global amount of electrical energy. This situation entails that a higher amount of electrical energy was extracted from the battery than the electrical energy accumulated into it.

Table 3 represents the relative errors, in percentage terms (Eq. 11), between the real measured daily values of solar generation, grid exchange, battery exchange and self-consumption index, and the corresponding simulated values, for the competition period.

$$Relative\ error(\%) = \frac{Measured\ values - Simulated\ values}{Measured\ values} * 100 \qquad (11)$$

Table 3
Simulation relative errors for the daily electrical energy balance, in percentage terms.

	Solar Generation	Grid Exchange	Battery Exchange	Self-consumption index
17/09/12	-3.6%	-13.6%	2.3%	11.7%
18/09/12	6.1%	-4.6%	20.9%	2.9%
19/09/12	7.8%	4.2%	18.5%	3.7%
20/09/12	14.9%	16.0%	-2.3%	2.1%
31/09/12	-0.2%	-1.7%	4.3%	0.0%
22/09/12	10.7%	10.4%	10.0%	0.0%
23/09/12	-0.4%	-8.1%	-2.2%	25.0%
24/09/12	3.2%	5.1%	-11.4%	0.0%
25/09/12	-0.5%	-6.1%	10.4%	1.9%
26/09/12	4.1%	6.3%	-1.9%	4.1%
27/09/12	-0.3%	-40.7%	14.3%	2.9%
28/09/12	-11.1%	-4.3%	-4.9%	26.2%
GLOBAL	**3.9%**	**0.2%**	**7.9%**	**4.1%**

As can be appreciated, the final global errors are sufficiently low to consider the proposed model as an accurate tool to predict the electrical energy balance of the designed PV system.

5. *Simulation of the electrical energy balance in annual terms*

Finally, this section shows the electrical energy balance of the designed PV system for a TMY in Madrid. In this sense, the simulated performance of the implemented electrical system is shown in monthly and annual terms. This analysis is very useful to take a wider view of the electrical performance of the PV installation, beyond the 2 weeks during which the competition took place.

The environmental information provided for the TMY in Madrid was used to estimate the monthly and annual electrical performance of the entire PV system. The load consumptions of the Patio 2.12 during the competition period were taken as the reference to carry out the electrical modeled performance of the system. The simulation model considered that these load consumptions were cyclically repeating going into the whole year.

Additionally, as input information to the simulation model, the maximum level of discharge, that the battery bank cannot exceed, was fixed to 30% during the period of analysis.

The monthly and the annual electrical energy balance are shown and discussed below. Firstly, the monthly electrical energy balance is shown in Fig. 14.

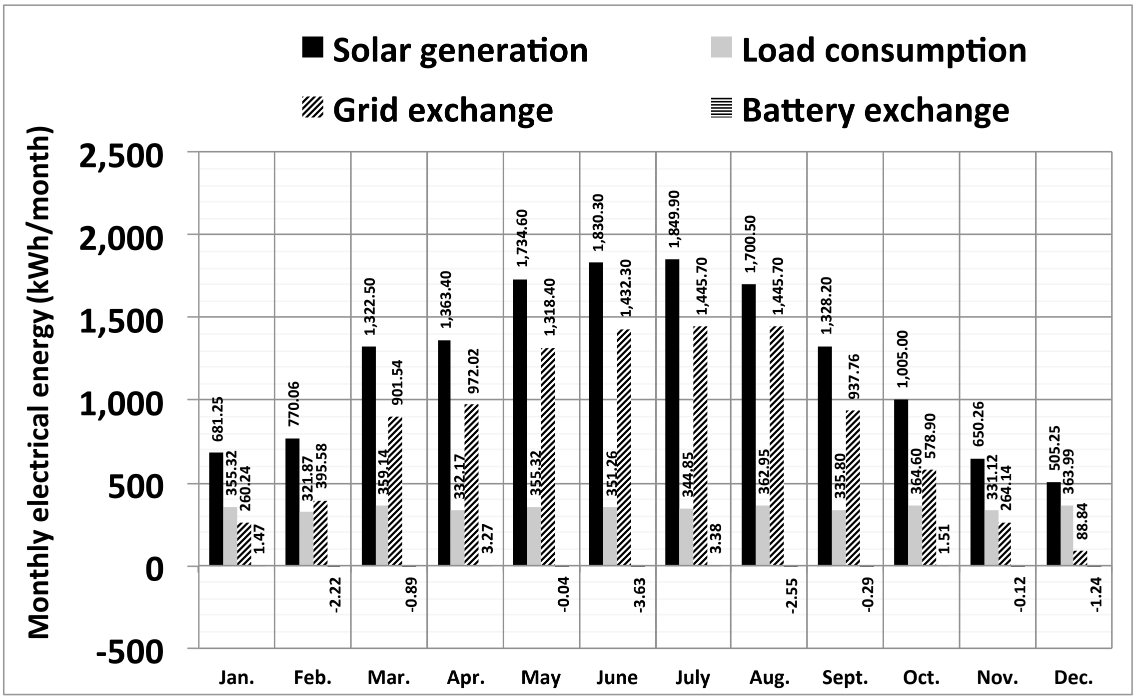

Figure 14. Monthly results of the electrical energy balance simulation.

It should be noted that the monthly amount of generated PV solar energy was always higher than the monthly electrical consumption needs. In addition, the monthly grid-exchanges were positive during the whole year. Table 4 shows the monthly and annual self-consumption indexes in order to summarize the global electrical performance of the system. These indexes show the level of achievement of the initial aim of the designed PV installation: Supplying the local loads demand from PV solar energy.

Table 4
Annual and monthly self-consumption index during the tried whole year.

	Self-consumption index
Jan.	0.82
Feb.	0.86
Mar.	0.91
Apr.	0.94
May	0.93
June	0.94
July	0.95
Aug.	0.95
Sept.	0.93
Oct.	0.87
Nov.	0.80
Dec.	0.70
Annual	0.88

The monthly simulated values for the self-consumption index were over 0.90 during seven months. The maximum and minimum values were 0.95 in August and 0.70 in December, respectively.

To conclude, Fig. 15 shows the annual electrical energy balance for the designed PV system. Solar generation, load consumption and grid and battery exchanges are depicted in Fig. 15.

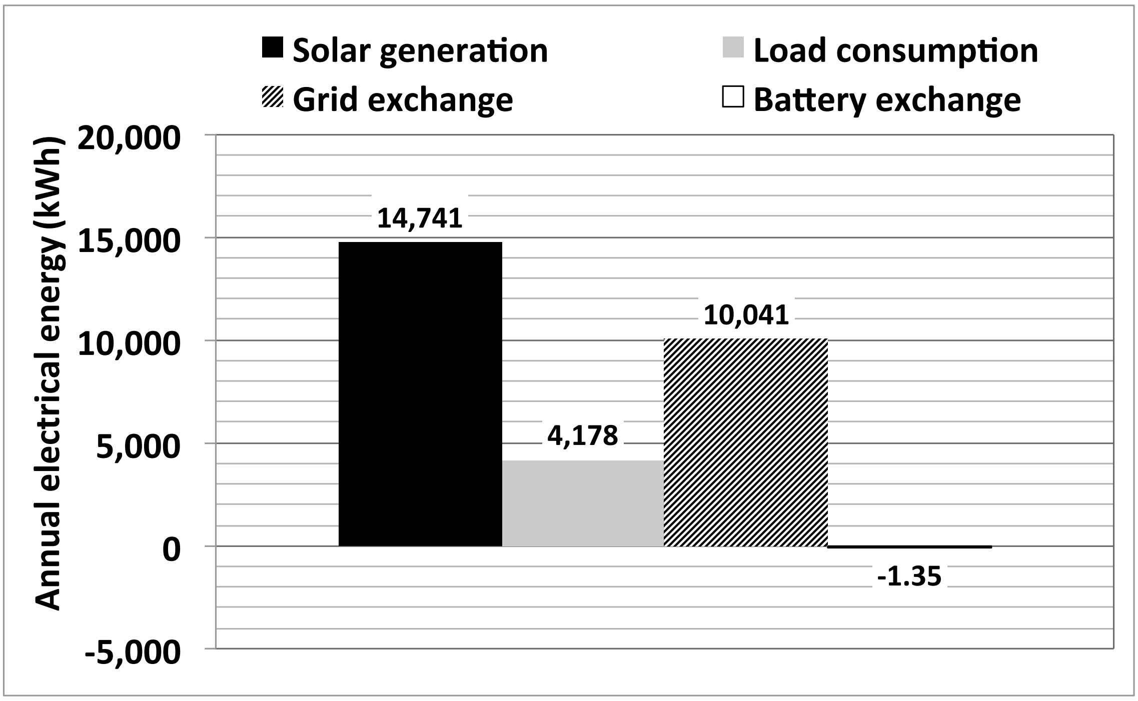

Figure 15. Annually results of the electrical energy balance simulation.

The obtained annual results conclude that the present PV installation is able to generate enough electrical energy to cover more than three times the local consumption needs. Moreover, the grid exchange reached an important high value; this situation implies that a big amount of electrical energy was ready to be injected into the conventional electrical grid. The negative value of battery exchange shows that 1.35 kWh were extracted from the battery bank more than injected into it, at the end of the analysis period.

It is also worthy to highlight that the annual performance ratio of the PV installation reached a value of 79%, and the average daily and final annual yield were of 3.56 kWh/kWp/day and 1,302 kWh/kWp/year, respectively.

6. Conclusions

The participation of Andalucía Team in the International competition of sustainable solar houses –SDE 2012- with the project “Patio 2.12” achieved very good results. This participation encouraged the design and development of a grid-connected PV system whose main function was to satisfy the electrical needs of the house with as much self-consumption as possible. The excellent performance of the system during the competition was remarkable, which resulted in the obtaining of first awards in contests related to the energy, such as, energy efficiency and energy balance.

The implemented PV system was composed of very high efficient PV modules. This high efficiency allowed producing enough PV electrical energy to cover, in more than three times, the electrical consumptions needs of the house, only using 55.45m2 of roof surface.

The inclusion of a global electrical energy management system, composed of a battery inverter, a battery bank and a self-designed electronic device, allowed managing the electrical energy flows of all the component elements of the PV installation, in a global way. The strategy of electrical energy management permitted to reduce the dependence of the conventional electric grid. In this sense, during the competition period, a self-consumption index up to 0.92 was obtained. By increasing the active participation of the final user on the way of consuming the PV generated electrical energy this self-consumption rate could reach values near to 1.

Moreover, this paper introduces a simulation model to estimate the global electrical energy balance of this kind of building integrated PV systems. The tried simulation model requires the environmental conditions and the load consumption as inputs to the modelling. The solar generation, the conventional grid and battery exchanges and the self-consumption indexes were estimated through this simulation model, obtaining fitted results when comparing them with the corresponding real data.

Finally, an estimation of the monthly and annual electrical performance of the PV installation was carried out for a TMY in Madrid. The obtained results show that the designed PV installation could satisfy the annual load consumptions needs in more than three times, with a great amount of annual electrical energy injected to the conventional grid.

Despite the excellent results obtained in the competition, the early experience extracted from this PV electrical installation shows that the electrical performance of the implemented system could be rather improved. For instance, the inclusion of improved tools related to the prediction of the solar resource must become a key part in this kind of PV systems. These techniques would allow maximizing the use of the generated PV electrical energy and optimizing -reducing- the PV system and battery bank size. Nowadays there are some predictive models based on artificial intelligence techniques that can be used to calculate the evolution of the irradiance for the following days, with the idea of programming the consumption loads in the most suitable period of time, increasing, in that way, the obtained the self-consumption index. Moreover, these proposed strategies could be used to promote the development of the decentralized and distributed generation with renewable energy, reducing the costs associated to the transport and the energetic infrastructures, due to the electrical energy consumption in same the place where it was generated.

---

[i] PV: Photovoltaic.
[ii] SDE: Solar Decathlon Europe.
[iii] IDEA: Investigation and development in solar energy.
[iv] TMY: Typical meteorological year.
[v] AC: Alternating Current.
[vi] SOC: State of Charge.
[vii] NOCT: Normal Operation Cell Temperature.
[viii] MPP: Maximum Power Point.
[ix] STC: Standard Test Conditions.
[x] DC: Direct Current.

References

[1] http://www.sdeurope.org/. Last access: 11th April 2014.

[2] http://www.andaluciateam.org/. Last access: 11th April 2014.

[3] http://vimeo.com/48493328. Last access: 11th April 2014.

[4] http://www.flickr.com/photos/sdeurope/sets/72157631550799795/. Last access: 11th April 2014.

[5] SD Europe. Rules. January 2011

[6] C. Rae, F. Bradley, Energy autonomy in sustainable communities - A review of key issues, Renewable and Sustainable Energy Reviews 16(9) (2012) 6497-6506. DOI: 10.1016/j.rser.2012.08.002

[7] E. McKenna, M. McManus, S. Cooper, M. Thomson, Economic and environmental impact of lead-acid batteries in grid-connected domestic PV systems, Applied Energy 104 (2013) 239-249. DOI: 10.1016/j.apenergy.2012.11.016

[8] M. Castillo-Cagigal, E. Caamaño-Martín, E. Matallanas, D. Masa-Bote, A. Gutiérrez, F. Monasterio-Huelin, et al, PV self-consumption optimization with storage and Active DSM for the residential sector, Solar Energy 85 (9) (2011) 2338-2348. DOI: 10.1016/j.solener.2011.06.028

[9] G. Strbac, Demand side management: Benefits and challenges, Energy Policy 36(12) (2008) 4419-4426. DOI: 10.1016/j.enpol.2008.09.030

[10] E. Caamaño-Martín, D. Masa-Bote, A. Gutiérrez, F. Monasterio-Huelin, J. Jiménez-Leube, M. Castillo-Cagigal, J. Porro, Optimizing PV use through active demand side management. 24th European Photovoltaic Solar Energy Conference, Hamburg (2009). DOI:10.4229/24thEUPVSEC2009-4BO.11.6

[11] E. Matallanas, M. Castillo-Cagigal, A. Gutiérrez, F. Monasterio-Huelin, E. Caamaño-Martín, D. Masa, J. Jiménez-Leube. Neural network controller for Active Demand-Side Management with PV energy in the residential sector, Applied Energy 91 (1) (2012) 90-97. DOI: 10.1016/j.apenergy.2011.09.004

[12] M. Sechilariu, B. Wang, F. Locment, Building-integrated microgrid: Advanced local energy management for forthcoming smart power grid communication, Energy and Buildings 59 (2013). 236-243. DOI: 10.1016/j.enbuild.2012.12.039

[13] http://www.sunpowercorp.co.uk/homes/products-services/solar-panels/e20/. Last access: 11th April 2014

[14] http://www.sma.de/en/products/solar-inverters-with-transformer/sunny-boy-2000hf-2500hf-3000hf.html. Last access: 11th April 2014.

[15] X. Zhang, H. Ni, D. Yao, R. Cao, W. Shen, Design of single phase grid-connected photovoltaic power plant based on string inverters, 1st IEEE Conference on Industrial Electronics and Applications art. no. 4025887 (2006). DOI: 10.1109/ICIEA.2006.257286

[16] J.M.A. Myrzik, M. Calais, String and module integrated inverters for single-phase grid connected photovoltaic systems-a review, IEEE Bologna PowerTech - Conference Proceedings 2 art. no. 1304589 (2003) 430-437. DOI: 0780379675;978-078037967-1

[17] D. Velasco De La Fuente, C.L. Trujillo Rodríguez, G. Garcerá, E. Figueres, R. Ortega Gonzalez, Photovoltaic Power System With Battery Backup With Grid-Connection and Islanded Operation Capabilities, IEEE Transactions on Industrial Electronics 60(4) art. no. 6189074 (2013) 1571-1581.

[18] Zong, Y., Mihet-Popa, L., Kullmann, D., Thavlov, A., Gehrke, O., Bindner, H.W. Model predictive controller for active demand side management with PV self-consumption in an intelligent building (2012) IEEE PES Innovative Smart Grid Technologies Conference Europe, art. no. 6465618 .

[19] E. Lorenzo, Electricidad Solar Fotovoltaica. Volumen II: Radiación solar y dispositivos fotovoltaicos, first edition, Progensa, Spain, 2006.

[20] R.G. Ross Jr., Characterization of photovoltaic array performance: An overview, Solar Cells 18 (3–4) (1986) 345-352.

[21] M. D'Orazio, C. Di Perna, E. Di Giuseppe, Experimental operating cell temperature assessment of BIPV with different installation configurations on roofs under Mediterranean climate, Renewable Energy, Volume 68, August 2014, Pages 378-396. DOI:10.1016/j.renene.2014.02.009.

[22] C.R. Osterwald, Translation of Device Performance Measurements to Reference Conditions, Sol. Cells 18 (3-4) (1986) 269–279.

[23] International Standard IEC 61724, Photovoltaic System Performance Monitoring—Guidelines for Measurement, Data Exchange and Analysis, first edition, International Electrotechnical Commission (IEC), Geneva, 1998.

[24] Piliougine, M., Cañete, C., Moreno, R., Carretero, J., Hirose, J., Ogawa, S., Sidrach-de-Cardona, M. Comparative analysis of energy produced by photovoltaic modules with anti-soiling coated surface in arid climates (2013) Applied Energy, 112, pp. 626-634

[25] N. Martin, J.M. Ruíz, Calculation of the PV modules angular losses and the field conditions by means of analytical model, Solar Energy Materials and Solar Cells 70(1) (2001) 25-38. DOI: 10.1016/S0927-0248(00)00408-6

[26] N. Martin, J.M. Ruíz, Annual angular reflection losses in PV modules, Progress in Photovoltaics: Research and Applications 13(1) (2005) 75-84 .
DOI:10.1002/pip.585.