SPANISH PARTICIPATION IN THE "SOLAR DECATHLON 2005": DESIGN AND SIMULATION OF THE PHOTOVOLTAIC SYSTEM

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ABSTRACT: In the fall of 2005 the Polytechnic University of Madrid (UPM) will contest in the "Solar Decathlon" competition, promoted by the U.S. Department of Energy and its National Renewable Energy Laboratory with an European proposal of house called "magic BOX". This paper describes the design and simulation of "magic BOX" Photovoltaic (PV) system, as well as the current results obtained from the testing campaign that is being carried out at present. In the PV design stage, two important facts have conditioned the process, on one hand the necessity to considerer two electrical codes, namely the U. S. National Electrical Code and Spanish code, and on the other hand the architectural functionality of the PV modules that has avoided the typical one-tilt angle position. In a second stage, the results obtained from the testing campaign are being used to optimize the system operation, as well as to improve the energy simulation performance through the use of actual values.
Keywords: Building Integration, Qualification and Testing, Simulation, Stand-alone PV systems.

1 INTRODUCTION

In the fall of 2005 the Polytechnic University of Madrid (UPM) will be representing Europe in the "Solar Decathlon" [1] competition, promoted by the U.S. Department of Energy and its National Renewable Energy Laboratory. The event is a truly "solar adventure" for today's students —tomorrow's engineers, architects, entrepreneurs, homeowners…— on the design, construction and demonstration of the most livable, energy-efficient and completely solar-powered houses. After spending almost two years designing and testing their prototypes (as well as preparing the competition), 18 teams representing universities and colleges from around the globe will test their homes in 10 contests encompassing all the ways we use energy in our daily lives: architecture, livability, comfort, energy performance and management, transportation using an electric car, etc.

From the Photovoltaic engineering point of view, the solar energy self-sufficiency requirement is to be achieved by a stand-alone PV system. However, the UPM team has had to face several challenges related to the competition requirements, as well as to the team's *"magic BOX"* concept, which have posed an added complexity to the usual system design process. On the one hand, the necessity to consider two electrical codes, namely the U.S. National Electrical Code (a competition requirement, the system must work in the National Mall of Washington D.C.) and the Spanish one (the house will be installed in Madrid after the Event), being the design approach to adopt the NEC code but respecting our own code in so far as possible. A second "architectural" difficulty comes from the fact that a PV cover is used as the house outer skin, thus being not only the most visible, but also one of the main regulators of the house energy behaviour, which has been designed according to bioclimatic principles [22]. This implies that a double functionality has been obtained from the Photovoltaic generator, so that an architectural value is added to the traditional electrical one: in this sense, innovative solutions have been searched in the PV market to achieve such objective. The last point taken into account in the PV system design has been the flexibility to adapt the system to different operation modes (grid-connected, as uninterruptible power supply). In this regard the PV micro-generation market possibilities have been profited, in order to find the best solution allowing the easiest modifications. Special emphasis has been also placed on security issues in all system aspects.

The PV system design has been complemented with an extensive energy analysis, using a computer program called *"Dimensiona"* developed by the Instituto de Energía Solar. This software, initially designed for traditional DC-coupled systems with only one generator tilt angle, has been adopted in order to simulate the PV system with the particularities mentioned above. In this regard, the software performs hourly calculations, starting from monthly mean daily horizontal irradiation data (easily available) using a synthetic series generation method when needed (input daily data less than 7 years). With these results, *"Dimensiona"* calculates the irradiation incident on the PV laminates, the energy flows and balances (the user can define a consumption profile), the SOC (State Of Charge) of the batteries and the LLP (Loss of Load Probability) [3] over the period that the system has been in service. These parameters are necessary to determine the reliability of the PV system, a most relevant aspect in the "Solar Decathlon" competition

Finally a testing campaign is being carried out on "magic BOX" in order to characterize in detail the PV system components, improve the system operation and obtain an energy simulation closer to the actual system.

2 PV SYSTEM DESIGN

Taking in account the design challenges mentioned before, the main characteristics of "magic BOX" PV system are the following:

- A particular shape of the house envelope, rather different from conventional stand-alone PV houses: instead of a PV generator with just one tilt angle, four different south-oriented surfaces integrate 77 PV laminates (glass-transparent

tedlar and glass-glass laminates, total nominal power of 8.1 kWp).
- A lead-acid battery system with four days of autonomy (approximately 90 kWh).
- A power conditioning system based on AC coupled principles, using six string inverters and two bi-directional inverters (total nominal power, 15 kW).

Figure 1 shows the block diagram of “magic BOX” PV system. Next the main components and their characteristics are summarized.

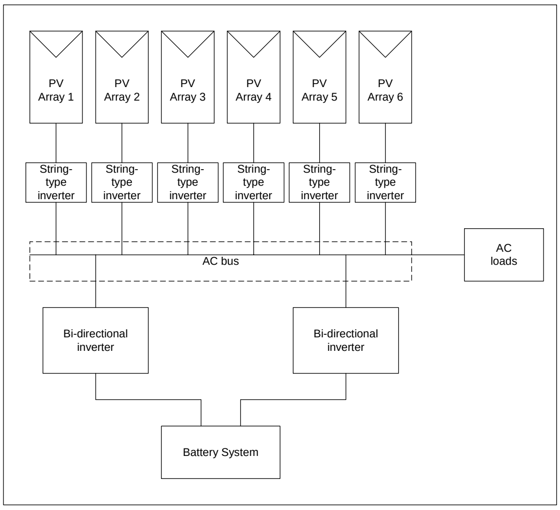

Figure 1: PV system block diagram

2.1 PV Generator

The next figure shows the different surfaces of the house where PV modules are integrated. The different tilt angles of each surface are 12º, 25º, 39º and 90º and all of them are south-oriented. As mentioned before, the reason of this multi-tilt angle distribution of the PV generator is architectural. From an energy point of view, this option represents a handicap with regard to the classical one-tilt angle: the optimal angle in Washingthon DC, under constant daily load is 60º.

Figure 2: “magic BOX” PV generator surfaces

Taking in account the different tilt angles and the electrical characteristics (nominal power and input voltage) of string inverters selected (Sunny Boy inverters manufactured by SMA Technologie), the PV generator has been divided into six arrays whose tilt angle and peak power (referred to the Standard Test Conditions) are shown in table I, together with the corresponding string inverters. The arrays are composed by five types of PV laminates, two already commercialized by our sponsor Isofotón and three custom-designed with solar cells also manufactured by Isofotón.

Array	Tilt angle	Peak power	Inverter selection
1	12º	1650W	SB-SWR 1700E
2	12º	1650W	SB-SWR 1700E
3	25º	1540W	SB-SWR 1700E
4	25º	1540W	SB-SWR 1700E
5	39º	990W	SB-SWR 1100E
6	90º	846W	SB-SWR 700E

Table I: Arrays characteristics and inverters selection

2.2 Electrical storage

A Stationary lead-acid type battery block has been selected, consisting of 30 series-connected individual cells of 2 volts (TYS 10 manufactured by Enersys). Total nominal voltage is 60 volts. The storage capacity characteristics of the cells are shown in the next table.

	10 hours rate (25ºC)	120 hours rate (25ºC)	240 hours rate (25ºC)
Nominal capacity (Ah)	1120	1525	1577

Table II: Capacity characteristics of battery cells

The battery system is installed in a separate locked room (see figure 3) to prevent accidental contact by persons or objects. Protection measures have been also taken against accessibility of live parts during routine maintenance, by means of insulated caps on each terminal.

Figure 3: Battery system (north façade of the house)

2.3 Power conditioning system

The power conditioning system is based on AC coupled principles and is composed, besides the six string inverters above mentioned, by two bidirectional inverters (Sunny Island 4500 manufactured by SMA Technologie) connected in parallel in a master-slave operation mode.

The main function of the string inverters is to obtain the maximum DC energy from the PV arrays, convert it into AC energy and feed it into the AC bus. On the other hand, the bidirectional inverters set the necessary AC voltage for the string inverters operation, convert the DC energy from the battery system into AC energy to AC bus and *vice versa*, perform the charge regulation of the battery system and control the AC bus operation through frequency variations that set the PV arrays operation point through their corresponding inverter [4]. Table III summarizes the main characteristics of the inverters.

	SB-SWR 1700E	SB-SWR 1100E
Input voltage (V)	139-400	139-400
Maximum input current (A)	12.6	10
Nominal output power (W)	1500	1000
Peak power (W)	1700	1100
Maximum efficiency (%)	93	93.5

	SB-SWR 700E	SI 4500
Input voltage (V)	125-250	41-81
Maximum input current (A)	6.2	125
Nominal output power (W)	700	3700
Peak power (W)	700	7000
Maximum efficiency (%)	93	>91

Table III: Inverters electrical characteristics

The inverters are installed inside an independent room called "Technical room" as it can be seen in figure 4.

Figure 4: Inverters location (Technical room)

2.4 Grounding system

For maximum protection against lightning-induced surges, "magic BOX" PV system has two grounding electrodes bonded together (see figure 5). One electrode (called primary grounding electrode) is the main system grounding electrode and the other is a supplemental one (called secondary grounding electrode) as close to the PV arrays as practical. The PV generator modules are laminated-types so that only the structure is connected directly to this grounding electrode, to provide as short a path as possible for lightning-induced surges to reach the earth. This electrode is bonded with a conductor to the main system grounding electrode. Besides, surge arresters are installed in the DC side of the system to get supplemental protection.

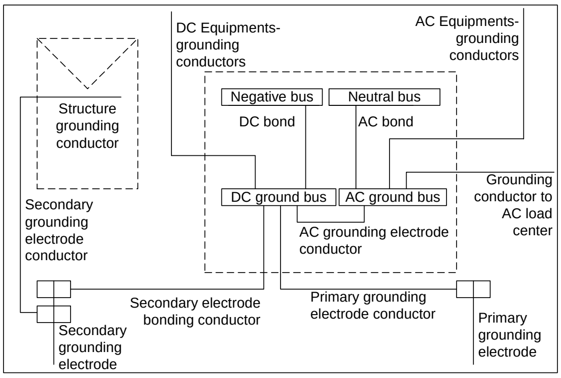

Figure 5: Grounding system

2.5 Cable sizing and protection devices

In regard to cable sizing and protections of the PV system, Article 690 of the NEC referred to PV systems has been mainly followed. The main aspects taken in account are the following:

- A procedure has been used for power cable sizing and overcurrent protection calculations, using as input data amperage ratings, expected operation temperatures and wiring methods selected.
- The negative and neutral cables must be grounded (NEC requirement), which means that one-pole overcurrent protections must be used.
- Due to the fact that there are PV modules installed on a roof, ground fault protections on the DC side of the system must be provided. In the PV system proposed, this protection is guaranteed by the use of double insulation on the DC side (PV modules, cables, connections) which prevents the occurrence of ground faults.

The grounding cables are sized as required by NEC. Generally, this will mean an equipment-grounding conductor size based on the size of the overcurrent device protecting each conductor.

3 BALANCE OF SYSTEM CHARACTERIZATION

In order to improve the PV system operation, an inverters and battery testing campaign has been carried out. The procedure used for the inverters characterization has been developed in the Instituto de Energía Solar [5]. The results obtained are described below.

3.1 Batteries

Figure 6 shows the discharge curve of an individual cell of the PV system battery block. The capacity measured was 1265 Ah in 40 discharge hours. If it is considered the capacity values in 10 hours and 120 hours, (1120 Ah and 1543 Ah respectively) and the fact that the cell was not conditioned (*i.e.* this was the first discharge once the battery was delivered), an excellent performance can be concluded in terms of capacity.

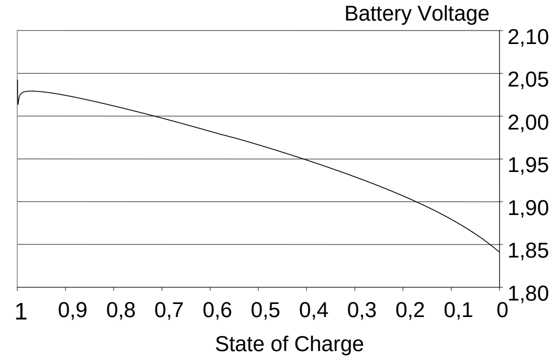

Figure 6: Individual battery block cell discharge curve

3.2 String inverters

The three types of inverters have been tested connected to a bidirectional inverter in the output, and a DC source in the input. Next, the main results concerning effciency, self-consumption and distortion are summarized.

First of all, the instantaneous conversion efficiency of the inverters was calculated from individual DC and AC measurements:

$$\eta_I = \frac{P_{\text{output}}}{P_{\text{input}}} = \frac{P_{AC}}{P_{DC}} = \frac{V_{AC,\text{rms}} \cdot I_{AC,\text{rms}} \cdot PF}{V_{DC} \cdot I_{DC}} \quad (1)$$

Individual values were represented versus the normalized effective output power:

$$p_0 = \frac{P_{\text{output}}}{P_{\text{nominal}}} \quad (2)$$

Then, the individual values calculated were fitted according to the following equation [6]:

$$\eta_I = \frac{p_0}{p_0 + (k_0 + k_1 \cdot p_0 + k_2 \cdot p_0^2)} \quad (3)$$

where k0, k1 and k2 are the conversion efficiency characteristic parameters. Then the inverter self-consumption losses was calculated as:

$$Self - consumption = k_0 \cdot P_{\text{nominal}} \quad (4)$$

Table IV shows the characteristic parameters and the self-consumption values obtained.

	SB SWR 1700E	SB SWR 1100E	SB SWR 700E
k_0 (%)	1.1	1.5	1
k_1 (%)	3.9	4.3	3
k_2 (%)	3.7	3.6	6.3
Self-consumption (W)	17	15	7

Table IV: String inverters characteristic parameters and self-consumption

Secondly, the distortion was characterized by representing the Total Harmonic Distortion factor of output current (THDi) versus normalized effective output power. The results obtained are shown in figure 7.

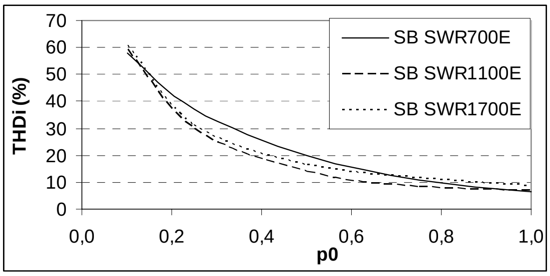

Figure 7: Inverters current distortion

Finally, the correct operation of the following inverter protections has been checked:

- Isolation failure.
- No output voltage.
- Overload.

3.3 Bi-directional inverters

The inverter has been tested connected to a resistive load bank in the output, and a battery system of 120Ah and 60V in the input. Next, the main results concerning to effciency, voltage and frequency regulation, distorsion and protections are summarized.

First the efficiency of the inverter was tested, individual DC and AC powers were measured together with equations 1, 2 and 3 for obtaining the characteristic parameters. Besides, the self-consumption was measured directly. The results obtained are shown in table V.

	Sunny island 4500
k_0 (%)	1.6
k_1 (%)	1.9
k_2 (%)	5.9
Self-consumption (W)	59.5

Table V: Bidirectional inverter characteristic parameters

Secondly, the voltage and frequency regulation was characterized by individual measures of output voltage and frequency for different values of output power; figure 8 shows the results obtained.

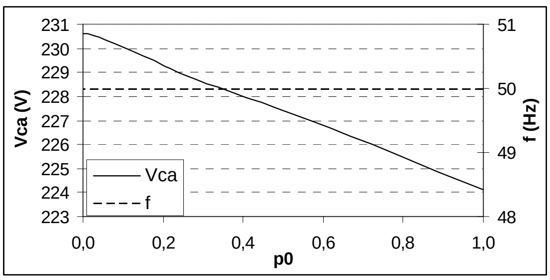

Figure 8: Voltage and frequency regulation

Next the distortion was characterized by measuring the Total Harmonic Distortion factor of output voltage (THDv), for different values of output power; figure 9 shows the results obtained.

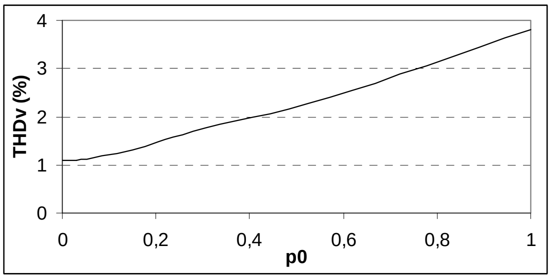

Figure 9: Sunny island distortion

Finally, the correct operation of the following inverter protections has been checked:

- Short-circuit.
- Overload
- Polarity inversion.
- Over-discharge of the battery.

Also the correct operation of the system composed by two bidirectional inverters connected in master-slave operation mode has been checked.

3.4 Results valuation

The results obtained in the inverters testing campaign confirm an appropriate operation of the system. There are, however, two remarkable aspects to mention, the voltage fall of output voltage for high output powers in the bidirectional inverters, and the high distortion of the output current of the string inverters

The first point is easy to improve through programming a higher nominal output voltage in the bidirectional inverter. The second point could be more important depending on the loads connected to the system (specific tests with the house appliances are being carried out). Nevertheless, in case any current distortion-sensitive load is found, filters can be installed to decrease the current distortion.

On the other hand, the results obtained are very similar to the values given by manufacturer data sheets except of string inverters self-consumption and current distortion. In the first case it must be taken in account that the string self-consumption can not be measured directly (see equation 4) thus the results obtained must be taken as approach and no as actual values. In the second case, the differences are because the values given in the manufacturer data sheet are related to the grid operation mode of the inverters, where the voltage distortion is lower than in AC-bus operation mode.

Finally, it is important to mention than the model used to characterize the inverters efficiency allows estimating the conversion losses in any situation and therefore it has been used to improve the energy simulation of the system.

4 ENERGY PRODUCTION SIMULATION

The Solar Energy Institute has developed a computer program which, among other things, is able to do an hour-by-hour simulation of a stand alone Phovoltaic system.

This software, "*Dimensiona"*, calculates the irradiation on an inclined surface, energy balances, the State of Charge of the batteries and the Loss of Load Probability of the system: key parameters to analyze the reliability of a photovoltaic installation. Based on this, a new version of *Dimensiona* has been developed which is designed to simulate "magic BOX" PV system

4.1 Irradiation

We use weather data of Sterling, VA which can freely downloaded in the web page of the Renewable Resource Data Center (http://rredc.nrel.gov/solar/). The Hourly Data Files are derived from the National Solar Radiation Data Base hourly data in synoptic format. They contain global horizontal solar irradiance, direct normal solar irradiance, and diffuse horizontal solar irradiance for each hour from January 1, 1961 through December 31, 1990 (if available) for each of the 239 sites in the National Solar Radiation Data Base.

In order to calculate the global irradiation over the different tilted surfaces a clasical methodology is used [6]. The process starts with the splitting of horizontal global irradiation into hourly horizontal direct and diffuse values. Each component is independently considered in order to calculate the respective value over the tilted surfaces. The model used to calculate the diffuse component considers the anysotropic behaviour of diffuse solar radiation [7]. In the case of direct solar radiation, a model which considers the angular reflection losses has been also implemented [8].

4.2 Electrical Loads

Solar Decathlon is a competition to design and build houses that demonstrate the advantages of a solar lifestyle. Because of this, the solar home should provide energy to the typical home appliances of a single-family American home. The list of domestic loads is imposed by the competition rules, which also indicates the use conditions. All the appliances were selected in terms of energy efficiency; the daily energy consumption values are shown in the table VI.

Domestic Load	**Energy (kWh/day)**
Refrigerator and freezer	1.2
Range Top	1.55
Oven and Microwave	0.12
Hood	0.06
Waste disposer	0.12
Dishwasher	0.8
Washing machine	1.02
Dryer	4.2
TV monitor	1.1
DVD set	0.23
Computer/Monitoring	1.44
Indoor Lighting	1
Outward Lighting	0.01
House control	0.40
Total	13.25

Table VI: Domestic loads and their energy per day

During the competition itself, we estimate that the house will require approximately 13.25 kWh of energy each day. In fact, the daily energy required will change throughout the competition week, because the tasks schedule foreseen.

Also, an electric car has to be supplied by the PV installation. To fully charge the car requires approximately 7.2 kWh, and under proper conditions, it will get up to approximately 45 kilometers on a charge.

Finally, the house climatic control, the monitoring and the hydraulic motor to move the living room between the winter and summer positions requires about 400 Wh per day. Figure 11 shows the hourly distribution of a typical day.

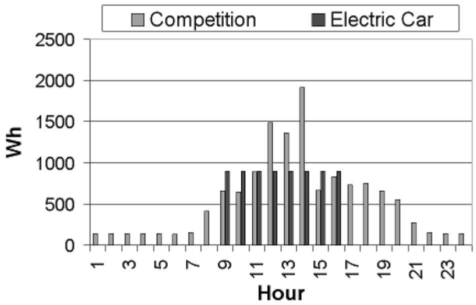

Figure 11: Hourly house electrical load distribution.

4.3 “magic BOX” simulation results

Table II shows the mean daily global irradiation values for all months of the year in the different tilted surfaces.

Month	G(0)	G(12)	G(25)	G(39)	G(90)
Jan	2.11	2.2	2.68	3.05	2.84
Feb	2.92	2.97	3.45	3.78	3.11
Mar	3.96	3.88	4.22	4.35	2.86
Apr	5.02	4.73	4.86	4.69	2.27
May	5.76	5.26	5.18	4.75	1.73
Jun	6.27	5.63	5.44	4.85	1.37
Jul	6.03	5.45	5.31	4.79	1.54
Aug	5.4	5.02	5.06	4.78	2.08
Sep	4.43	4.27	4.52	4.54	2.67
Oct	3.36	3.38	3.82	4.08	3.09
Nov	2.27	2.32	2.76	3.07	2.74
Dec	1.81	1.88	2.32	2.65	2.53

Table VII: Daily mean solar irradiance (kWh/m^2) incident on a horizontal surface and the different arrays

Figure 12 shows the monthly energy balance. It should be considered that the negative values obtained do not include the energy stored in the batteries; i.e. the energy balance parameter can not be used to predict the reliability of the PV system. It is usual to quantify this reliability in terms of the Loss of Load Probability, *LLP*, defined as the fraction of time during which electricity is unavailable. This is calculated, or simulated, over the period that the installation has been in service. Figure 13 shows the *LLP* for “magic BOX” PV system, given the electrical consumption previously estimated. As it can be seen, the minimum value is obtained in December, because the considered daily load is constant for all the year and this month has the minimum electricity production; the LLP for this month is 0.008, this can be interpreted as 0.8 % of the electricity needs not supplied by the PV system. However, a PV stand alone system like this is to have a significant feedback from the users: when the battery State of Charge is low, the consumption of several appliances (such as the electric car), could be reduced.

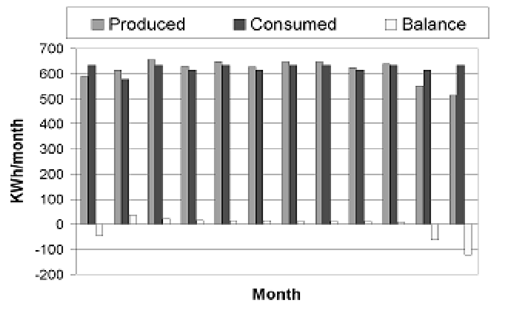

Figure 12: Energy balance (production-consumption)

Figure 13: Monthly LLP

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REFERENCES

[1] Richard J. King and Ruby Nahan, “Solar Decathlon: Energy We Can Live With”, *19th EPVSEC*, Paris, 2004.
[2] E.Caamaño-Martin and M.A. Egido, this conference.
[3] M.A. Egido and E. Lorenzo, ‘*The sizing of stand-alone PV systems: a review and a proposed new method*’, Solar Energy Materials and Solar Cells, 26, 51-69, 1992.
[4] M. Wollny, M. Meinhardt, M. Rothert, A. Engler, “New Generation of V/f-Statics Controlled Battery Inverter Sunny Island - The Key Component for AC Coupled Hybrid Systems and Mini Grids”, *14th PVSEC*, Bangkok, 2004.
[5] J. Muñoz, E. Lorenzo, “*On the specification and testing of inverters for stand-alone PV systems*”, Progress in Photovoltaics: Research and Applications, to be published.
[6] M. Jantsch, H. Schmidt, J. Schmid, “Results of the concerted action on power conditioning and control”, *11th EPVSEC*, Montreux, 1992.
[6] E. Lorenzo and all, *Solar Elecricity*, Ed. J. Wiley & Sons, 1995
[7] R. Perez and all, “*A new simplified version of the Perez diffuse radiation model*”, Solar Energy 1987; 39:221
[8] N. Martín and J. M. Ruiz, “*Annual Angular Reflection Losses in PV Modules”*, Progress in Photovoltaics: Research and Applications, 2005; 13:75–84.