# Simulation of PV Power Plant's Output in Uruguay

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*Abstract*—**Uruguay is currently undergoing a major transition in the way that energy is generated and used. The introduction of non conventional renewable energy sources, such as wind and solar power, play a key role in the national energy policy. However, the development of PV systems has been scarce in comparison with wind power. The first on-grid PV power plant was installed in the North of the country in 2013 through a Japanese collaboration (JICA). This early effort shows that the technology was applicable in Uruguay and, as a consequence, contracts for 240 MW of grid-connected PV power plants have been recently authorized by the national electricity utility. In this work we simulate the output of the JICA's PV power plant on an hourly basis to derive an estimation of the capacity factor and validate our model with the ground-truth power output of the PV plant. Then, we use the model to generate a long term estimation for the South part of the country where long-term series of ambient temperature data are available. Hourly solar irradiation series are obtained using a pre-existing satellite-based model especially adjusted to the target territory.**

*Index Terms*—**PV modelling, Capacity Factor, Renewable Energy, Satellite-based Model, Uruguay**

## I. Introduction

The use of photovoltaic solar energy begins in Uruguay mainly associated with rural electrification. The first recorded experience dates back to 1992 where UTE (the national electricity utility) started a pilot project in which PV equipments were installed in schools, police stations and hospitals in rural areas. In 2004 there were 613 PV systems installed along the country for a total capacity between 5-6 kWp. All schools and police stations in rural area were covered. Also, some PV systems have been installed in small villages. Between 2004 and 2008 a total of 1000 solar PV systems financed by the national Energy Efficiency Program (GEF grant) was reached [18].

Uruguay has a short-term, medium-term and long-term energy policy that has been agreed between all policy-makers of all political parties. This policy is based on the energy matrix's diversification with a special focus on renewable energy sources. In this context, there were two milestones that nowadays are pushing the development of PV applications in Uruguay: a decree (173/010) that authorizes house-holds' microgeneration and a decree (133/013) that promotes sales contracts of solar photovoltaic energy sources to the public electricity utility. Based on these decrees, a total of 240 MW of PV are expected to be installed in the country by the end of 2015 [16], [17].

In March 2013 a photovoltaic solar plant, called *Asahi*, was the first PV power plant to be installed and operated in the country. The installed capacity is of 480 kWp. It was possible due to a well-known Japanese Collaboration Program (JICA) [19]. At present, another central of similar characteristics is under development in the South of the country.

In this work we simulate the output of PV power plants in Uruguay on an hourly basis. Local meteorological data and satellite-based irradiation data are used together with a locally implemented PV Power Plant's model. With the available data it was possible to validate the method using a series of 1 year of hourly measurements of the Asahi's electrical power output. Finally, the model was used to derive a long-term estimation of the capacity factor in the Southern part of the country using a data-series of 14 years of hourly ambient temperature and satellite-derived irradiation.

## II. Locations and meteorological data

The inputs of the PV power plant, that is described in Section IV, are ambient temperature and irradiation data on horizontal surface. Two sites' concurrent series of hourly mean ambient temperature and hourly global irradiation derived from satellite information were used in this work. Solar hourly irradiation on tilted surface is estimated using a model to obtain it from the solar global irradiation in horizontal surface. This is explained in Subsection IV-A. The decision about which locations to use for the simulations was made taking into account the best database of temperature and irradiation available

The sites chosen are: Salto (31.27 S, 57.89 W) and Las Brujas (34.67 S, 56.34 W). The first one is in the North of the country and is coincident with the location of the Asahi's power plant. The second site is in the South of the country and is coincident with an agronomic research facility of the National Institute for Agronomic Research[1] where several meteorological variables are recorded. In Fig. 1 the location of both sites are shown.

### A. Satellite-based irradiation data

Solar irradiation was obtained from GOES-East satellite information using a locally implemented irradiation model. There exist several satellite-based irradiation models [4]–[6]. The model used is a modification of a pre-existing statistical model [3] that greatly improves its performance. The modified model is called BD-JPT [1], [2]. As a statistical model, it relies on a set of parameters that were locally adjusted. The
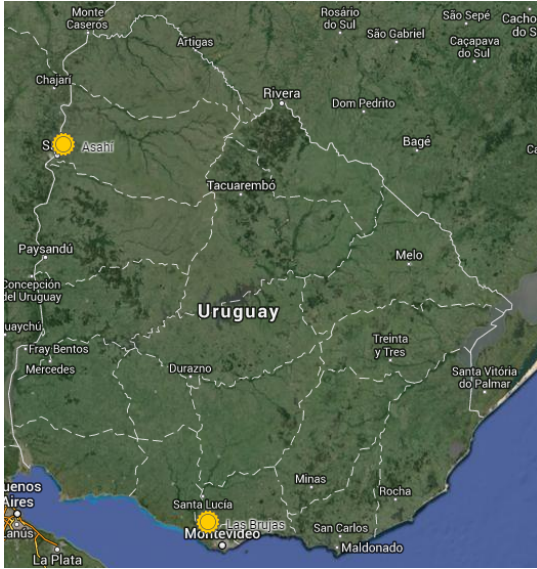
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[1] INIA/Uruguay, http://www.inia.uy/

Figure 1. Location of the PV Power Plants

data-sets used to adjust the model belong to the national solar radiation's network, that is administrated by the Solar Energy Laboratory[2]. These measurements are of controlled quality and are obtained using CMP6 Kipp & Zonnen field pyranometers.

The parametrization of the model is given in Eq. (1), where $I$ is the hourly global irradiation in horizontal surface, $I_{h0}$ is the hourly solar constant, $F_n$ is the correction for the Sun-Earth distance due to the eccentricity of the Earth orbit and $\cos\theta_z$ is the cosine of the zenithal angle.

$$
I = \begin{cases} I_{h0}F_n\cos\theta_z\left(a_1 + b_1\cos\theta_z + c_1\cos^2\theta_z\right) + \dots \\ \qquad \dots + d_1\left(F_{rm}^2 - F_{r0}^2\right) \quad \text{if } F_{rm} \leq F_r^{th} \\ \\ I_{h0}F_n\cos\theta_z\left(a_2 + b_2\cos\theta_z + c_2\cos^2\theta_z\right) + \dots \\ \qquad \dots + d_2\left(F_{rm}^2 - F_{r0}^2\right) \quad \text{if } F_{rm} > F_r^{th} \end{cases}
$$
(1)

$F_{rm}$ and $F_{r0}$ are hourly values of reflectance factor obtained from the visible channel from GOES-East imagery. $F_{rm}$ is the mean observed reflectance factor in a cell of $10' \times 10'$ around the location of interest for given date and time. $F_{r0}$ is reflectance factor of the cell for the same date and time, but in clear sky conditions. $F_{rm}^{th}$ is a threshold which classified the values of reflectance factor into two sets, i.e., clear sky hours and cloudy hours. More information of this satellite-based model can be found in [1], [2].

When compared with independent measurements in the target region (measurements not used to adjust the parameters) the model reports a root mean squared deviation of 14% of the mean value for hourly data, and 7% for the daily values [1]. This imply that the performance of the model in the Uruguay's territory is excellent, for instance, in a daily basis its uncertainty is comparable to the uncertainty of a field pyranometer.

[2]LES/Uruguay, http://les.edu.uy

Using this model together with 14 years of GOES-East satellite information it is possible to obtain hourly irradiation data from 01/2000 to date for any location in Uruguay with a minimum spatial resolution of about 1 km (nominal resolution of the satellite images). This was done for the two sites studied in this work, Las Brujas y Salto.

### B. Datasets of temperature and irradiation

Ambient temperature data was provided by INIA/Uruguay and it was carefully recorded at the agronomic research facilities of Las Brujas and Salto. The experimental facility in Salto is only 2.5 km away from Asahi's exact location, so using this set of temperature data does not contribute to significant errors.

Only data-sets in which concurrent ambient and solar irradiation were available have been used. In Table I the time periods of the series that were used in this work are shown.

Table I
*Data series for ambient temperature and solar irradiation.*

| site | start date | finish date | years |
|---|---|---|---|
| Salto | 01/2010 | 12/2013 | 4 years |
| Las Brujas | 01/2000 | 12/2013 | 14 years |

### III. TYPES OF PV PLANTS SIMULATED

The plant's model made presents similar characteristics to Asahí's PV plant. The modelling is, therefore, easier, because the entire layout and equipment that is being used are known. Also, it is justified because the idea is to compare the constructed model with Asahí's power output, so, a similar model must be used. In the Table II, the general characteristics of the PV Plants are presented.

Table II
*General Characteristics of the PV Plants.*

| Power Plant | |
|---|---|
| Rated Power ($kW$) | 480 |
| Peak Power ($kW$) | 481.6 |
| **Solar Panels** | |
| Type | PolySi |
| Power ($W$) | 215 |
| Quantity | 2240 |
| Tilt angle | 30° (fixed structure) |
| $I_{cc}$ ($A$) | 7.92 |
| $V_{oc}$ ($V$) | 36.7 |
| $I_{mpp}$ ($A$) | 7.37 |
| $V_{mpp}$ ($V$) | 29.2 |
| **Inverters** | |
| Power ($kW$) | 250 |
| Quantity | 2 |
| Input Voltage Range ($V$) | 225-600 |
| Output Voltage ($V$) | 400 |
| Frequency ($Hz$) | 50 |

### IV. MODELLING

#### A. Radiation on tilted surface

The global incident radiation ($G_i$) on a tilted surface is composed by three components: direct radiation from the Sun ($G_{bi}$), diffuse radiation from the sky ($G_{di}$) and reflected

radiation in the ground ($G_{ri}$) [10]. This magnitudes are related by Eq. (2).

$$G_i = G_{bi} + G_{di} + G_{ri} \qquad (2)$$

The model used in this paper to determine the incident radiation on a tilted surface was proposed by the authors Hay, Davies, Reindl and Klucher [10] and is known as HDKR model. This model considers the fact that the diffuse radiation comprises an isotropic, a circumsolar and a horizon brightness component. The equation proposed by HDKR for the incident radiation $G_i$ is given in Eq. (3) [10]. The equation has three terms, that represent respectively the magnitudes $G_{bi}$, $G_{di}$ and $G_{ri}$.

$$
\begin{aligned}
G_i &= (G_{bh} + T_b G_{dh}) R_b \\
&+ G_{dh} v \left[ (1 - T_b) \left( \tfrac{1+\cos\beta}{2} \right) \left( 1 + \sqrt{(1 - f_d)} \sin^3(\beta/2) \right) \right] \\
&+ G_h \rho_g \left( \tfrac{1-\cos\beta}{2} \right)
\end{aligned}
\qquad (3)
$$

The magnitudes $G_{bh}$ and $G_{dh}$ are the beam a diffuse components on horizontal surface. We use a pre-existing hourly global-to-diffuse model known as Ruiz-Arias' model [9] to estimate the diffuse fraction $f_d$ based into the actual value of the global horizontal irradiation.

In order to have a preliminary validation of the use of this model, the output obtained from the HDKR model was compared with actual values of irradiation on tilted surface during one year. The measurements were acquired by LES/Uruguay. In Fig. 2 is shown the deviation of the model (in Wh/m$^2$) when it is compared to the measured values. In some specific days, the difference between the model and measurements reach more than 200 Wh/m$^2$, mostly at midday. The hourly root mean square deviation obtained was of 25 % of the irradiation mean value. It is noted that model deviation has a certain seasonality, tending to overestimate irradiation in summer and underestimate it in winter. When we consider the deviation at a yearly basis, the measurements values in comparison to the output of the model report a difference less than 3 %, which we found acceptable. This can be observed in Fig. 3.
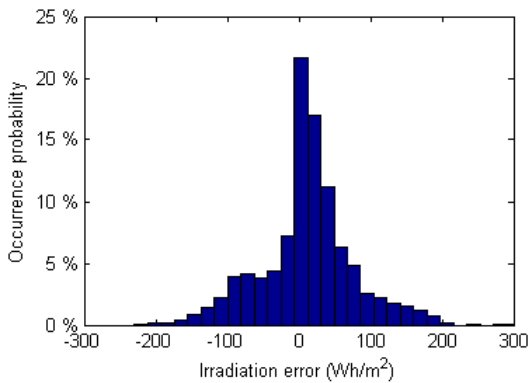


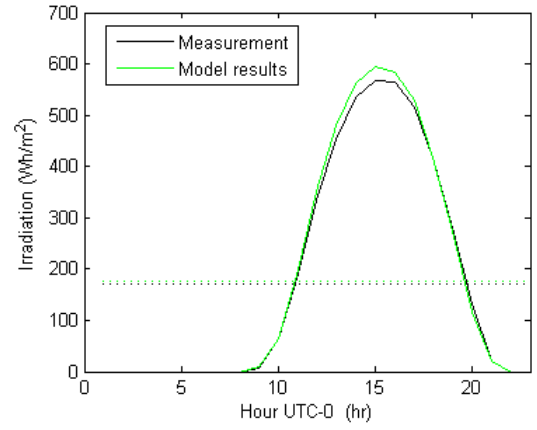Figure 2. *Irradiation model error histogram.*



Figure 3. *Average annual irradiance measurements and model output comparison in an hourly basis.*

## B. Panel electrical model

The equivalent electrical circuit of a PV cell is shown in figure 4. The current-voltage characteristic can be expressed according to the Eq. (4)
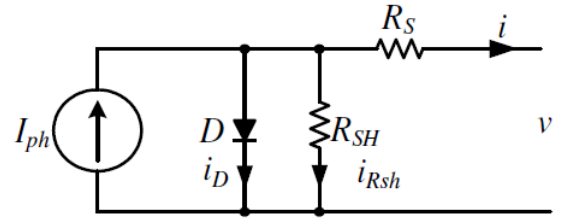


Figure 4. *PV module electrical model scheme.*

$$i = I_{ph} - I_o \cdot (e^{\frac{v + R_s \cdot i}{n_s \cdot V_t}} - 1) - \frac{v + R_s \cdot i}{R_{sh}} \qquad (4)$$

Where :

- $V_t = (A k_{T_{STC}})/q$ is the junction thermal voltage
- $I_{ph}$ - the photo-generated current in STC
- $I_o$ - dark saturation current in STC
- $R_s$ - panel series resistance
- $R_{sh}$ - panel parallel shunt resistance
- $A$ - diode quality-ideality factor

The components of $V_t$ are:

- $k$ - Boltzmann's constant
- $q$ - the elemental charge
- $T_{STC}$ - temperature at STC

Therefore, the PV model can be determined by finding the five parameters mentioned ($I_{ph}, I_o, R_s, R_{sh}, A$). These parameters can be found using part of the data provided

by manufacturers in the data-sheets of commercial modules as:

- $I_{sc}$ - short-circuit current in STC
- $V_{oc}$ - open-circuit voltage in STC
- $V_{mpp}$ - voltage at the Maximum Power Point (MPP) in STC
- $I_{mpp}$ - current at the MPP in STC
- $P_{mpp}$ - power at the MPP in STC
- $k_i$ - temperature coefficient of the short-circuit current
- $k_v$ - temperature coefficient of the open-circuit voltage

The first three equations consist in evaluating the i-v characteristic of the PV in different operating points, while the other two are developed by evaluating the derivative of the p-v and i-v equations in two of these points as it follows [11].

Short circuit in STC conditions ($v = 0$):

$$I_{sc} = I_{ph} - I_o \left( e^{\frac{R_s . I_{sc}}{n_s . V_t}} - 1 \right) - \frac{R_s . I_{sc}}{R_{sh}} \tag{5}$$

Open circuit in STC conditions ($i = 0$):

$$I_{oc} = 0 = I_{ph} - I_o \left( e^{\frac{V_{oc}}{n_s . V_t}} - 1 \right) - \frac{V_{oc}}{R_{sh}} \tag{6}$$

Maximum power point:

$$I_{mpp} = I_{ph} - I_o \left( e^{\frac{V_{mpp} + I_{mpp} . R_s}{n_s . V_t}} - 1 \right) - \frac{V_{mpp} + I_{mpp} . R_s}{R_{sh}} \tag{7}$$

The curve $P(V)$ evaluated in the MPP has zero derivative at MPP:

$$\left. \frac{dP}{dV} \right|_{\substack{V = V_{mpp} \\ I = I_{mpp}}} = 0 \tag{8}$$

The shunt resistance $R_{sh}$ is determined by the derivative of the curve $i(v)$ in short circuit current conditions:

$$\left. \frac{dI}{dV} \right|_{I = I_{sc}} = -\frac{1}{R_{sh}} \tag{9}$$

The constructed system consists of five non-linear equations, therefore it must be solved using a numerical method.

This PV model is valid only in STC conditions. In order to get a precise model, the effect of temperature must be considered. To get an estimation of the cell temperatures, the INOCT (Installed Normal Operating Cell Temperature) model was used. The cell temperature was calculated with the following equation:

$$T_c = T_{amb} + (NOCT - 20 - 3)\frac{G}{800} \tag{10}$$

where $T_c$ and $T_{amb}$ are the cell and ambient temperatures respectively, $G$ the irradiation on tilted surface, and $NOCT$ a temperature provided by the manufacturers data-sheets. The $3\,^oC$ term is the contribution to the NOCT model due to the physical disposition and installation of the PV modules.

Now the effect of temperature may be considered. The following equations represent the photogenerated and dark saturation currents in generic temperature and irradiance conditions respectively.

$$I_{ph}(G,T) = I_o(G,T)e^{\frac{V_{oc}(G,T)}{n_s V_t}} + \frac{V_{oc}(G,T)}{R_{sh}} \tag{11}$$

$$I_o(G,T) = \left( I_{sc}(G,T) - \frac{V_{oc}(G,T) - I_{sc}(G,T)R_s}{R_{sh}} \right) e^{-\frac{V_{oc}(G,T)}{n_s V_t}} \tag{12}$$

According to [11], the dependence of $V_{oc}$ and $I_{sc}$ parameters responds to the next two equations:

$$V_{oc}(G,T) = ln\left( \frac{I_{ph}(G)R_{sh} - (V_{oc}(G) + k_v(T - T^{stc}))}{I_0 R_{sh}} \right) n_s V_t \tag{13}$$

$$I_{sc}(G,T) = I_{sc}^{stc} \frac{G}{1000}\left( 1 + \frac{k_i}{100}(T - T^{stc}) \right) \tag{14}$$

Several loss factors were considered to simulate the PV plants. The following list mentions the ones that were imposed based on the literature [12], [13], [14], [15]:

- Shading losses - $2.0\,\%$
- Dirt losses - $3.0\,\%$
- Angular reflectance losses - $3.0\,\%$
- Mismatch losses - $5.0\,\%$
- Transformer losses - $1.0\,\%$
- Inverter losses - $1.5\,\%$
- Annual degradation losses - $0.7\,\%/yr$ (starting from $97\,\%$ in the first year)

The temperature losses are excluded from the list because they are intrinsically considered in the model. Also, the ohmic losses were calculated based on the plant's layouts.

*C. Panel model validation*

The validation was performed from the RISEN SYP235S (235 Wp) solar panel data sheet. The $p - v$ and $i - v$ characteristic curves were compared according to the irradiance and the $i - v$ curve as a function of temperature.

Curves of equal characteristics to the data sheet were made with the designed panel model. The results are shown in Figs. 5, 6 and 7, where black dots represent the output of the model.

It is important to mention that the error seen in Fig. 7 for temperatures in the $-10\,^oC$ to $0\,^oC$ is neglectable when a yearly output is considered, due to the low occurrence of temperatures this low in the region. Fig. 8 illustrates this fact.
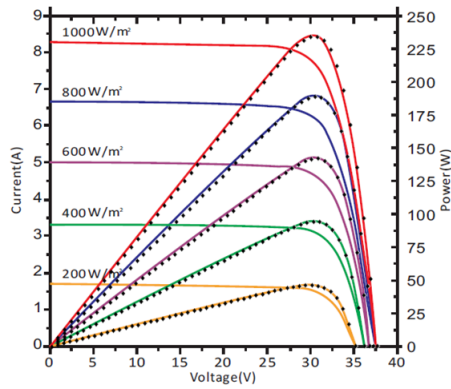
Figure 5. *P-V manufacturer and model output curves comparison with varying irradiance.*
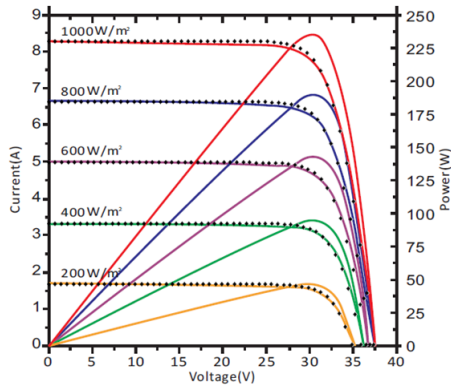


Figure 6. *I-V manufacturer and model output curves comparison with varying irradiance.*
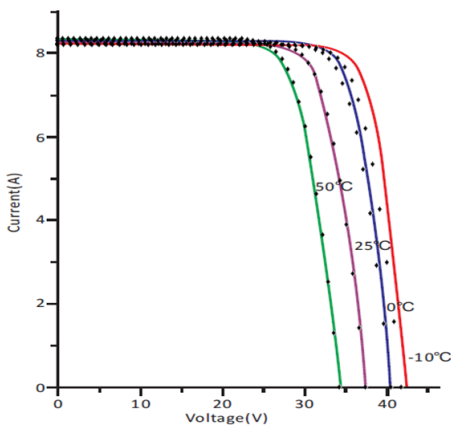


Figure 7. *I-V manufacturer and model output curves comparison with varying cell temperature.*

## V. MODEL OUTPUT

After defining the modelling of each part of the system, a Simulink model was develop in order to perform the simulations of the system.
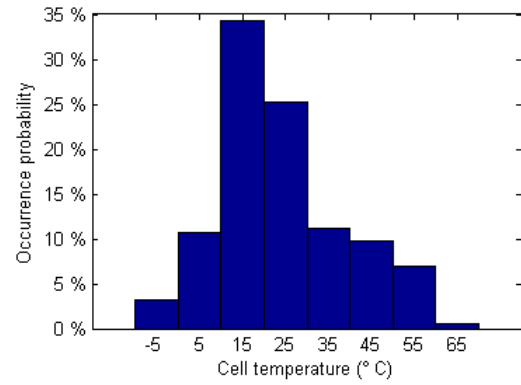


Figure 8. *Modelled cell temperature histogram in Salto from 2010 to 2013.*

### A. Salto PV plant validation

Counting with the ground-truth power output measurements of Asahí PV plant, the Capacity Factor (CF) was calculated, resulting 17.5 % on a yearly basis (starting from August 2013). To validate the complete model, the simulated CF of the plant was determined, using the satellite based irradiation data and the ambient temperature measurements available in Salto (from 2010 to 2013). These yearly simulations were performed independently, which means the annual degradation in the four considered years is not cumulative. The results are shown in table III, where it can be seen that the actual CF of the plant is very close to the total simulation results for each year. A mean value of 17.6 % and a standard deviation of 0.3 % was found for that period of time. The actual value for Asahi's capacity factor is included in this range.

Table III
*Simulated Capacity Factor for Asahi PV plant*

|  | Capacity Factor (%) | | | |
| --- | --- | --- | --- | --- |
|  | 2010 | 2011 | 2012 | 2013 |
| January | 22,2 | 19,6 | 21,8 | 21,7 |
| February | 20,1 | 19,0 | 21,1 | 22,2 |
| March | 19,3 | 20,0 | 20,1 | 19,8 |
| April | 16,4 | 17,3 | 17,3 | 18,6 |
| May | 11,7 | 14,3 | 14,4 | 11,7 |
| June | 10,6 | 11,0 | 12,9 | 11,9 |
| July | 12,2 | 13,3 | 15,6 | 13,1 |
| August | 14,2 | 14,5 | 13,2 | 16,6 |
| September | 17,6 | 18,6 | 17,2 | 17,5 |
| October | 20,7 | 19,4 | 19,6 | 20,4 |
| November | 21,8 | 22,6 | 21,8 | 19,7 |
| December | 21,1 | 21,9 | 19,4 | 21,7 |
| Total | 17,3 | 17,6 | 17,8 | 17,9 |

### B. Las Brujas plant simulation results

After the model has been verified, a long term simulation for a PV power plant located in Las Brujas can be run. Fig. 9 shows these results from year 2000 to 2013 (excluding 2009, year for which the series of ambient temperature data was incomplete). Also, the degradation tendency can be observed.

An average capacity factor of 15.5% was obtained, this number is bellow the capacity factor of the Salto facility be-
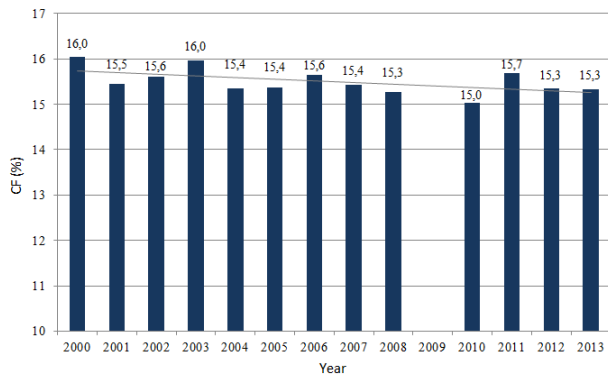
Figure 9. *Las Brujas PV plant power factor simulation per year.*

cause of two facts: (i) the location is further South than Asahi's power plant and (ii) a 14 years degradation is considered. Also, in the first year of operation a capacity factor of 16.0 % was obtained, which is minor than the ones obtained for Salto. This is explained only because of the location of the plant.

## VI. Conclusion

This paper presents a complete modelling of a real and installed 480 kWp photovoltaic plant located in Uruguay. This model was validated using actual measurements of irradiance, ambient temperature and power generation of the plant, since it is operational. After performing this validation, it was possible to use the model to calculate the generated energy and consequently the capacity factor of a plant settled in the South of the country.

The model (which was developed in Simulink) is flexible and can quickly be adapted to the general conditions of the plant that it to be simulated. The simulation was performed in an hourly basis, which can capture even intra-day behaviour and be used for applications other than those shown in this work.

The model is composed of two blocks. The first one is in charge of converting the global solar irradiation on horizontal surface into tilted surface. This part of the model was validated using independent measurements and a mean year deviation of 3 % from the mean value that was obtained from this model. The second one is the plant model itself. A validation of the whole model was done using the capacity factor obtained for Asahi. The value obtained for it was 17.5 %. A 4 year simulation was done (year by year) for this site and a mean capacity factor of 17.6 ± 0.3 % was obtained. The values found in the simulation are very close to the mean CP calculated with the measurements, and it is consistent with the inter annual variability that was found for the 4 year period that was simulated.

In medium-term, Uruguay has some ambitious objectives regarding the inclusion of non-conventional renewable energy sources into it's primary energy matrix. The inclusion of PV solar energy source is experiencing a great impulse from the National Energy Office and the national electricity utility. In

that sense, it is important to develop tools that are validated with local data. This allows project developers and decision makers themselves to predict the performance of a PV system located in Uruguay with less uncertainty. The reduction of the uncertainty in the production of a PV power plant has a great impact in technology development and access to financial support for the installation projects.

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