ASSESSMENT OF THE INTER-ANNUAL VARIABILITY OF THE GLOBAL HORIZONTAL IRRADIANCE IN THE ATACAMA DESERT OF CHILE

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ABSTRACT: The inter-annual variability (IAV) of the solar resource is an important uncertainty component in annual energy production (AEP) estimates of photovoltaic (PV) plants. Based on studies in the Mediterranean and Black Sea region, a figure of 4 to 6% is sometimes used by consultants. For the extremely arid climates in the Atacama Desert in the North of Chile such generic values are expected to unnecessarily penalise developers seeking project financing. In the absence of reliable and consistent long-term ground measurements for this region, and based on previous in-house validation work and industry experience, long-term mesoscale satellite-derived datasets from the SolarGIS® database were found to be the best available data source to estimate the IAV of the global horizontal irradiance (GHI). It was found that none of the 14 sample sites considered in this study displayed an IAV exceeding 2%. While this result is subject to limitations, the observed performance of the model relative to measured data suggests that the uncertainty in the IAV value is small compared to the systematic error that otherwise arises from using a 4 to 6% generic figure for sites in the Atacama.

Keywords: Inter-annual Variability, Solar Radiation, Evaluation

1 INTRODUCTION

The prediction of the annual energy production (AEP) of a photovoltaic (PV) plant is subject to a number of uncertainties. These can be grouped into three main categories:

i. variability of the solar resource (depending on the time period considered),
ii. uncertainty in relation to the measurement of the solar resource, and
iii. uncertainty associated with the simulation.

The inter-annual variability (IAV) of the solar radiation, which is the main driver of category i), is therefore a key input into the financial assessment and valuation of a PV project. It quantifies how much a yearly value can vary from the long-term average, and ultimately influences the debt-ratio and return on investment as it directly intervenes in the Pxx[1] calculation.

A generic value of 4 to 6%, calculated in [1] for the Mediterranean and Black Sea region, is sometimes used in the industry for the IAV of the global horizontal irradiance (GHI). The study carried out in [1] covers a wide variety of climates and geography, and shows that the IAV can range from below 2% in the arid regions to 10% in the more mountainous regions of the studied area.

The present study focusses on the Atacama Desert in the North of Chile, which the World Wide Fund for Nature defines as the ecoregion extending from a few kilometres south of the Peru-Chile border to about 30° southern latitude, spreading over 10° in latitude. It has the highest average GHI in the world and is also the driest region, where in some locations no rain is recorded for years.

Considering the geographic and climatic characteristics present within this area, the aforementioned generic 4 to 6% figure obtained from [1] is hypothesised to be conservative, and an attempt will be made to estimate a more realistic value within this study.

Figure 1: Yearly average GHI in the northern half of Chile. Source: SolarGIS [2]

[1] Pxx: Banks and investment firms working on renewable energy projects often require P90, P95 or P99 values

2 DATA AND METHODOLOGY

2.1 SolarGIS database

The SolarGIS® satellite-to-irradiance model takes input from 4 geostationary satellites (MSG, MFG, GOES and MTSAT), covering the almost entire surface of the Earth. Data for South America, and particularly Chile, is entirely collected by the GOES-EAST mission. Figure 2 shows the structure of the model generating SolarGIS [3] databases.

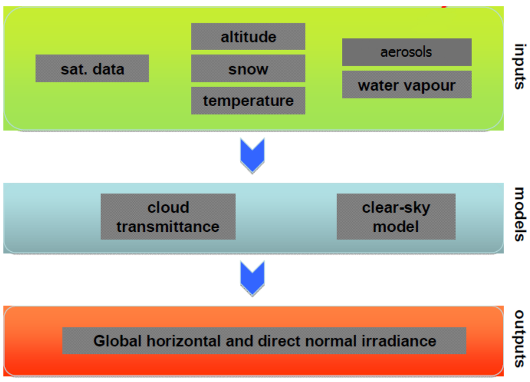

Figure 2: GeoModel Solar scheme. Source: SolarGIS [3]

Other inputs to the model include [4]:

- Cloud Index and Snow Index calculated from Meteosat and GOES satellites [5]
- Water Vapour derived from GFS database [6]
- Atmospheric Optical Depth calculated from MACC database [7]
- Snow Depth from GFS and CSFR [8]
- Elevation and horizon profile calculated from Digital Elevation Model SRTM-3 [9]

The calculation methodology for cloud transmittance and clear-sky irradiance is described in several papers [10], [11], [12], [13].

The model outputs used in this study are long-term[2] hourly time-series of GHI provided at the model node nearest to the required location[3].

2.2 Ground measured data and model validation

Ground measured data from various sites across the world have been used by SolarGIS® for validations of the model. As in [1], the present study also assessed the accuracy of the modelled data within the study region.

It is difficult to source suitable historic measured reference data in Chile. Only as recent as in 2009, the Comisión Nacional de Energía (CNE) started a public measurement campaign, implementing a network of 9 solar irradiance measurement stations across the Atacama region for the benefit of renewable energy industry. Given its specific objective, this network is the most reliable of all public measurement networks and, despite some of its shortcomings (such as lack of publicly available maintenance records), was selected for the validation of the modelled data. In addition to the 9 CNE sites, measured data from 6 stations operated by project developer Mainstream Renewable Power (MRP), relating to a further 5 locations, was included in the comparison. Figure 3 shows the location of the 14 sites considered. They are reasonably representatively placed to cover the study area, which is approximately 280,000km^2 in size.

Figure 3: Location of ground measurement stations from both CNE and MRP networks.
Base map: © OpenStreetMap contributors [14].

For comparison, 90 sites were used in [1] to cover an area of about 10.5 million km^2. In all cases, measured data is recorded every 2 seconds and averaged every 10min, providing 10min time-series for up to 3.7 years depending on the site, see Table 1.

It is important to note that while both MPR and CNE provide secondary standard measurements, only MRP provide a thorough record of the regular cleaning regime of the pyranometers, maintenance and calibration parameters. Therefore, CNE data is assumed to be less reliable.

Both CNE and MRP networks have a measurement station installed within 5km from each other at the location Pozo Almonte. A comparison was therefore additionally carried out between measured data from these two stations, over a 19 months concurrent period. It was found that the mean bias for the whole period was 1.9% of the average GHI measured at the MRP station, daily RMSE is 3.4%, and monthly RMSE is 2.6%. Despite the aforementioned shortcomings of the CNE datasets, the bias and RMSE were small and it was concluded that using this data should not significantly affect the IAV estimation.

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[2] 14 years (from 1999 to 2012), except for one site which has only 13 years (1999 to 2011).

[3] The model has a spatial resolution of 1km.

Sites - North to South	Validation period [years]
MRP 2	2.5
MRP 1	0.9
Pampa Camarones	3.1*
Pozo Almonte	3.7*
MRP 3	2.6
Crucero	3.6
Salar	1.8*
San Pedro de Atacama	3.7*
Puerto Angamos	2.5*
Cerro Armazones	2.8*
Salvador	0.5
MRP 4	2.5
Inca de Oro	2.6*
MRP 5	0.3
MRP 6	1.3

**Validation period is not continuous.*

Table 1: Length of validation period for each site.

As in [1], biases and root mean squared errors were calculated for the daily and monthly mean irradiance obtained from the nearest model node for each site. Table 2 summarises the results.

Site (from N to S)	RMSE Daily [%]	RMSE Monthly [%]	Bias [%]
MRP2	12.8	9.9	-5.5
MRP1	5.6	1.9	-1.5
P Camarones	4	1.5	-0.8
Pozo Almonte	5.3	3.8	1.8
MRP3	4.2	2.5	-2.3
Crucero	3.3	1.3	-0.8
Salar	8.8	8.4	4.5
S Pedro de Atacama	4.6	2.7	2
P Angamos	6.7	5	2.4
C. Armazones	4.6	2.8	-2.7
Salvador	2.7	1.5	-0.5
MRP4	4.8	1.8	-1.4
Inca de Oro	3.5	1.9	-1.4
MRP5	5.9	4.1	-3.5
MRP6	5.5	1.6	-0.7

Table 2: RMSE and bias of modelled data relative to measured data over the concurrent period.

2.3 Inter-annual variability

The IAV is defined as:

$$IAV = \frac{\sigma(X)}{E(X)}$$

Where:

- $X = \{X_{year\ 1}, X_{year\ 2}, X_{year\ 3}, \ldots\}$ is the considered variable, in this study monthly or yearly mean GHI.
- σ is the standard deviation of X
- E is the mean value of X.

If we consider the annual mean GHI at a site, the IAV will quantify statistically how far the mean GHI of one year is likely to deviate from the long-term mean at that site.

Mathematically, a minimum of 3 years of data are required to calculate a value of the IAV. In practice, however, a 3-year period does not capture low frequency modulations and is unlikely to be representative of the long-term IAV of the site. Where reliable long-term measured datasets are not available, like in the case of Chile, long-term modelled datasets, when they have been validated, are therefore the only suitable option to estimate the IAV.

Monthly, yearly sums, and IAV of the GHI were calculated from the satellite-derived datasets at each site.

3 RESULTS

3.1 Variability of the GHI

Table 3 shows the IAV values calculated for the 14 sites across the Atacama Desert, from the modelled datasets. For the Pozo Almonte location where a CNE and a MRP station operate in close vicinity, only the value from the MRP station is reported.

It can be observed that there is a tendency for the IAV to present higher values in those stations that are located closer to the coast. This may be related to the occurrence of the coastal fog typical to parts of the Chilean coast, called “Camanchaca”, which can influence the resource at sites below a certain altitude. Overall, none of the studied locations shows an IAV above 2%.

Sites (North to South)	IAV (14 years)
MRP2	1.8%
MRP1+	1.3%
Pampa Camarones	1.1%
MRP3	1.1%
Crucero	0.8%
Salar	0.9%
San Pedro de Atacama	1.5%
Puerto Angamos	1.8%
Cerro Armazones	0.4%
Salvador	0.8%
MRP4	0.9%
Inca de Oro	0.8%
MRP5	0.9%
MRP6	1.4%

+only 13 years of data available

Table 3: Long-term modelled average GHI and IAV.

Figure 4 shows the spread of the yearly averages around the long-term average (marked by a black cross) for each site.

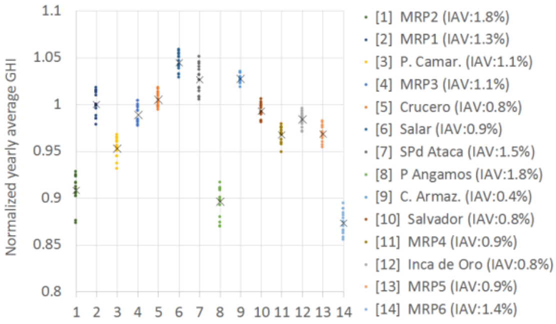

Figure 4: Distribution of the individual years around the long-term mean (marked by a black cross). All GHI values are normalized to the average yearly GHI at the location of the MRP 1 station. IAV value at each site is stated in parenthesis next to the site name for reference.

Figure 5 displays the relative difference of extreme years in relation to the long-term average.

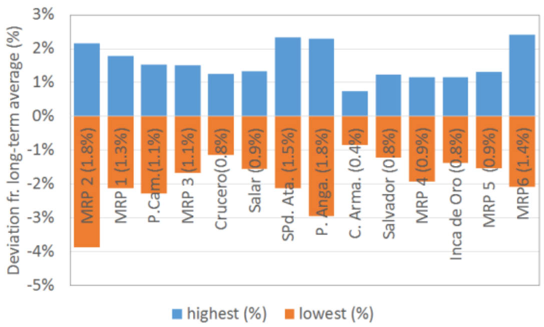

Figure 5: Relative deviation of years with lowest and highest GHI in relation to the long-term mean (IAV value in parenthesis next to site name)

These two figures highlight that the IAV is not necessarily normal distributed around the long-term mean. In a desert region like the Atacama, where cloudy days are very rare, outliers tend to be on the lower side of the long-term average (i.e. more days with clouds) as opposed to on the higher side where there is a natural upper limit (i.e. all days without clouds).

Describing IAV with a single number therefore may result in a loss of information, where two sites with the same IAV number may actually display quite different distributions (such as Puerto Angamos and MRP 2).

3.2 Inter-annual variability, by month

Tables 4a and 4b shows the inter-annual variability of the monthly averages, in order to identify seasonal patterns within the year.

For all sites, it appears that the month with the lowest IAV are November and December, which is late spring and early summer in the southern hemisphere, with an IAV not exceeding 4%. During the winter months, the IAV is generally elevated (up to ca. 8%).

Additionally, most sites in the northern part of the study region appear to be influenced by a second pattern

Month	Cerro Armazons	Crucero	Pampa Camarones	MRP 3	Salar	San P. de Atacama	MRP 1
Jan	1.8	3.1	5.4	4.5	3.9	7.1	11.2
Feb	2.9	4.3	5.0	5.8	5.5	7.8	8.9
Mar	1.3	2.1	2.6	2.8	2.7	4.3	5.0
Apr	1.2	1.6	3.2	2.1	1.5	1.8	1.8
May	1.9	2.0	2.5	2.3	1.6	3.2	1.9
Jun	1.8	2.2	3.1	1.8	1.5	3.3	1.5
Jul	1.9	1.9	5.1	2.2	1.5	2.7	2.6
Aug	1.1	2.1	4.0	2.5	1.8	3.0	2.4
Sep	1.0	1.3	3.6	1.3	1.2	1.7	1.9
Oct	0.9	1.6	1.9	1.5	1.4	1.7	1.1
Nov	0.7	1.2	2.1	1.5	1.3	1.4	2.1
Dec	0.7	1.2	2.9	2.0	1.5	2.0	2.6

Table 4a: Seasonal variation of IAV (in % of GHI), northern inland sites affected by the "Bolivian Winter"

which can lead to high IAV values in January and February (summer), and can exceed even the winter IAV values in these locations. This could be explained by the occurrence of the "Bolivian Winter", which is a regional meteorological phenomenon in which humid air masses from the Amazonas region influence the north of the Atacama region during the summer months of some years, leading to increased amounts of rainfall.

The effect is less pronounced at sites that are closer to the coast and sites in the southern half of the study region.

Month	Puerto Angamos	MRP 2	MRP 6	MRP 5	Inca de Oro	MRP4	Salvador
Jan	2.2	6.2	1.7	1.3	1.6	1.5	1.4
Feb	3.6	6.1	3.9	2.6	2.4	2.8	2.7
Mar	2.5	3.4	3.0	1.8	1.6	1.4	1.6
Apr	3.0	6.0	3.5	2.4	1.9	2.1	2.3
May	5.2	4.0	6.5	4.7	4.3	3.7	3.7
Jun	4.3	7.1	6.0	4.6	3.3	3.4	3.4
Jul	7.5	7.3	5.1	3.8	3.4	3.0	2.8
Aug	3.4	8.4	4.6	2.7	2.0	2.0	2.3
Sep	4.9	6.5	2.4	1.4	1.4	1.2	1.4
Oct	4.4	2.5	3.1	2.9	2.7	1.9	2.3
Nov	2.6	2.7	2.3	1.5	1.0	1.0	0.8
Dec	2.2	3.7	3.0	1.0	1.2	1.5	1.2

Table 4b: Seasonal variation of IAV (in % of GHI), coastal and southern sites

It is noted that the most stable month can still have a higher variability than the annual value. This is likely to be a result of several mechanisms, such as annual weather patterns that do not always fall in the same month, random events over the course of the year which can cancel each other out or a larger sample size for the annual figures relative to the monthly figures.

4 CONCLUSIONS

The density of measurement locations available to validate the modelled data is higher than in previously acknowledged study and bias and RMSE are within the same range or lower. This suggests that the methodology adopted for the Mediterranean and Black Sea region is also suitable for the North of Chile.

None of the sites considered in this study showed an IAV of the GHI above 2%. This result supports the working hypothesis that a generic 4% to 6% IAV figure used for PV projects in the North of Chile is overly conservative, and a 1% to 2% figure would be more realistic. When assessing the AEP of a PV plant using the best possible estimate of the IAV will impact on the P90/P50 ratio, thus avoiding to penalize project developers unnecessarily who are seeking project finance.

Satellite-derived data such as SolarGIS can be a useful tool for estimating a project IAV value, in particular if a site-specific validation of this data is possible. Further validation of this study with long term ground measure datasets would be to verify that satellite-derived irradiance datasets capture low frequency climatic phenomenon such as the “El Niño Southern Oscillation”[4].

5. ACKNOWLEDGEMENTS

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