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Solar Energy Resource Assessment in Chile: Satellite estimation and ground station measurement

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Abstract

The progress from the last four years in solar energy resource assessment for Chile is reported, including measurements from a ground station network spanning from two to three years of data, and satellite estimations from the recently developed Chile-SR model including two full years of data. The model introduces different treatments for the meteorological variables and the effective cloud cover computations which allow estimation of the global horizontal irradiation on an hourly basis. The BRL model of diffuse radiation is then applied in order to estimate the diffuse fraction and diffuse irradiation, from which the Direct horizontal irradiation is then computed. Direct normal irradiation is computed by applying proper solar geometry corrections to the direct horizontal irradiation. The satellite estimation model was developed as an adaptation from Brazil-SR model, with an improved formulation for altitude-corrected atmospheric parameters, and a novel formulation for calculating effective cloud covers while at the same time detecting and differentiating it from snow covers and salt lakes. The model is validated by comparison with ground station data. The results indicate that there are high radiation levels throughout the country. In particular, northern Chile is endowed with one of the highest solar resources in the world, although the resource variability is higher than previously thought.

Keywords: *Solar resource assessment, Chile, ground measurements, satellite estimation, cloud cover estimation.*

1. The Need for Solar Energy Data in Chile

Renewable Energy promotion in Chile has obtained institutional support by means of a law that mandates a renewable energy quota of up to 10% of the electrical energy generated, which must be met by

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2024, with public announcements already being made that would modify this goal in order to achieve 20% of power generation by 2020 from renewable energy [1]. This plan has sparked interest in introducing renewable energy systems to the country´s electricity system. Solar energy is currently at the initial stages of market penetration, with several projects being announced including PV, CSP, and industrial heat supply plants. However, strong barriers still exists due to the absence of a valid solar energy database, adequate for energy system simulation and planning activities. In fact, the current state of Solar Energy utilization in Chile is rather unsatisfactory. Even as the country is being endowed with an exceptional solar potential, the contribution of solar energy to the energy mix in Chile is negligible. Only 3.44 MW of PV have been deployed and are currently operating with 69 MW being built [2], and even when there have been several announcements for commercial and demonstration plants, no other projects are currently being executed -either PV or CSP- but for the process heat plant being built at Minera El Tesoro in northern Chile [3]. As of June 2013, the environmental impact assessment system listed a total of 4012 MW of solar plants already approved that have not yet initiated construction and 2201 MW entered for evaluation, of which 360 MW correspond to a single CSP project (4x90 MW) and the rest are PV plants. However, according to the Chilean Government Renewable Energy Center (CER) [4], none of the projects has already secured funding and are facing serious financial difficulties. Regarding solar heating and cooling systems, statistics from the "Solar Program" at the Energy Ministry indicate that as of 2011 there are 58,000 m^2 of installed solar thermal collectors for both the residential and commercial sectors, projected to reach 190,000 m^2 by 2015 [5]. There are currently no solar desalination projects in Chile. One of the several reasons that explain this difficulty in financing solar projects lies in the lack of adequate resource assessment activities that could allow reducing the risk associated to the real energy yield of the solar plants to be deployed in Chile. The efforts of our research team aim to produce and make available to the public and industry a proper set of solar radiation data able to allow project development with lower resource-related uncertainty.

Previous reports by the authors identified several databases of solar radiation which are available for Chile and discussed their merits and shortcomings. It has been found that significant deviation exists between sources, and that all ground station measurements display unknown uncertainty levels, thus highlighting the need for a proper, country-wide long-term resource assessment initiative. However, the solar energy levels throughout the country can be considered as high, and it is thought that they are adequate for energy planning activities –although not yet for proper power plant design and dimensioning. As a general conclusion, the previous work by the authors demonstrated that although for Chile there are several databases of ground measurements, a weather simulation model, and satellite-derived data, none of these data sources are completely valid and therefore a nationwide effort of resource assessment was needed [6-8].

As context, it is possible to mention that solar radiation data for large spatial regions can be obtained from ground station networks that provide discrete data points from which a continuous map can be obtained by means of a proper interpolation scheme. In addition, surface radiation can be estimated by satellite data processing. The latest Brazilian Solar Atlas [9], for example, combines both measurement techniques in order to obtain data with low uncertainty levels. Pyranometer-based measurements from ground stations typically have lower uncertainty levels that satellite-derived data obtained by radiative transfer models, although this cannot be guaranteed for locations in between stations for data that has been computed by means of interpolation schemes. However, it has been shown that uncertainty levels for ground stations data are higher than satellite-derived measurements whenever the distance between stations is larger than 35 km [10, 11], and thus, a sensible resource assessment campaign will try to use satellite-derived irradiance for ample terrain coverage, at the same time as the use of ground stations for monitoring and validation purposes. As reference regarding proper time periods for measurement campaigns, the temporal variability of solar irradiance indicates that 5-year data sets can help determine the long-term average solar radiation with a fair degree of accuracy (estimated to be slightly larger than 5%), but do not contain enough information to accurately represent year-to-year variability. A 15-year data set can show inter annual patterns and trends, although statistically these variations are complex and do not follow a simple bell shaped curve of a random distribution. However, as mentioned by [12] a long term accurate average can be obtained by this data. The characteristics of solar irradiance can be described with a high degree of statistical confidence by analyzing 30-year data sets [13]. The current efforts in assessing the solar resource in Chile aim to produce databases that satisfy the previously stated conditions.

This report updates the previous article by presenting the advances made during the last four years regarding solar energy resource assessment in Chile. A network of ground stations aiming to achieve BSRN standard of operation has been deployed in the country and can provides developers, researchers and policymakers with good quality data. This network includes rotating shadowband radiometer devices (RSBR), also deployed in isolated locations of scientific interest such as high altitude places, salt lakes, snow covered terrain, and others. Finally, a new satellite estimation model has been developed, building upon the Brazil-SR model partially developed by researchers at the Instituto Nacional de Pesquisas Espaciais (INPE) of Brazil, and introducing different treatments for the meteorological variables and the effective cloud cover computations. The report presents results and comparisons for the described data sources. Validation of the Chile-SR model is also presented, in which becomes apparent that the model is properly estimating solar radiation for the range of climates present in Chile. In what follows, we will first describe the ground station network and the characteristics of its data. The satellite-based Chile-SR model is then described. Finally, a comparison between the data produced by the two allows us to validate the data produced by Chile-SR.

2. The UC-FONDEF ground station network

Starting in January 2010, a research project directed by the authors and financed through FONDEF grant D08i1097 has deployed a network of 12 ground stations, of which 4 are designed and operated under BSRN standards, and the remaining 8 are of three different configurations of RSBR. The stations designed following BSRN standards are composed of Kipp&Zonnen Solys 2 trackers, sun sensors, CMP 11 and 21 pyranometers, heating and ventilation units, CGR4 pyrgeometers, CHP1 pyrheliometers, CUV4 UV meters, and also temperature, atmospheric pressure, relative humidity, wind speed and direction sensors, all connected to Campbell CR1000 dataloggers, with power supplied from the grid. Both scan and save rates follow BSRN guidelines, as well as the maintenance activities. Table 1 indicates the name, type, and start date of operation for the stations, whose approximate locations is displayed in the map as in Figure 1.

The RSBR devices can have any of three different configurations. The basic configuration includes an Irradiance Inc. RSBR2 or RSBR2x device, composed by a Licor radiometer, the motor controller and rotating shadow band, temperature, atmospheric pressure, relative humidity, wind speed and direction sensors, all connected to Campbell CR1000 dataloggers, with power supply from a small-scale PV system. A second configuration lacks all meteorological sensors, and is used in locations that have a meteorological station in order to avoid repeated sensors. A third configuration is similar to the first one, with the addition of a CMP11 pyranometer for a redundant measurement of global horizontal radiation. This is used in sites where radiation conditions are particularly interesting and which have personnel readily available for maintenance and cleaning of the CMP11 device.

Figure 2 shows two different configurations of the ground stations: one RSBR, and one BSRN-designed station deployed in the field,. These stations have the objective of supplying data that satisfies international standards and criteria for design, operation and maintenance, thus providing high quality data for project developers and policymakers, and for the Chile-SR satellite estimation model described in a following section. Calibration certificates for these stations are still valid, and it is planned to trace them to the world reference as suggested by international standards during the first half of 2013. Data qualification algorithms have been transferred from INPE to UC and will allow analyzing the quality of data being generates in the stations.

Table 1: Ground station network.

Station name	Tipe	Start date of operation
1. Arica	RSBR	01-08-2011
2. Pozo Almonte	RSBR	04-04-2012
3. Sur Viejo	RSBR	07-07-2011
4. Crucero	RSBR	05-12-2011
5. Coya Sur	RSBR	05-07-2011
6. El Tesoro	RSBR	2009
7. San Pedro	Sun tracker	03-12-2010*
8. Diego de Almagro	RSBR	16-06-2011
9. PUC	Sun tracker	22-12-2010
10. Curicó	Sun tracker	09-08-2012
11. Talca	Sun tracker	09-08-2012
12. Marimaura	RSBR	09-08-2012

* Operation finished in 04-07-2011

Figure 1 (right): Northern and Central Chile, and the approximate locations of the ground stations of the UC-Fondef network.

Figure 3 shows daily totals of solar radiation for 2011-2012 at two different sites: Sur Viejo, located at 20° S, and Santiago, located at 33°S. Sur Viejo is located in the Atacama Desert, in extremely arid conditions. We have chosen to present the data from july 2011 to july 2012 as this is the period in which our measurements overlap with the processed satellite estimations. It is commonly said that the Atacama Desert exhibits a large number of clear days throughout the year, with people referring to the place as where the sun always shine. However, the measurements show otherwise: the radiation levels are effectively high, but display a marked variability with cloudy days occurring every month. Both GHI and DNI are high and can be considered as excellent resources for both PV and CSP plants. The next graph in Figure 3 corresponds to Santiago, located further south in what is referred to as the central zone of Chile. With a Mediterranean climate, the solar resource variability in this city is high, with occurrences of cloudy and clear days throughout the year. Due to the higher latitude, Santiago displays a stronger yearly cycle for GHI and DNI with radiation in summer clearly higher than in winter.

Figure 2 RSBR station in Crucero and one station with tracker, pyrheliometer, and pyranometers in Talca.

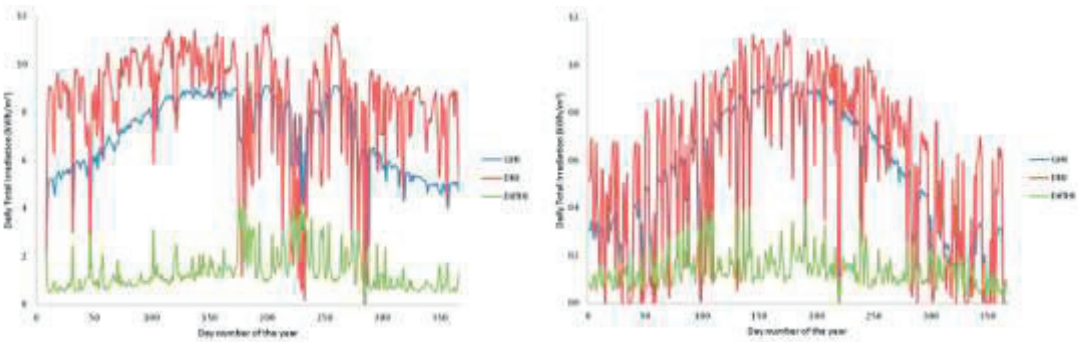

Figure 3: Daily totals of solar radiation from july 2011 to july 2012: Sur Viejo (20° S) and Santiago (33° S)

With a total of 358 days of measurements for Sur Viejo and 364 for Santiago, the daily averages in a year for GHI are 6,998 kWh/m^2 and 5,365 kWh/m^2, giving yearly totals of over 2505 kWh/m^2 and 1952 kWh/m^2, respectively. This clearly shows that even in central Chile the available solar resource is comparable to places where a large scale development of solar plants has been produced.

3. Chile-SR Satellite-based Estimation Model

It has been noted before that ground measurement campaigns, although accurate, are expensive and prone to equipment failure, with poor maintenance leading to data of higher uncertainty. Satellite estimation is cheaper yet sufficiently accurate, and it covers a large geographical area with adequate spatial and temporal resolution. The authors aimed at developing a satellite estimation model that could produce accurate and low uncertainty data for Chile by taking into account the different climatic characteristics that the country displays, with enough spatial and temporal resolution to be used for project development. The Chile-SR model has been developed as a modification of the existing Brasil-SR model developed by INPE within the SWERA project (swera.unep.net), taking its basic algorithm and modifying it in order to create an adaptation especially suited for the largely different conditions that Chile presents. In the northern regions of Chile is the Atacama Desert, characterized, moving further south, first a Mediterranean climate is found in the country´s center region, which gives way to a cold forest region in southern Chile. The model is able to capture all this climates and provide accurate estimations. Figure 4 shows a summarized description of the Chile-SR model, its inputs, the atmospheric parametrization, and related outputs.

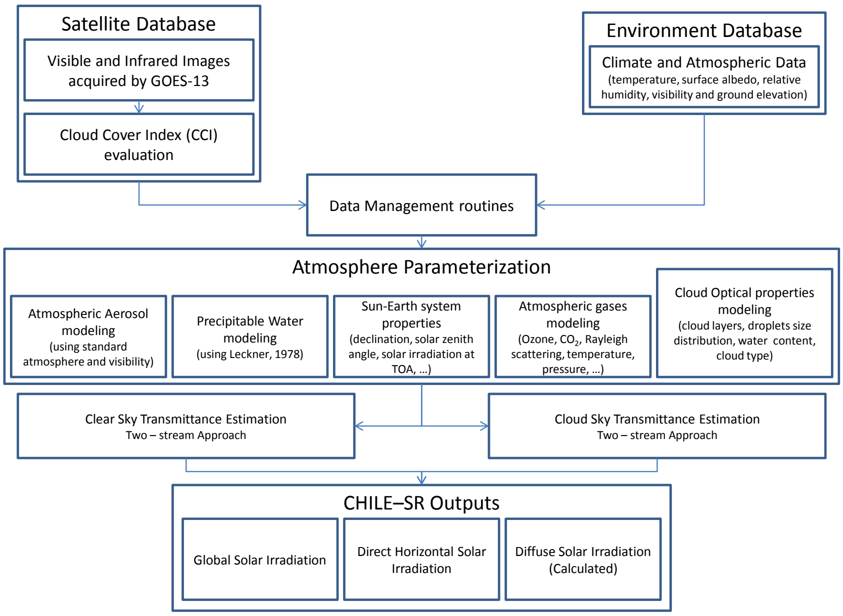

Figure 4: General description of the Chile-SR model.

The Chile-SR model is made specific for the conditions of Chile by including updated altitude-corrected weather data (temperature, relative humidity, and atmospheric pressure), topography, and surface albedo. GOES images for visible and IR channels are used as input to first classify cloud types, and then determine an effective cloud cover. The output data from the Chile-SR model is composed of global horizontal radiation and direct horizontal radiation in hourly basis. Figure 5 illustrates the sequence of main steps that Chile-SR takes in order to estimate radiation for April 12, 2012, at 16:40 UTC, for a region of the Atacama Desert in northern Chile. Channel 1 (visible) and channel 4 (IR) from GOES images are utilized in order to identify and classify the type of cloud, which in turn helps determine the effective cloud cover that coupled to the atmospheric transmittance algorithm allows estimating the global horizontal irradiance and the direct normal component.

It can be seen from the visible channel picture that cloud formations were present in the Pacific Ocean, and also covering part of the territory in northern Chile. This picture also illustrates an additional difficulty that the research team has faced, in the form of salt lakes and snow covers that in a visible channel picture might appear as cloud covers. The IR channel complements the visible channel image by giving information about the temperatures of each region. By properly combining the information from both channels, a cloud classification can be made, thus determining if a particular region is clear of clouds or if it has cloud covers. The next step is processing the cloud type and comparing the instantaneous information from each image to a monthly-established reference, which allows determining an effective cloud cover CCI_{eff}. It can be observed that there is high GHI up to 1200 W/m^2, and that cloud covers decrease the GHI down to about 400 W/m^2, the same as along the Andes Mountains. DHI values are also high, well in excess of 1000 W/m^2, and are severely diminished by the presence of cloud covers. It is interesting to note that contrary to common belief –and as already indicated in the discussion about figure 3- northern Chile does exhibit many days with cloud covers that can take DHI to values close to zero. Thus, we contest the view that in the Atacama Desert all days are identical and sunny, and propose that more research is needed and also that statistical representativity of any database for this region must include long-term estimations and measurements.

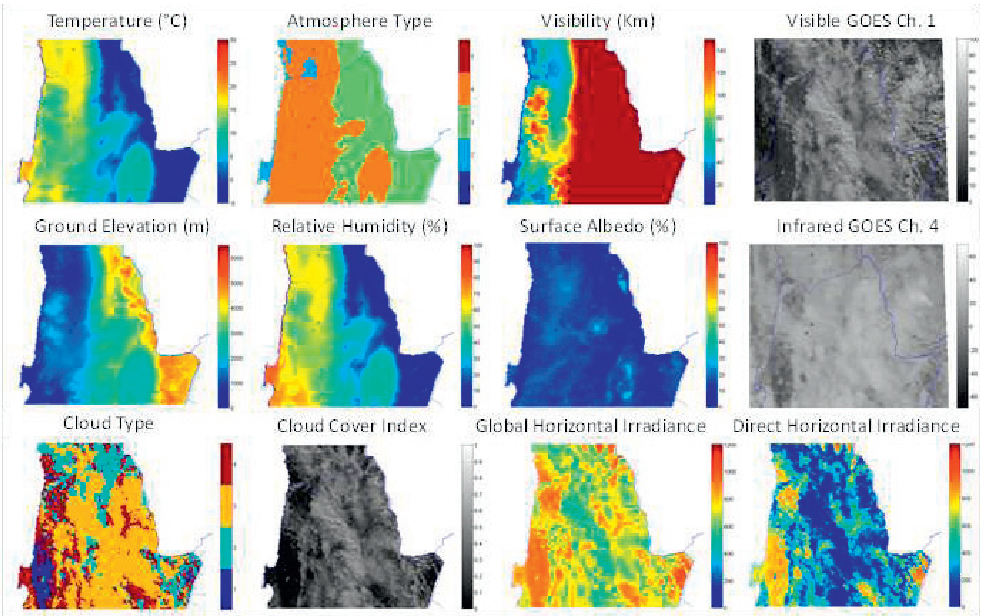

Figure 5: Input data and results of the Chile-SR model for April 12 2012 at 16:40 UTC.

4. Comparison: Chile-SR satellite-derived data and ground stations

Figure 6 shows the comparison for satellite-derived data and ground measurements for clear days in Crucero and Santiago. It can be observed that maximum levels for GHI at Crucero (23°S) reach 1200 W/m^2, while at Santiago (33°S) reach about 1165 W/m^2. This indicates that in clear days the available radiation in central Chile is comparable to that of northern Chile. It can also be seen that excellent agreement between satellite estimations and ground measurements are found for clear days at the two locations (desert and Mediterranean climates

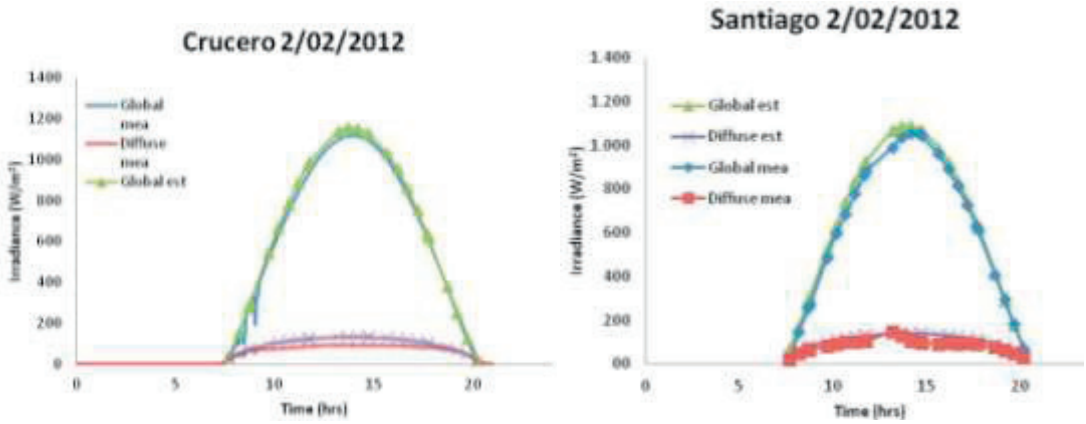

Figure 6: Comparisons between satellite and ground data at Crucero (23° S) and Santiago (33°S).

Figure 7 shows a comparison of satellite estimations and ground station data for daily totals combining the data available for all ground stations for the period 2010-2013. It can be seen that there is good agreement between satellite and ground station data, resulting in a rRMSE of 8.9%.

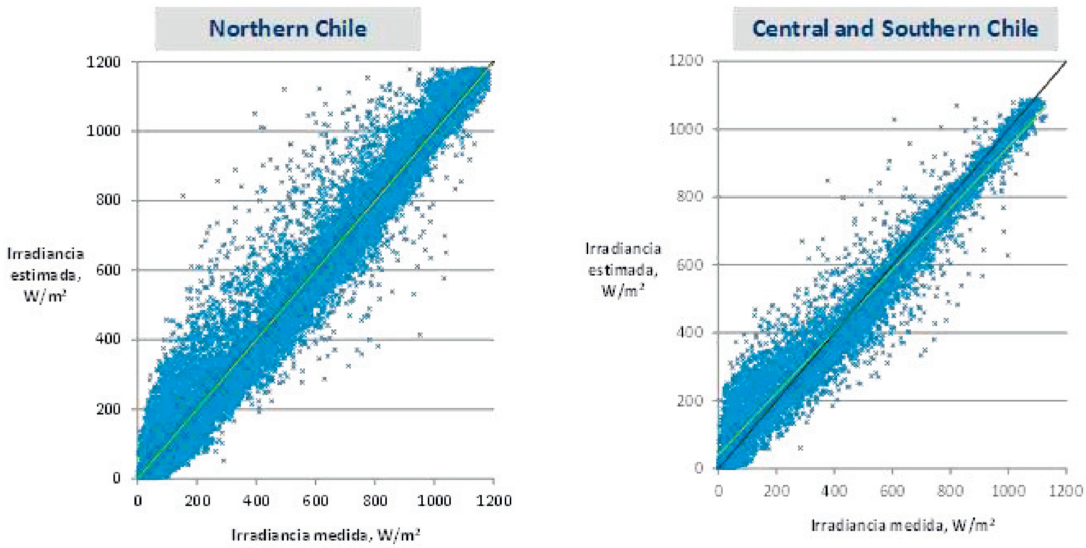

Figure 7: Comparisons between satellite and ground data considering daily totals of irradiation.

5. Conclusions

Renewable Energy promotion efforts in Chile aim to achieve a power production quota of 10% to be met by 2024. This plan has sparked interest in solar energy among other renewable sources, with PV, CSP, and industrial heat supply plants being announced, although only two small scale projects have materialized. Previous reports by the authors have identified several databases of solar radiation finding that significant deviation exists between sources, with most data from ground station measurements displaying unknown uncertainty levels, which highlighted the need for a proper, country-wide long-term resource assessment initiative. This report updates the situation in Chile by considering the efforts performed in the last three years by a resource assessment program based on the development of a satellite estimation model, complemented by a modern measurement ground station network. The UC-FONDEF program has deployed a network of twelve ground stations which are producing data according to international standard and good practices. A satellite estimation model has been developed to account for the particular conditions found in Chile, which is already producing data and it is currently being validated. Data from the Chile-SR model has been compared to ground station data and good agreement is found with rRMSE of 8.9%, thus validating the satellite data.

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