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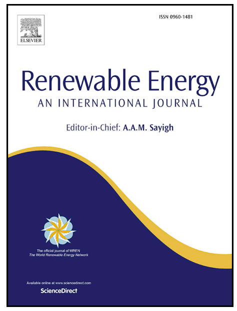


A solar irradiation GIS as decision support tool for the Province of Salta, Argentina

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# Title: A Solar Irradiation GIS as Decision Support Tool for the Province of Salta, Argentina

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**Abstract**: The province of Salta is characterized by its solar energy high potential. The use of solar resource would improve living conditions in the area, diversify the energy matrix, promote more sustainable production systems and reduce greenhouse gases emissions. However, there are only a few studies that describe in high spatial resolution the variability of the solar resource in Argentina. Multidimensional tools, that consider the environment and the socio-economic situation, have to be considered for adequate support decision-making, such as solar collector location assessment and photovoltaic potential. In this sense, a deep evaluation of the solar resource is needed first, as solar irradiation is an essential input variable for the design and evaluation of solar application systems.

In this paper, we detail the methodology used to elaborate a GIS tool to support decisions related to renewable energy policies and solar technology design. A comparison between global solar irradiation measurements in situ, empirical models, and data provided by Land Surface Analysis Satellite Applications Facility (LSA-SAF), is performed in daily, monthly and annual basis for a seven-year period. This analysis validates the use of this satellite data for the determination of solar irradiation in the region.

***Keywords:*** *Solar Irradiation GIS, LSA-SAF, Satellite imagery, Decision Support Tool.*

## 1. Introduction

The energy system of a country is a strategic factor to boost its economic growth and to enable its social development. In this sense, the possibility of increasing the energy supply based on renewable sources also contributes to the production and the environment, resulting in a decisive input in the production process and ensuring a low impact on the environment. The use of solar resources would improve living conditions in the area, diversify the energy matrix, promote more sustainable production systems and give answers to environmental issues [1] such as: strong pressure on renewable natural resources (e.g. firewood, forests), undisclosed use of conventional energy resources (fossil fuels), and pollution by emission of carbon dioxide (with consequences in global warming).

However, the lack or inadequate planning of renewable energy projects has left a long list of difficulties in economic, social, environmental and institutional aspects. In Argentina, the main remarkable difficulty is that the energy problem has not been solved yet, both macro and local scale. Despite the fact that there is legislation [2] and there are numerous efforts to implement solar energy technology [3,4], the main remarkable difficulty of Argentina is that the energy problem has not been solved yet, both at macro scale (non-diversified energy matrix) and at local level (unsatisfied basic needs, solar equipment without use, cost overruns for the implementation of

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renewable energy projects, disengagement from social actors). The development of integrative planning tools that bridges the gap presented in this sector are therefore necessary [5-7]. In this sense, GIS-based decision support tools for planning and decision-making in the introduction and promotion of Renewable Energy have proved to be very useful as evidenced by many experiences around the world [8-11].

Nowadays, the Non-Conventional Energy Research Institute of the Argentinean National Scientific and Technical Research Council is working on the development of a Decision Support System for the incorporation of Renewable Energy in the province of Salta, Argentina. In order to achieve such an integral tool is essential to acknowledge the potential of renewable resources in the region. In the study area, ground measurements of solar irradiation are punctual, scarce and scattered. The lack of information makes it difficult to characterize the behavior of the irradiation in Salta, a province with great altitudinal and geographical variability. Furthermore, there are only a few studies that characterize in high spatial resolution the variability of the solar resource in the region. These studies use satellite imagery as a new data source to estimate solar irradiation [12,13]. At country scale, a recent work of development and analysis of a new solar radiation atlas for Argentina from four ground-based measurements and satellite data is highlighted [14].

*1.1 Background of solar irradiation mapping*

For a couple of decades now, GIS-based decision support tools have been used as a crucial tool for energy management. The spatial distribution of renewable resources, their dependence on the site characteristics and its connection to other spatio-temporal attributes, makes this tool a key element for the planning of renewable energies. This can be observed in multiple studies around the world, among them: Spain [5], India [15], Greece [9], and Colombia [16].

In the worldwide context regarding to GIS solar energy potential models, there is a remarkable difference between countries, like Germany, USA or Spain, that started their "energy turnaround" years ago and those, like Argentina, Uruguay, Chile or Brazil, that started the process few years ago. The energy transition processes of industrialized countries (e.g. Germany) have encouraged studies on a detailed scale to promote the maximum use of solar energy at a household level. Consequently, those countries are most focused on the development of accurate methodologies to estimate solar potential in urban and suburbs areas [17-22] while the interest in addressing solar potential estimates in rural areas has been left behind. Nevertheless, there are countries, like Brazil, which present extensive rural areas with a high solar potential in which the development of GIS-based decision support tools for renewable energy management and planning in rural environments are critical [10].

Various methods are used for solar irradiation mapping. Naturally, it is highly recommended to count with ground measured historical data of solar irradiation from calibrated meteorological stations network. This would allow evaluating the behavior of the solar resource with great precision. However, high costs of installation, maintenance, and communication to centralize the data have promoted the development of different models to estimate the global solar irradiation from available data. These models can be grouped into three categories:

- *Empirical Methods.* Journée and Bertrand [23] classify the empirical models into three categories: sunshine-based (clear sky) models, temperature-based models, and cloud-based models. In general, a well-calibrated sunshine-based model can provide better solar radiation estimates than cloud-based or temperature-based models [24,25]. Other applications of empirical models at the local and regional level are based on statistical correlations with geographical variables such as altitude and latitude [26,27].

- *Interpolation/extrapolation approaches of in situ measures.* These methods are frequently used in the development of irradiation maps in different spatial scales. It consists in the interpolation or extrapolation by statistical or geostatistical methods of solar irradiation values from ground measurements [28]. Errors in the evaluation of global solar irradiation by interpolation or extrapolation are given by the density of the network: a large distance between stations leads to serious errors. Methods of interpolation were applied in the development of the solar irradiation maps for Argentina [29-31].

- *Data obtained from satellite imagery.* The accelerated development of satellites in the last decades has favored the scientific community with a large amount of environmental and climatic data. Numerous services associated with these satellites provide data for mapping global solar irradiation [32-34]. Satellite-modeled data is frequently quoted as being more accurate than empirical or interpolation/extrapolation approaches at distances greater than 34 km from a weather station [35]. Solar irradiation data derived from satellite imagery is used for several photovoltaic solar projects purposed in zones that are distant from ground measurement stations and other applications [36,37]. A decision support tool for photovoltaic and thermal solar energy based on satellite historical data of solar irradiation was developed for Chile [38].

The models grouped in these categories are usually combined so as to compare and validate them.

Generally, solar radiation studies combine data from satellite imagery with empirical models and the combination is validated with ground reference stations. However, most of these works only present assessments of solar radiation for specific locations [10]. With a greater scope, other models around the world are oriented to the development of GIS and thematic maps of radiation with potential application in energy planning as is the case of Spain [39], Uruguay [40], Republic of Djibouti [41] and Chile [38].

In previous work, estimates from empirical methods, satellite data and data from one ground station were compared [12,13,42] in order to determine the source of global solar radiation data with the best possible spatio-temporal resolution for the Lerma Valley, located in the middle of the province of Salta, Argentina. Results showed that LSA SAF Land Surface Analysis Satellite Applications Facility (LSA SAF) is a satisfactory alternative to compensate the lack of ground measurements in the valley. From this point, we expand the study area covering the entire province of Salta while maintaining the high spatial resolution. Moreover, we enhance the methodology to a GIS method creating daily, monthly and annual solar irradiation layers. These maps are mainly based in satellite irradiance data, that was validated with estimates generated by empirical methods, commonly used in the area, and to in situ available data from five regional ground stations through a seven-year period. This work presents a novel methodology and results in the Argentinean context where available solar irradiation maps are based on interpolation methods of ground station measurements

[20,31] or data based on satellite imagery with scarce or any validation [14,43,43], causing the results to be inaccurate.

*1.2 Purpose of this study*

A solar irradiation GIS is a key input to achieve the development of integral tools that promote renewable energies in the region. The present study is part of a larger project that seeks to create a Decision Support System, which systematically incorporates the multiple dimensions that are considered in the development of energy policies in the province of Salta [45].

Therefore, a more accurate characterization of the solar resource is needed first. This study aims to develop a solar irradiation GIS for the province in a suitable spatial-temporal resolution; applying solar irradiation satellite data evaluated with in situ available data and estimates from empirical methods. This GIS is presented in accessible formats for diverse stakeholder groups related (government, academic institutions, NGO, and population).

The methodology developed in this works presents superior benefits in relation to punctual analyzes of solar radiation or solar radiation mapping based on interpolation methods with few measured radiation data available in the region. Moreover, it improves spatial precision by covering the entire territory of the province and facilitating the selection of sites with high photovoltaic and thermal solar potential for different applications (insertion of electricity to grid and isolated, improvement of small and large scale primary production systems, provision of energy in households). The time scale used in the results is adequate for the pre-design of multiple solar technologies.

This paper is sectioned as follow; Firstly, materials and methods are presented with an overview of the geographical area concerned, a description of the data sets, an explanation of the methodology for the development of the solar irradiation GIS and the software used in this study. Secondly, the results are presented and explained. Thirdly, the results are discussed and, in the last section, the conclusions are drawn.

## 2. Materials and Methods

### *2.1. Study area*

The geographical area of this study is the province of Salta, located in the Northwest of Argentina. Its bounding box coordinates are (in WGS84): East: 62.360128 W, West: 68.569034 W, North: 21.993606 S, South: 26.382889 S. Salta shares land borders with Bolivia to the north and the province of Jujuy; with Paraguay and provinces of Formosa and Chaco to the east; with provinces of Catamarca, Tucumán and Santiago del Estero to the south, and with Chile and Jujuy to the west. The total area of Salta is 155.488 $km^2$.

Salta is characterized by a diversity of landscapes due to its large size and the distribution of its territory. Salta's topography is stepwise decreasing in altitude generally from west to east as seen in Figure 1. According to the classification of solar radiation worldwide [46], Salta is inserted in zone 7 with the highest radiation in the world (up to 2000 $kWh/m^2$ annually). Although this classification presents Salta as a great promise for solar energy use, more detailed studies are necessary to optimize solar projects location assessment.

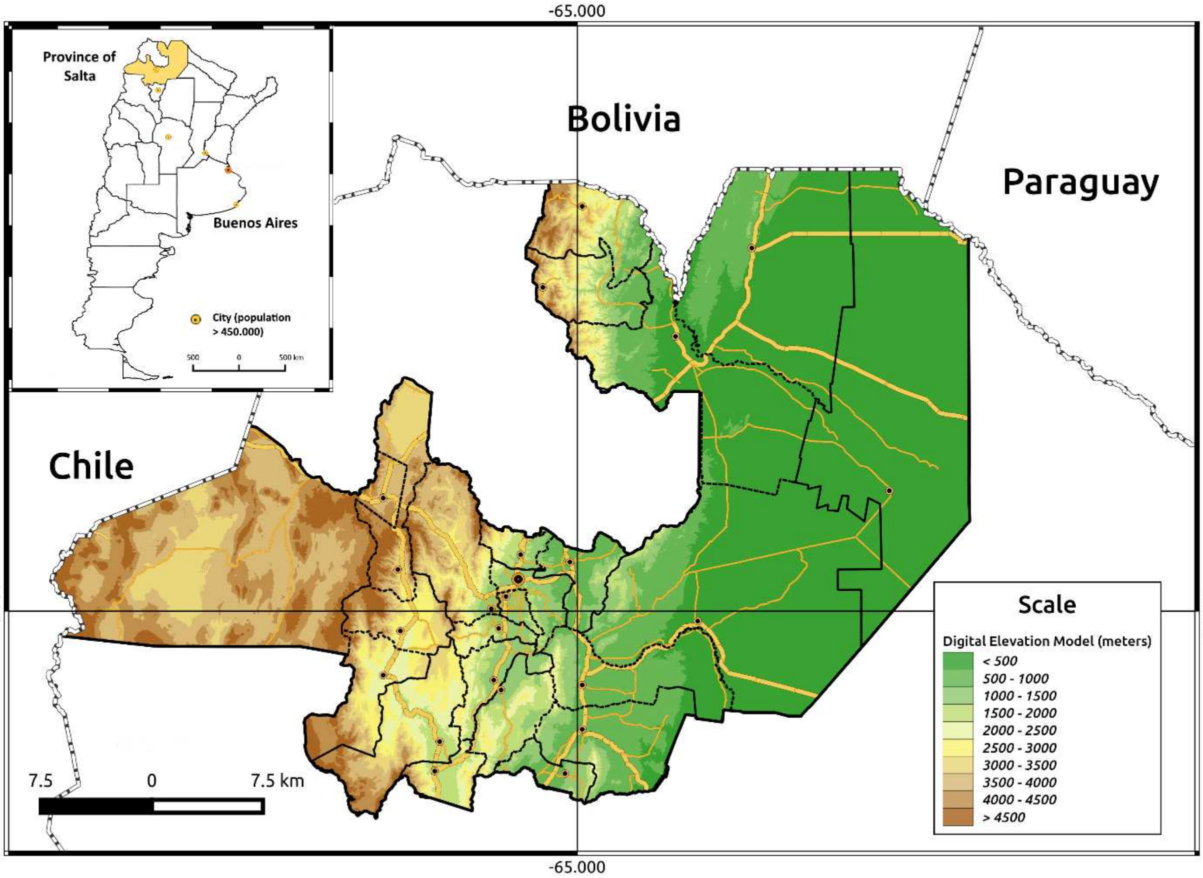



***Fig. 1***. Digital Elevation Model of the Province of Salta, based on data from NASA [48].

Different base layers of the province of Salta were compiled for the solar irradiation GIS. Most of the layers were downloaded from the National Institute of Geography (NIG), a public institution that develops geographic information and maps of Argentina. The maps are in different formats and can be freely downloaded from its web page [47]. In Table 1 there is a summary with basic data of the maps used.

**Table 1.** List of the main base layers used.

| Thematic Layers | Type | Source |
|---|---|---|
| Political and administrative divisions (countries, provinces, and counties) | Vector (Polygons) | National Geographic Institute of Argentina |
| Main Locations | Vector (Points) | National Geographic Institute of Argentina |
| Road network: roads and routes | Vector (Lines) | National Geographic Institute of Argentina – Open Street Map |
| Hydrographic network (rivers, lakes, and dikes) | Vector (Lines / Polygons) | National Geographic Institute of Argentina |
| High and medium voltage electrical network | Vector (Lines) | Energy Secretariat of Salta Province |
| Digital Elevation Model (DEM) | Raster | NASA [48] |

## *2.2. Methodological Development*

A methodological process diagram is presented in Figure 2. The process basically includes three general stages: acquisition of data from various sources, comparative analysis and processing of the data collected and, finally, the edition of the GIS and its dissemination.

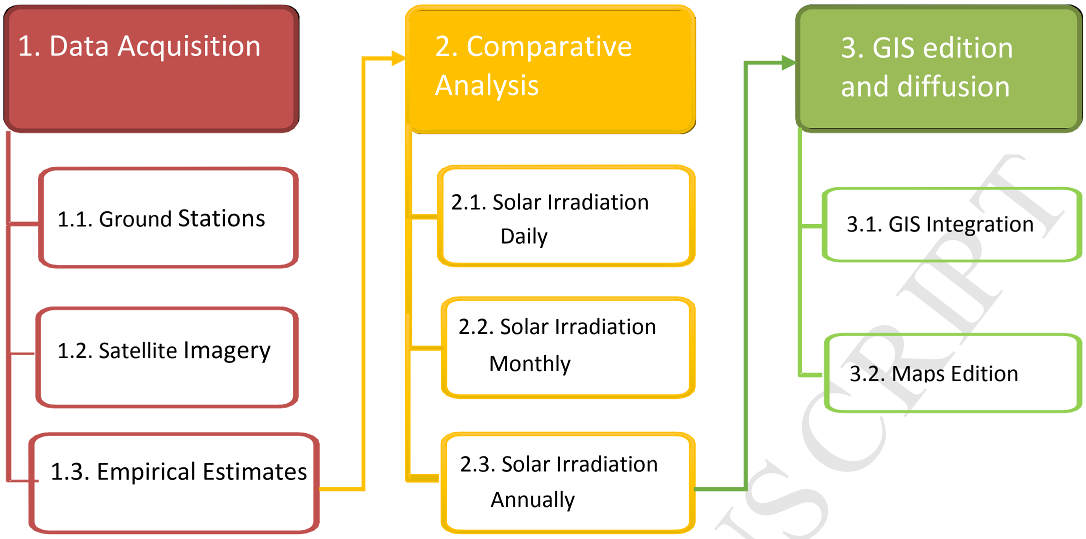



***Fig. 2.*** Methodology Process Diagram

### ***2.2.1*** *Data acquisition and pre-processing*

Three data sets of solar irradiance are used in this study: a) Data derived from Meteosat Second Generation (MSG) satellite images generated by LSA-SAF, b) Ground measurements from five meteorological stations located around the study area and c) Estimates generated by empirical methods.

*Ground measurements stations*

There are few records available of ground measurements for solar radiation in Argentina, especially in Northern Argentina. However, data from five pyranometers installed in the region by public institutions and companies for the analyzed period (2009-2015) were collected. The basic data from each station is resumed in Table 2 and Figure 3 shows their location. The stations are distributed in a range of 979 to 3463 m.a.s.l.

In all cases, the solar irradiation values were measured with Davis Vantage Vue equipment. It must be considered that ground data may present intrinsic variations due to the measurement instruments, which are not the scope of this work.

**Table 2.** Summary of the characteristics ground stations used in the analysis.

| **Place** | **Longitude** | **Latitude** | **Altitude (meters above level sea)** | **Temporary Period** | | **Frequency of data** (minutes) |
|---|---|---|---|---|---|---|
| | | | | **Since** | **Until** | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Abra Pampa (Jujuy) | 65.4933 W | 22.4756 S | 3463 | October 2011 | January 2016 | 5-15 |
| El Pongo (Jujuy) | 65.0831 W | 24.2255 S | 979 | Sept. 2006 | February 2016 | 15 |
| La Viña (Salta) | 65.3105 W | 25.1821 S | 1198 | June 2009 | Dec. 2016 | 15 |
| El Rincón (Salta) | 67.0222 W | 24.0112 S | 3800 | May 2006 | March 2016 | 60 |
| Cafayate (Salta) | 65.5826 W | 26.0833 S | 1620 | Sept. 2008 | May 2016 | 30-60 |

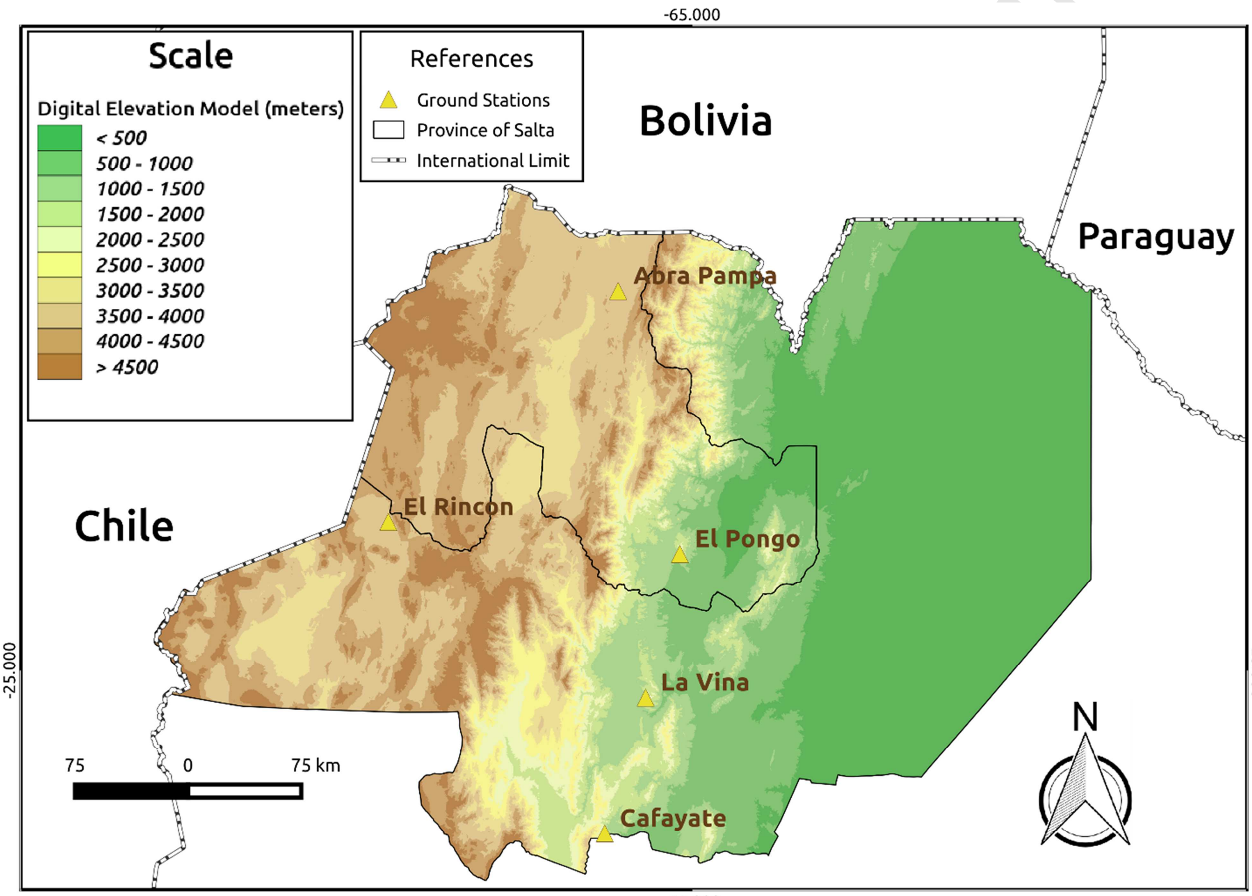



***Fig. 3.*** Location of measurements stations.

The compilation of solar irradiance data series implied hard work as this information is not available and disseminated in public and private institutions. The general steps that the management followed were: 1) Make a data base of organizations established in the study area 2) Find out if the organization had irradiation data. 3) Make first contact with the organization and explain research objectives. 4) Establish agreements. 5) Set up meetings with people in charge of the data. 6) Group and centralize data.

*Satellite imagery from MSG by LSA SAF*

The variable downloaded from the satellite images was Down-welling surface shortwave flux (DSSF). DSSF refers to the radiative energy in the wavelength interval [0.3µm, 4.0 µm] reaching the Earth's surface per time and surface unit and corresponds to the most important quantity involved in the surface radiation budget [49]. This variable is comparable to the concept of global solar irradiation on horizontal plane. DSSF is derived from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument on board of MSG and is calculated making use of an algorithm developed by Météo-France, which is kept up to date since 2004. This algorithm originally appeared in 1999 [49] and was validated for the first time by Geiger et al. [50]. Posterior validation works can be found in [12,13,51-54].

The data from LSA-SAF was obtained in packages of 1000 images in HDF5-format file through their web form and the ftop of the LSA-SAF website; data for each half an hour from 2009 and 2015 was downloaded from the part of the disk where the region is located. Since and standard day consists of 48 files, one image every 30 minutes, out of 17520 maps that could be obtained for each year, an average of 17356 per year was obtained instead. 2013 and 2014 omit 4 entire days of data and the rest of the missing maps are distributed irregularly over the length of the year [50].

The data has a spatial resolution of 4.8 km for the study area. The data in HDF5-format was transformed to Geotiff in order to be geo-referenced into code EPSG 22183 ("POSGAR 94 / Argentina 3"). The library used for the transformation was the Geospatial Data Abstraction Library (GDAL) [55]. The conversion of the satellite maps into common units (Wh/m$^2$) was performed in order to allow comparisons to be made. The programming language R [56] in the integrated development environment R-Studio [57] was used for this transformation using the package raster [58] and its arithmetic functions.

The comparisons were performed on daily and monthly aggregated solar energy basis. LSA-SAF data, which corresponds to instant solar irradiance, was accumulated into daily energy using the Equation (1). It is assumed that the irradiance remains unaltered in each 30 minutes period, setting the first raster map at 00:00 a.m and the last one at 11:30 p.m.

$$I = \sum_{i=0}^{47}(0.5\, h * r_i) \qquad (1)$$

I: $daily\ aggregated\ irradiation\ (W.h/m^2)$

$r_i$: $raster\ map\ with\ DSSF\ values\ (W/m^2)$

Once the entire satellite database was collected in daily; the maps were grouped in monthly basis adding all daily maps of each month. Finally, values of the five ground measurements locations were extracted from daily and monthly maps according to the comparisons performed. The procedures were also performed in R using the libraries: sp [59], raster [58] and rgdal [60], generating at the end output files with the equal format as the ground measurements final files.

*Estimates generated by empirical methods*

In order to validate the satellite data, an estimation of the solar irradiation based on empirical models was made. The combination of two clear sky models was used to this calculation: Hottel [61] and ARG-P [62]. Both models estimate horizontal global solar irradiance in clear sky conditions and they are regularly used in the region [27, 63, 64].

Hottel expresses atmospheric transmittance, as a function of the zenith angle (greater transmittance in vertical direction, less towards the horizon), height above sea level (higher transmittance at higher altitude) and climate type. While ARG-P uses extra-terrestrial irradiance and the altitude above sea level to generate a clearness index. Since ARG-P presents satisfactory performance at high altitude it was used for stations located up 2500 meters above sea level and Hottel method was applied for stations placed under those conditions.

A program in C language was developed to calculate irradiation in daily and monthly basis using the empirical models. Since both models need solar geometric angles, such as zenith angle, azimuth angle and incidence angles. The Solar Position Algorithm (SPA) developed by the National Renewable Energy Laboratory [65] was used for this purposed. This algorithm calculates the solar zenith and azimuth angles in the period from the year -2000 to 6000, with uncertainties of +/- 0.0003 degrees based on the date, time, and location on Earth [66].

The input variables of the program are latitude, longitude, and altitude of ground stations and the output is 24 columns with daily solar irradiation for 12 characteristic days and monthly solar irradiation.

*2.2.2. Comparative analysis*

Diverse comparisons of global horizontal solar irradiation of LSA-SAF data from 2009 to 2015, available ground measurements and empirical estimates by clear sky models, were performed:

a) *Average solar irradiation accumulated in a daily basis of each month.* The characteristic days used in the comparisons were selected following Duffie and Beckman [61]. Table 3 presents the characteristic days used in the daily comparisons. Characteristic days of all months have been used for daily comparisons.

**Table 3.** Characteristic days used [61].

| Month | Date | Julian Day |
|---|---|---|
| January | 17 | 17 |
| February | 16 | 47 |
| March | 16 | 75 |
| April | 15 | 105 |
| May | 15 | 135 |
| June | 11 | 162 |
| July | 17 | 198 |
| August | 16 | 228 |
| September | 15 | 258 |
| October | 15 | 288 |
| November | 14 | 318 |
| December | 10 | 344 |

*b) Average solar irradiation accumulated for each month:* All twelve months are used for monthly comparisons.

*c) Average solar irradiation accumulated in a year.*

The performance of the DSSF product was evaluated using statistical indices and measures of error regularly used [13, 53, 54, 67, 68]: a) The root-mean-square deviation (RMSE %) - Equation (2), b) The mean bias error (MBE %) – Equation (3), c) Determination coefficient $R^2$ ,and d) Relative error ( $E_{r.}$).

$$RMSE\% = 100 * [\sum_{i=1}^{n}(\bar{H}_{i-ground} - \bar{H}_{i-satellite})/n]/(\sum_{i=1}^{n}\bar{H}_{i-ground}/n) \quad (2)$$

$$MBE\% = 100 * \sum_{i=1}^{n}(\bar{H}_{i-ground} - \bar{H}_{i-satellite}) / \sum_{i=1}^{n}\bar{H}_{i-ground} \quad (3)$$

$\bar{H}$ *ground: monthly global solar irradiation of the ground station.*

$\bar{H}$ *satellite: monthly global solar irradiation from the satellite image.*

*2.2.3. GIS edition and diffusion*

Based on the results obtained in the comparisons, the solar irradiation maps were developed and adjusted for Salta province. The processing was performed for characteristic day layers, monthly and annual solar irradiation.

A GIS project was developed in the software Quantum GIS (QGIS) in order to integrate and centralize the basic layers and the solar irradiation maps. All the edited maps were designed to be easily understandable and readable by any interpreter. Moreover, a Keyhole Markup Zip (kmz) file was also developed with all the irradiation data, as a widely disseminated format.

Several dissemination strategies were proposed to reach the different stakeholder groups: scientific-academic seminars, website, meeting with government and records of the results in virtual formats.

*2.3. Software*

In this study, many software programs in combination with own software codes were used during the whole process. Table 4 presents a summary of the software programs, its applications, and its licenses.

**Table 4.** Software used.

| Software | Applications | License |
|---|---|---|
| R | Mathematical functions of aggregation. Statistical analysis. Comparisons and correlations. | GNU – General Public License v3 |
| R - Studio | Used as an integrated development environment (IDE) for the R programming language and graphics plotting. | GNU - Affero General Public License v3. |
| Own Software | Developed to pre-process ground measurements and | GNU – General Public |

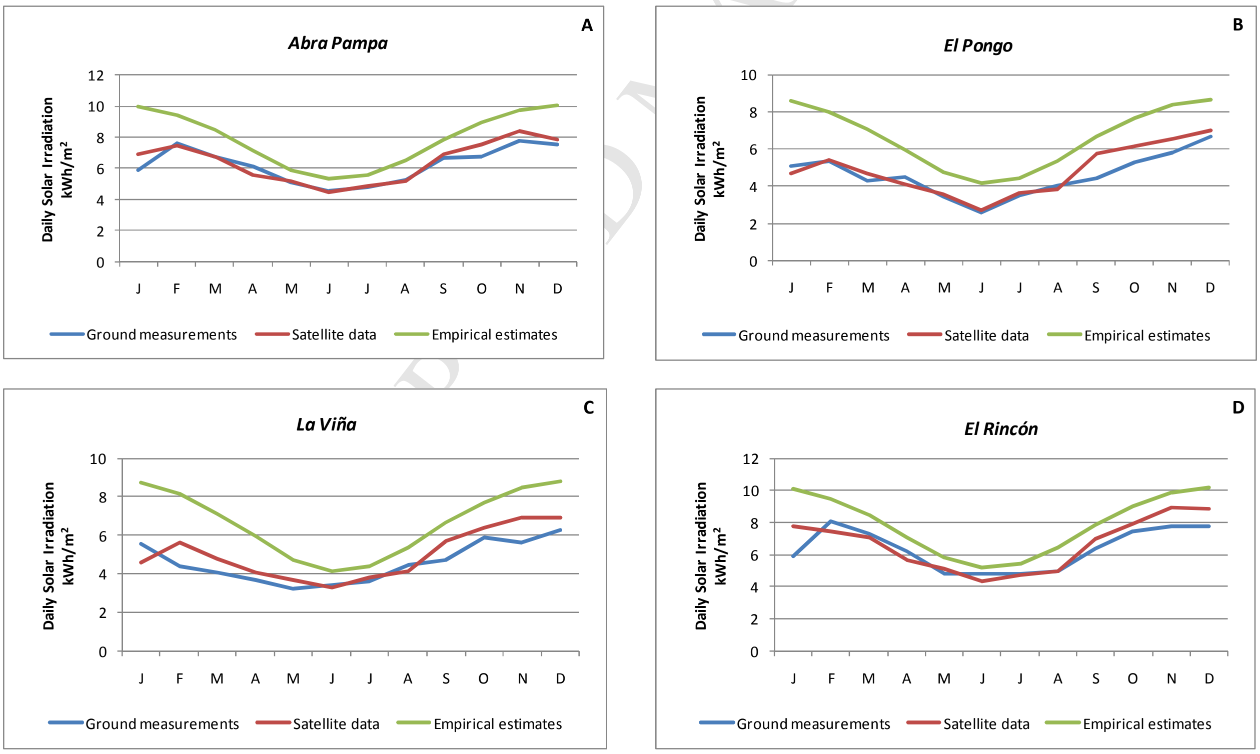
| | | |
|---|---|---|
| Code in R language | satellite data. | License v2 |
| Own Software Code in C language | Program developed by the working group for the estimation of global solar irradiation under clear sky conditions. | GNU – General Public License v2 |
| Q GIS | Organization of the Geographical Information System, visualization of thematic layers and maps edition. | GNU - General Public License v3 |
| GDAL | Maps re-projections and conversions of satellite image formats. | MIT License |

## 3. Results

### *3.1. Comparisons and analysis*

*Solar irradiation of characteristic day*

Comparative analyzes of the daily horizontal global solar irradiation between satellite data, ground measurements and empirical estimates, are presented for the five stations available in Figure 4. The Abra Pampa and El Rincon stations have higher solar irradiation values, in concordance to their altitude.



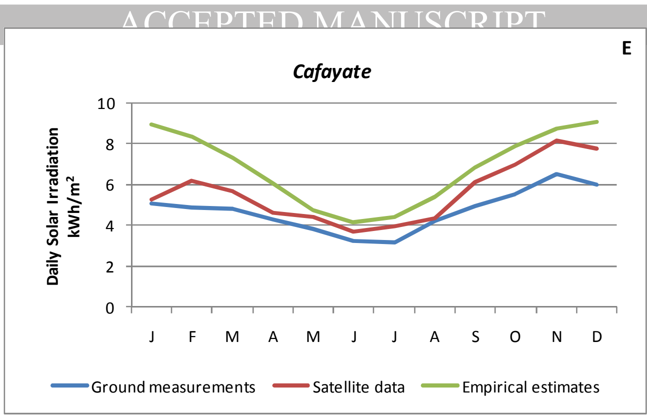



***Fig. 4.*** Comparative graphic for characteristic daily horizontal global solar irradiation at points corresponding to the ground stations: A- Abra Pampa (Jujuy); B- El Pongo (Jujuy); C- La Viña (Salta); D- El Rincón (Salta); E- Cafayate (Salta)

In the comparison performed between satellite and measured data in Table 5. and 6., MBE % is under 10% in all the stations while the maximum value that reaches during months of September and November is 17%. The values of RMSE % oscillates between 7 % and 22 % in ground stations while there is a pick in June where the RMSE value reaches the 25%.

In all cases, the satellite and ground data is below the curve of the data corresponding to the empirical estimates throughout the year. This is because the empirical estimates were made with clear sky methods that do not take into account atmospheric and climatic variables. In winter time (June-August), the smallest differences between the values of clear sky models, satellite values and measured are observed, due to the dry season. In contrast, the greatest differences are found during the wet season (September - April), where more cloudiness and precipitation occurs. The values are almost identical for the dry season (autumn-winter), showing greater variability in the summer months due to the causes explained above (Table 6).

**Table 5.** Statics indicators for data from LSA-SAF in relation to ground measurements for each ground station.

| Ground Stations | RMSE% | MBE% | $R^2$ |
|---|---|---|---|
| Abra Pampa | 7 | -3 | 0.90 |
| El Pongo | 12 | -6 | 0.86 |
| La Viña | 16 | -9 | 0.74 |
| El Rincón | 13 | -5 | 0.78 |
| Cafayate | 22 | -19 | 0.93 |

**Table 6.** Statics indicators for data from LSA-SAF in relation to ground measurements for the characteristic day of each month.

| Months | RMSE% | MBE% | $R^2$ |
|---|---|---|---|
| January 17$^{th}$ | 19 | -6 | 0.59 |
| February 16$^{th}$ | 14 | -6 | 0.84 |
| March 15$^{th}$ | 10 | -6 | 0.96 |
| April 15$^{th}$ | 9 | 3 | 0.90 |

| | | | |
|---|---|---|---|
| May 11$^{th}$ | 9 | -7 | 0.93 |
| June 17$^{th}$ | 25 | -10 | 0.09 |
| July 16$^{th}$ | 9 | -6 | 0.87 |
| August 15$^{th}$ | 4 | 1 | 0.88 |
| September 15$^{th}$ | 17 | -16 | 0.95 |
| October 14$^{th}$ | 14 | -13 | 0.83 |
| November 10$^{th}$ | 17 | -16 | 0.84 |
| December 17$^{th}$ | 14 | -12 | 0.49 |

*Monthly solar irradiation*

The comparative results of the monthly global horizontal irradiation are presented in Figure 5. Data from monthly solar irradiation refers to the sum of all the days of the considered month divided by the number of years taken into account, in this case 7. Tables 7 and 8 show the results of the statistical indices for the monthly comparisons. The correlation between the satellite and measured data is over 88% for all stations. In general, the behavior of the curve is similar for the different stations considered. The analysis for the period April and September (dry season) indicate better adjustments. For the summer months, a greater variability is observed, highlighting an underestimation of the solar irradiation satellite values for the month of January and an overestimation for the months of October, November, and December. As it can be seen in Table 8. The values of RMSE and MBE have a remarkable difference in these months, especially in November and December reaching: 23 % and 22% (RMSE) -29 % and 27% (MBE) respectively.

Based on this comparative analysis, adjustment factors were determined for the months of January, October, November and December, where the differences between satellite and measured data of the five stations are greater than 10% (Equation 5).

$$A.F_j = \left(\frac{\sum_{i=0}^{4} \bar{H}_{i-ground}}{\bar{H}_{i-satellite}}\right)/n \qquad (5)$$

$Adjustment\ Factor_j = Adjustment\ Factor\ for\ monthly\ horizontal\ global\ solar\ irradiation,$
$with\ \ j = January,\ October,\ November\ and\ December.$

$\bar{H}_i = Monthly\ average\ horizontal\ global\ solar\ irradiation, with\ i\ varying\ in\ each\ station.$

$n\ = Number\ of\ ground\ stations$

The calculated adjustment factors are January 1.07, October 0.93, November 0.833, December 0.811. These factors were applied to the satellite maps, adjusting the solar irradiation monthly values to the terrestrial ones. As it can be seen in Figure 5, the curve “Adjusted satellite data” from Cafayate ground station approximates significantly to the curve from terrestrial data in months from October to December when the adjustment factors are applied. Table 7. and 8. show a valuably improvement in the statistic indicators (RMSE % - MBE %) and the determination coefficient ($R^2$) in the data adjusted. The most remarkable case is Etchart ground station as it goes from 26 RMSE%, -20 MBE% and $R^2$ 0.77 values to 16 RMSE% , -15 MBE% $R^2$ and 0.95 values.

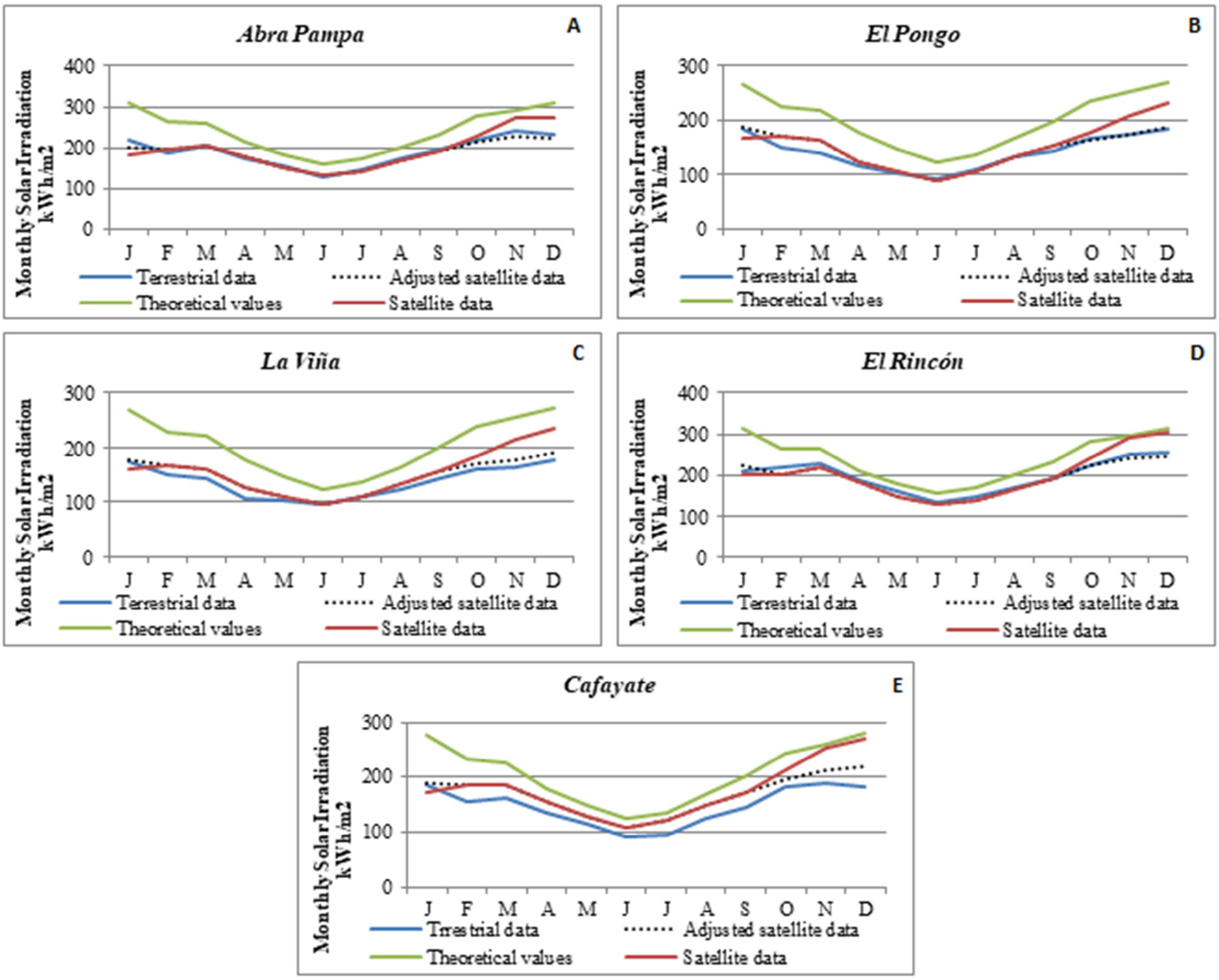



*Fig. 5.* Comparative graphic for monthly horizontal global solar irradiation at points corresponding to the ground stations: A- Abra Pampa (Jujuy); B- El Pongo (Jujuy); C- La Viña (Salta); D- El Rincón (Salta); E- Cafayate (Salta)

**Table 7.** Statics indicators for data from LSA-SAF with and without adjustment factors in relation to ground measurements for each ground station.

| | Satellite Data vs Ground Measurements | | | Adjusted Satellite Data vs Ground Measurements | | |
|---|---|---|---|---|---|---|
| **Ground Stations** | **RMSE%** | **MBE%** | **$R^2$** | **RMSE%** | **MBE%** | **$R^2$** |
| Abra Pampa | 10 | -2 | 0.85 | 4 | 2 | 0.97 |
| El Pongo | 14 | -8 | 0.88 | 7 | -4 | 0.94 |
| La Viña | 19 | -12 | 0.81 | 5 | -8 | 0.96 |
| El Rincón | 11 | -2 | 0.91 | 16 | 2 | 0.96 |
| Etchart | 26 | -20 | 0.77 | 16 | -15 | 0.95 |

**Table 8.** Statics indicators for data from LSA-SAF, before and after applying the adjusted factor, in relation to ground measurements for each month

| | Satellite Data vs Ground Measurements | | | Adjusted Satellite Data vs Ground Measurements | | |
|---|---|---|---|---|---|---|
| **Month** | **RMSE%** | **MBE%** | **$R^2$** | **RMSE%** | **MBE%** | **$R^2$** |
| January | 10 | 9 | 0.62 | 5 | -1 | 0.62 |
| February | 11 | -6 | 0.83 | 11 | -6 | 0.83 |
| March | 9 | -6 | 0.96 | 9 | -6 | 0.96 |
| April | 9 | -7 | 0.95 | 9 | -7 | 0.95 |
| May | 7 | -1 | 0.92 | 7 | -1 | 0.92 |
| June | 8 | -3 | 0.84 | 8 | -3 | 0.84 |
| July | 10 | -2 | 0.74 | 10 | -2 | 0.74 |
| August | 7 | -4 | 0.83 | 7 | -4 | 0.83 |
| September | 9 | -6 | 0.85 | 9 | -6 | 0.85 |
| October | 11 | -10 | 0.89 | 5 | -2 | 0.89 |
| November | 23 | -22 | 0.87 | 7 | -2 | 0.87 |
| December | 29 | -27 | 0.71 | 9 | -3 | 0.71 |

*Annually solar irradiation*

Table 9. presents the results of Relative Error of ground measurements with satellite data and ground measurements with adjusted satellite data. The relative error was measured in each station and as it can be seen in Table 9, the performance of relative error improves significantly when adjusted satellite data is considered. The highest relative error, between satellite data with ground measurements, is from Etchart ground station with a value equal to 29 %. While considering adjusted satellite data versus ground measurements, the relative error value of the same ground station only reaches 9 %.

**Table 9.** Relative error for data from LSA-SAF, before and after applying the adjusted factor, in relation to ground measurements in annual basis.

| | Satellite Data vs Ground Measurements | | | Adjusted Satellite Data vs Ground Measurements | | |
|---|---|---|---|---|---|---|
| **Station** | **Ground Measurements** | **Satellite Data** | **Relative Error %** | **Ground Measurements** | **Satellite Data** | **Relative Error %** |
| Abra Pampa | 2104.10 | 2321.00 | 10 | 2104.10 | 1943.26 | -7 |
| El Pongo | 1568.46 | 1837.48 | 17 | 1568.46 | 1568.02 | 0.0 |
| La Viña | 1530.37 | 1860.45 | 21 | 1530.37 | 1577.83 | 3 |
| El Rincón | 2196.98 | 2413.59 | 10 | 2196.98 | 2035.28 | -7 |
| Etchart | 1639.14 | 2114.23 | 29 | 1639.14 | 1786.53 | 9 |

*3.2 Solar Irradiation GIS*

The solar irradiation GIS with a high spatial resolution for the whole surface of Salta was developed from LSA-SAF satellite imagery. It is the most remarkable result of this study. This tool enables to consider the spatial-temporal distribution of irradiation in the same framework. The solar irradiation GIS includes raster layers associated to the variables: 12 daily global horizontal solar irradiations (one day a month), 12 monthly global horizontal solar irradiation and 1 annual global horizontal solar irradiation, expressed in kWh/m$^2$. This solar irradiation GIS is presented in print and digital format.

The analysis of the generated maps indicates an excellent potential of the solar resource for the province of Salta (Figure 6). The west region, where the highest mountainous areas are located, has the highest radiation values, exceeding an annual solar irradiation of 2300 kWh/m$^2$. This value places the region within the 7 zones with the highest solar irradiation values in the world [51]. The central and the east region have annual values between 1600 and 2000 kWh/m$^2$, confirming a satisfactorily potential for solar energy applications.

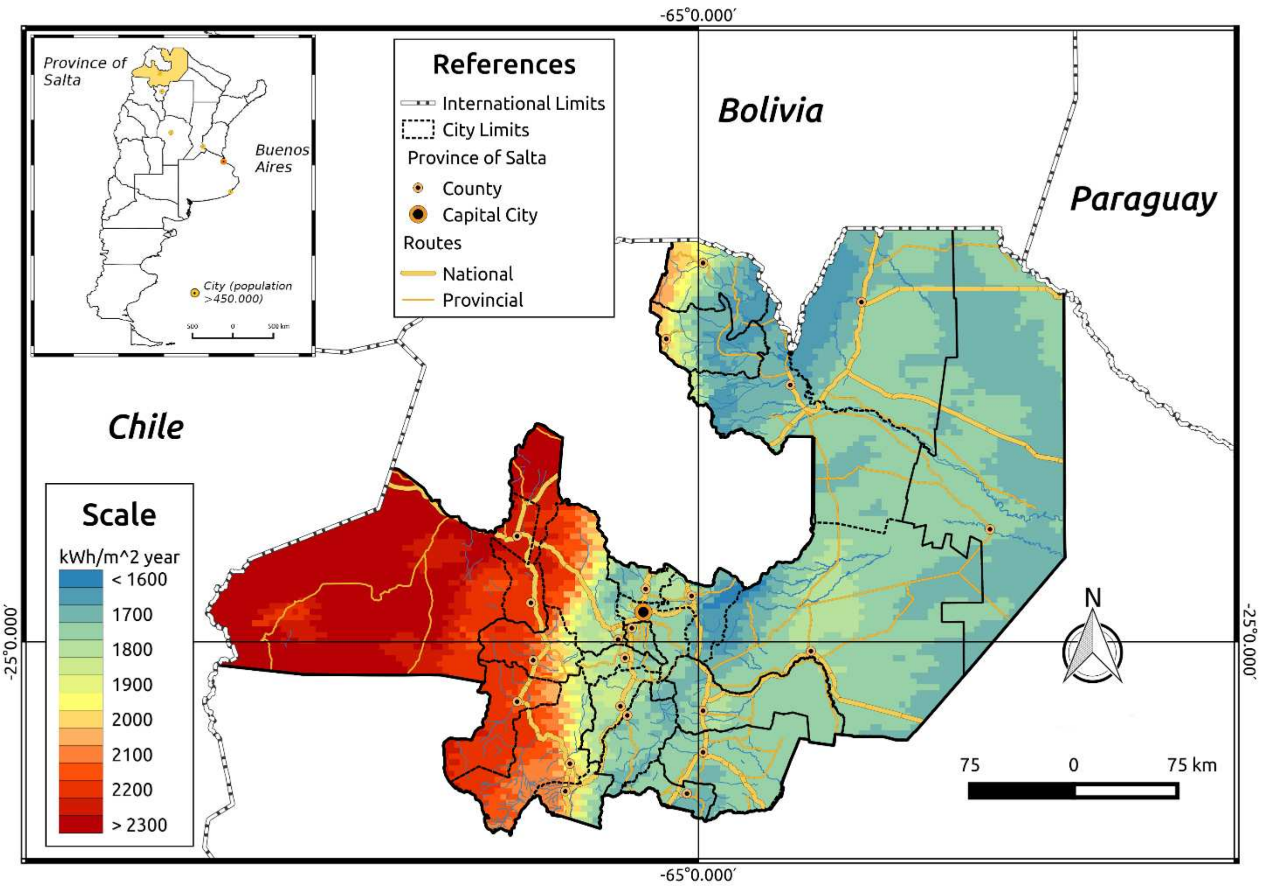



***Fig. 6.*** Annual average global horizontal solar irradiation map.

Regarding the distribution of irradiation during the year, the maximum values of daily solar irradiation are concentrated in November (6 to 9 kWh/m$^2$) and the minimum in June (2.5 to 5 kWh/m$^2$). The central zone valley presents the fewest global horizontal solar irradiations in the summer months, that can be associate with effects of cloudiness and precipitations that characterize this geographical area. It is necessary a deep work to ensure this assumption. However, Carmona et al. [14] present maps of monthly mean effective cloud cover (ECC) obtained from the CERES-SYN1 product for the whole Argentine Republic and the highest ECC values in Salta are located during summer months

Figure 7 exemplifies the distribution of monthly solar irradiation for the months of December (summer) and June (winter) in Salta province.

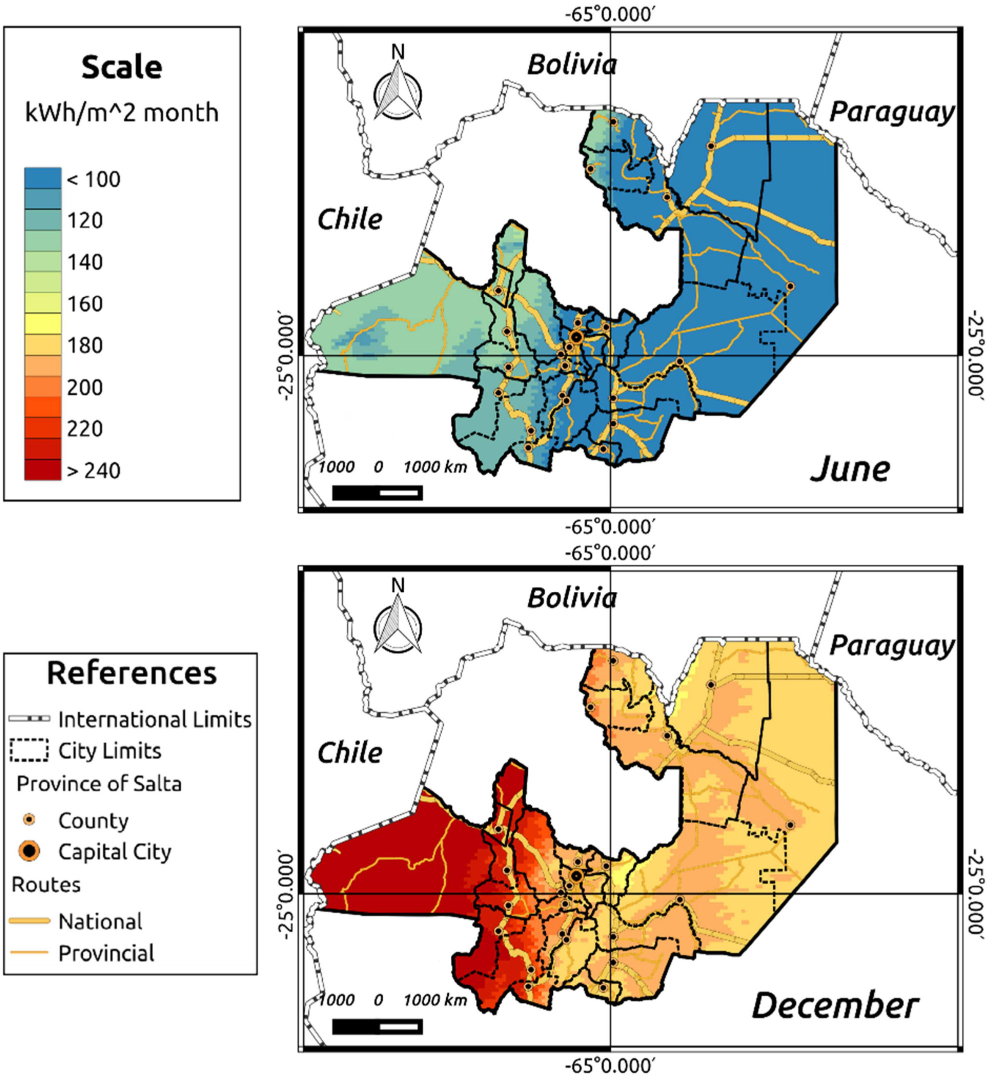



***Fig. 7.*** Monthly solar irradiation distribution in June and December.

In correspondence to the annual values, the solar irradiation daily and monthly increases with altitudinal variations of the terrain (Figure 1). Elevated areas show the highest values of irradiation during all the months of the year.

## 4. Discussion

Diverse comparisons of global horizontal solar irradiation of LSA-SAF data from 2009 to 2015, available ground measurements and empirical estimates by clear sky models, were performed: characteristic daily comparisons, monthly solar irradiation

The comparative analyzes, between ground stations, in characteristic daily basis, presented in Figure 3, show that the Abra Pampa and El Rincon stations present the higher solar irradiation values that is explained by their altitude: 3463 and 3800 m.a.l.s respectively.  On the other hand the smallest differences between the values of clear sky models, satellite values and measured data are observed during the dry season (June-August). In contrast, the greatest differences are found during the wet season (September - April), where more cloudiness and precipitation occurs.

Results of comparisons performed in monthly basis, show that the dry season, from April to September, indicates a satisfactory adjustment while summer months presents a greater variability, highlighting an underestimation of the solar irradiation satellite values for the month of January and an overestimation for the months of October, November, and December. For this reason, adjustment factors for these months were applied, obtaining substantially better statistical indicators results. The most remarkable case is Etchart ground station as it goes from 26 RMSE%, -20 MBE% and $R^2$ 0.77 values to 16 RMSE% -15 MBE% and $R^2$ 0.95 values.

Consistently, performance of the comparison of solar irradiation values from LSA-SAF and ground measurements in annual basis improves significantly when adjusted satellite data is considered. Relative error between adjusted satellite data and ground measurements oscillates between 0 -10 %, while non adjusted satellite data presents relative error values up to 29%.

All this considered, the results of this work illustrate that solar irradiation data of the LSA-SAF is a satisfactory alternative to compensate the scarcity of ground measurements available data in the Northwest region of Argentina. The comparison of the global horizontal solar irradiation data of the LSA-SAF with the measurements of five pyrometers in a seven-year period is a satisfactory validation of the source. Moreover, similar values of indicators (e.g MBE, RMSE) used in this work and in other validation papers from Europe, evidence a good reproduction quality of the data source [12,13].

A previous study [69], conducted in the same area, compares measured monthly mean solar radiation and estimated monthly values from three satellite databases. The satellite sources considered are: SWERA, SoDa and SSE and results of the RMSE% are 12%, 23%, and 23% respectively. While, results of RMSE% of LSA SAF and data from the closest ground station considered in Salazar is 7%. LSA-SAF is superior regarding to high spatial resolution and its performance is better in this case.

In a national context, Carmona's work performs the comparison between CERES_SYN1 data and four ground-based observations of the monthly mean daily global solar radiation. This comparison presents a close-to-perfect agreement between CERES_SYN1 data and ground-based observations for monthly mean daily global solar radiation (R2 = 0.995), with a MBE factor close to zero [14].Although LSA-SAF has a better spatial definition (0.015 degree versus one degree) the performance of the indexes is not in any of the cases close to zero, what opens a new line of research to compare and evaluate the performance of CERES_SYN1 data and solar radiation data from ground stations located in Salta.

The relative error values between the annual irradiation of measured values and adjusted satellite data for all stations are within 10%, highlighting the El Pongo station where the Er is zero. The performance of adjusted satellite data is very satisfactory, considering that although the solar radiation data from ground stations are considered “certain” in this work, however that data can also contain errors. Those errors can be associated to: the measurement equipment (calibration, installation and maintenance) and the management of data (accuracy of measurements, data processing, collection and storage system). It is not possible to quantify this since the degree of maintenance of the stations (cleaning of domes, leveling, etc.) is unknown.

Although, there are many examples of works that seek to validate solar irradiation satellite data with ground measurements [40,41,70], there is nothing agreed in the number of stations needed for a certain area. However, it is evident that the more number of stations the better, as it enables an exhaustive evaluation. In the present work, the number of ground measurements and its time period is considered satisfactory for the present analysis. There are several works with larger territorial surface than Salta where satellite radiation data was validated using fewer measurements with a shorter period of time [14,40,41]. On the other hand, the present methodology improves simplistic solar assessment methods generally employed by photovoltaic actors such as interpolation of ground station measurements [20,31] or data based on satellite imagery with scarce or any validation in the concerned area [14,43,46].

The methodology presented here enables the development of high resolution irradiation maps with adequate accuracy using free access data from an internationally source (LSA-SAF), not commonly used in countries outside Europe, and empirical estimations models with high solar geometry accuracy. On the other hand, this work presents for the first time new LSA-SAF data comparisons with more than one in-situ measurements in the American context.

The global horizontal solar irradiation layers from satellite images with high spatial resolution allow a more detailed analysis of the behavior of solar irradiation in the whole province. In comparison with previous works, that identified four irradiation isolines in the province [70], this study presents a considerable improvement in the spatial resolution.

In the local academic context, some subsequent validations have been made, obtaining pleasant adjustments [71].  Also, GIS solar irradiation is being used in the design of prototypes, the installation of solar photovoltaic plants and planning processes. Its application in both governmental and private sectors is very useful since it allows the evaluation of solar technology on a small and large scale.

## 5. Conclusion

The use of solar resources would improve living conditions in the area, diversify the energy matrix, promote more sustainable production systems and give answers to environmental issues. However, there are only a few studies that describe in high spatial resolution the variability of the solar resource in Argentina. Solar radiation ground measurement data is scarce, punctual and mainly not available, so information derived from satellite images can contribute to filling the current gaps. Even though there are works, concerning solar radiation within the national circumscription, that consider satellite imagery, data from LSA-SAF,a internationally renowned free access data source, is not taken into much consideration. The results of this work show that the use of a satellite database provided by LSA SAF is adequate for solar resource mapping in the province of Salta. This data is compared with clear sky estimates and ground station measurements in daily, monthly and annual basis. The monthly variations due to the satellite method are corrected applying an adjustment factor in the summer months. In the case of the average daily solar radiation maps for characteristic days, this adjustment is not made because there are few available terrestrial stations and series of short and incomplete measurements.

The maps generated, with irradiation annual values between 1600-2300 kWh/m$^2$, suggest a high potential of solar energy in the province of Salta, highlighting a strong increase in solar irradiation as a function of altitude.

The information, now available in geospatial format, is a contribution to the decision making related to energy planning at both macro and local scale, contributing in the evaluation of solar energy projects, pre design of solar technology such solar collector location assessment and photovoltaic potential. Moreover, the present solar irradiation tool incorporates the advantages offered by the GIS technology in order to use the sources of solar energy in an adequate manner, respecting the potentialities and limitations of each geographical region and territorial environment in general. In this sense, it is intended to make the solar irradiation GIS available to interested institutions and to the public in general.

As mentioned at the beginning of the document, this GIS tool is part of a larger project that seeks to create a Decision Support System, which systematically incorporates the multiple dimensions that are considered in the development of energy policies in the province of Salta. These dimensions refer to: quality, quantity and accessibility, incorporating solar energy in an integral way that guarantee the sustainability of the energy system, generate impact on employment, favor productive development, promote environmental care, and ensure generation and energy access for the full development of people.

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**Highlights:**

- Development of a solar irradiation GIS in high spatial resolution for the first time in Argentina
- Comparisons LSA-SAF and five ground stations solar irradiation data for a seven-year period
- LSA-SAF compensate the lack of ground measurements in an area with great geographical variability
- The solar irradiation GIS is a contribution to the decision making related to energy planning