An Overview of Solar Resource Assessment Using Meteorological Satellite Data

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Abstract— **Earth observation data from meteorological satellites provide essential information for solar resource assessment (SRA). SRA is the statistical characterization of solar radiation at a specific location on Earth and it is a key part of feasibility studies for solar thermal and solar photovoltaic projects. Cloud climatology and the Clear Sky model are the two main building blocks of any satellite-based resource assessment method. This paper provides an overview of SRA methods and provides examples of data products derived from satellite images.**

Keywords: solar resource assessment, meteorological satellite data, global horizontal irradiance, solar energy

I. INTRODUCTION

Earth observation data from meteorological satellites provide essential information for solar resource assessment (SRA). SRA is the statistical characterization of solar radiation at a specific location on Earth and it is a key part of feasibility studies for solar thermal and solar photovoltaic projects. This paper will highlight some of the recent advances in the field of SRA and illustrate the advantages of satellite-based methods by giving practical examples from the work performed at Turquoise Technology Solutions Inc. ("Turquoise"), a Canadian company specializing on satellite-based SRA.

The "fuel" of all solar energy systems is irradiance, defined as the power received from the sun at a specific area (generally measured in watts per square meter). Understanding the natural variation of irradiance at the Earth's surface, and characterizing its behavior across different averaging periods (e.g., daily, monthly, annually) is essential for the optimal design and operations of solar energy systems.

With a properly performed SRA, we can determine both the overall level of solar radiation at a project site, as well as its variability over time. These two pieces of information help set realistic expectations for a solar energy investment: if the solar resource is overestimated, the actual energy output will be well below the projected one resulting in a possible financial loss. If, on the other hand, the resource is underestimated, the final system design will be suboptimal, producing less energy than possible.

The yield, or output, of solar energy systems is not constant over time. Depending on certain meteorological factors, such as cloud cover, the energy output can change drastically from one year to the next. This variation, also called intermittence, is one of the disadvantages of renewable energy systems. Solar resource assessment is a key tool for understanding and managing the intermittence of solar energy systems. One way to address intermittence is to use a historical data set (ideally covering 10 years or more of hourly solar radiation data). In this way, it is possible to fully capture the variation around the long-term average value using histograms and averaged resource charts (monthly, seasonal and annual).

II. BACKGROUND ON SOLAR RADIATION

The amount of solar radiation reaching the top of the atmosphere is considered constant in many solar radiation models (1367 watts/m2), although the 11-year solar cycle and the relative distance of Earth from the Sun throughout the year slightly change the solar flux reaching Earth. However, this simplification can help reduce the level of complexity of the models without a drastic impact on the results. The other advantage of using the solar constant is the ability to build a deterministic model, also called the Clear Sky model, to estimate the solar radiation at the surface of the Earth. Even though the amount of solar radiation at the top of the atmosphere is relatively constant, various atmospheric phenomena such as aerosols affect the level of radiation reaching the surface of the Earth. These phenomena are factored in by incorporating solar geometry, altitude and turbidity data into the Clear Sky model. Since the solar radiation estimates based on the Clear Sky model assume that there is no cloud cover, they provide the upper bound of radiation values.

Determining the long-term characteristics of cloud cover ("climatology") is also an essential part of solar radiation modeling. Clouds have a significant impact on the amount of solar radiation reaching the surface of the Earth. By absorbing the incoming radiation and reflecting some of the energy back into space, they play a complex role in shaping our climate. Generally speaking, about 20% of the incoming radiation is absorbed by gases and clouds, and another 20% is reflected back to space. Thus, determining the cloud cover over a project site is an integral part of solar resource assessment.

Cloud climatology and the Clear Sky model are the two main building blocks of any satellite-based resource assessment method. By integrating cloud data, derived from meteorological satellite images, into the Clear Sky model, Turquoise can estimate the solar radiation levels at the surface of Earth with a high degree of accuracy. Specifically, the following three components of solar radiation are estimated using the proprietary database and software of the company:

- Global Horizontal Irradiance (GHI): Irradiance produced by solar radiation on a horizontal surface on the Earth. GHI is particularly relevant for photovoltaic applications.
- Direct Normal Irradiance (DNI): Irradiance produced by the direct solar radiation on a surface perpendicular to the sun's rays. DNI is particularly relevant for solar thermal systems and concentrating solar applications.
- Diffuse Horizontal Irradiance (DHI): Irradiance produced by the diffuse solar radiation on a horizontal surface on Earth. Diffuse radiation is the portion of solar radiation that reaches the Earth after being scattered by various atmospheric molecules and aerosol particles.

A. Solar radiation data sources

For a solar energy project, the ideal data source is collected using on-site measurements over multiple years. Unfortunately, for many parts of the world, ground station data is scarce. Therefore, unless a project site happens to be right next to a meteorological ground station, the chances of obtaining on-site measurements from third-party providers is quite unlikely. Another alternative is to make dedicated in-situ measurements for a site (e.g., by installing a pyranometer) and to collect data for at least a year before an investment decision is made. Although this option guarantees access to data, it requires a painstaking effort to acquire the measurements. The instruments have to be cleaned, maintained and calibrated. The data loggers have to be configured for manual or automatic data download. Furthermore, the necessity to wait for data collection and the associated costs can quickly render it impractical for many investors.

The alternative approach is to estimate the irradiance by using a Clear Sky model along with meteorological satellite data to build a "cloud index". The cloud index is shown in Figure 1 (middle panel).

B. Satellite data for Solar Resource Assessment

An important advantage of satellite data is the wide spatial coverage, as well as the capability to generate time series data which spans multiple decades without having to wait for in-situ data collection. Both the spatial and temporal coverage are very useful for solar resource assessment, as discussed below.

Meteorological satellites, such as the GOES series of NOAA or the METEOSAT series of EUMETSAT are located in the Geostationary Earth Orbit (GEO). From this vantage point, these satellites are capable of imaging the entire disk of Earth at frequent intervals. Typically, these satellites carry imagers operating at the visible and thermal infrared bands, ideal for detecting clouds (Figure 1, top panel, shows a GOES 11 image taken on Feb 10, 2007 at 9pm GMT).

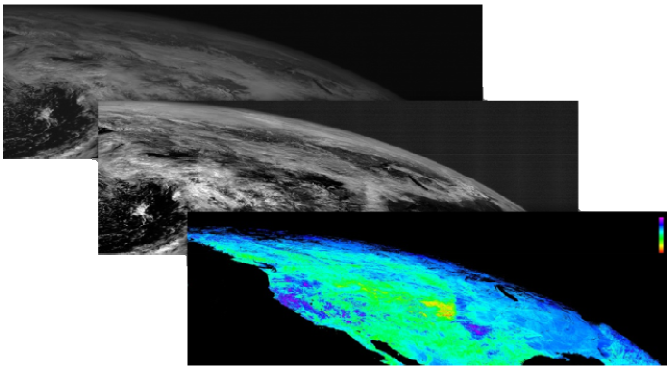

Figure 1. SRA image processing steps (source: Turquoise)

The archival images of meteorological satellites are very useful for solar resource assessment. Given that the first operational meteorological satellite, TIROS, was launched more than fifty years ago, there is a vast archive of meteorological satellite imagery available today. By acquiring and processing archived imagery, it is possible to build time series data for SRA going back multiple decades. This is a great advantage for satellite data: due to variations in meteorological activity from one year to the next, the amount of solar energy reaching the surface of Earth can vary significantly from one year to the next. For example, for Toronto, Canada, the amount of solar energy accumulated on a flat surface (such as a solar panel) can vary significantly from one year to the next (Figure 2). In fact, variations as high as 10% from the long term average value are possible.

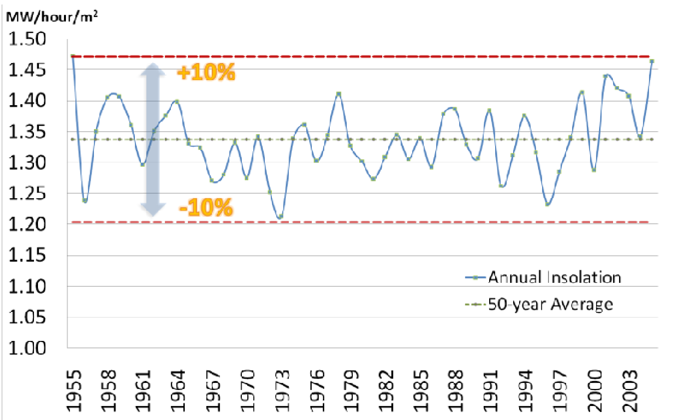

Figure 2. GHI recorded at a Toronto ground station from 1955 to 2005 (source: Turquoise, Environment Canada)

Given that the average lifetime of a solar photovoltaic system is approximately 20 years, it is essential to have an accurate estimate of the long-term average value of the solar resource. However, estimating the long-term average value is not sufficient for a proper assessment. Without taking into account the amount of variation over many years, the SRA is incomplete.

III. SATELLITE-BASED SRA TECHNIQUES

Using satellite-based methods for solar resource assessment is a relatively recent development. Starting with the initial work of Cano et al. [1], various researchers have demonstrated the accuracy and reliability of these methods by providing extensive comparisons to ground-based data sources [2][3]. As the quality and temporal frequency for meteorological satellite data improved over the years, the accuracy of the satellite-based estimates improved further. These estimates can be used in a variety of ways, ranging from solar energy maps (Figure 1, bottom panel) to time series analysis (Figure 3).

Satellite-based solar resource assessment techniques are used on an operational basis in various countries. For example, in Spain, creditors routinely ask for satellite-based SRA reports before they make lending decisions for solar energy projects [4].

Research shows that beyond a 25-km radius from a ground station collecting solar radiation data, satellite-based methods are more accurate than interpolating ground station data.

A. Validation of satellite-based estimates

As part of a quality assurance process, it is essential to validate the satellite-based estimates by comparing them to the in-situ solar radiation data measured at ground stations. Typically, the validation results are reported using well established statistical methods to measure the performance of the model, such as the root mean squared error (RMSE). Figure 3 illustrates the comparison of satellite-derived data and in-situ measurements for a validation campaign completed for Edmonton, Canada. The variation of the GHI over the course of a year can be observed as well as the close match between the estimates and the actual measurements. For many ground stations in Canada, Turquoise reported RMSE values of less than 100 watts/m^2.

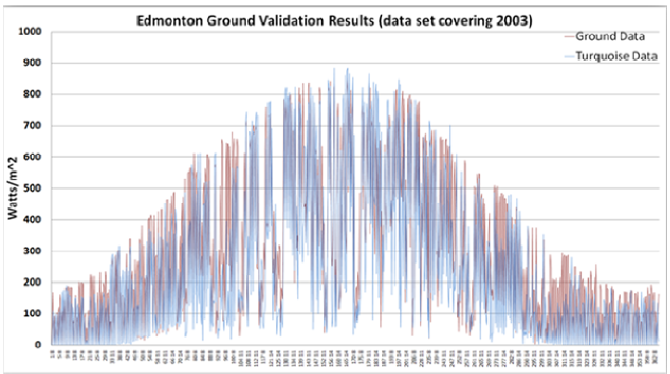

Figure 3. Ground validation results (source: Turquoise)

B. Case Study: Solar energy data products for Ontario (Canada)

This section aims to provide concrete examples of satellite-based solar resource assessment. Specifically, the data products developed for the province of Ontario in Canada will be described and various examples, including histograms, averaged resource charts and P95 values, will be illustrated.

Finding good quality datasets is one of the biggest challenges in solar energy project development. To this end, Turquoise designed two data products to address this need for solar energy data: Turquoise Solar Basic and Turquoise Solar Premium. These products cover an 11-year period (from 2000 to the end of 2010) based on archived GOES images. For a selected site, more than 100,000 images are processed to generate hourly time series data.

As discussed above, the ability to analyze the full distribution of the solar resource is important for making sound investment decisions. An example of this is provided in Figure 4, the histogram of daily GHI totals for a site in Ontario. This graph is useful for many design decisions, for example, the daily total GHI rarely surpasses 8000 Wh/m^2/day, a key consideration for sizing the solar energy system. Based on the 11-year dataset, the long-term average GHI value at this site is 3780 Wh/m^2/day. Average insolation at this site (the sum of irradiance over the course of a year) is 1381 kWh/m^2/year.

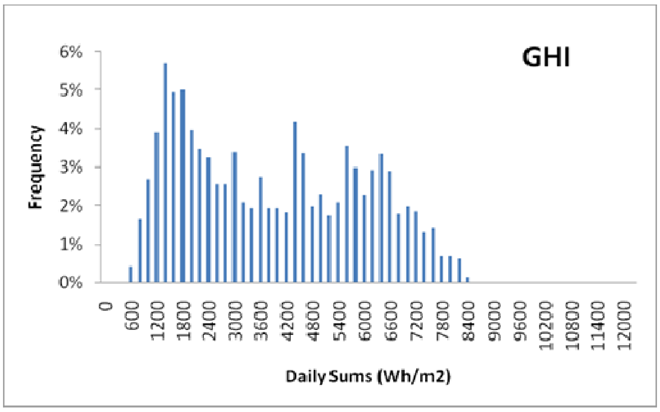

Figure 4. Histogram of daily totals of GHI (source: Turquoise)

Another advantage of satellite-based SRA is the capability to visualize the effect of seasonality on the solar resource. For example, Figure 5 shows the average, minimum and maximum hourly values for each month in the 11-year dataset. It is not surprising to see that the average values are much lower in winter months. However, an interesting finding is the wide variation between the minimum and maximum values in the spring, summer and autumn, in contrast to the relatively low variance in winter months.

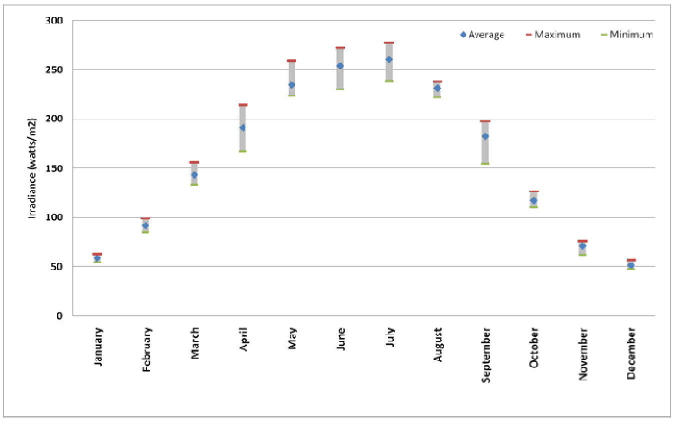

Figure 5. Variation of hourly GHI values across the calendar year (source: Turquoise)

The final example is the P95 value, a popular metric in the finance community. This value, also called the exceedance probability, represents the minimum level of solar radiation that will be accumulated on a project site for a given period of time (e.g., for a year) with a 95% chance (P50, the fiftieth percentile represents the mean radiation value). In this way, rather than basing financial calculations on averages, the full distribution of future outcomes is used. This approach provides much more information about the risks of a project compared to the basic statistics of a distribution (e.g., mean and standard deviation). Banks and other financial institutions are interested in the P95 value, as it provides a convenient way to assess the financial risks of a project.

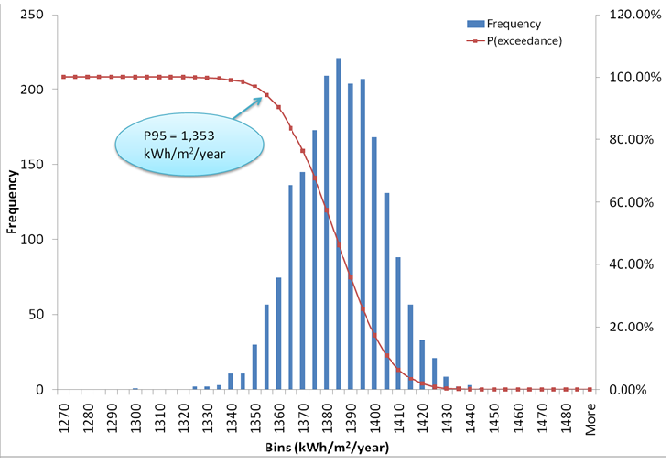

Figure 6. The P95 value of the GHI at the project site (source: Turquoise)

In Figure 6, the P95 indicates that, although the long-term average of GHI at this site is 1381 kWh/m^2/year, there is a 95% chance that the insolation will surpass 1353 kWh/m^2/year. During the due diligence process of a solar energy investment, using this value, instead of an arbitrary pessimistic or optimistic estimate, helps both the project developer and the creditor by setting more realistic expectations for both parties.

IV. THE FUTURE OF SOLAR RESOURCE ASSESSMENT

From a basic roof-top installation to utility-scale photovoltaic systems, there is one common necessity for all solar energy investments: the need to accurately determine the solar resource. Today, this is possible by generating long-term statistics based on historical data derived from meteorological satellites. In the field of SRA, current research and development activities are focusing on near real-time radiation estimates and forecasts. These additional capabilities will gain more importance as more solar energy systems are integrated into the electrical grid. In order to diagnose performance issues (e.g., due to malfunctioning equipment) or to maintain the stability of the electrical grid, a new generation of tools and capabilities are needed to ensure the safe and efficient operations of solar energy systems. There is no doubt that SRA using meteorological satellites and other space assets will continue to play an important role as the adoption of solar energy increases all around the world.

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