Downscaling satellite derived irradiation using topographic shading analysis.

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EXECUTIVE SUMMARY

The main goal of this task is to account for the effect of topography on the solar resource of Southern California and other urban areas with high PV penetration across the state.

The main tools required are an Irradiation Database and a Digital Elevation Model (DEM). The irradiation is taken from the enhanced Solar Anywhere database, developed and provided by Clean Power Research. It contains GHI and DNI data for the year 2009, with 30 minute temporal resolution, and a 36 arc-seconds (~1km) spatial resolution. This data allow quantifying the solar potential in absence of topographical shading.

The DEMs used are “SRTM1” (~30m spatial resolution) and “GLOBE” (~1km spatial resolution), which allow calculating the horizon of every point in the study area, with a spatial resolution of 1 arc-second (~30m).

These data allow quantifying the effect of topographic shading on the daily irradiation, effectively downscaling the satellite derived irradiation database to a higher resolution (from 1km to 30m). All horizons were stored in a public database which can be easily integrated into PV performance mdoels. Finally, an example of application is given.

1. **HORIZON CALCULATION**

The horizon (obstruction angle) at a given direction is calculated by finding the maximum elevation angle between the location and all the points along that direction following the method outlined in Bosch et al. (2010). For practical purposes resolving the horizon with 5 degree azimuthal steps (or 72 horizon points) is a good compromise between accuracy and computational time.

To calculate the distant horizon, GLOBE DTM is used, with a 2-degrees square centered around the site. To better account for local obstructions and elevations that cannot be detected in the 1-km GLOBE grid, we use a 0.5x0.5 degrees area with a 30m resolution (SRTM1). The final horizon elevations of both the 2 degree, 30 arc seconds and 0.5 degrees, 30 m calculations are stored in the database for each point.

2. SHADING AND IRRADIATION ANALYSIS

Once the horizon is calculated the shading analysis can be performed for a given day, by overlapping the sun path and the horizon (Fig. 1). From the horizon calculations, we obtain the actual local hours of sunrise and sunset for each day.

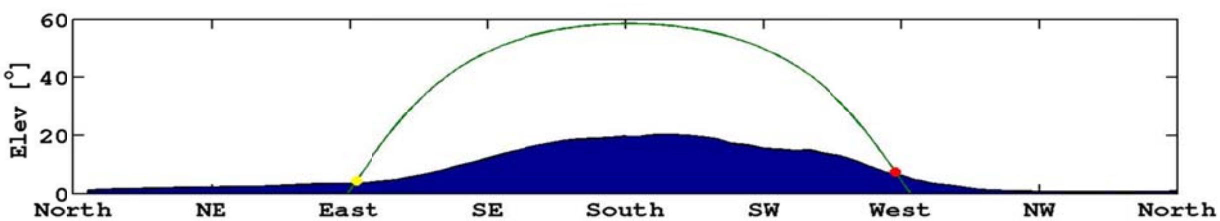

Fig. 1. Sunpath and horizon for an inland site in San Diego, CA (Latitude 33°, Longitude -117°) for March 25th. The actual local sunrise (yellow circle) is later and actual sunset (red circle) is earlier than if no obstructions existed.

Global irradiation on the PV panel can be calculated using the Solar Anywhere irradiation database as the sum of direct and diffuse irradiance incident on the plane-of-array. While the sun is obstructed by the horizon, the direct irradiance is zero, which constitutes a loss in power production due the topographic shading. Losses in diffuse irradiance are typically small and are ignored here. Fig. 2 shows an example of irradiation losses for a case with PV tilt equal to latitude and south orientation. For this day the shading is responsible of 7.6% losses (1.3 MJ).

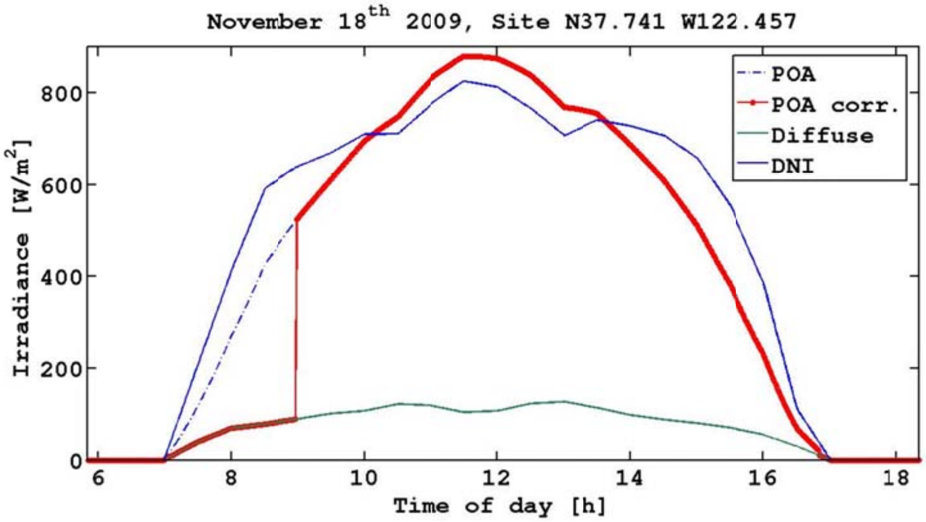

Fig. 2. Correction due to obstruction of direct irradiation by topography. The red line shows the corrected plane-of-array (POA) irradiance and the dashed blue line shows the ideal POA irradiance in absence topographic shading. Location and time information are provided in the title.

3. SOLAR RESOURCE MAPPING EXAMPLE FOR SAN FRANCISCO

The topographical shading correction allows a more accurate assessment of the solar resource and PV power production especially in hilly or mountainous areas. As an example, this method has been applied to an area in San Francisco's Twin Peaks neighborhood (Fig. 3). Horizons and irradiation were computed for a ~4X4 km² area around Twin Peaks at ~30m resolution resulting in 20736 points.

The elevation maps around the site are shown in Fig. 4.

Fig. 3. Solar Anywhere selection interface (left with 1km grid lines) and Google Earth image (right) for the selected area © Google and Clean Power Research

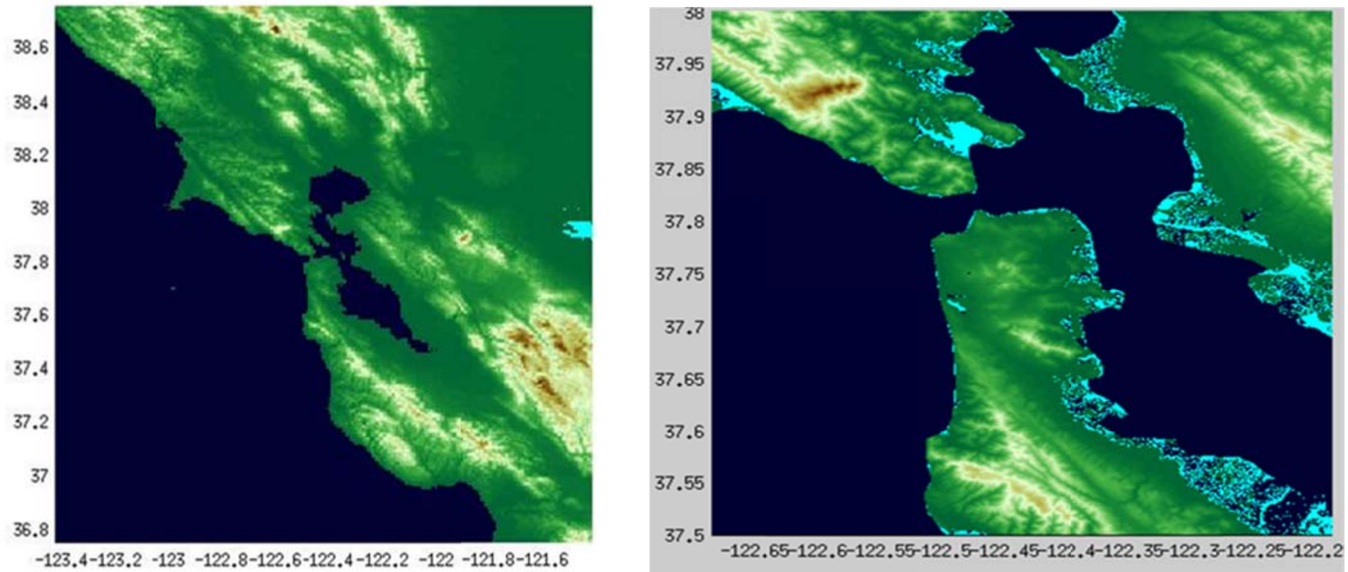

Fig. 4. 2x2 degrees GLOBE area (left) and 0.5x0.5 degrees SRTM1 digital elevation model (right) around the location shown in Fig. 3.

The *Day Fraction (DF)* is the proportion of daylight time that the sun is above the local horizon. For example, if for a given latitude May 25th would have 10 hours of sun without obstacles (e.g. over the open ocean), but the sun is only 8 hours above local horizon, then DF = 0.8. DF allows a first general and relative estimation of the horizon effects on irradiation without having to consider a specific PV system. Fig. 5 shows the day fraction for the study area for January 1st. The areas with lowest DF (lowest DF = 0.7) are located in north-south valleys (blocking the sun during the morning and evening).

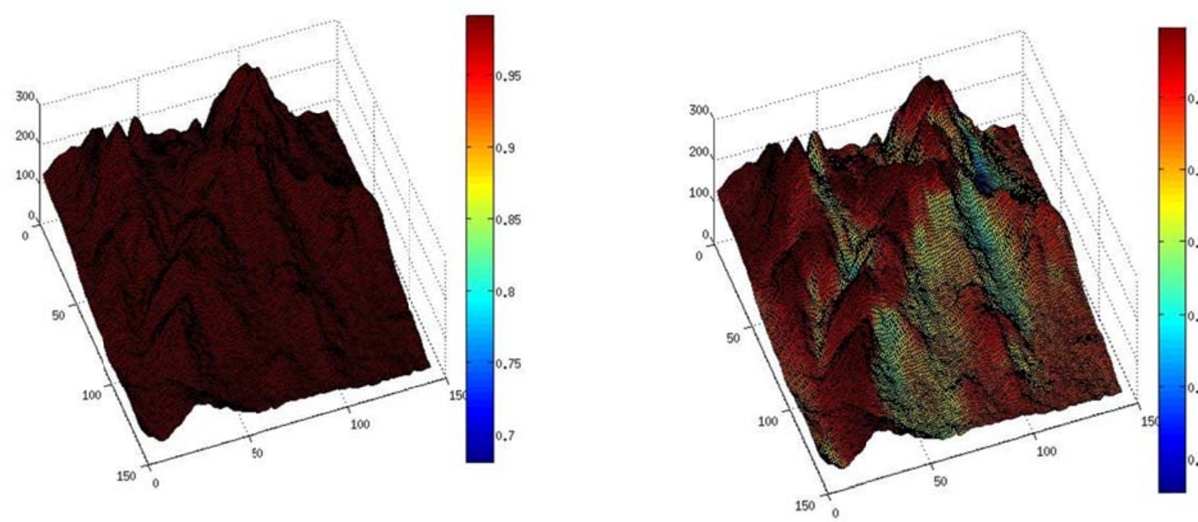

Fig. 5: Day fraction for the area shown in Fig. 3. If no horizon is considered, *DF* = 1 (left). With the horizon day fractions vary between 0.7 and 1. The lowest values are observed near steep topographic features. North is to the top.

However, DF overestimates the irradiation losses since for most solar systems the majority of the shading occurs in periods of low irradiation. Ultimately the annual irradiation loss for a specific system is the most relevant metric. After applying the topographic shading correction for 2009 (Fig. 6) we find maximum daily losses of 2.15 MJ m^{-2} day^{-1} and accumulated losses of 37 kWh m^{-2} $year^{-1}$ corresponding to 2% of yearly irradiation.

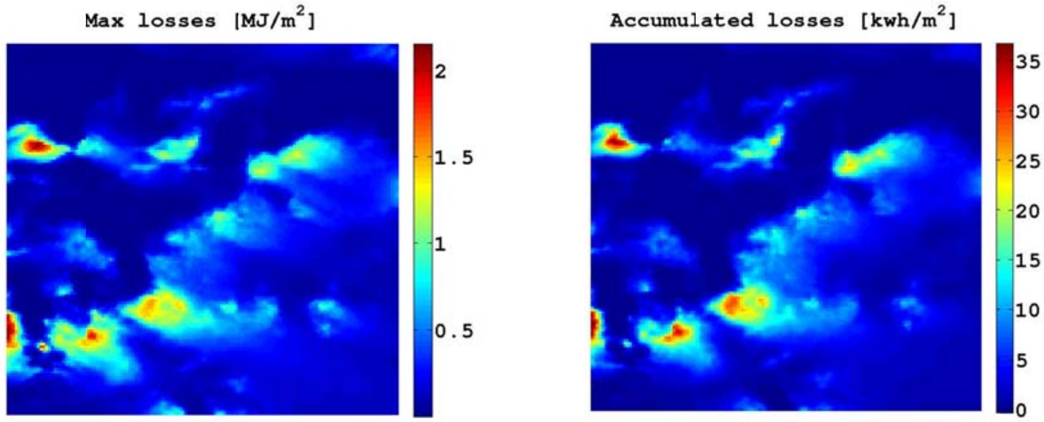

Fig. 6. Maximum daily losses (left) and accumulated yearly irradiation losses for the study area for a PV panel at south orientation and latitude tilt.

4. DATABASE DESCRIPTION

The horizon at each point is stored in a vector of 72 values. The azimuth is defined as 0^o in the north direction increasing clockwise (90^o is East and so on). Consequently, the first element in the vector is the horizon elevation in degrees at 5^o azimuth (which defines the interval [2.5^o,7.5^o[. The rest of elevations correspond to clockwise steps of 5 degrees.

Storing one horizon file per point at 30 m resolution would result in an extremely large number of files so the files have been grouped in *Tiles*. Each [1^o latitude x 1^o longitude] area contains 400 tiles. Each tile consists of a 3x3 arc-minutes (~6x6 km) area corresponding to [5x5] values of the enhanced Solar Anywhere database, and 32400 horizon ([180x180] SRTM1) points.

The tiles are stored as *Matlab* files containing a 3-D matrix with dimensions 180x180x72. The file name gives the coordinates of the center of the tile (e.g. N37.775W122.475.mat).

For tile *N37.775W122.475* the first element in the 180x180 matrix corresponds to a latitude of 37.770 and longitude of -122.500. The points are arranged then with a 1 arc-second separation from west to east (columns) and from north to south (rows). The 3rd dimension corresponds to the 72 azimuth angles (Section 2).

To reduce disk space usage, the tiles are saved using the format *uint16* (unsigned integer of 16 bits). The horizon elevation angles are multiplied by 10 and then saved as integers, so they have a 0.1 degrees precision.

Computing the horizons for the entire state of California was computationally impossible. About 60,000 processor hours were spent to compute the horizons in areas with the highest expected PV penetration and where topographic shading is expected to be an issue. The area computed covers Southern California (latitudes below 35 degrees including San Diego, Imperial, Orange, Riverside, Los

Angeles, Ventura, Santa Barbara. San Bernardino, Kern and San Luis Obispo Counties) completely due to the mountainous area and the large amount of utility scale solar power plants being planned there. In addition, horizons for the San Francisco Bay area were computed. Fig. 7 shows the area covered by the database.

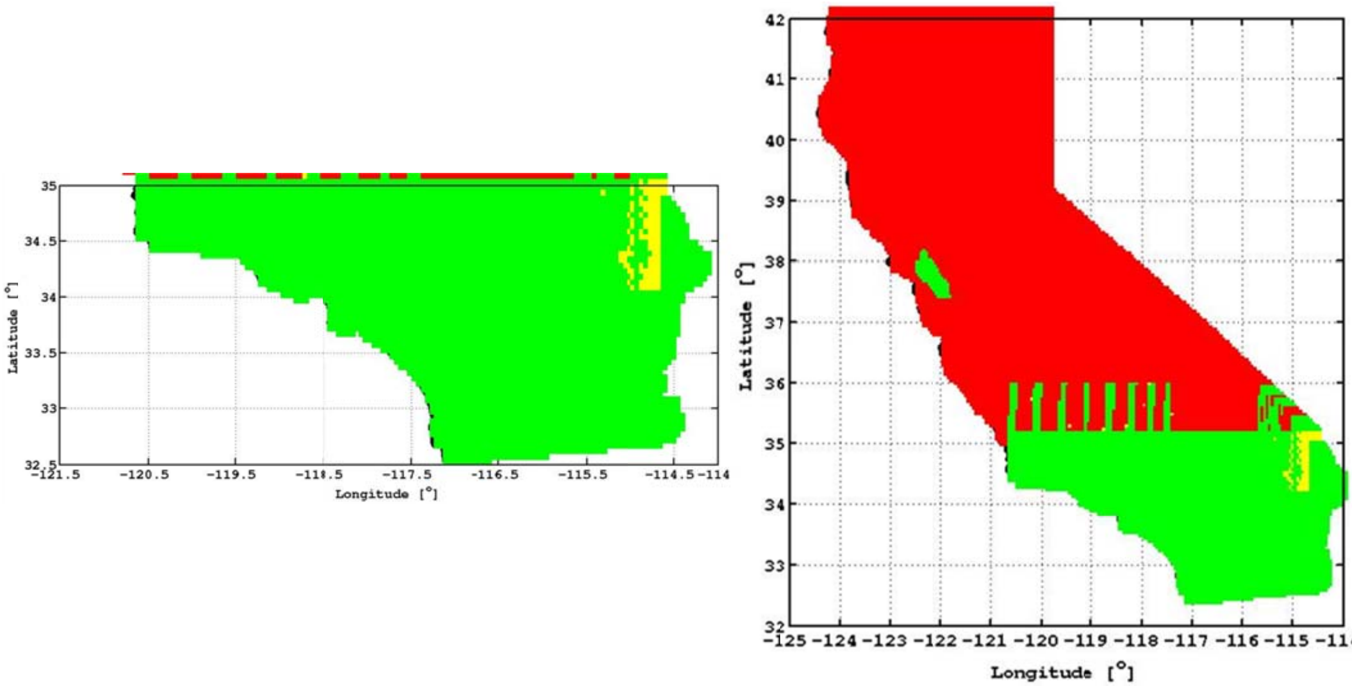

Fig. 7. Available horizon files for Southern California (left) and the whole state of California (right). Green indicates available files and red and yellow indicates not available files.

5. DATA ACCESS

The horizon files are posted on the CSI website for download. This horizon at 5 degrees increments can be used as an input to PV performance programs. It is available directly to users of the Clean Power Research PV Simulator to compute the losses due to topographical shading in absence of any other information on the local obstructions (such as local fish-eye photographs).

References

Bosch, J.L., Batlles, F.J., Zarzalejo, L.F. & López, G. Solar resources estimation combining digital terrain models and satellite images techniques. *Renewable Energy*, 35(12): 2853-2861.