

Solar Potential Calculation Method for Rooftops in the Ústí Region

Method Overview

A custom computational tool was developed in Python and C for modeling rooftop solar potential, combining functions from the pvlib Python library (a library for simulating photovoltaic system performance; Holmgren et al. 2018) with custom implementations for local shading analysis. Calculations are performed with a 15-minute time step for each month of the year.

Input Data

Geodata

- **Digital Surface Model (DSM):** Elevation model of terrain, vegetation, and buildings with 1 m spatial resolution, acquired using Airborne Laser Scanning (ALS LiDAR)
- **Roof Polygons:** Vector boundaries of roof surfaces from the Czech Land Registry (Cadastré of Real Estate)

Meteorological Data

Long-term measurements from meteorological stations in the Ústí Region, specifically at Tušimice (1984 - 2023), Doksany (2003 - 2023), and Kočkov (1984 - 2023) stations.

Measurements of the following variables were used:

- Global Horizontal Irradiance (GHI) - all three stations
- Diffuse Horizontal Irradiance (DHI) - only Tušimice and Doksany stations

CSDF Model (Clear Sky Diffuse Fraction)

Climate Parameters

The model uses three key parameters derived from meteorological data:

1. Clearsky Index (k_c)

$$k_c = \text{GHI}_{\text{measured}} / \text{GHI}_{\text{clearsky}}$$

Ratio of actually measured global irradiance to modeled irradiance under clear atmosphere. Expresses the effect of cloudiness on solar radiation attenuation. Calculated as monthly average from multi-year measurements.

2. Diffuse Fraction (k_d)

$$k_d = \text{DHI}_{\text{measured}} / \text{GHI}_{\text{measured}}$$

Proportion of diffuse irradiance to total global irradiance. This parameter determines the decomposition of global irradiance into direct (DNI) and diffuse components. Calculated as monthly average from multi-year measurements.

3. Linke Turbidity (T_L) Dimensionless quantity expressing the influence of aerosols and water vapor in the atmosphere on solar radiation attenuation. Values are estimated from empirically established tables depending on geographic location and season (implemented in pvlib).

4. Albedo Albedo expresses the surface's ability to reflect solar radiation (values 0-1, where 0 = no reflection, 1 = complete reflection). Value set to 0.18 as a compromise between reflection from roofs and surrounding agricultural landscape.

Computational Workflow

Step 1: Clear Sky Irradiance Simulation (pvlib)

For the center of the area of interest, global horizontal irradiance under clear atmosphere is simulated using the Ineichen-Perez clear sky model (function `pvlib.irradiance.get_clearsky()`; Ineichen and Perez 2002) with application of Linke turbidity. Calculation proceeds in 15-minute intervals.

Step 2: Clearsky Index Application

Clear sky global irradiance is multiplied by the monthly average clearsky index to obtain an estimate of actual global horizontal irradiance under typical cloudiness:

$$\text{GHI} = \text{GHI}_{\text{clearsky}} \times k_c$$

Step 3: Decomposition into Direct and Diffuse Components

Global irradiance is decomposed into Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) using diffuse fraction:

$$\begin{aligned} \text{DHI} &= \text{GHI} \times k_d \\ \text{DNI} &= (\text{GHI} - \text{DHI}) / \cos(\text{zenith}) \end{aligned}$$

Step 4: Local Horizon Calculation (Custom Implementation)

For each DSM cell (1×1 m) in the roof raster, the local horizon is calculated using a custom algorithm implemented in C/Python. The algorithm evaluates horizon elevation angle (with

correction for Earth's curvature) in 36 radial directions (every 10°) with 1 m step along each ray.

Outputs are:

- **Horizon elevation angles:** Array of 36 horizon elevation angles for each cell
- **Sky View Factor (SVF):** Proportion of visible sky from a given cell, calculated as:

$$SVF = (1/n) \times \sum \cos^2(\text{horizon_elevation_i})$$

where $n = 36$ (number of directions)

Step 5: Shading Application

For each time step, the following are evaluated:

Direct Irradiance Shading If the current sun position (azimuth, elevation) is below the local horizon in the corresponding direction, direct irradiance is zero for that cell.

Diffuse Irradiance Reduction Diffuse irradiance is reduced according to the Sky View Factor:

$$DHI_{\text{reduced}} = DHI \times SVF$$

Step 6: Irradiance Transposition to Tilted Surface (pvlib)

Global, direct, and diffuse irradiance are recalculated for the actual orientation and tilt of each roof cell using the function `pvlib.irradiance.get_total_irradiance()`.

This function implements:

- Geometric transposition of direct component according to angle of incidence.
- The Perez model for the diffuse component (Perez et al., 1990), which is a recognized standard in solar energy and accounts for the non-uniform distribution of diffuse radiation across the sky.
- Ground-reflected irradiance contribution according to specified albedo.

The output is Plane of Array Irradiance (POA) for each cell.

Step 7: Aggregation

POA values from all 15-minute intervals are summed for the entire month, resulting in an estimate of monthly irradiation [kWh/m²] for each roof cell.

Scenarios

Three scenarios are defined based on statistical evaluation of variability in monthly values of clearsky index and diffuse fraction (Fig. 1):

- **Realistic Scenario:** Use of monthly average parameters

- **Optimistic Scenario:** Use of upper quartile values (Q3) - less cloudiness, greater proportion of direct irradiance
- **Pessimistic Scenario:** Use of lower quartile values (Q1) - more cloudiness, greater proportion of diffuse irradiance

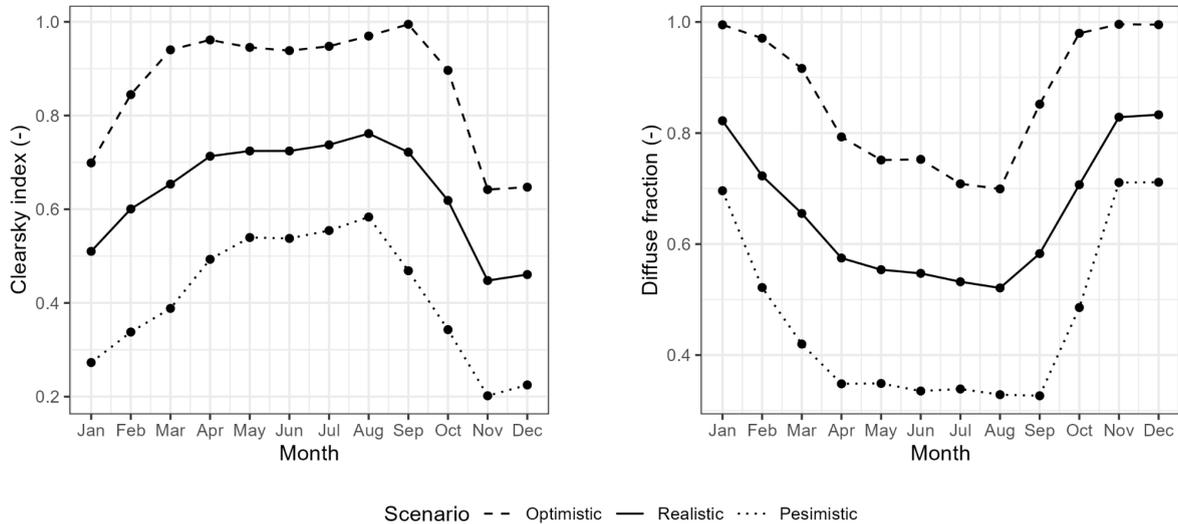


Figure 1. CSDF model parameters for three scenarios: optimistic, realistic, and pessimistic.

Validation

The model was validated on the same meteorological station data. Validation was performed by comparing modeled global irradiance (for the corresponding geographic location of the station) with monthly averages (averaged across years) of station measurements of global irradiance at all three stations (Tušimice, Doksany, Kočkov). Model agreement with measured values was compared visually (Fig. 2) and using metrics of normalized root mean square error (nRMSE) and relative mean error (rME). The CSDF model shows very good agreement in predicting global irradiance (nRMSE = 5.1%; rME = 3.2%).

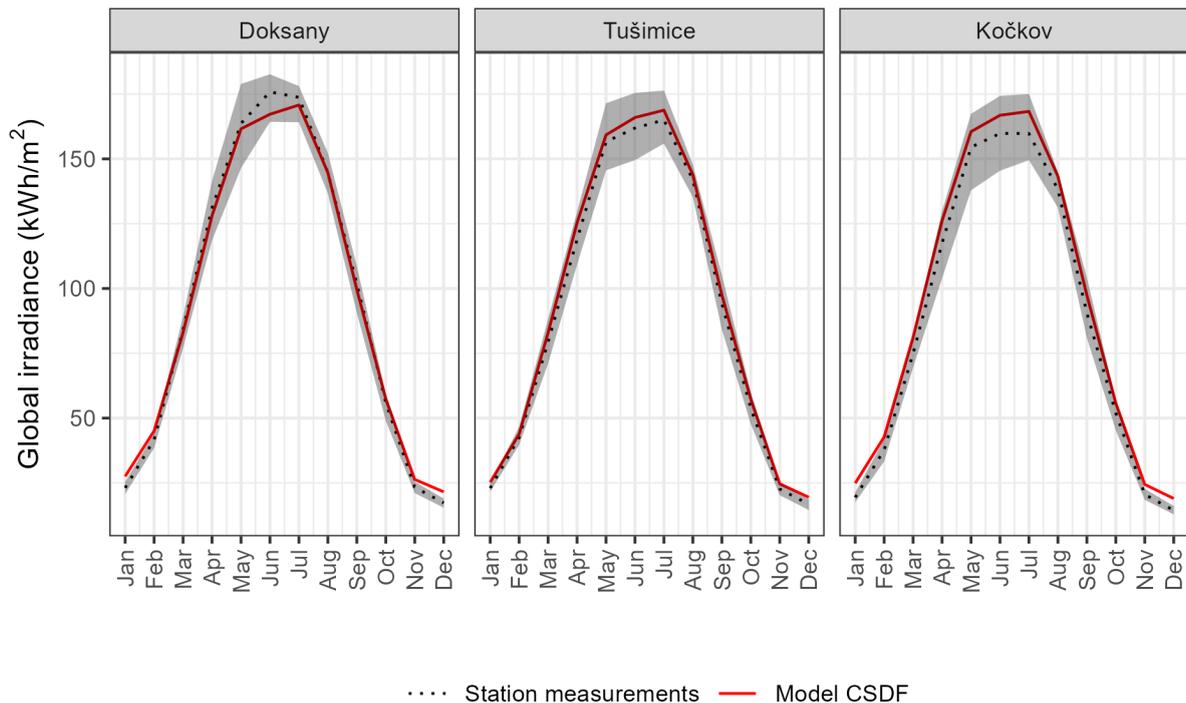


Figure 2. CSDF model validation for global irradiance.

Output Data

For each roof cell (1×1 m), the following are calculated:

- Monthly irradiation values [kWh/m²/month] for 12 months and all three scenarios (realistic, optimistic, pessimistic)
- Annual irradiation sum [kWh/m²/year] for the realistic scenario

Software Tools and Libraries

pvlib-python: Open-source library for modeling photovoltaic systems (Holmgren et al., 2018)

- Clear sky models, irradiance transposition, solar geometry

Custom implementation:

- Local horizon and Sky View Factor calculation (C/Python)
- Integration of meteorological parameters
- Workflow management

References

- Holmgren, W. F., Hansen, C. W., & Mikofski, M. A. (2018). pvlib python: a python package for modeling solar energy systems. *Journal of Open Source Software*, 3(29), 884.
 - Ineichen, P., & Perez, R. (2002). A new airmass independent formulation for the Linke turbidity coefficient. *Solar Energy*, 73(3), 151-157.
 - Perez, R., Seals, R., Ineichen, P., Stewart, R., & Menicucci, D. (1987). A new simplified version of the Perez diffuse irradiance model for tilted surfaces. *Solar Energy*, 39(3), 221-231.
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Note: The results represent a model-based estimate of solar potential based on available geodata and climate parameters. Actual photovoltaic system production depends on a range of additional factors including panel and inverter type and efficiency, installation orientation, and interannual weather variability.