NREL
Transforming ENERGY

The "Fresnel Equations" for Diffuse radiation on Inclined photovoltaic Surfaces (FEDIS)

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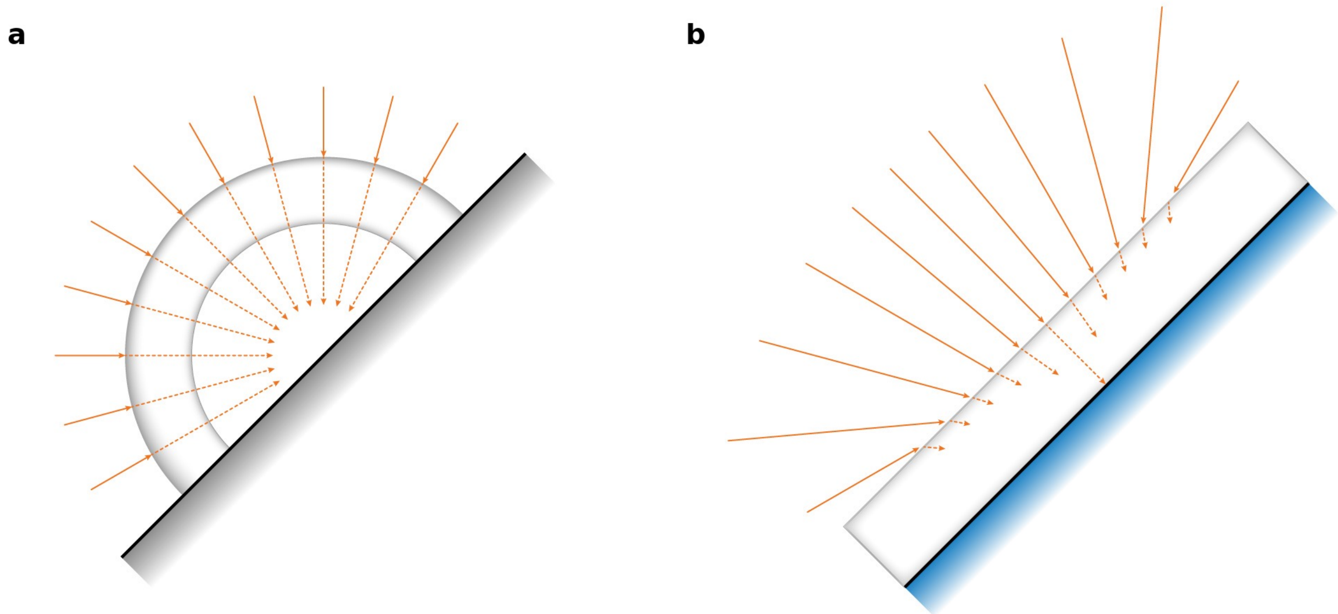
Inconsistent Data from Pyranometer and PV



- Solar energy resource is interpreted using pyranometer observation.
- The thermopile sensor is domed by a protective lens and enables perpendicular incidence for direct and diffuse radiation.
- PV modules are covered by a flat glass leading to reduced transmission through the off-normal incidence.

How Large is the Difference?

- For direct radiation, the energy loss due to the reflection by PV: 5%-10%.
  For diffuse radiation, the energy loss due to the reflection by PV : 11%-15%.
  (Based on measurements at Manfredonia, Causi et al. 1995.)
  There is significant overestimation of PV production if the pyranometer observation is not corrected by a model.

- Impact on the monthly solar energy yield: 1.3%-14.8%.
  Impact on the annual solar energy yield: 3%-7.5%.
  (Based on measurements from 10 European sites, Martin and Ruiz, 2001)
  The bias is comparable to satellite remote sensing of solar radiation.

The difference between the surface instruments is significant! It must be corrected by a model.

The Physical Model

Relative transmittance model

$$PV = c \times pyranometer$$

Fresnel equations for direct

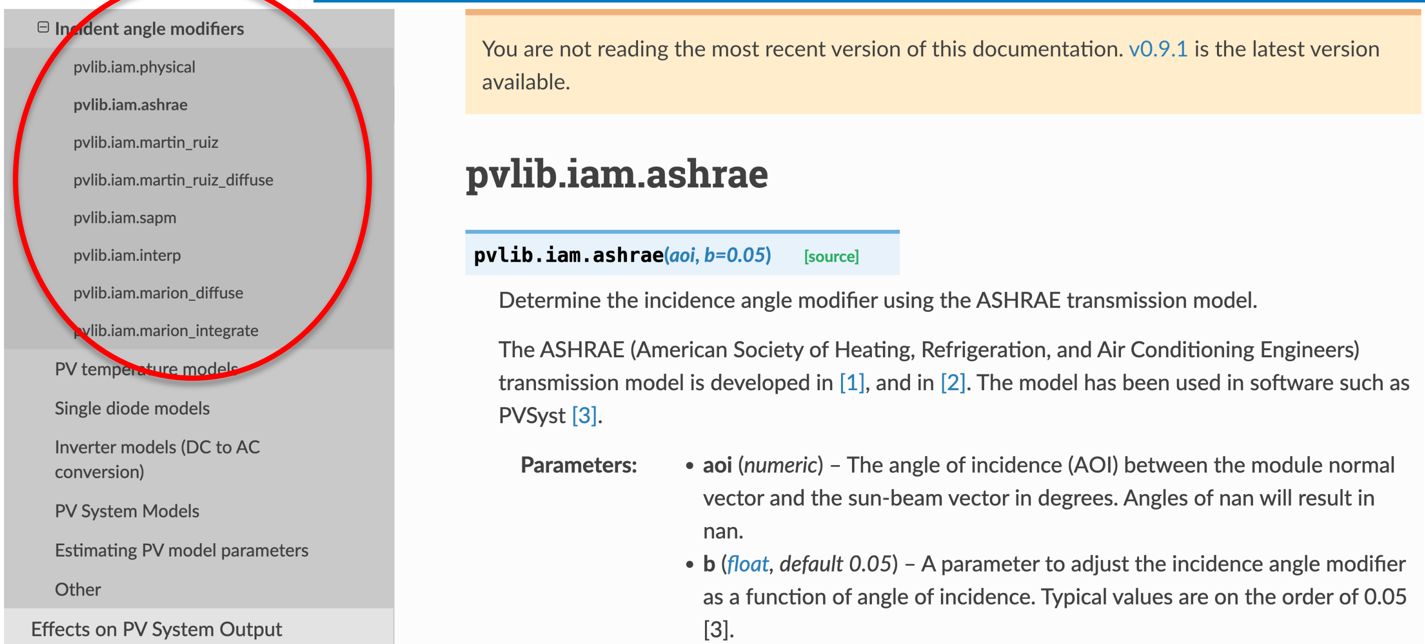
$$c_i = \frac{T_i}{T_0} \qquad T_i = 1 - \frac{sin^2(\theta' - \theta_t')}{2sin^2(\theta' + \theta_t')} - \frac{tan^2(\theta' - \theta_t')}{2tan^2(\theta' + \theta_t')}$$

Fresnel equations for diffuse

$$c_{uk} = \frac{2}{\pi(1 + cos\beta)} \int_0^{2\pi} \int_0^{\Theta'} c_i cos\theta' sin\theta' d\theta' d\varphi$$

The physical models use the Fresnel equations to analytically solve the beam transmission through the instrument covers. The transmission of diffuse radiation is computed by integrating the Fresnel equations over the PV surfaces.

The Current Models



⊟ Incident angle modifiers

- pvlib.iam.physical
- pvlib.iam.ashrae
- pvlib.iam.martin_ruiz
- pvlib.iam.martin_ruiz_diffuse
- pvlib.iam.sapm
- pvlib.iam.interp
- pvlib.iam.marion_diffuse
- pvlib.iam.marion_integrate

PV temperature models

Single diode models

Inverter models (DC to AC conversion)

PV System Models

Estimating PV model parameters

Other

Effects on PV System Output

You are not reading the most recent version of this documentation. v0.9.1 is the latest version available.

pvlib.iam.ashrae

`pvlib.iam.ashrae`(*aoi, b=0.05*) [source]

Determine the incidence angle modifier using the ASHRAE transmission model.

The ASHRAE (American Society of Heating, Refrigeration, and Air Conditioning Engineers) transmission model is developed in [1], and in [2]. The model has been used in software such as PVSyst [3].

Parameters:

- **aoi** (*numeric*) – The angle of incidence (AOI) between the module normal vector and the sun-beam vector in degrees. Angles of nan will result in nan.
- **b** (*float*, *default 0.05*) – A parameter to adjust the incidence angle modifier as a function of angle of incidence. Typical values are on the order of 0.05 [3].

8 incidence angle modifier models (relative transmittance models) are used in the current pvlib.

https://pvlib-python.readthedocs.io/en/v0.9.0/generated/pvlib.iam.ashrae.html

- ➢ The **ASHRAE** model: An empirical model based on observations of pyranometer and PV.
- ➢ A model developed by **Marion (2021)**: A curving fitting of the numerical computation of the integration of the Fresnel equations.

FEDIS

Fresnel equations for direct

$$c_i = \frac{T_i}{T_0} \qquad T_i = 1 - \frac{sin^2(\theta' - \theta_t')}{2sin^2(\theta' + \theta_t')} - \frac{tan^2(\theta' - \theta_t')}{2tan^2(\theta' + \theta_t')}$$

Fresnel equations for diffuse

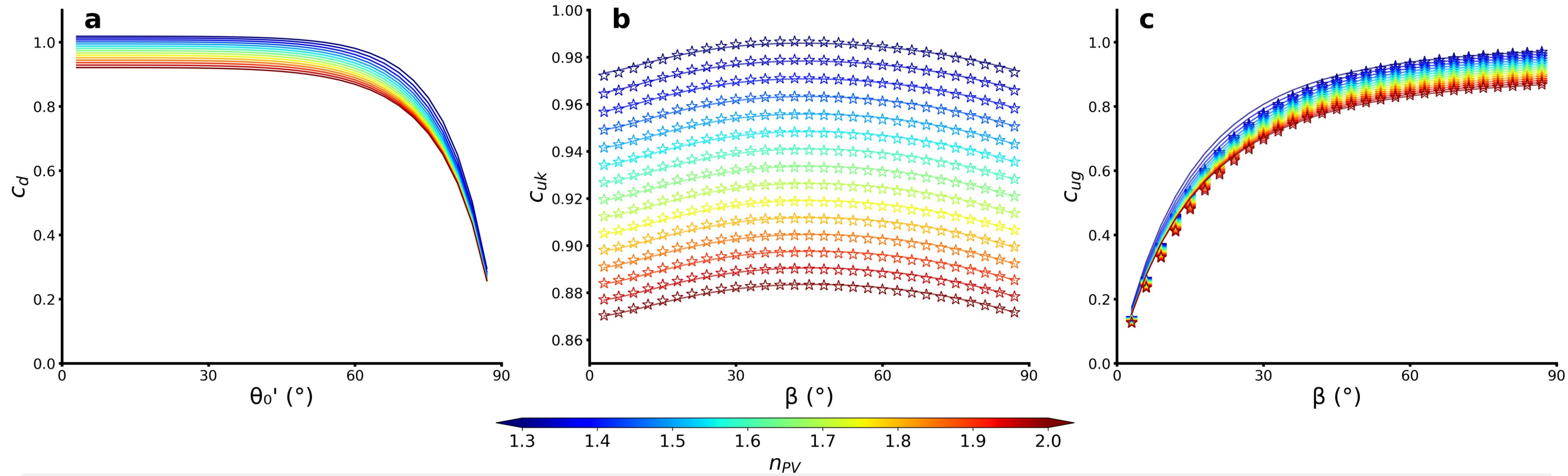
$$c_{uk} = \frac{2}{\pi(1 + cos\beta)} \int_0^{2\pi} \int_0^{\Theta'} c_i cos\theta' sin\theta' d\theta' d\varphi$$

Alternate of Fresnel equations (Schlick, 1994)

$$c_i = w[1 - (1 - cos\theta')^5]$$

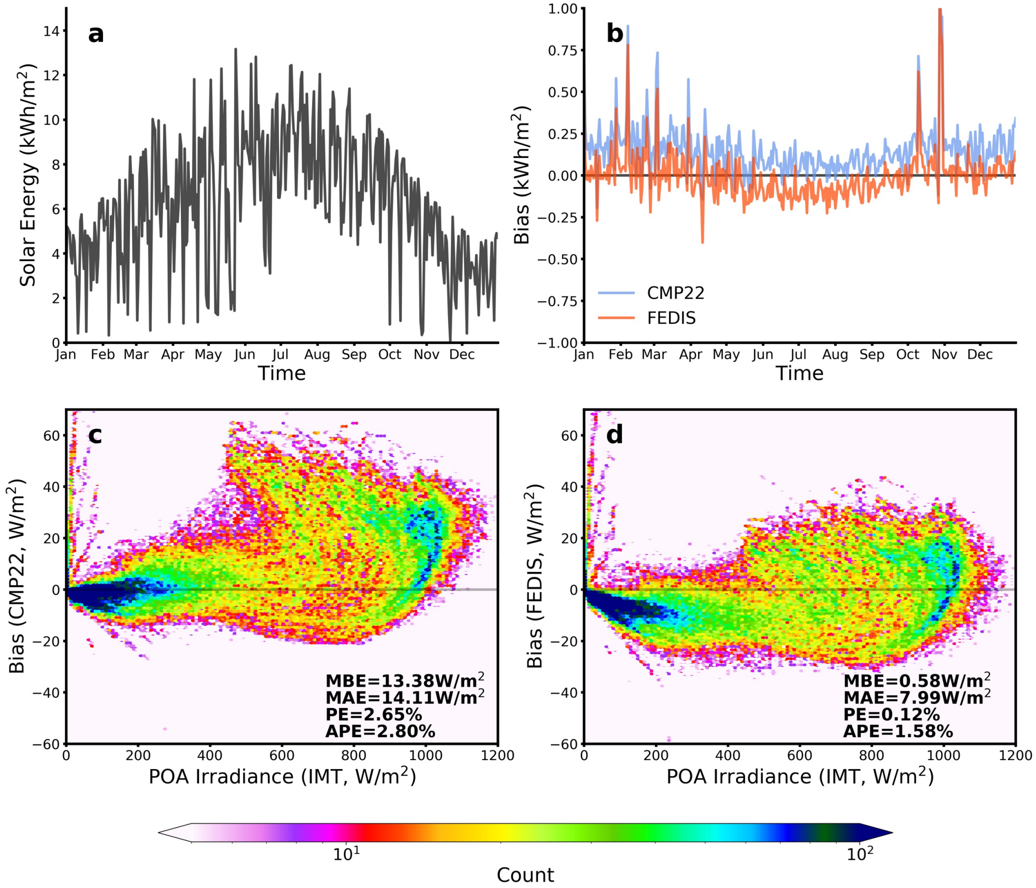
Given an alternate form of the Fresnel equations initially proposed by Schlick and adopted by extensive applications for direct radiation, the space integration of transmittance can be analytically solved for inclined PV surfaces.

FEDIS



- ➢ The analytical solution is based on the integration, but much faster. The numerical integration can be used to validate FEDIS.
- ➢ FEDIS well coincides with the idealized physical model. Ground reflection contributes a limited portion of solar energy compared with the direct and diffuse radiation from the sky. Thus, it is usually negligible for a small PV tilt angle.

Validation using 1-year SRRL data



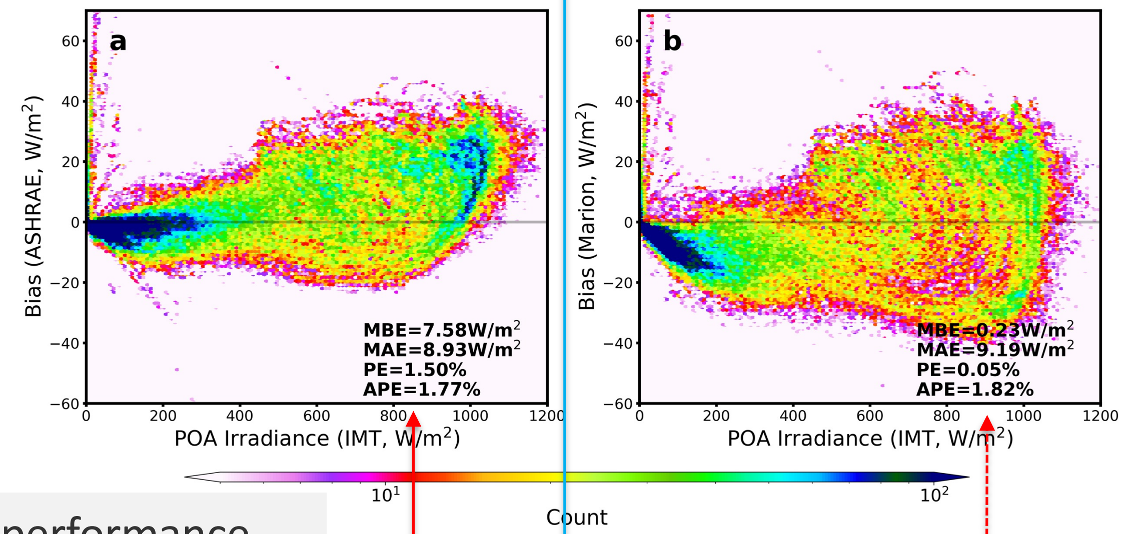
- POA irradiances are measured by a CMP22 and an IMT reference cell on a 1-axis tracking system at NREL SRRL.
- The measurements by the CMP22 and those corrected by FEDIS are compared with the reference cell data.
- FEDIS reduces the PE from 2.65% to 0.12%.

Xie, Y., M. Sengupta, A. Habte, A. Andreas, The "Fresnel Equations" for Diffuse radiation on Inclined photovoltaic Surfaces (FEDIS), Renewable & Sustainable Energy Reviews, 161, 112362.

Comparison with the other models from pvlib

FEDIS

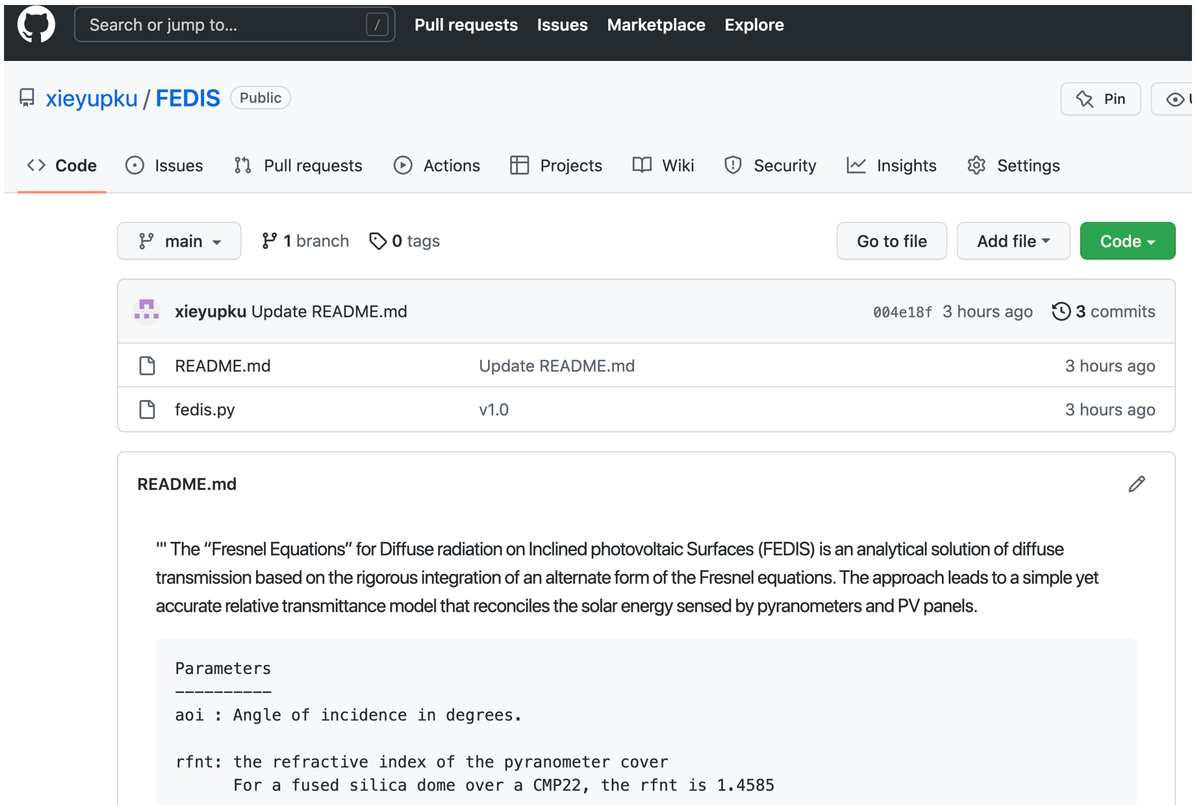
MBE = 0.58 W/m² MAE = 7.99 W/m² PE=0.12% APE=1.58%



- ✓ Better performance than the **ASHRAE model** based on all the error metrics.

- ✓ Slightly higher MBE and PE.
- ✓ Lower MAE and APE.
- ✓ **Marion model** only considers 2 typical glass models.
- ✓ FEDIS is much more flexible on the glass types.

We Want to Share the Code



- We have received a free software record from NREL (SWR-22-64).
- The FEDIS code in Python has been published in Github.
- Will submit a pull request to the pvlib.
- We'd like to work together to make it publicly available.
- More details can be found in our recent publication.

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