Scientific documentation for the WO2PV code (Weather outputs to photovoltaics)

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September 8, 2020

Foreword

WO2PV aims at estimating the electrical production at the output of a solar panel operating at the maximum power point (MPP), given meteorological conditions (essentially solar irradiance, temperature and wind). It does not account for downstream elements, as for instance the inverter performance. This documentation presents the structure of the WO2PV Python code and provides the main equations on which the code is based. It does not detail all the available options, which are commented in the code with the appropriate bibliographical references provided here. The reader is invited to refer to *Lindsay et al.* (2020) for more details and should cite this paper if using the code. As this is the first release of the code, users are invited to report any failure, to provide feedback, and may make requests on additional features that might be worth including.

1 Structure of the code

The code takes as inputs weather parameters (gathered in an *Atmosphere* object), panel characteristics (gathered in a *Panel* object, and all options prescribed in a *Namelist* object. Based on this information, the *pv_power* function (via the *pv_interface* function which handles multi-processing) is called that performs a series a calculations detailed in the following section, making use of functions gathered in the *tools* module of the *Tools* directory. This directory also contains a data *directory* containing generic data (reference spectra, spectral albedos etc.) which can be completed by the user.

1.1 *Atmosphere*

This object contains all the required geophysical information (spatio-temporal time series) that drives the production of a solar panel. First and foremost it contains the direct and diffuse irradiances on a flat surface in a number of

Atmosphere			
Attribute	**Dimension**	**Definition**	**Comment**
latitude	(column)	-	-
longitude	(column)	-	-
dates	(time)	sec. since 2000-01-01	-
swdir	(column, time, swband)	Direct irradiance	-
swdiff	(column, time, swband)	Diffuse irradiance	-
α_{dir}	(column, time, swband)	direct albedo	from weather or user
α_{diff}	(column, time, swband)	direct albedo	from weather or user
sza	(column, time)	Solar Zenith Angle	comp. from lat, lon, dates
saa	(column, time)	Solar Azimuth Angle	comp. from lat, lon, dates
sw_toa	(column, time)	Solar constant	comp. from lat, lon, dates

Table 1: Geophysical parameters needed for the WO2PV model, where ncol, nt and nbands refer to the spatial, temporal and spectral dimensions. Note that space is treated with a single dimension.

spectral bands (this can be a single one) whose limits should be provided in the *Namelist* object (section 3). Direct and diffuse surface albedos (needed to compute the contribution of reflected radiation) are either provided by the user with the same spectral resolution as the irradiance inputs, or can come from external databases (*Tools/data* direcotry). In addition, wind speed (at 10 m or at the level of the panel depending on the temperature model used) and ambient temperature should be provided. The latitude, longitude and UTC times corresponding to the geophysical data are also required. The code is designed to handle netcdf files containing all the variables mentioned above (and summarized in Table. 1), from which the *Atmosphere* object is built, but this layer can easily be skipped.

1.2 *Panel*

The code allows to simulate both fixed and tracking solar panels. Tracking panels always remain perpendicular to the Sun. A panel is characterized by its energy gap (or equivalently wavelength gap), its spectral response (which can be ideal or empirical) and a number of electrical performance information generally indicated in the product datasheet. These performance are usually provided for standard test conditions (STC), corresponding to specific atmospheric conditions and panel configuration. Note that no masking effects are accounted for in the code, whether they would come from the geophysical environment or from other panels. The geometry of the panel and solar illumination is illustrated in Fig. 1 and the attributes summarized in Table 2.

Panel		
Attribute	Definition	Comment
name	familiar name	-
type	cell technology	-
technology	panel technology	'fixed' or 'tracker'
A	panel surface (m^2)	-
Ncells	cells per panel	-
Acell	single cell surface (m^2)	-
tcell	cell temperature (K)	-
λ_{gap}	direct albedo	-
Nmodules	direct albedo	-
$P_{\mathrm{max,STC}}$	Max power (W m^{-2})	-
$V_{\mathrm{mpp,STC}}$	Max voltage per cell (V)	-
$I_{\mathrm{mpp,STC}}$	Max intensity per cell area (A m^{-2})	-
$V_{\mathrm{OC,STC}}$	Open-circuit voltage per cell (V)	-
$I_{\mathrm{SC,STC}}$	Short-circuit intensity per cell area (A m^{-2})	-
FF_{STC}	Fill factor	-
$C_{\mathrm{T,P_{max}}}$	Temperature coefficient (% K^{-1})	-
$C_{\mathrm{T,V_{OC}}}$	Temperature coefficient (% K^{-1})	-
$C_{\mathrm{T,I_{SC}}}$	Temperature coefficient (% K^{-1})	-
$T_{\mathrm{c,STC}}$	cell temperature in STC	-
NOCT	cell temperature in NOCT	
$\mathrm{ta_{NOCT}}$	air temperature in NOCT	-
$\mathrm{sw_{NOCT}}$	POA in NOCT	-
$\mathrm{ta_{STC}}$	air temperature in STC	-
$\mathrm{sw_{STC}}$	POA in STC	-
$V_{\mathrm{T,STC}}$	thermal voltage	-
R_s	series resistance	-
β	panel inclination	time-varying if 'tracker'
γ	panel azimuth	time-varying if 'tracker'
λ_{gap}	wavelength gap of semi-conductor	-
SR	spectral response at ARTDECO resolution (A W^{-1})	ideal, empirical or user supplied
$\mathrm{SR_{astm}}$	spectral response at ASTM resolution (A W^{-1})	-
α_{SR}	scaling coefficient of the spectral response	to match datasheet performance

Table 2: Panel characteristics used in the WO2PV model.

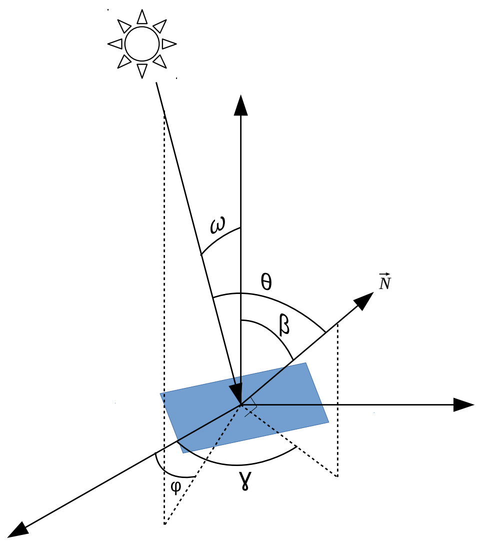

Figure 1: Geometry of the solar illumination and panel orientation. The solar zenith and azimuth angles are denoted ω and ϕ, the panel is facing direction γ and has an inclination β. The angle between the Sun direction and the normal to the plane is denoted θ.

1.3 *Namelist*

The *Namelist* object contains all information to be defined by the user (see Table 3), including panel basic description and options for the computations internal to the code.

1.4 Using the code

Once the three aforementioned objects have been defined, they are used by the *pv_power* function to compute the instantaneous PV power of a panel, or a power normalized by unit area, which is useful for computing atlases of potential production for instance. The call to *pv_power* is made through the *main* program, which can be called through command-line (syntax in this case is *python main.py forcing output option [n1] [n2]*) or by editing the file manually. The main program interfaces to *pv_power* via the *pv_interface* function that handles the loops on the column and time dimensions and also handles multi-processing if set up. Option can be *atlas* or *timeseries* depending on the type of simulations you're performing. This simply specifies on which dimension the

Namelist		
Attribute	Definition	Comment
datadir	path to data directory	-
sw_bands	list of wavelengths corresponding to irradiance inputs	should increase
method_gap	how is λ_{gap} set	-
method_POA	transposition method	-
method_OL	optical losses method	-
method_VOC	VOC computation method	-
method_FF	FF computation method	-
resolution	spectral resolution of spectral response	-
SR_method	how is the spectral response computed	-
albedo	how is surface albedo computed	user supplied or weather input
artdeco_resolution	spectral resolution of ARTDECO reference spectra	-
nthread	multi-processing if > 1	-
maxlen	time series split in maxlen segments	-

Table 3: Most important options available in the *Namelist* object, excluding the panel characteristics defined there and the quantities intrinsic to the various models used.

multi-processing is performed. The *Forcings* directory contains some examples of forcings in *netcdf* format that can be used straightforward and highlight the expected structures of the files. A Meso-NH forcing file is provided (*MNH*), to show how to handle the irradiance input with ecRad spectral resolution (in this case spectral bands have been reordered). Likewise, a small domain of AROME is provided (*atlas_AROME_subset*) to enhance the atlas capability of the code. The *Tests* directory contains time series of PV power measured at SIRTA, to be compared to those obtained from the SIRTA forcing files.

2 From sunlight to PV power

2.1 Electrical quantities

The instantaneous power P of a solar cell, assumed to work at MPP, is commonly defined as:

$$P = FF \cdot V_{\text{OC}} \cdot I_{\text{SC}}, \tag{1}$$

where FF is the fill factor, V_{OC} the open circuit voltage and I_{SC} the short-circuit intensity. The code aims at expressing these 3 contributing factors in terms of the incident irradiance and ambient conditions. I_{SC} is proportional to the useful fraction of solar power received by the cell, that is the irradiance at the cell level irradiance multiplied by the spectral response SR of the solar cell:

$$I_{\mathrm{SC}} = \left[\int\limits_{\lambda} \mathrm{SR}(\lambda) F_c(\lambda) \mathrm{d}\lambda \right] \cdot \left(1 + C_{T,I_{sc}} \left(T_c - T_{c,\mathrm{STC}}\right)\right), \tag{2}$$

where T_c is the cell temperature, STC refers to the standard tests conditions and $C_{T,I_{\mathrm{sc}}}$ is the temperature dependence of $I_{\mathrm{SC,STC}}$, which is generally provided by the manufacturer.
The spectral response (in A W^{-1}) can be either provided by the user as an ascii file with two columns (wavelength, spectral response), taken from a reference set of spectral responses for various technologies, or computed as an ideal response from the gap energy E_{gap} of the semi-conductor material making the solar cell. In this former case, a gap wavelength (λ_{gap}) should be prescribed, from which the spectral response is computed as:

$$\mathrm{SR}_{\mathrm{ideal}}(\lambda) = \begin{cases} q\dfrac{\lambda}{hc} & \text{if } \lambda < \lambda_{\mathrm{gap}} \\ 0 & \text{otherwise,} \end{cases} \tag{3}$$

where q is the elemental charge, h the Planck constant and c the speed of light in vacuum. This definition comes from the fact that the generated photocurrent (C s^{-1}) depends on the number of electron excited by solar radiation. Any photon with energy hc/λ will result in one excited electron. On the contrary, if the photon is not energetic enough it won't generate any current. A power of one W at wavelength λ corresponds to $N = \lambda/hc$ photons per second, hence Eq. 3. This ideal spectral response is multiplied by a spectrally flat scaling factor α to account for deviations from a perfect semi-conductor. This coefficient is computed from the following equality:

$$\alpha \int\limits_{\lambda} \mathrm{SR}_{\mathrm{ideal}}(\lambda) F_{c,\mathrm{ASTM}}(\lambda) \mathrm{d}\lambda = I_{\mathrm{SC,STC}}, \tag{4}$$

and $F_{c,\mathrm{ASTM}}$ is computed following all the steps detailed in the next paragraphs from the direct and diffuse ASTM spectra (themselves obtained with the radiative transfer code ARTDECO[1]).
V_{OC} is computed as:

$$V_{\mathrm{OC}} = V_t \ln\left(\frac{I_{\mathrm{SC}}}{I_0}\right), \tag{5}$$

where the thermal voltage $V_t = k_B T_c/q$ (k_B the Boltzmann constant) and I_0 is the reverse saturation current, which is computed as:

$$I_0(T_c) = C_0 T_c^3 \exp\left(-\frac{E_g}{k_B T_c}\right). \tag{6}$$

The constant C_0 can be derived from Eqs. 5 and 6 applied at $T_{c,\mathrm{STC}}$:

[1] http://www.icare.univ-lille1.fr/projects/artdeco

$$C_0 = \frac{I_{\mathrm{sc,STC}}}{T^3_{c,\mathrm{STC}}} \exp\left(\frac{E_g/q - V_{\mathrm{OC,STC}}}{V_t\left(T_{c,\mathrm{STC}}\right)}\right). \tag{7}$$

Finally, the fill factor FF is expressed as (Eq. 12 of *Green* (1982)):

$$\mathrm{FF} = \mathrm{FF0}(1 - 1.1r_s) + r_s^2/5.4, \tag{8}$$

where $r_s = R_s/(V_{\mathrm{OC}}/I_{\mathrm{SC}})$, and FF0 is computed as (Eq. 5 of Green):

$$\mathrm{FF0} = \left(v_{\mathrm{OC}} - \ln(v_{\mathrm{OC}} + 0.72)\right)/(v_{\mathrm{OC}} + 1), \tag{9}$$

where $v_{\mathrm{OC}} = V_{\mathrm{OC}}/V_t$. s_s is the series resistance which can be computed by solving Eq. (7) of Green in STC:

$$\mathrm{FF}_{\mathrm{STC}} = \mathrm{FF0}_{\mathrm{STC}}(1 - 1.1r_{s,\mathrm{STC}}) + \frac{r^2_{s,\mathrm{STC}}}{5.4}, \tag{10}$$

where $\mathrm{FF}_{\mathrm{STC}} = \dfrac{P_{\mathrm{MPP,STC}}}{V_{\mathrm{OC,STC}} I_{\mathrm{SC,STC}}}$.

Finally, the quantities to be computed are the irradiance impinging on the cell F_c and the cell temperature T_c.

2.2 Cell temperature

To compute the cell temperature, a variety of models are implemented which typically depend on the wind speed, the ambient temperature and the plane-of-array irradiance F_{POA}, that is the irradiance projected on the plane containing the panel. For instance, *King et al.* (2004) suggest that the panel temperature T_p reads:

$$T_p = F_{\mathrm{POA}} \exp(a + bU_{10\mathrm{m}}) + T_a, \tag{11}$$

and T_c is related to T_p via:

$$T_c = T_p + \frac{F_{\mathrm{POA}}}{F_{\mathrm{ref}}} \Delta T. \tag{12}$$

While the previous equations are widespread in the PV community the specificity of WO2PV is the treatment of $F_c(\lambda)$. Several steps are needed to estimate $F_c(\lambda)$. First, the direct and diffuse irradiance provided by in situ measurements or atmospheric model outputs should have their spectral resolution increased to match the sharp spectral features of the spectral response. These high spectral resolution direct and diffuse irradiances are then projected onto the panel to obtain POA irradiance, which is called transposition. Finally the irradiance at the cell level is computed accounting for optical losses through the panel the surface due to absorption and reflection. These steps are detailed and illustrated in the following.

2.3 High spectral resolution direct and diffuse irradiances

In NWP models, direct and diffuse solar irradiances are generally computed in a number of spectral bands (whose limits are denoted λ_k) so that these spectral irradiances could be output by the model. Conversely, standard radiation measurements are generally broadband. The following procedure aims at taking advantage as much as possible of the spectral information contained in the irradiance inputs of the PV model. The objective is to build a high resolution spectrum $F(\lambda)$ from the inputs F_k. To this end, a set of reference spectra for clear-sky conditions was built with the ARTDECO radiative transfer model. These spectra were obtained with a single atmosphere (US Standard 1976) but various solar zenith angles (SZA, denoted ω) to span a wide range of air masses. The main idea is that the shape of the spectrum in one band of the irradiance input is taken from the clear-sky profiles corresponding to the closest SZA (through linear interpolation), but that the integrated irradiance over the band should be conserved. This practically writes:

$$F(\lambda) = F_k \frac{F_{\mathrm{ref}}(\lambda)}{\int\limits_{\lambda_k}^{\lambda_{k+1}} F_{\mathrm{ref}}(\lambda)\mathrm{d}\lambda} \tag{13}$$

Note that this equation is applied independently for direct and diffuse irradiances, the reference spectra containing both direct and diffuse spectra. This procedure is illustrated in Fig. 2.

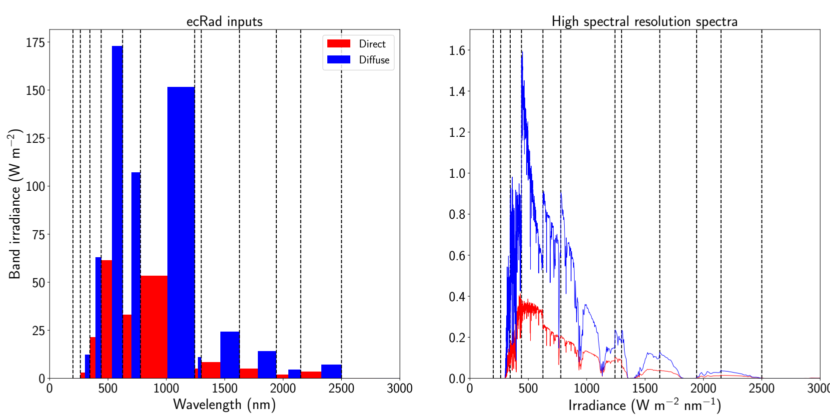

Figure 2: From left to right, increasing the spectral resolution of the narrowband inputs.

2.4 Transposition

These high spectral resolution irradiances are then projected onto the panel. The projection of the direct flux is straightforward and reads:

$$F_{\mathrm{POA}}^{\mathrm{dir}} = \begin{cases} \dfrac{F^{\mathrm{dir}}}{\cos\omega}\cos\theta & \text{if } \theta < \pi/2 \\ 0 & \text{otherwise,} \end{cases} \tag{14}$$

where θ is the angle between the Sun direction and the normal to the panel and is given by:

$$\cos\theta = \cos\omega\cos\beta + \sin\omega\sin\beta\cos(\phi - \gamma), \tag{15}$$

with ϕ the Sun azimuth angle. The diffuse irradiance and that reflected by the ground can be treated in various ways depending on the assumptions made on the distribution of diffuse radiation. Below we provide the equations for the isotropic assumption (*Badescu*, 2002) but the reader is referred to the code for more complex expressions accounting for non-uniform distribution in the sky (e.g. *Perez et al.*, 1990) .

$$F_{\mathrm{POA}}^{\mathrm{diff}} = F^{\mathrm{diff}}\frac{3 + \cos 2\beta}{4} \tag{16}$$

$$F_{\mathrm{POA}}^{\mathrm{refl}} = (\alpha^{\mathrm{dir}}F^{\mathrm{dir}} + \alpha^{\mathrm{diff}}F^{\mathrm{diff}})\frac{1 - \cos 2\beta}{4} \tag{17}$$

2.5 Optical losses

The last step takes into account the difference between irradiance on the surface of the panel, and at the cell level. Optical losses due to refraction at the surface and due to absorption within the front cover of the panel reduce by a few percent the available energy for the cell. Practically here these losses are assumed independent of the wavelength, so that the spectral POA irradiance is simply scaled by the following coefficient:

$$C = \begin{cases} 1 - \dfrac{1}{2}\left(\dfrac{\tan^2(\theta - \theta_r)}{\tan^2(\theta + \theta_r))} + \dfrac{\sin^2(\theta - \theta_r)}{\sin^2(\theta + \theta_r)}\right) & \text{if } \theta > 0 \\ 1 - \left(\dfrac{1 - n_0/n_1}{1 + n_0/n_1}\right)^2 & \text{otherwise} \end{cases} \tag{18}$$

where θ_r is the refraction angle corresponding to the incident angle θ such that:

$$n_0 \sin\theta = n_1 \sin\theta_r, \tag{19}$$

n_0 the refractive index of air, and n_1 that of the front cover of the panel.
This holds when absorption is neglected, otherwise another scaling of the form $\exp(-kL/\cos\theta_r)$ has to be accounted for, L being the thickness of the cover front and k its absorption coefficient.

Conclusion

This code was developed to optimally use the information from atmospheric models in order to estimate instantaneous PV power at the cell/panel level. It is meant to be versatile and can be upgraded to any practical need that may appear useful. All the blocks of the code can be individually improved and extended. Likewise, more refined reference spectra could be built with varying cloud optical depth for instance to even better account for the subtle shape of irradiance spectra. Users are more than welcome to report their problems to the authors and to make suggestions for improvement.

References

Badescu, V. (2002), 3d isotropic approximation for solar diffuse irradiance on tilted surfaces, *Renewable Energy*, *26*(2), 221–233.

Brandemuehl, M., and W. Beckman (1980), Transmission of diffuse radiation through cpc and flat plate collector glazings, *Solar Energy*, *24*, 511–513.

De Soto, W., S. A. Klein, and W. A. Beckman (2006), Improvement and validation of a model for photovoltaic array performance, *Solar energy*, *80*(1), 78–88.

Green, M. A. (1982), Accuracy of analytical expressions for solar cell fill factors, *Solar Cells*, *7*(3), 337–340.

Kasten, F., and A. T. Young (1989), Revised optical air mass tables and approximation formula, *Applied optics*, *28*(22), 4735–4738.

King, D. L., J. A. Kratochvil, and W. E. Boyson (2004), *Photovoltaic array performance model*, United States. Department of Energy.

Klucher, T. M. (1979), Evaluation of models to predict insolation on tilted surfaces, *Solar energy*, *23*(2), 111–114.

Lindsay, N., Q. Libois, J. Badosa, A. Migan-Dubois, and V. Bourdin (2020), Errors in pv power modelling due to the lack of spectral and angular details of solar irradiance inputs, *Solar Energy*, *197*, 266–278.

Loutzenhiser, P., H. Manz, C. Felsmann, P. Strachan, T. Frank, and G. Maxwell (2007), Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation, *Solar Energy*, *81*(2), 254–267.

Martin, N., and J. Ruiz (2001), Calculation of the pv modules angular losses under field conditions by means of an analytical model, *Solar Energy Materials and Solar Cells*, *70*(1), 25–38.

Perez, R., P. Ineichen, R. Seals, J. Michalsky, and R. Stewart (1990), Modeling daylight availability and irradiance components from direct and global irradiance, *Solar energy*, *44*(5), 271–289.

Skoplaki, E., A. Boudouvis, and J. Palyvos (2008), A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting, *Solar energy materials and solar cells*, *92*(11), 1393–1402.