Evaluation of spectral effect on module performance using modeled average wavelength - preliminary results

Giorgio Belluardo
Introduction

1) How to evaluate spectral effects on PV?

- air mass
- useful fraction
- spectral mismatch correction
- average photon energy
- average wavelength
- ...

Solar Spectrum Characterization Index
Introduction

2) Solar spectrum

modeled spectra based on satellite retrieved cloud information
Spectral modelling: SPECMAGIC

Institute for Applied Remote Sensing (J. Wagner)

- Based on Lookup Tables LUTs (pre-computed RTM results)
- Transmittance is extracted from the LUTs by interpolation

Input parameters:
- aerosol optical depth (from monthly climatologies)
- surface albedo (using land use maps)
- single scattering albedo (fixed value)
- total column ozone (fixed value)
- water vapor column (from monthly climatologies)
- sun - earth distance
- solar zenith and azimuth angle
Spectral modelling: SPECMAGIC

Institute for Applied Remote Sensing (J. Wagner)

- Extraterrestrial incoming solar flux density
- Calculated transmittance
- Direct and global clear sky spectral irradiance
- Cloud index (MeteoSwiss)
- Shading diagram
- Height correction
- Isotropic distr. of diffuse rad.
- Actual direct and global spectral irradiance on different planes
- Fixed value surface albedo
- Actual direct and global spectral irradiance

Giorgio Belluardo
Validation of simulated data

Meteo station at Bolzano Dolomiti Airport (ABD)

- 3 x pyranometers
- 6 x ref. cells (c-Si and KG5-filtered)
- pyrheliometer
- albedometer
- 45 x Pt100s
- Ambient temperature sensor
- ultrasonic anemometer
- Sunphotometer

Sensors: 1 minute acquisition frequency
Validation of simulated data

Experimental part - 24 different technologies & manufacturers
Validation of simulated data

<table>
<thead>
<tr>
<th>Technology</th>
<th>Module</th>
<th>Wp</th>
<th>Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>m-Si</td>
<td>Solarwatt M230-96 GET AK</td>
<td>220</td>
<td>Germany</td>
</tr>
<tr>
<td>m-Si</td>
<td>Solarwatt 32 GEG opaque LK</td>
<td>124</td>
<td>Germany</td>
</tr>
<tr>
<td>m-Si</td>
<td>Solarwatt 36 GEG LK</td>
<td>140</td>
<td>Germany</td>
</tr>
<tr>
<td>BC m-Si</td>
<td>SunPower WHT 300</td>
<td>300</td>
<td>USA</td>
</tr>
<tr>
<td>p-Si</td>
<td>AlfaSolar PYR60</td>
<td>222</td>
<td>Germany</td>
</tr>
<tr>
<td>p-Si</td>
<td>Solarworld SW225-POLY</td>
<td>225</td>
<td>Germany</td>
</tr>
<tr>
<td>p-Si</td>
<td>Trina TSM-230-PC05</td>
<td>230</td>
<td>China</td>
</tr>
<tr>
<td>p-Si</td>
<td>REC 225-PE</td>
<td>225</td>
<td>Norway</td>
</tr>
<tr>
<td>p-Si</td>
<td>Kyocera KD210GH-2PU</td>
<td>210</td>
<td>Japan</td>
</tr>
<tr>
<td>p-Si</td>
<td>Canadian Solar CS6P</td>
<td>230</td>
<td>Canada (China)</td>
</tr>
<tr>
<td>p-Si</td>
<td>Day4Energy 48MC-S</td>
<td>175</td>
<td>Canada</td>
</tr>
<tr>
<td>HIT</td>
<td>Sanyo HIP-215NKHE5</td>
<td>215</td>
<td>Japan</td>
</tr>
<tr>
<td>Ribbon</td>
<td>Evergreen ES-A-205-fa3</td>
<td>205</td>
<td>USA</td>
</tr>
<tr>
<td>Thin-film a-Si</td>
<td>SchottSolar Asi Thru 30SG</td>
<td>27</td>
<td>Germany</td>
</tr>
<tr>
<td>Thin-film a-Si</td>
<td>Parabel UNIFLAT</td>
<td>272</td>
<td>USA</td>
</tr>
<tr>
<td>Thin-film a-Si</td>
<td>EPV Solar 50</td>
<td>50</td>
<td>USA</td>
</tr>
<tr>
<td>a-Si</td>
<td>Inventux X115</td>
<td>115</td>
<td>Germany</td>
</tr>
<tr>
<td>a-Si semi</td>
<td>SchottSolar Asi TM 100+</td>
<td>100</td>
<td>Germany</td>
</tr>
<tr>
<td>a-Si &amp; μ-cryst.</td>
<td>Sharp NA-F135 G5</td>
<td>135</td>
<td>Japan</td>
</tr>
<tr>
<td>μ-crystalline</td>
<td>Bosch Solar Module μm-Si +</td>
<td>110</td>
<td>Germany</td>
</tr>
<tr>
<td>CIGS</td>
<td>Solyndra SL-001-182</td>
<td>182</td>
<td>USA</td>
</tr>
<tr>
<td>CIGS</td>
<td>Würth WSG0036E80</td>
<td>80</td>
<td>Germany</td>
</tr>
<tr>
<td>CIS</td>
<td>Sulfurcell SCG55-HV-F</td>
<td>55</td>
<td>Germany</td>
</tr>
<tr>
<td>CdTe</td>
<td>First Solar FS 277</td>
<td>77.5</td>
<td>USA</td>
</tr>
</tbody>
</table>
Validation of simulated data - integral values

Global Horizontal Irradiance: 15-min data

2011 – Global horizontal irradiance: measured vs simulated

G measured / W/m²

G simulated / W/m²

unfiltered

clear sky
Validation of simulated data - integral values

Global Tilted (30°) Irradiance: 15-min data

2011 – Global tilted irradiance: measured vs simulated

unfiltered

clear sky
Average wavelength

Wagner J.E., S. Hasel, W. Laube, P. Weihs, M. Rennhofer, R. Leidl, K. Berger, D.J. Baumgartner, Investigation of spectral variability under outdoor conditions on the energy yield of a-Si, c-Si and CdTe Modules, 26th PVSEC (2011)
Average wavelength

01.03.2012

time

average wavelength / nm

Horizontal plane
Average wavelength

Global irradiance
PV module performance vs solar spectrum

1) Data filtering:
   - Operational conditions ($P_{dc}>0$, $G>0$)
   - Clear sky conditions (global/diffuse < 0.25)
   - AOI < 50°
   - $PR \pm \sigma_{PR}$ (68% values included)

2) Temperature correction (25° C)

3) Normalization of efficiency (to $\eta_{AM=1.5}$)
PV module performance vs solar spectrum

Polycrystalline Silicon

normalized efficiency pc–Si – 2011

f(x) = 0.00065x + 0.55
PV module performance vs solar spectrum

**Micromorph**
PV module performance vs solar spectrum

normalized efficiency CIGS – 2011

f(x) = −0.00218x + 2.50

average wavelength / nm

normalized efficiency / −

CIGS

Giorgio Belluardo
PV module performance vs solar spectrum

Cadmium Telluride

normalized efficiency CdTe – 2011

\[ f(x) = -0.00133x + 1.92 \]
PV module performance vs solar spectrum

Amorphous Silicon
PV module performance vs solar spectrum

<table>
<thead>
<tr>
<th>Technology</th>
<th>Efficiency variation (%/nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pc-Si</td>
<td>+0.07</td>
</tr>
<tr>
<td>micromorph</td>
<td>-0.25</td>
</tr>
<tr>
<td>CIGS</td>
<td>-0.22</td>
</tr>
<tr>
<td>CdTe</td>
<td>-0.13</td>
</tr>
<tr>
<td>a-Si</td>
<td>-0.51*</td>
</tr>
</tbody>
</table>

*Staebler-Wronski effect included
Limits and outlook

- Integral values: normal plane
- Other spectral simulation tools (SMARTS?)
- Other indices (APE)
- Spectral comparison: volunteers?
Thank you for the attention

Giorgio Belluardo

giorgio.belluardo@eurac.edu