Spectral Albedo in Bifacial Photovoltaic Modeling: What can be Learned from Onsite Measurements?

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Outline

1) Background
2) Methods
3) Results
Albedo Overview

• Albedo of a surface is defined as the percentage of incident sunlight that it reflects

\[ \alpha = \frac{RHI}{GHI} \]

• Upwelling (RHI) / downwelling (GHI) shortwave radiation

• Depends on:
  – Sky diffuse fraction, solar angle, surface: mineral content, roughness, moisture, slope, and if shaded/unshaded.

• Historically, measured [mainly] by pyranometers
  – But BiFi applications call for spectral albedo information
A basic understanding of albedo is sufficient for monofacial PV modelling

\[ G_{\text{Reflected}} = \alpha \cdot GHI \cdot \left( \frac{1 - \cos \beta}{2} \right) \]

\[ \beta = 30^\circ \]

Example:
GHI = 725 W/m²
DrHI = 580 W/m²
SolZenith = 45°
Albedo (\(\alpha\)) = 0.2

\[ \frac{G_{\text{Reflected}}}{G_{\text{POA}}} = 1\% \]
A basic understanding of albedo is sufficient for monofacial PV modelling

\[ G_{\text{Reflected}} = \alpha \cdot GHI \cdot \left(1 - \cos \beta \right) \]

\[ \beta = 30^\circ \]

\[ \frac{G_{\text{Reflected}}}{G_{POA}} \leq 3\% \]

*for most conditions where \( \beta < 45^\circ \)*
Ground reflected light contributes significantly to bifacial PV energy production

- Typically, 5 to 10% of total irradiance comes from the back
- The backside irradiance consists primarily of ground reflected light
Ground reflected light contributes significantly to bifacial PV energy production

- Typically, 5 to 10% of total irradiance comes from the back
  - Encompasses very low to very high frontside POA irradiances
  - The backside irradiance consists primarily of ground reflected light

Fixed tilt bifacial system over grass at DTU
Spectral Albedo and Bifacial PV

- Albedo has a pronounced spectral dependence
  - Not highly structured like sun spectrum
  - Can vary considerably with time and season

Example Spectral Albedo Curves from Database
Source: SMARTS 2.9.5 (ASTER)
Spectral Albedo and Bifacial PV

- PV devices are spectrally selective
  - Backside QE is not the same as frontside (possible exceptions: SHJ, IBC)
  - Indoor rating (IEC 60904-1-2) is under AM1.5G, but in the field…
  - Backside POA spectral distribution deviates heavily, even when frontside exposed to AM ≈ 1.5G

Example Spectral Albedo Curves from Database
Source: SMARTS 2.9.5 (ASTER Library)

SR of Select Bifacial Cells Measured at DTU
Considerations for continuous onsite spectral measurements using spectroradiometers

• **Cost**
  – Difficult for industry to justify when annual spectral impact on Silicon (frontside) is small (< 2%).
  – A high-resolution spectrometer is overkill for albedo monitoring
    -> but can it e.g., help design a low-cost narrow band filter set for bifacial PV applications?

• **Sensitivity of instruments**
  – Small misalignments in mirrors, fibers etc have strong effect on measurements
  – Annual calibration recommended (cost)

• **Uncertainty and lack of complete range with single detector**
  – High uncertainty in UV and detector edges
  – Coverage in the full range where Si (e.g., PERC) is active only possible with two detectors (more cost)

• **Data handling**
  – A spectrometer with 2048 pixels provides 2048 values per measurement
  – Can accumulate into hundreds of millions of records every year!
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Calibration

- Performed before measurement campaign
- NIST traceable FEL-type lamp at 50cm
- Done in-house every 1 – 2 years
  - 1 year preferable
- We have participated in ISRC, but…
  - We find that measurements of the broadband lamp are better at detecting wavelength shifts and kinks.
Calibration

• We have participated in ISRC, but…
  – We find that measurements of the FEL lamp are better at detecting wavelength shifts and kinks.

• Example: DTU’s measurement artifacts @675nm were not detectable at ISRC ‘18
  – ISRC alone not sufficient to maintain quality spectral measurements

Galleano R. et al. EUPVSEC20192019-5CV.3.3
Measurement set up

Beam Spectrum DNI(\(\lambda\))

Diffuse Horizontal Spectrum DfHI(\(\lambda\)):

\[
DfHI(\lambda) = GHI(\lambda) - DNI(\lambda) \cdot \cos \theta_Z
\]

Three EKO MS711s measured every 5 minutes
Measurements: 300nm – 1100nm
SMARTS simulations: 1050nm – 1200 nm
Bifacial PV modeling

- Opensource Python library `pvfactors` [1] – Feature-rich and independently validated

- The DfHI(λ), DNI(λ), and α(λ) data are passed to `pvfactors` the same way broadband data would be, except…

- Our model loops through each wavelength λ from 300 to 1200 nm (in steps of 1 nm)

- With this approach we calculate spectral GPOA(λ) for front and backside of:
  - Fixed tilt (25°) and single axis trackers
    • Spectral non-uniformity (segments)

Spectral Mismatch

• *Many* options for analyzing the dataset:
  • SR weighted albedo, BifiGain, spectral bins etc.
  • …But we’ll keep it at SMM for now.

• SMM calculated for the front and back side
  • Cell types: p-PERC, n-PERT and IBC
  • Bifaciality factors: 0.76, 0.91 and 0.99

• Recall that:
  • SMM > 1 implies $I_{SC}$ **gains** relative to AM1.5G
  • SMM < 1 implies $I_{SC}$ **losses** relative to AM1.5G

\[
SMM_j = \frac{E_{ref} \int E_{meas,j}(\lambda)S_{DUT,j}(\lambda) d\lambda}{E_{meas,j} \int E_{ref}(\lambda)S_{DUT,j}(\lambda) d\lambda}
\]

- $E_{ref}$ = Reference spectrum (IEC 60904-3)
- $E_{meas}$ = The calculated GPOA spectrum
- $S_{DUT}$ = Spectral response
- $j$ = denotes either front or backside
Measurement Timeline

- **Feb – May 2020**: Healthy grass
- **Jul – Sep 2020**: Dry grass
- **Sep – Dec 2020**: Gravel (>95% coverage)
- **Jan – Feb 2021**: Periodic snow
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Spectral Mismatch (SMM) Summary

- View factors (ground→PV) change dynamically in tracker case
  - Therefore, the range of SMM is higher than static tilt
  - The magnitude of SMM on backside is significantly higher than frontside
Results: Healthy Grass

- Highest spectral albedo at low sun angles
  - Same behavior as expected for broadband albedo
- SMARTs spectral albedo files are measured at SZA ≈ 53°
  - Relative shape of measurements agrees well to SMARTs
Results: Healthy Grass

- Measurements and SMARTS give good SMM agreement in this case
Results: Dry Grass

- Our measured ‘dry grass’ still contains some chlorophyl
- Likely the source of discrepancy w.r.t. SMARTs in VIS range
Results: Dry Grass

• Measurements can help capture seasonal spectral shifts in albedo
Results: Gravel

- Good agreement to SMARTS except around 700 – 800 nm
- Likely due to different mineral content in our gravel vs. SMARTS
Results: Gravel

• Assumptions for spectral albedo can misrepresent spectral effects.
Results: Snow

- Spectral albedo nearly constant on a 100% diffuse day
  - Same behavior as expected for broadband albedo
- Some measurement ‘kinks’ apparent in this case
Results: Snow

- Somewhat extreme case compared where spectral grass albedo is used as the SMARTS assumption, instead of snow albedo.
SMM Nonuniformity in Backside POA

• Simulations of tracker system w/ p-PERC modules above healthy grass.
  – Segment 1 is the West module edge
  – Segment 20 is the East module edge

• View factors (Sky→PV, Ground→PV) varying to create a ‘spectral gradient’, but only at steep tilt angles
SMM Nonuniformity in Backside POA

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![Diagram showing East and West module edges with varying SMM Backside values over a 24-hour period.](image-url)
SMM Nonuniformity in Backside POA

• Simulations of static tilt system w/ p-PERC modules above healthy grass.
  – Segment 1 is the North module edge
  – Segment 20 is the South module edge

• View factors (Sky→PV, Ground→PV) varying create a ‘spectral gradient’

![Diagram of North and South SMM Backside with Height and Length measurements, and a graph showing Tilt Angle over Hour with segments 1 to 20 marked.](image-url)
Summary

• Albedo is highly spectrally dynamic, and GPOA rear spectrum deviates strongly from AM1.5G

• Onsite spectral albedo measurements are advisable in some capacity at bifacial PV sites
  – E.g., Si sensors w/ narrow band filters, or at very least, si-photodiode albedometers

• Use of single spectral albedo curve (e.g., SMARTS database) can lead to rear irradiance deviations on the order of 5% (dry grass) to 20% (snow).

• TODO:
  – Down sample the spectral resolution and investigate impact on results
  – Perform continuous front and back POA spectral measurements

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Thank you!