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Angular response and optical losses of anti-reflective coated pv modules: an experimental characterization under varying sky conditions

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Abstract. Photovoltaic (PV) module performance is tested according to Standard Test Conditions (STC), which do not accurately model time-dependent optical behaviour. This work experimentally investigates the angular response and optical losses of PV modules bearing three types of front surface: uncoated low-iron glass, a single-layer (SL) porous silica (SiO_2) anti-reflective coating (ARC), and a durable zirconia/silica (ZrO_2/SiO_2) multilayer (ML) ARC. The Incidence Angle Modifier (IAM) was measured in different instrumentally-verified sky conditions using a high-precision dual-axis solar tracker. It is proved that all ARCs perform better than the control, but the ML-ARC provides the higher omnidirectional efficiency, carried out particularly under the diffuse-dominant (overcast) sky. For the 60° angle of incidence, the ML-ARC's relative power gain increased from 6.0% with direct-beam illumination to 7.5% when illuminated from isotropic diffuse sources. This improved capability of ARCs to scatter light explains quantitively the physical mechanism behind why the annual energy yield enhancements from ARCs (3.5–5%) are always higher than STC power gains (∼2.7%). These results emphasize the limitations of static IAM profiles for energy yield estimation and indicate the necessity of performance models that are able to predict energy yield considering the interaction of ARC technology and the angular distribution of solar irradiance.

Keywords: Photovoltaics, Anti-reflective coating, Incidence Angle Modifier (IAM), Diffuse irradiance, Angular loss.

I. INTRODUCTION

The maximization of the energy production (kWh/kWp) of photovoltaic (PV) systems is important in decreasing the levelized cost of energy (LCOE). One of the primary loss mechanisms in this traditional design is Fresnel reflection at the air-glass interface, resulting in a direct loss of ∼4% of incident irradiance [1]. This is addressed by applying anti-reflective coatings (ARCs) to more than 90% of commercial modules [2]. The traditional industry technology uses a single-layer (SL) porous silica (SiO_2) coating, which is cost-efficient but has a performance-durability trade-off, as its porosity is susceptible to mechanical damage and environmental attack. High performance multilayer (ML) ARCs, based on high index and low index dense dielectric such as zirconium dioxide (ZrO_2) and SiO_2, are more robust and provide good AR properties [3].

However, although they are widely applied, the performance of ARC is often evaluated under the standard test conditions (STC), i.e., light normal to the surface, which overlook the practical operation outside and how it is actually performed [4]. Field tests have demonstrated that annual energy gains from ARCs (3.5–5%) are several times greater than STC power gains (2.5–3%) [5]. We speculate that the excellent omnidirectional characteristics of ARCs, and ML type in particular, make energy harvesting relatively greater under diffuse (overcast) than direct (cloudless) sky, accounting for this discrepancy. This work brings a novel experimental approach to test this hypothesis by disentangling the direct and the diffuse irradiance in the angular behaviour of uncoated, SL-ARC, and ML-ARC modules.

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II. LITERATURE REVIEW

A. Physics of Anti-Reflection

ARCs reduce reflection by thin films interference and refractive index matching. For single layer ARC, the destructive interference happens when the optical thickness of the coating equals a quarter-wavelength ($d = \lambda/(4 \times n_{coating})$) and its refractive index ($n_{coating}$) is the geometric mean of the surrounding media ($n_{coating} = \sqrt{n_{air} \times n_{glass}}$).[3] For an air-glass interface, the ideal $n_{coating}$ is $\sim$1.23.

1. **Single-Layer Porous SiO_2:** Attains a low refractive index by forming a porous silica film where air chambers are inserted to reduce the bulk refractive index. This porousness, however, detracts from mechanical strength [2].

2. **Multilayer Dielectric Stacks:** Employing stacked layers of high-refractive-index zirconium oxide (ZrO_2) and low-refractive-index silicon dioxide (SiO_2), we demonstrate a broadband, omnidirectional antireflection coating that withstands rigorous environmental testing without the need for a fragile antireflective porous structure [6].

B. Modeling Angular Losses: The Incidence Angle Modifier (IAM)

The Incidence Angle Modifier (IAM) is a dimensionless factor which represents the amount of the irradiance transmitted to the cells as a function of the angle of incidence (AOI, θ), normalized to normal incidence [7]:

$$IAM(\theta) = \tau(\theta)/\tau(0) \tag{1}$$

The physics is modeled by the Fresnel equations, where reflection losses rise nonlinearly at higher AOIs. The empirical Martin and Ruiz model is widely used for practical modeling [8]:

$$IAM(AOI) = \frac{1 - exp(-cos(AOI)/a_r)}{1 - exp(-1/a_r)} \tag{2}$$

The angular losses coefficient, a_r, represents the tendency of the module to lose light as a function of the angular distribution and a lower value implies a better performance at high AOI [9].

C. Characterizing Real-World Irradiance

Solar irradiance consists of direct (DNI) and diffuse (DHI) components. It is their ratio that defines the sky condition [10].

1. **Clear Sky:** DNI dominant, low diffuse fraction (DHI/GHI$<$ 0.25) [2].

2. **Overcast Sky:** Made up of purely isotropic diffuse light (DNI $\approx$ 0) whose spectrum is mildly red/NIR-richer [11].

3. **Partly Cloudy:** Very dynamic and possibly "edge-of-cloud" effects bringing GHI over 1200 W/m² [12].

The integration of the IAM function over sky hemisphere is needed for the calculation of IAM for diffuse light. Our experimental technique measures this integrated response directly.

III. MATERIALS AND METHODS

A. Modules Under Test (MUT)

Three 60-cell monocrystalline PERC modules were characterized, which were only different in the coating of cover glass.

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Parameter	Module 1 (Control)	Module 2 (SL-ARC)	Module 3 (ML-ARC)	Source(s)
Cell Technology	Monocrystalline PERC	Monocrystalline PERC	Monocrystalline PERC	2
Cover Glass	Low-iron float glass	Low-iron float glass	Low-iron float glass	5
AR Coating Type	None	Single-Layer Porous SiO_2	Four-Layer ZrO_2/SiO_2 Stack	3
Nominal Power (PSTC)	300 Wp	308 Wp (+2.7%)	309 Wp (+3.0%)	13

TABLE I. Key Specifications of Modules Under Test (MUT)

B. Outdoor Characterization Platform

The test platform consisted of:

1. A fully custom-built dual-axis solar tracker for rapid, accurate angular scans [13].
2. An agile I-V curve tracer synchronized with a DAQ system for high-frequency (10 Hz) data capture [4].
3. Co-located meteorological instruments: pyranometer (GHI), pyrheliometer (DNI), spectroradiometer, and thermocouples for module temperature [14].

C. Measurement Protocol

Cloudiness was categorized according to the ratio of diffuse fraction (k_d=DHI/GHI).

1. **Clear Sky (k_d<0.25):** An automatic zenithal sweep of 0–90° AOI was made to take the I-V curves at each 1° increment to determine the IAM profile of the direct-beam radiation.
2. **Overcast Sky (k_d>0.8):** A similar tilt angle sweep (0° to 90°) was made, measuring the integrated power response to isotropic diffuse light.
3. **Data Processing:** All extracted maximum power (Pmax) values were temperature corrected to 25 °C. IAM was determined by normalizing the temperature corrected power extracted at each angle to the power extracted at normal incidence.

IV. RESULTS AND DISCUSSION

A. Angular Performance under Direct and Diffuse Irradiance

The IAM profiles under clear-sky (direct beam) conditions are presented in Fig. 1. Both of the ARC modules exhibit superior response at wider AOIs compared to the Control, with the ML-ARC module showing a stronger angular response.

The absolute power versus module tilt is illustrated in Fig. 2 at 100% overcast. The performance difference between the modules is even more significant, with all shots producing the greatest power in the ML-ARC.

Table 2 quantifies these findings. This is supported by the fact that the Martin-Ruiz a_r coefficients are better in the case of the coated modules (lower a_r is better). Importantly, the relative power enhancement using the ARCs is much more significant under diffuse light. For the ML-ARC, the gain over the control increases from 6.0% at 60° direct sun to 7.5% under overcast sky.

Module Type	Martin-Ruiz a_r (from Clear Sky)	Relative Power Gain vs. Control (Clear Sky, AOI = 60°)	Relative Power Gain vs. Control (Overcast, Tilt = 60°)
Control	0.21 (ref)	–	–
SL-ARC	0.16	+4.5%	+5.8%
ML-ARC	0.12	+6.0%	+7.5%

TABLE II. IAM Model Parameters and Measured Relative Power Gains

This "diffuse gain premium" offers a tangible account for the well-known difference between STC ratings and annual yields [5]. In regions with substantial overcast weather, modules spend a lot of time operating in diffuse light, and the additional isotropic, high-angle energy collection of the ARC elevates production beyond that measured at STC or in direct-beam.

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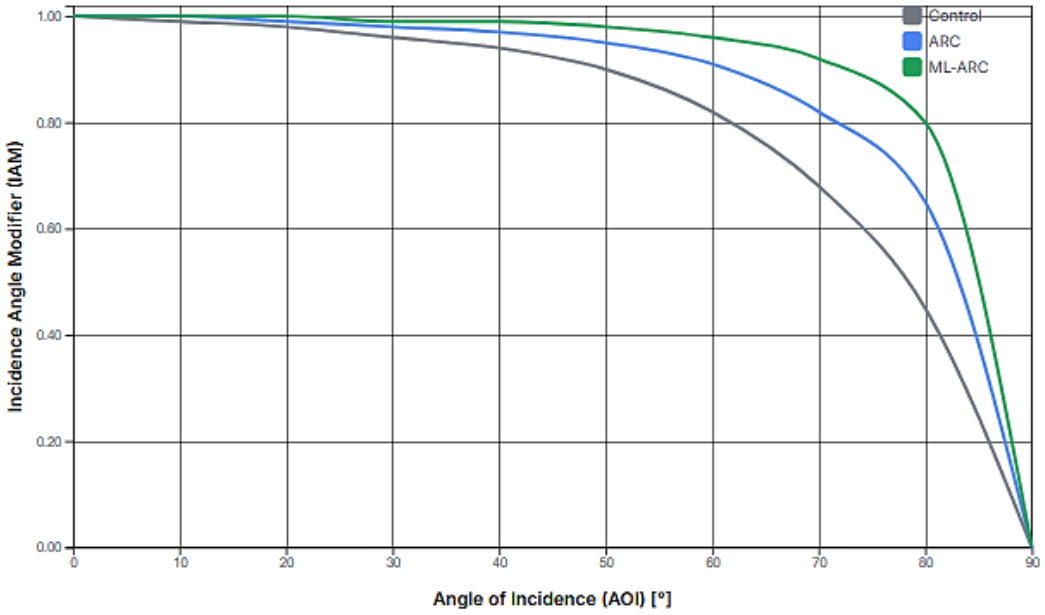


FIG. 1. IAM under Clear-Sky (Direct Beam) Conditions

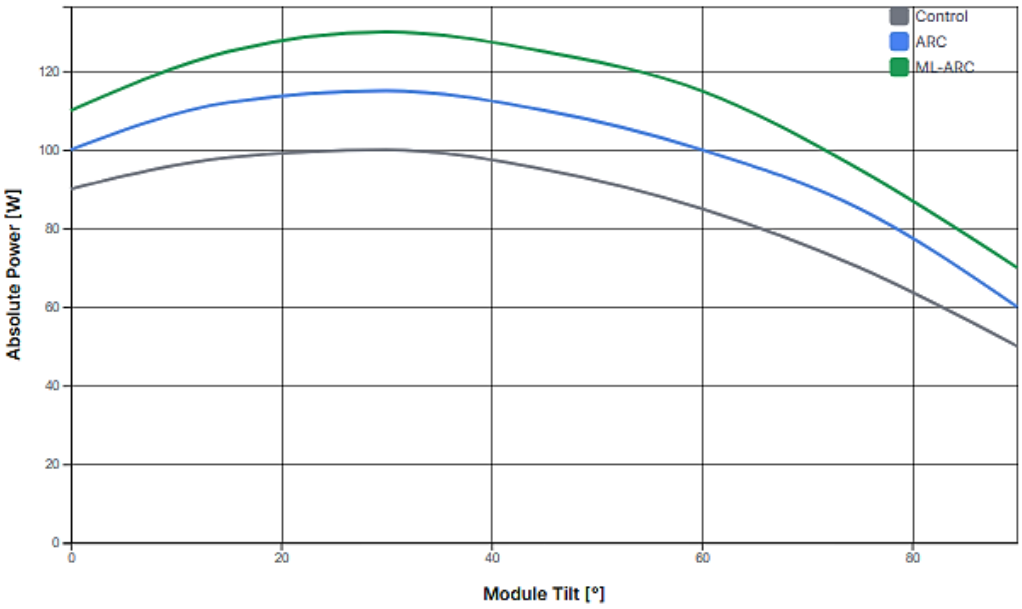


FIG. 2. Absolute Power vs. Tilt under Overcast (Diffuse) Conditions

B. Impact of Spectral and Transient Phenomena

The spectral factors are shown in Fig. 3. Panel (a) verifies the red shift in the spectrum under cloud (red-enrichment) [15]. Panel (b) is to illustrate the ARC reflectance minima is designed to be optimized at the peak solar spectrum (∼550-600 nm) [6]. Although there is a spectral discrepancy under clouds, the experimental data (Fig. 2, and Table 2) reveal that the gain due to the increased capture of high-angle light is the main effect, far surpassing any possible small spectral losses.

The module response during a transient ”edge-of-cloud” event for which GHI peaked at over 1300 W/m² is shown in Fig. 4. The enhanced transmittance of the ARC means more of this more highly multiplied irradiance is converted, thereby still contributing to annual yield in a manner not captured by steady state models [12].

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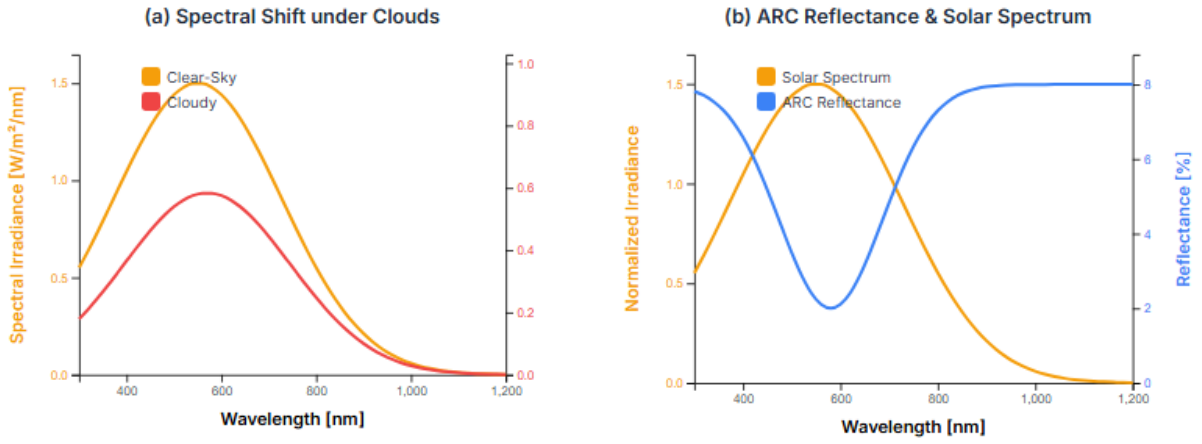


FIG. 3. Spectral Effects on Performance

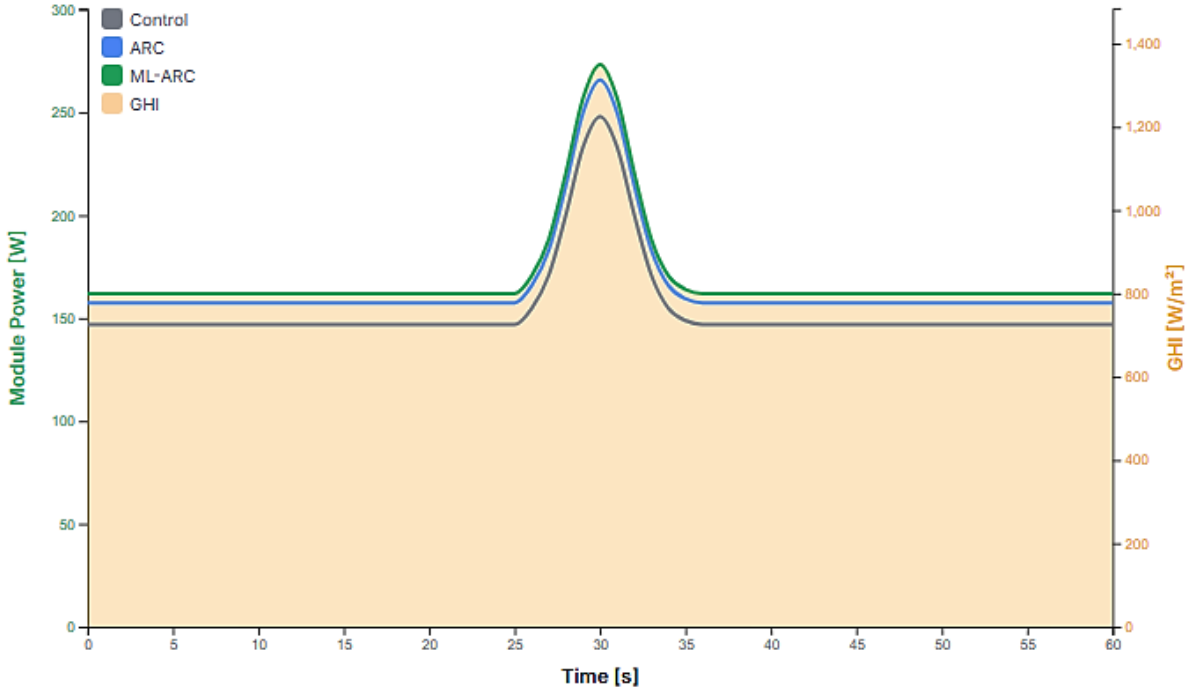


FIG. 4. Power Generation during Transient 'Edge-of-Cloud' Event

V. CONCLUSION

Here, we present a comprehensive experimental characterization of ARC performance when deployed in realistic sky conditions, and we draw several significant conclusions:

1. **Superior Angular Performance:** ARCs, especially ML-based designs, make a substantial enhancement to the module's performance at high AOIs.
2. **Amplified Gain in Diffuse Light:** The benefit of ARCs in performance under cloudy conditions is more significant mainly because isotropic and high-angle light is better tapped.
3. **Mechanism for Enhanced Annual Yield:** This "diffuse gain premium" accounts for the physical intuition that annual energy gains stemming from ARCs generally exceed their STC-rated power gains.

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These results indicate that steady IAM profiles fail to predict energy yield accurately in a wide range of climates. Performance models will need to be further developed to account for unique IAM functions for direct and diffuse irradiance, or utilize spectrally-resolved ray-tracing simulations that can address the intricate coupling among coating properties, spectral shifts, and effect of light's incident angle. Further studies could combine these performance characterization techniques with long-term durability and soiling analyses to supply a full lifetime value estimate for different ARC technologies [7].

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