Soiling Spectral and Module Temperature Effects: Comparisons of Competing Operating Parameters for Four Commercial PV Module Technologies

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Abstract: The choice of a particular PV technology for best performance is sometimes based upon a single factor or single operating condition. However, many parameters have functionalities that oppose each under actual operating conditions. In this paper, the comparisons of different PV module technologies under moderate environmental conditions (Tropical Climate Zone, Belo Horizonte, Brazil) are explored based upon the two competing parameters of soiling-layer spectral effects and panel operating temperature. Specifically, low-bandgap PV technologies (e.g., Si or Cu(In,Ga)(SSe)2) are reported to have performances less affected by the absorption of incoming sunlight than higher-bandgap absorbers (e.g., a-Si:H or CdTe). However, the opposite is true for operating temperatures, with higher bandgaps having advantages under higher-temperature operating conditions. We present a simple comparative soiling-temperature model with experimental collaborative data to address the following question: What is the controlling parameter of the combination of soiling spectral effects and temperature on lower- and higher-bandgap module technologies? Temperature coefficients are measured for groups of modules for the four technologies having bandgaps ranging from 1.1 to 1.7 eV. Additional optical absorption for the soiling layers in the range of 300 nm to ~600 nm is confirmed by transmission measurements. The data from our soiling monitoring stations indicate that these potential spectral effects are based on consistent differences in soiling ratios and soiling rates. Some differences between the model predications and experimental observations are discussed. This paper reports temperature and soiling regions of “best-of-class” performances for these four commercial PV technologies in this climate region based upon the two competing parameters.

Keywords: photovoltaics; soiling; spectral effects; temperature effects; competing operating parameters; technology comparisons

1. Introduction

The exponential growth of PV production and expanding markets have led to 2022 being the year in which the mark of 1-TW cumulative installations has been reached [1–5]. The multi-decade performance, durability, and reliability of these solar systems are product priorities to ensure continued PV growth, technology acceptance, and consumer confidence. Although some degradation mechanisms are irreversible, the loss of electricity through climate conditions is one aspect that can be mitigated. Soiling, the sedimentation of particulate matter on the exposed surfaces of solar collectors, is now an established area of photovoltaics (PV)
concern and growing research investment [6–17]. The condition of this “surface of first interaction” for the incident photons is critical because this soiling layer can reduce the power output significantly—by levels that can severely limit the financial payback from the solar plant or require significant investments in maintenance [9,18–23]. The severity of soiling conditions is highly location dependent, with power losses ranging from <1–5%/month in moderate situations to 15–30%/month in severe soiling environments [8,12,23–27]. A loss of 5% in the cumulative power delivered is equivalent to the 2020 PV power produced by modules installed in the rapidly growing markets in India and South Korea combined [1,4,5].

Due to the range of inherent electro-optical absorber properties, various PV technologies can be affected differently operating under the same climate conditions. This current study is motivated by the experiences of some complex concepts that are encountered in electro-optical materials that have properties that are contradictory. For example, a transparent conductor requires high optical transparency, inferring a large bandgap. However, the conductivity constraint necessitates a high carrier concentration that is typically associated with a low bandgap. Photovoltaic technology is often used in situations where such opposing properties seem to make the choice of the proper technology problematic. In many cases, one of these counterintuitive properties might be ignored without adequate consideration of its impact.

The spectral effects of accumulated dust layers have been previously reported [15,28–40]. Specifically, the critical region is in the additional optical absorption in the solar spectrum range of ~300 nm to ~600 nm. The spectral responses from the modules of this present study (Si, CIGS, CdTe, and a-Si:H) are experimentally compared to the AM1.5G spectrum in Figure 1. These data conclude that the effect of such soiling layers is more significant for higher bandgap (lower-wavelength spectral region) semiconductors than for Si because a larger portion of their responses is in that critical wavelength region [20,21]. This depends on the nature of the soiling (e.g., chemistry/composition, layer thickness, coverage, and possibly some conditions, such as particle geometry and humidity) [41–44]. The main point is that these soiling spectral influences have a direct impact on the power output of PV modules of differing solar-cell technologies/bandgaps. Much of the reported literature highlights these spectral effects, showing, for example, soiling diminishes the performance of CdTe more than Si modules. This implies that Si should always be superior for dust-rich regions. However, these data are presented as normalized for irradiance—and temperature. In this study, we present a simple model to begin to answer our initial question:

*What is the controlling parameter of the combination of spectral effects and temperature on Si and CdTe module technologies? What are the ranges in which these competing parameters act to dominate the module output?*

This paper evaluates this model with detailed experimental comparisons and validations for crystalline Si, thin-film CdTe, thin-film CIGS, and thin-film a-Si:H module technologies. We utilize the modeling analysis to also identify regions of “best-of-class” performance for this range of PV absorbers. The spectral effects of accumulated dust layers are characterized for the chemistry/composition and optical transmission and absorption of samples collected from module surfaces in Brazil’s tropical climate region (equatorial tropical climate–Aw, Köppen–Geiger classification [45,46]), specifically in Belo Horizonte (19.92° S, 43.99° W), Minas Gerais. These optical properties are correlated with the physical nature of the films gathered through measured gravimetric densities and optical characterization using the Figgis dust microscope [47]. The gravimetric densities are further correlated with the SRatios through previously reported modeling [48,49]. The temperature characteristics of these four module technologies are measured to evaluate specific power-temperature coefficients of the modules used in these investigations. The models are tested against data collected over several years using our soiling monitoring systems in Belo Horizonte [49–51]. The model and these data are used to identify the conditions under which these different technologies might have operational advantages—the major objective and contribution of this paper.
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Figure 1. Spectral response comparisons of c-Si, CdTe, CIGS, and a-Si:H modules from this study, indicating responses in various spectral regions compared to AM1.5 solar spectrum (following the method of J. John et al.) [30]. Region from 300 to ~600 nm (shaded) has been identified as critical for dust absorption of the solar irradiation in several geographical regions, including those in this study. This graph indicates that the greater effect on power output is for the lower bandgap absorber technologies due to possible spectral absorption by the soiling layer in the lower wavelength regions.

2. Methodology and Experimental Details

The model uses a simple linear approach using conditions (SRate) and temperature evaluations [51,52]. The experimental evaluations are based upon the soiling properties monitored for mc-Si and thin-film modules.

Module Temperature Characterization

The distinguishing characteristic for the thermal properties of the modules used in these studies is the module power temperature coefficient ($T_k$). Experimental measurements of the temperature characteristics of the modules used in this study are shown in Figure 2. The ranges (between the two $T_k$ lines of each technology) represent analyses of 3 to 9 modules as indicated in Table 1. The measured values compare well with the manufacturers’ specifications. The module power outputs are normalized for comparison.

Table 1. Summary of measured PV module properties (this study).

| Module Technology (Absorber) | $P_{max}$–Range [W] | $T_k(P_{max})$–Range [%/°C] | Number of Modules Measured |
|-----------------------------|---------------------|----------------------------|---------------------------|
| Multicrystalline Si         | 263–272             | −0.424 to −0.458           | 6                         |
| CdTe (thin film)           | 112–119             | −0.284 to −0.299           | 9                         |
| Cu(In,Ga)(S,Se)$_2$ (thin film) | 177–180           | −0.375 to −0.384           | 4                         |
| a-Si:H (thin film)         | 44.1–52.5           | −0.181 to −0.192           | 3                         |
where $P_{\text{max}}$ were estimated in order to understand and compare their combined impacts. The linear analyses in this study in order to determine the temperature coefficients $[T_k(P_{\text{max}})]$. The separation of the lines represents the range of measurements for several modules of each type (see Table 1).

3. The Model

The analytical prediction incorporates: (1) The module temperature coefficient, $T_k(P_{\text{max}})$ to determine the normalized module $P_{\text{max}}$ at the particular panel operating temperature. The maximum power parameters are used in order to avoid non-uniform soiling complications [53,54]. These conditions can lead to the misinterpretation of the soiling rates. The buildup of soiling, especially around the frames (depending on the module orientation) can affect the bypass diode circuits, for example, in Si module and the resulting shape of the I–V characteristics. This can lead to hot spots and more serious degradation of the module [54]. In the present study, the soiling was moderate and fairly uniform based on visual observations and periodic checks of the I–V curves. Additionally, (2) daily soiling rates ($S\text{Rate}$) were extracted from the $S\text{Ratio}$ over the period of performance for the particular location [49]. The relative contribution of these two competing parameters (spectral effects of soiling layer and operating temperature) were estimated in order to understand and compare their combined impacts. The linear analytical model superimposes the competing parameters to determine the normalized module maximum power:

$$P_{\text{max}}(T, d)/P_{\text{max}}(T, d_i) = 1 - [S\text{Rate} \cdot d + (T_{\text{mod}} - 25) \cdot T_k(P_{\text{max}})]$$  \hspace{1cm} (1)

where $P_{\text{max}}(T, d)$ is the maximum power of the module measured on soiling day “d”; $P_{\text{max}}(T, d_i)$ is the module maximum power measured in the initial day; $S\text{Rate}$ is the soiling rate determined for the dry period for that module; $d$ is the soiling day; $T_{\text{mod}}$ is the temperature of the module in °C; and $T_k(P_{\text{max}})$ is the temperature coefficient of the module.

The model calculation comparing Si and CdTe is presented graphically in Figure 3, with the normalized $P_{\text{max}}$ as a function of module temperature for the four module technologies in this study in order to determine the temperature coefficients $[T_k(P_{\text{max}})]$. The separation of the lines represents the range of measurements for several modules of each type (see Table 1).

![Figure 2. Normalized module $P_{\text{max}}$ as function of module temperature for the four module technologies in this study in order to determine the temperature coefficients $[T_k(P_{\text{max}})]$. The separation of the lines represents the range of measurements for several modules of each type (see Table 1).](image-url)
Figure 3. Modeling of normalized change in $P_{\text{max}}$ as function of soiling exposure days for various module temperatures, comparing Si with thin-film CdTe module. The crossover point (days) for each temperature pair (solid line for Si and dashed line for CdTe) indicates the predicted point at which the spectral absorption begins to dominate the module operating temperature.

Figure 4. Modeling of normalized change in $P_{\text{max}}$ as function of module temperature for various module soiling exposure times, comparing Si with thin-film CdTe module.
Spectral and Physical/Compositional Properties of the Soiling Layers

The fact that the soiling layers absorb different portions of the solar spectrum has been reported [28–40]. The soiling particulates collected from the surface of the modules in the present study have been analyzed [53–55], with component constituents (specifically hematite and calcite) that are similar to those reported as having additional absorption in the low-wavelength range of the AM1.5 solar spectrum [51,56,57]. The optical transmission wavelength characteristics of the module glass itself are presented in Figure 5a for both the mc-Si and CdTe module-glass covers. Figure 5b shows the measurement of the normalized transmission as a function of exposure or soiling layer gravimetric thickness for the mc-Si module glass. This confirms the additional absorption in the regions 300 nm to about 630 nm for the accumulated soiling layers at this location. All outdoor measurements were taken under standard conditions [53,58], during the same time of the year and time of day to minimize any angular solar incidence effects [21], and with samples and modules mounted at the same angle for this latitude.

Figure 6 shows the particulate deposition observed as a function of time using the Figgis dust microscope [47]. These micrographs also correlate with the optical properties (transmission) for samples evaluated for gravimetric densities and for the soiling rates determined from the soiling stations. The data from either the mc-Si or CdTe glass covers show the same coverages. Using the modeling of Coello and Boyle [48] and Costa et al. [49], the measured gravimetric densities for these layers are shown to follow the SRatios. This is represented in Figure 7, showing the modeled dependence of the gravimetric density of the deposited layer as a function of the SRatio (red line). To further validate this modeling, separate experimental measurements (blue squares) were superimposed onto the characteristics. The experimental gravimetric densities were measured by weighing the module glass sample (of each type) exposed on the module surface (same tilt, location) as a function of exposure time. The optical transmission was evaluated on the same samples recorded with Figgis microscopes.
Figure 6. Figgis dust microscope images of soiling layers on module glass as a function of exposure time in Belo Horizonte, Brazil [41,44]. Particle-size distribution peak is about 10 µm, and gravimetric densities are those represented in Figure 7.

Figure 7. Comparison of gravimetric density upon SRatio for Belo Horizonte, Brazil, based on modeling by Coello and Boyle [42] and Costa [43]. Experimental data from present study (blue squares) show good agreement with this analytical evaluation.

4. Experimental Model Validation

The major objective of this paper was to demonstrate the importance of examining opposing parameters leading to a possible “technology of choice” based upon operation under specific climate and soiling conditions. We provided the results for four technologies operating in the moderate soiling (0.1%/day to 0.25%/day and climate conditions in Belo Horizonte, Brazil [45,46,49]). We also discussed extending the analysis toward more severe climate and soiling condition locations.
4.1. Silicon and Cadmium Telluride

Our soiling monitoring focused on mc-Si and thin-film CdTe module technologies that have been major investments in the current world PV installations. These have been part of a six-year research program evaluating the soiling effects in various climate zones in Brazil. Data acquisition and methodologies utilize commercial Atonometrics soiling monitoring stations [53,59]. These systems provide a powerful method to store and access a variety of information (e.g., coincident irradiance, spectral and meteorological data, panel operating parameters, and full I-Vs,) over selected time intervals and under IEC standard conditions [58].

Figures 8 and 9 present the normalized $P_{\text{max}}$ as a function of days of outdoor soiling exposure for the mc-Si and thin-film CdTe modules. These represent more extensive experimentation and analysis than the initial results on these two technologies that we reported in a previous conference paper [52]. The experimental data were acquired over ~4 years and filtered to only show solar irradiance $>500$ W/m$^2$, for time periods between 11 am to 1 pm, and exclude periods of precipitation (i.e., consider only the dry periods having more than a 14-day duration [52,60,61]). The temperature coefficients were measured for the specific modules used (Figure 2) in this study. For comparison, on each of the characteristics in Figures 8 and 9, the model is shown by the line (solid for Si and dashed for CdTe from Figure 3). For both technologies, fair correlations to the predictions are shown, with a linear fit of the data shown by the dotted line. However, the scatter in the data is relatively large. This is due to several circumstances. First, following periods of precipitation, the modules are not completely cleaned, sometimes with residues from the rain leaving some moisture and soiling trails. Second, with longer periods of exposure, the soiling layer thickness may vary due to wind effects, leading to a lower $S_{\text{Rate}}$, or to thickness variations as the layers build on the soiling particulates rather than on the panel glass surface—leading to a higher $S_{\text{Rate}}$.

![Figure 8. Normalized $P_{\text{max}}$ for c-Si modules at different temperatures as a function of the soiling exposure in Belo Horizonte, Brazil. The model predictions (solid lines) are included as well as a corresponding linear fit to the data (dotted lines). The red data points are for an extended single, dry period (37 days) showing better fit to the model predictions.](image)
The data fit is better for the CdTe than the Si. This is due to two important observations: (1) the frameless CdTe modules are less prone to non-uniform soiling, and (2) the framed and circuited Si modules have less uniform temperature distributions. To illustrate this, thermal IR mapping comparisons are presented for the two module technologies in Figure 10. The Si case shows the cooling from the frames and some non-uniformity of the cells in the strings—all of which are more critical variations in operating temperatures. Thus, departures from the model are presumed due to non-uniformity of the module temperature (especially as higher module temperatures), variations in the SRate at longer exposure times, and inconsistencies in the cleanliness of the surface following rainfall.

To investigate this further, we examined data collected only from an extended dry period (<30 days), following the cleaning of each of the exposed Si and CdTe modules. These data are shown by the red data points highlighted in Figures 8 and 9. The better correlation to the prediction is apparent, with these data lying more closely to the model for this shorter and dry period.
Figure 10. Representative thermographic scans of (a) CdTe module, and (b) Si module under normal operating ambient conditions, indicating more prevalent temperature areal variations for the Si module because of framing and mismatched cells in the strings.

Additional demonstrations of the validity of the model are the “crossovers” (see Figure 1). These represent the points at which one technology has a better performance over the other because of bandgap differences. In the simulation of Figure 3, the crossover is defined at a specific exposure time (days) at a particular module temperature. Table 2 provides a summary of these crossover points. For example, at 40 °C, the CdTe module has a better performance for the first 27.3 days of soiling. Subsequently, the spectral effect would start to dominate in favor of the Si technology. The model and the experimental data validate the idea that the module temperature is the important parameter for normal operating conditions.

Table 2. Comparison of predicted (model) crossover points (days of soiling) with experimental data crossover points. The experimental crossovers are determined from the fitted data. The crossover is the point in the soiling duration time (days) at which the Si module starts to have a better normalized Pmax (better performance) than the CdTe or a-Si:H modules because of spectral effects at that particular module temperature. The experimental data show the general trends predicted by the model. At 25 °C, the Si module performs better than either other technology because of the increased absorption by the soiling layer in the low-wavelength region that affects CdTe and a-Si:H more than Si.

| Module Temperature (°C) | Multicrystalline Silicon vs. Cadmium Telluride | Multicrystalline Silicon vs. a-Silicon:Hydrogen |
|-------------------------|-----------------------------------------------|-----------------------------------------------|
|                         | Model Crossover Point (Days) | Experiment Crossover Point (Days) | Model Crossover Point (Days) | Experiment Crossover Point (Days) |
| 25                      | 0 (Si better)                  | 0 (Si better)                             | 0 (Si better)                 | 0 (Si better)                     |
| 30                      | 9.1                           | 12.2                                      | 12.9                           | 15.2                             |
| 35                      | 18.2                          | 20.2                                      | 25.9                           | 23.1                             |
| 40                      | 27.3                          | 31.0                                      | 38.7                           |                                  |
| 50                      | 45.4                          | 50.1                                      | 64.5                           |                                  |
| 60                      | 63.0                          |                                          | 90.3                           |                                  |
4.2. Amorphous Silicon: Hydrogen and Copper (Indium, Gallium) Sulfide Selenide

The validation of the model has been extended to two additional commercial thin-film technologies to further document the spectral effects and the performance competition under similar climate conditions. The two technologies present information on bandgaps higher (a-Si:H, up to 1.7 eV) than Si and CdTe, and for Cu(In,Ga,)(SSe)₂ near Si at 1.2 eV, for comparisons. The graphical representations of the model comparing a-Si:H with Si are shown in Figure 11. This predicts that the higher bandgap material is more affected by the spectral effects at lower temperatures. Additionally, the crossover from the temperature to spectral control of performance presents a higher range in which temperature dominates for the a-Si:H than for the lower bandgap CdTe with stabilized efficiencies ~3–4%. These were about 15 years old and selected from a group that had modules that completely failed compared to ones in the highest range. These a-Si:H or CIGS modules were older manufacture-age technologies, but these had bandgaps that were appropriate for the investigation of the spectral effects. The a-Si:H modules were single junction, with stabilized efficiencies of ~3–4%. These were about 15-years old and selected from a group that had modules that completely failed compared to ones in the highest range. The modules were decommissioned from a system about three years before the initiation of this study and stored in the dark in an open-circuit condition. They were then left in a load operating condition for two months before the start of the present study to stabilize their characteristics. The CIGSSe modules were manufactured >6 years ago, with efficiencies in the 8–10%-range. These selected a-Si:H and CIGSSe modules were evaluated in their clean surface condition after approximately three months of operation for this study and showed changes in I–V parameters.

![Figure 11. Model prediction of normalized change in P_max as function of soiling exposure days for various module temperatures, comparing Si with thin-film a-Si:H module.](image)

Figure 12 presents the experimental results for each of these module types, evaluating the competing spectral and temperature effects on performance. The dashed lines represent the specific model calculations, with the comparison to the crystalline-Si module (as in Figure 3) represented by the solid lines. These data (dots) were obtained over a dry period of 22 days. The CIGSSe case is on the left-hand side (with a bandgap close to Si, ~1.2 eV); the a-Si:H
(E<sub>g</sub>~1.7 eV) is on the right side of the figure. The overall good agreement with the model predictions is noted for this period. There was no precipitation during this monitoring time, ensuring no inadvertent changes to the condition of the modules’ surfaces from rain. The case for the a-Si:H module exhibits more scatter in the data, especially at higher exposure times. It is likely that the lower power outputs at higher exposures were due to higher soiling layer gravimetric thicknesses on the modules, but this was not confirmed. The data were obtained at a different time than for the CdTe and Si modules (Figures 8 and 9). Additionally, both of these modules had remnants of antireflection coatings left (the modules in Figures 8 and 9 did not), and this could have contributed to some non-uniformities in the soiling deposition due to the ARCs and surface temperatures [62–65]. As noted, these modules are of an older generation. Visual inspections show some minor conditions of corrosion on contact areas. However, more importantly, the TCO shows discoloration in some areas on the edges where there have been non-uniform temperatures reported during operation [66]. The visual inspections of the CIGSSe modules did not report any corrosion, contact, or delamination issues.

Figure 12. Comparison of experimental data with model predictions (lines) for CIGSSe and a-Si:H thin-film modules (dashed lines) to Si module (solid line) over a dry period of 24 days.

4.3. Potential Differences for More Severe Climate Regions

The conditions considered in the model and the experimental conditions considered in the previous sections focused on moderate soiling (<0.2%/day) and temperature (module operating temperature < 60 °C) conditions. The observed “crossover points” from where the spectral effects dominate (and the better performance of Si over CdTe) to where the temperature effects are more important are shown in Figure 13. The line is calculated from the model, using the moderate soiling conditions for Brazil (as in Figures 3, 8 and 9).
4.3. Potential Differences for More Severe Climate Regions

The spectral effects could also be expected to be more critical for lower-bandgap technologies in regions that have higher UV incident solar content. Additionally, in those regions having higher soiling rates (e.g., >0.4%/day in India to >1%/day in the Middle East), the onset of both the domination of the module temperature on the module output power and the point at which the transmission of the incident light becomes very low were because of the soiling level coverage and thickness. The absorption in the critical spectral region of 300 nm to 600 nm also depended on the physical and optical properties of the deposited soiling layer. Compositions differ in different locations in the world—and data indicate that “dust” in India is not only chemically distinct from that in Brazil, but also differs in the various climate zones in India itself [29,30]. Additionally, the absorption of light by the soiling layer is higher in some of those regions than that reported in this paper [29]. Additionally, due to the higher deposition rates, the competing effects of optical absorption in the lower-wavelength region by the soiling layer occur earlier in the daily exposures.

The conditions considered in the model and the experimental conditions considered noted in previous studies. The effects of the higher gravimetric thicknesses on the spectral effects and the module temperature were not evaluated in the present study.

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Figure 13. Crossover from Si to CdTe dominations as a function of soiling exposure time and module temperature. For example, analysis supported by experiments predicts that at a module operating temperature of 50 °C, spectral effects of the soiling layer would only start to be effective for soiling exposure days more than ~58 days of exposure for Si over the CdTe technology.
5. Summary

The motivation for these studies was to evaluate the relative performances of different PV technology modules operating under two competing conditions. The objective was to determine whether the reported spectral absorption by soiling layers would dominate temperature effects for mc-Si, thin-film CdTe, CIGSSe, and a-Si:H modules operating under the same irradiation conditions.

The validation process included:

1. The establishment of soiling layer properties:
   - Direct optical transmission measurements of soiling particulate layers showed optical absorption in the low-solar-wavelength (300–600 nm) region. This confirmed the previous reports and the optical absorption properties of the soiling layers in this geographical region.
   - The deposition of the natural soiling particulates was reported using the Figgis digital soiling microscope. Gravimetric densities were determined experimentally and compared to reported models—as well as the images obtained from the Figgis instrument. Using coupons identical to the module cover glass to determine the gravimetric densities confirmed that the soiling layers had the same gravimetric densities as the modules (with the soiling stations positioned side-by-side at the location).
   - The Coello–Boyle model was used to calculate the SRatio as a function of the gravimetric densities, with experimental data further confirming the deposition conditions of CdTe and Si modules.

2. Experimental correlation with analytical model for soiling layer’s deposition and temperature:
   - A linear analytical model was presented using superposition soiling layer deposition and specific module temperature characteristics.
   - Temperature coefficients were measured for mc-Si, thin-film CdTe, thin-film CIGSSe, and thin-film a-Si:H modules used in these investigations.
   - Experimental data from soiling stations were correlated with temperature and soiling conditions to validate model predictions for all four technologies—also directly demonstrating the spectral effects of soiling as a function of the bandgap of the absorber material. The relative ranges for soiling layer spectral effect versus temperature dominance were identified and the crossover points correlated with model predictions.
   - Differences in model predictions could be associated with non-uniform module temperatures (mainly, the case of mc-Si modules with frames), some non-uniform soiling, and non-consistent soiling rates over longer periods of exposure. This was presumed for the measurements of the a-Si:H and CIGS modules that had aged and had some remnants of ARCs that provided non-uniform soiling.
   - The situations for more severe climates were discussed, regions where there would be higher soiling rates, differences in the composition of the soiling particulates, higher UV content in the solar spectrum, and much higher operating temperatures. These would lead to different inputs to the model—but basically, the dominance of the module temperature would be expected over the spectral effects for normal system operating conditions.

The spectral effects of soiling layers on the $P_{\text{max}}$ of modules operating under climate and soiling conditions in Belo Horizonte, MG Brazil were demonstrated. The major conclusion of this study is that temperature is the major control for “best-of-class” module performance, especially with operations at temperatures beyond the 40–50 °C range. Although the spectral effects are of concern and interest in current research studies, these are minor compared to the normal operating temperatures for most modules installed in deployed systems.
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