Reduction of Operating Temperatures of PV Modules using Thermally Conductive Backsheets: Site Dependence

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Reduction of Operating Temperatures of PV Modules using Thermally Conductive Backsheets: Site Dependence

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Abstract — Photovoltaic (PV) packaging materials impact the module operating temperatures. This paper compares the thermal performance of thermally conductive backsheets (TCB) with the benchmark Tedlar-polyester-Tedlar (TPT) backsheet. In this work, the nine-cell modules with TCB\textsubscript{A} and TCB\textsubscript{B} typically operate at lower cell temperatures under desert climatic conditions with low wind speed whereas TCB\textsubscript{C} and TCB\textsubscript{D} modules operate at lower backsheet temperatures but at almost similar cell temperatures under temperate climatic conditions. The Nominal Operating Cell Temperature (NOCT) of modules with thermally conductive backsheet is lower than TPT with a temperature difference as high as 2 °C. All TCBs have higher thermal conductivity values as compared to TPT. TCBs can perform better, worse or equal compared to TPT depending on the dynamic site conditions. This paper presents only the thermal performance of backsheets and does not present any data on reliability and durability of these backsheets.

Index terms — backsheet and cell temperature, NOCT, seasonal trend, thermally conductive backsheet

I. INTRODUCTION

Module temperature plays the second largest role, next to irradiance, in determining the performance of PV modules. Every degree Celsius increase in temperature results to decrease in voltage typically by 0.4 % and decrease in power by 0.45 % for crystalline silicon modules. Various intrinsic design factors such as module encapsulation/backsheet materials, cell packaging density and module structure affect the module performance and improvements have been made in these factors to lower module operating temperatures. The extrinsic factors such as ambient temperature, irradiance, wind, humidity, and geographical location might also affect the field operating module temperatures. Innumerable new methods are under research in the PV industry to cool PV modules [1, 2]. One such approach is passively cooling modules by replacing conventional PV backsheets with thermally conductive backsheets. Various module materials have different heat transfer rates which could cause variability within cell temperatures. Different module structures and weather parameters could also cause about 2 °C cell-to-cell temperature differences [3, 4].

In this paper, we show that module and cell temperatures could be typically lowered using thermally conductive backsheets in nine-cell modules. As compared to one-cell module structure reported in another paper of this conference, the nine-cell modules closely replicate the commercial module structure with center cell surrounded by eight other cells on all sides and corners. TPT was used as the conventional and baseline/benchmark PV backsheet material for comparison. Two TCBs have already shown to typically lower the module temperature by about 1°C in one-cell modules [5]. In [5], [6] one-cell module data using TCB\textsubscript{A} and TCB\textsubscript{B} was analyzed and compared with TPT at all three sites: hot/desert-low wind speed (Arizona); hot/desert-high wind speed (Arizona); temperate (North Carolina). Two more TCBs with thermal conductivities lower than TPT were also selected for this study. In this work, the thermal performance of four TCBs and TPT are compared in nine-cell modules installed at three sites. Also, data for all four TCBs and TPT is compared in nine-cell modules at one site. This paper presents only the thermal performance of backsheets and does not present any data on reliability and durability of these backsheets.

II. TEST SETUP

The nine-cell modules were fabricated closely replicating the commercial module with cells packed close to each other and at least one cell surrounded by other cells. The module structure comprised of glass – ethylene-vinyl acetate copolymer (EVA) encapsulant – cell – EVA encapsulant – back sheet. A conventional TPT backsheet, with thickness 0.34 mm was used as a baseline backsheet and four TCBs from different manufacturers namely TCB\textsubscript{A}, TCB\textsubscript{B} [5], TCB\textsubscript{C} and TCB\textsubscript{D} were selected for the comparison. TCB\textsubscript{A} backsheet

Fig. 1. Back-view design of nine-cell module with dimensions in inches (left) and fabricated nine-cell module measuring center, corner and edge cell temperature as indicated by red dots (right)
CB_C and TCB_D backsheets were 6 TC (3 cell, 3 backsheet).

TCB_B has a structure of polyvinylidene fluoride (PVDF)-PET-EVA and TCB_B backsheet has layers of polyamide (PA)-
aluminum-PET-PA. TCB_C backsheet has a structure of encapsulant -PET-ECTFE (fluoropolymer barrier layer) and TCB_D backsheet has layers of Polyamide-Core layer- E layer (modified polyolefin layer). T-type thermocouples were attached on the backsheet (outside the laminate) after fabricating the module and cell (inside the laminate) during fabrication of nine-cell modules for temperature measurement. Fig. 1 shows design of nine-cell modules and a fabricated nine-cell module along with locations measuring cell temperatures. (center, corner and edge)

A total of 20 nine-cell modules were installed at 3 different sites: AZ-1 (8 modules; hot-dry with low average wind speed climate) and AZ-2 (6 modules; hot-dry with high average wind speed climate) in Arizona and NC site (6 modules; temperate climate) in North Carolina, USA [6]. These modules were installed on an open rack per NOCT test conditions as shown in Fig. 2. All the three sites have identical rack set-ups and placement of the modules. All the modules are installed at 45° tilt, facing south on an open-rack system. At each site, 6 thermocouples (3 cell, 3 backsheet) were placed on 1 module from each backsheet type. All other modules had only 1 thermocouple at the center to measure backsheet temperature. Note that 1 TCB_A and 1 TCB_B modules were only installed at AZ-1 site. AZ-1 site records data every 30-second interval while AZ-2 and NC site records data every one-minute.

III. RESULTS AND DISCUSSIONS

A. Thermal Conductivity of Backsheets

The specific heat capacity of all the backsheets measured using differential scanning calorimeter (DSC) was used to determine axial and radial thermal conductivity. Since all backsheet materials are made of 2-4 different polymeric layers, anisotropic thermal conductivity measurements were performed. The thickness of these backsheets was very thin (0.3–0.4 mm), therefore several layers were stacked eliminating the air gap to efficiently measure thermal conductivity values. The thermal conductivity values of TPT, TCB_A and TCB_B have already been reported [5]. The axial and radial thermal conductivity values for TCB_C and TCB_D backsheets were measured. Axial thermal conductivity is measured through-plane and would account for heat transfer between various encapsulated materials within the module. The axial thermal conductivity

<table>
<thead>
<tr>
<th>Back sheet manufacturer</th>
<th>Axial Thermal Conductivity (W/m·K)</th>
<th>Radial Thermal Conductivity (W/m·K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPT</td>
<td>0.153</td>
<td>0.486</td>
</tr>
<tr>
<td>TCB_A</td>
<td>0.259</td>
<td>0.371</td>
</tr>
<tr>
<td>TCB_B</td>
<td>0.382</td>
<td>13.53</td>
</tr>
<tr>
<td>TCB_C</td>
<td>0.256</td>
<td>0.387</td>
</tr>
<tr>
<td>TCB_D</td>
<td>0.238</td>
<td>0.343</td>
</tr>
</tbody>
</table>
conductivity values of all TCBs are greater than conventional TPT as seen in Table I. These higher axial values can be attributed to better heat dissipation from solar cell to the backsheets.

B. Backsheet and Cell Temperature

To statistically compare the performance of TCBs over TPT, ΔT_{backsheet} (backsheet temperature difference between TPT and TCB), an average value of two modules per backsheet per site was calculated and compared between TPT and TCB. The data process was limited to the following weather conditions: >400 W/m² irradiance, >0.25 m/s wind speed, and 9 am–3 pm. Wind direction blowing from east-west direction was not considered for this site.

Fig. 3 (a) and (b) show the monthly ΔT_{backsheet} values between TPT and TCB_C and TCB_D respectively at 3 different sites during Fall 2018 and Winter 2019 season. Full year analysis would be presented in future publication. The median ΔT_{backsheet} values between TPT and TCB_C/TCB_D are about 0.5 °C at NC site. Both TCB_C and TCB_D do not operate at lower temperatures than TPT at AZ-1 and AZ-2 site. To see the effect of different seasons at different sites on ΔT_{backsheet} values, monthly data was divided into seasons: Fall starting on 21st September, Winter starting on 21st December. Fig. 4(a) shows ΔT_{backsheet} values between TPT and TCB_C and TCB_D at 3 sites during Fall season. Since only 1 module per backsheet measures both cell and backsheet temperatures as seen in Fig. 2, only one module per backsheet is considered for this analysis. The median ΔT_{backsheet} values between TPT and TCB_C are about 0.5 °C and between TPT and TCB_D are about 0.8 °C at NC site.

The cell temperatures are less affected by environmental parameters as compared to backsheet temperatures. To study the effective impact of TCBs, center cell temperatures of TPT and TCB were also compared as shown in Fig. 4(b). The median ΔT_{cell} values between TPT and TCB_C and TCB_D are between 0.2 °C - 0.5 °C at AZ-1 and AZ-2 sites. The ΔT_{cell} values between TPT and TCB_C are as high as 7 °C, 4 °C and 4 °C at AZ-1, AZ-2 and NC sites respectively. On the other hand, ΔT_{cell} values between TPT and TCB_D are as high as 3 °C.
In Fig. 5(a) and (b), $\Delta T_B$ represents temperature differences between backsheet and ambient and $\Delta T_C$ represents temperature differences between cell and ambient where 1, 2, 3 stands for TPT, TCB_C and TCB_D respectively. For example, $\Delta T_B$ is difference between TPT backsheet and ambient temperatures and $\Delta T_C$ is difference between TPT cell and ambient temperatures.

The backsheet temperatures in AZ are higher, causing higher differences between backsheet and ambient temperatures as seen in Fig. 5(a). The higher differences between ambient and backsheet temperatures leads to higher radiative loss. This results into higher cell temperature variability at AZ sites as seen in Fig. 5(b). Therefore, we can indicate that:

Radiative loss: AZ-1 site > AZ-2 site > NC site
Cell-temperature variability: AZ-1 site > AZ-2 site > NC site

This results into lower $\Delta T_{\text{backsheet}}$ values compared to $\Delta T_{\text{cell}}$ values at AZ sites as seen from Fig. 4. But it can be seen that NC site has higher $\Delta T_{\text{backsheet}}$ values between TPT and TCBs but nearly same $\Delta T_{\text{cell}}$ values. This maybe attributed to lower radiative loss from backsheet because of lower temperature differences at the backsheet with respect to ambient.

C. Comparison between TPT and 4 TCBs at AZ-1 site

The performance of TCB_A and TCB_B at AZ-1 using one-cell modules was analyzed and presented [5]. To compare whether the TCBs still operate at lower temperatures than TPT in nine-cell modules replicating realistic PV modules, one nine-cell module was fabricated using TCB_A and TCB_B each. Since, AZ-1 site consists of nine-cell modules fabricated using all 4 TCBs, it was selected for the comparison analysis in this section. Fig. 6(a) and (b) shows the comparison between TPT and TCBs for Fall and Winter months installed at AZ-1 site. 1 nine-cell module per backsheet measuring backsheet and cell temperatures were used for comparison. As expected, the $\Delta T_{\text{cell}}$ values providing actual cell temperature differences between TPT and all TCBs, are higher than $\Delta T_{\text{backsheet}}$ values [5]. The median $\Delta T_{\text{cell}}$ values between TPT and TCB_A nine-cell modules is about 2 °C which correlates to values seen in one-cell modules. The median $\Delta T_{\text{cell}}$ between TPT and TCB_B nine-cell modules is about 1 °C and between TPT and TCB_C/TCB_D are about 0.4 °C. Both Fall and Winter season have consistent $\Delta T_{\text{cell}}$ trends but different $\Delta T_{\text{backsheet}}$ trends. This may

Fig. 5. $\Delta T$ trends between TPT and 2 TCBs at three sites during Fall and Winter season where 1: TPT, 2: TCB_C and 3: TCB_D (a) $\Delta T_B$ represents temperature differences between backsheet and ambient (b) $\Delta T_C$ represents temperature differences between cell and ambient.

Fig. 6. $\Delta T$ trends between TPT and 4 TCBs at AZ-1 site during Fall and Winter season (a) $\Delta T_{\text{backsheet}}$ (b) $\Delta T_{\text{cell}}$
be attributed to direct effect of weather parameters on backsheet temperatures.

The cell-to-cell temperature differences were also investigated for modules at AZ-1 site. The center cell of all the modules operate at about 2.3 °C higher than edge and corner as seen in Table II. This may be attributed to the number of surrounded cells reducing heat dissipation. It is important to note that this temperature difference in the TPT module is higher compared to TCB modules indicating that most of the TCB-based modules (except TCB_C) maintain more uniform temperature throughout the module compared to the TPT-based module. The standard deviation of cell temperature values is higher for TPT and TCB_C as compared to other backsheets. Fig. 7 compares cell-to-cell differences of cell and backsheet temperatures between center, corner and edge cells. It clearly shows that the differences in the median values of cell temperatures are as high as 2 °C. On the other hand, the differences in backsheet temperatures are about 0.7 °C.

![Fig. 7. Cell-to-cell T_{cell} and T_{bs} (within a module) trends between TPT and 4 TCBs at AZ-1 site during Fall season (a) TPT (b) TCB_A (c) TCB_B (d) TCB_C (e) TCB_D](image)

**TABLE II**

<table>
<thead>
<tr>
<th>Backsheet types</th>
<th>Median (Center cell)</th>
<th>Median (Corner cell)</th>
<th>Median (Edge cell)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPT</td>
<td>55.7</td>
<td>53.47</td>
<td>54.06</td>
<td>1.16</td>
</tr>
<tr>
<td>TCB_A</td>
<td>53.88</td>
<td>52.67</td>
<td>52.42</td>
<td>0.78</td>
</tr>
<tr>
<td>TCB_B</td>
<td>54.88</td>
<td>53.12</td>
<td>53.07</td>
<td>1.03</td>
</tr>
<tr>
<td>TCB_C</td>
<td>55.72</td>
<td>53.44</td>
<td>53.7</td>
<td>1.25</td>
</tr>
<tr>
<td>TCB_D</td>
<td>55.6</td>
<td>53.82</td>
<td>54.12</td>
<td>0.95</td>
</tr>
</tbody>
</table>

The thermal performance of the backsheet materials in a packaged PV module may also be investigated by determining the NOCT of the modules. The NOCT represents the cell temperature under specific environmental conditions: 800 W/m² irradiance, 20 °C ambient temperature, and 1 m/s wind speed. The individual NOCT of all the nine-cell modules was determined by taking the average of NOCT measured on three

![Fig. 8. NOCT values of nine-cell modules with 5 different backsheets (1 TPT and 4 TCBs)](image)
clear sunny days in November. As seen from Fig. 8, the NOCT of the TCB modules is clearly lower than that of the TPT module. The NOCT of TCB_A and TCB_B using one-cell modules was also reported to be about 2 °C and 1.2 °C lower than TPT respectively [5]. The NOCT of TCB_A is about 2 °C lower than TPT as seen from Fig. 8. The differences seen in NOCT values for TCB_A and TCB_B nine-cell modules as compared to TPT are consistent with one-cell modules [5]. The NOCT analysis obtained for multiple months would be reported in future publication.

IV. SUMMARY

The thermal conductivity measurements clearly showed that the investigated TCBs have higher axial thermal conductivities than TPT. The NOCT values of nine-cell modules are typically lower for TCB than TPT with temperature difference as high as 2 °C in TCB_A. In addition, cell-to-cell differences of cell temperatures between center, corner and edge are larger than backsheet temperatures.

TCB_C and TCB_D nine-cell modules typically operate at lower backsheet temperatures than TPT under temperate climatic conditions but at almost similar cell temperatures (TCB_A and TCB_B not tested under temperate climatic conditions). This may be attributed to lower radiative loss from backsheet because of lower temperature differences between backsheet and ambient. On the other hand, they perform practically same or worse at AZ sites. TCB_A and TCB_B operate at lower cell temperatures under desert climatic conditions with low wind speed. None of the TCBs perform better under desert climatic conditions with high wind speeds. Therefore, it can be concluded that TCBs can perform better, worse or equal compared to TPT depending on the dynamic site conditions.

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