Decreasing PV Module Temperature with Thermally Conductive Backsheets

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Introduction

Why lowering PV module temperature?

- Efficiency increase
  - Thermal property of solar cell
    - $\downarrow T_{\text{cell}} \Rightarrow P_{\text{max}} \uparrow$
      - $P_{\text{max}}: -0.5\%/^\circ\text{C}$

- Longer lifetime of PV module
  - Less thermal stress

Cell: $\sim 0.6\text{V}$

Module: 72 cells, $\sim 43\text{V}$

System: 2100 PV modules, 600 – 1500V, 500 kWdc
Introduction

1. Conventional backsheets
   - Tedlar/PET/Tedlar (TPT)
     - Polyvinyl fluoride (PVF)
2. Thermally conductive backsheets (TCB)
   - Polyvinylidene fluoride (PVDF)/PET/EVA → TCB_A
   - Polyamide (PA)/Al/PET/PA → TCB_B
3. Glass substrate: G/G

Passive cooling method
1-cell Module Fabrication

- **Material specification**
  - Cells: 156 x 156 mm$^2$ mono c-Si solar cells
  - Glass: 8” x 11” Solite low iron Solar glass (3.2 mm thickness)
  - Encapsulant: EVA
  - Backsheets: TPT, TCB_A, TCB_B, Glass
  - Tabbing and bus wires: Sn/PB (60/40)

- 8 modules were fabricated.
  - 2 TPT, 2 TCB_A, 2 TCB_B, 2 G/G

- Thin (36 AWG) thermocouple was attached to the back of the solar cell prior to lamination.
Characterization and Installation

- Characterization
  - I-V
  - Electroluminescence (EL)
  - Infrared (IR)
  - Thermal conductivity
    - Hot Disk TPS 2500S

- Rack
  - South facing
  - 45° fixed tilt

- Data acquisition system
  - Campbell scientific CR 1000
  - Every 30s
  - Temperature (cell & module), $V_{oc}$ and weather data

- Modules are in open-circuit condition

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### I-V Parameters

<table>
<thead>
<tr>
<th>Backsheet Type</th>
<th>$I_{sc}$ (A)</th>
<th>$V_{oc}$ (V)</th>
<th>$I_{mp}$ (A)</th>
<th>$V_{mp}$ (V)</th>
<th>$P_{max}$ (W)</th>
<th>FF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPT</td>
<td>8.902</td>
<td>0.626</td>
<td>8.094</td>
<td>0.4285</td>
<td>3.469</td>
<td>62.2</td>
</tr>
<tr>
<td>TCB_A</td>
<td>8.744</td>
<td>0.623</td>
<td>7.995</td>
<td>0.4218</td>
<td>3.372</td>
<td>61.9</td>
</tr>
<tr>
<td>TCB_B</td>
<td>8.975</td>
<td>0.625</td>
<td>8.067</td>
<td>0.4269</td>
<td>3.444</td>
<td>61.4</td>
</tr>
</tbody>
</table>
Both TCBs show higher thermal conductivity than TPT.

TCB_B has extremely high radial thermal conductivity due the presence of thin aluminum layer.
Nominal Operating Cell Temperature (NOCT)

- NOCT: a reference characterization test procedure to quantify the module cell temperature for different module designs in a standard reference environment.
- NOCT testing condition (IEC 61215)
  - Irradiance: 800 W/m²
  - Ambient temperature: 20°C
  - Wind Speed: average 1 m/s
  - 45° tilt
- Measured at ASU-PRL (Mesa, AZ)
- 3 clear sunny days were selected for NOCT data collection and calculation
TCB_A shows 1.1-1.2°C lower NOCT than TPT.
It clearly indicates that TCB lowers the cell temperature by at least 1°C at NOCT conditions.
NOCT of G/G is 1°C higher than TPT
Data range
- >400W/m² irradiance
- >0.25m/s wind speed
- 9 am to 3 pm time window
- Removed east (70°-110°) and west (250°-290°) wind direction

Daily Operating Temperature

- NOCT is an expected cell temperature only at NOCT weather condition.
- NOCT condition does not exist throughout the day or on all days in a month or year.
- Performance of TCB will vary depending on the weather condition.

Overall, TCB_A shows higher ΔT than TCB_B.
At least one data with ΔT higher than 2°C was observed everyday for the whole month except for two days (May 14 & 15) which were highly cloudy day.
A daily temperature of >2°C median ΔT is observed for 5 days in a month (May 2017).
About 0.8°C ΔT observed from TCB_B.
A daily temperature of >2°C median ΔT is observed for 15 days in a month (May 2017).

At least one data with ΔT higher than 2°C was observed everyday for the whole month except for one day (May 14th), which was an extremely cloudy and windy day.

ΔT as high as 5.8°C observed

In May 2017, at least 15 out of 31 days experienced daily average ΔT higher than 2°C.

The results clearly indicate that TCB_A reduces the operating temperature by at least 2°C as compared to TPT.
Daily Operating Temperature

\( T_{\text{Voc}} \) vs. \( T_{\text{cell}} \) vs. \( T_{\text{backsheet}} \)

- Daily average \( \Delta T_{\text{cell}} \) is higher (0.1-0.3°C) than that of \( T_{\text{backsheet}} \) for a few days.

- Highest average and median \( \Delta T \) was observed from \( \Delta T_{\text{cell}} \)

- \( \Delta T_{\text{cell}} \) appears to be slightly better as compared to the one estimated by \( \Delta T_{\text{backsheet}} \)

Note: A theoretical Voc temperature coefficient of 2.1 mV/°C is used to calculate delta T (Voc)
Monthly variations were observed from TCB_A modules.

Lower thermal performance in August, September, and March.

Overall, TCB_A shows lower temperature than TPT.
Seasonal Effect on TCB Modules

- Less seasonal influence than TCB_A modules
- Best thermal performance is in January
- 0.5-0.7 °C median ΔT year around
Seasonal Effect on G/G Module

- G/G module showed ~1 °C lower temperature than TPT module in January, February, and March while all other months showed higher temperature than TPT.
- G/G module installation may be a good option for cold region.
TCB modules are less affected by seasonal change, especially for ambient temperature, while G/G module shows about 1 °C lower temperature at Winter season.

- TCB_B shows stable ΔT through the year.
Empirical Thermal Model

\[ T_{\text{cell}} = w_1 \cdot E + w_2 \cdot T_{\text{amb}} + w_3 \cdot WS + c \]

- \( T_{\text{cell}} \): cell temperature (°C)
- \( E \): irradiance (W/m²)
- \( T_{\text{amb}} \): ambient temperature (°C)
- \( WS \): wind speed (m/s)
- \( w_1, w_2, w_3 \): coefficients
- \( c \): constant.

<table>
<thead>
<tr>
<th>Types</th>
<th>( E ) (( w_1 ))</th>
<th>( T_{\text{amb}} ) (( w_2 ))</th>
<th>( WS ) (( w_3 ))</th>
<th>( c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCB_A</td>
<td>0.0300</td>
<td>0.997</td>
<td>−1.484</td>
<td>1.106</td>
</tr>
<tr>
<td>TCB_B</td>
<td>0.0312</td>
<td>1.007</td>
<td>−1.439</td>
<td>0.406</td>
</tr>
<tr>
<td>TPT</td>
<td>0.0315</td>
<td>1.004</td>
<td>−1.424</td>
<td>0.725</td>
</tr>
<tr>
<td>Backsheet Average</td>
<td>0.0309</td>
<td>1.003</td>
<td>−1.449</td>
<td>0.746</td>
</tr>
<tr>
<td>G/G</td>
<td>0.0324</td>
<td>1.024</td>
<td>−1.146</td>
<td>−0.265</td>
</tr>
</tbody>
</table>

- Data collected between 7 am–6 pm during two periods: May 1–31, 2017 (six glass/backsheet modules), and June 9–July 12, 2017 (six glass/backsheet modules and two G/G modules).

- Linear regression was used.
- The primary differentiator for temperature differences regarding TPT, TCB, and glass substrates is the irradiance level (solar gain due to reduced radiative and conductive losses).
- Wind speed level plays secondary role for the temperature difference regarding backsheets and glass substrates, but not between backsheet types.
Empirical Thermal Model

\[ T_{cell} = 0.0300 \cdot E + 0.997 \cdot T_{amb} + (-1.484) \cdot WS + 1.106 \]

\[ T_{cell} = 0.0312 \cdot E + 1.007 \cdot T_{amb} + (-1.439) \cdot WS + 0.406 \]

\[ T_{cell} = 0.0315 \cdot E + 1.004 \cdot T_{amb} + (-1.424) \cdot WS + 0.725 \]

\[ T_{cell} = 0.0324 \cdot E + 1.024 \cdot T_{amb} + (-1.146) \cdot WS + (-0.265) \]

The trend lines of all plots above have a good fit, as indicated by the high R\(^2\) values.
Summary

➢ Thermal conductivity was measured on TPT and TCBs, and obviously TCB showed higher thermal conductivity than TPT.

➢ NOCT of TCB used module is 1.2 °C lower than TPT module.

➢ G/G module showed 1 °C higher NOCT than TPT module.

➢ Empirical thermal model using linear regression was developed and validated.

➢ TCB backsheet contributes to a decrease in the average cell temperature of more than 1 °C in general, and of more than 2 °C on hot sunny days (as high as 5 °C at certain time on hot sunny days).
THANK YOU FOR YOUR ATTENTION