Decreasing PV Module Temperature with Thermally Conductive Backsheets

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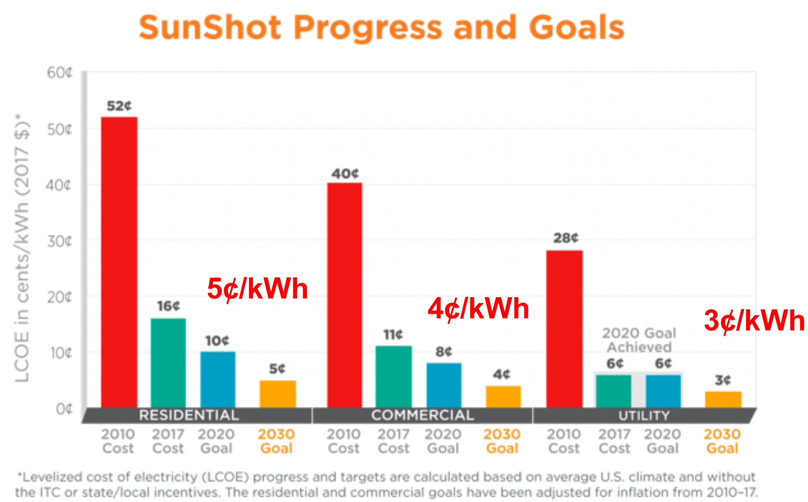
Introduction

Why lowering PV module temperature?

- **Efficiency increase**
  - Thermal property of solar cell
    - ✓ ↓ $T_{cell} \Rightarrow P_{max}$ ↑
      - P_{max}: −0.5%/°C
- **Longer lifetime of PV module**
  - Less thermal stress

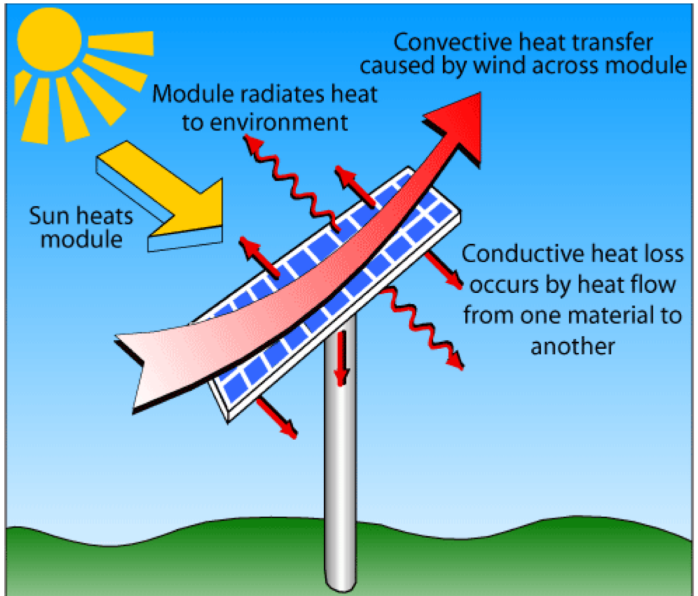


Cell: ~0.6V

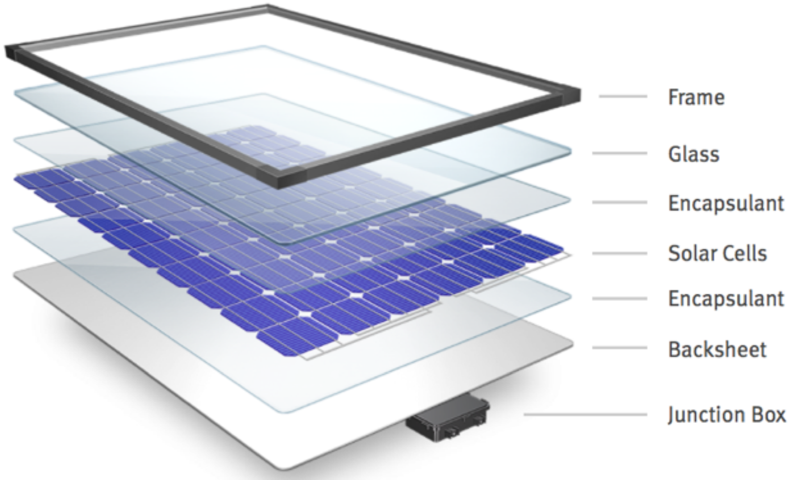
Module: 72 cells, ~43V

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

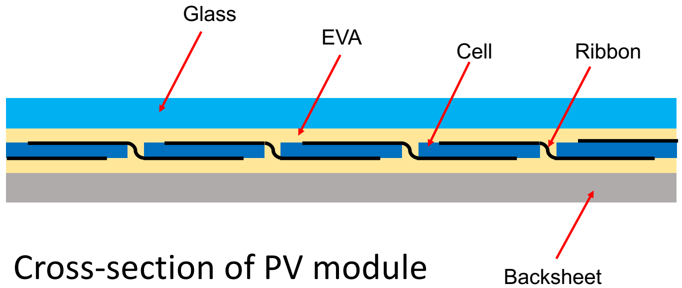
Introduction



Source: http://www.pveducation.org/pvcdrom/modules/heat-loss-in-pv-modules



Source: http://www.dupont.com/products-and-services/solar-photovoltaic-materials/what-makes-up-solar-panel.html#



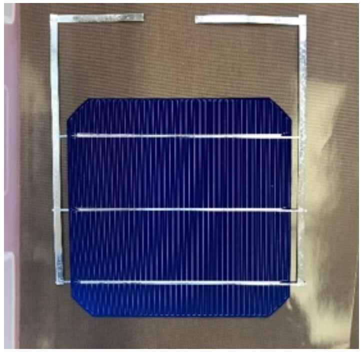
Cross-section of PV module

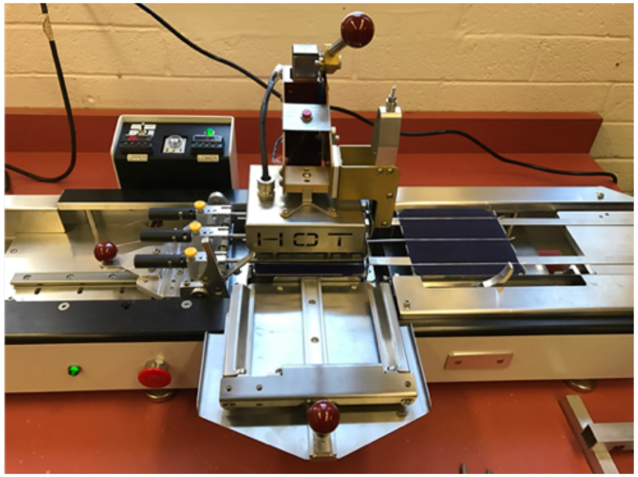
1. Conventional backsheet
   - Tedlar/PET/Tedlar (**TPT**)
     - ✓ Polyvinyl fluoride (PVF)
2. Thermally conductive backsheet (TCB)
   - Polyvinylidene fluoride (PVDF)/PET/EVA → **TCB_A**
   - Polyamide (PA)/Al/PET/PA → **TCB_B**
3. Glass substrate: **G/G**

➢ **Passive cooling method**

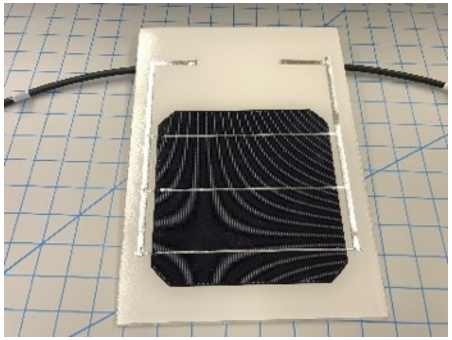
1-cell Module Fabrication

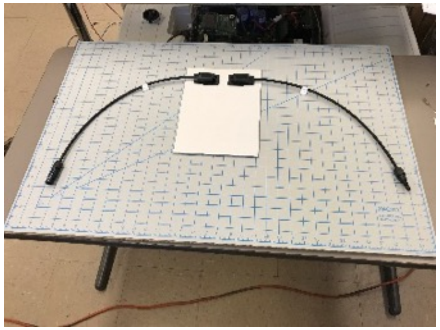
- **Material specification**
  - Cells: 156 x 156 mm^2 mono c-Si solar cells
  - Glass: 8” x 11” Solite low iron Solar glass (3.2 mm thickness)
  - Encapsulant: EVA
  - Backsheets: TPT, TCB_A, TCB_B, Glass
  - Tabbing and bus wires: Sn/PB (60/40)





✓ 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.

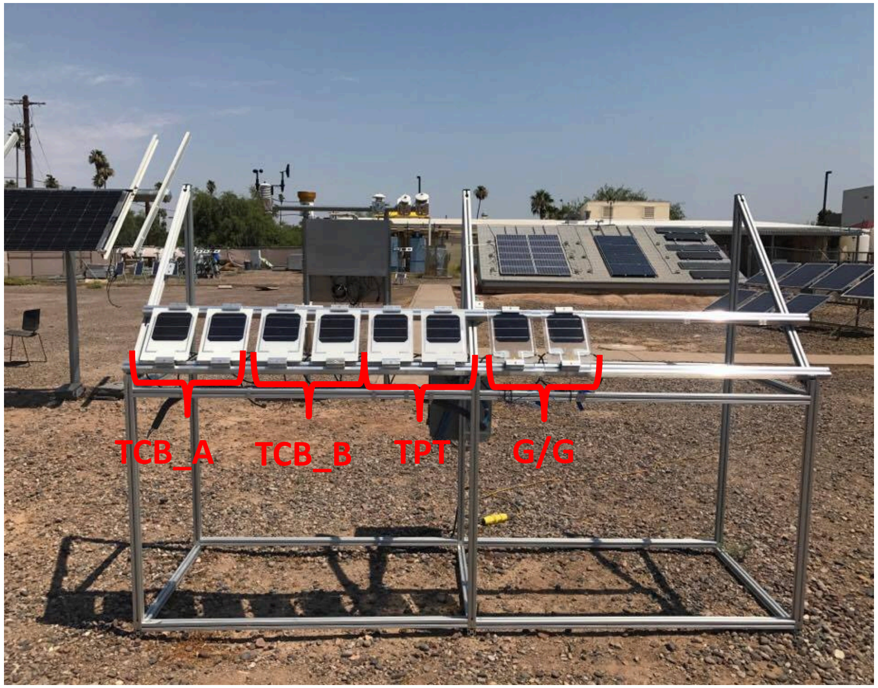
Characterization and Installation

- 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

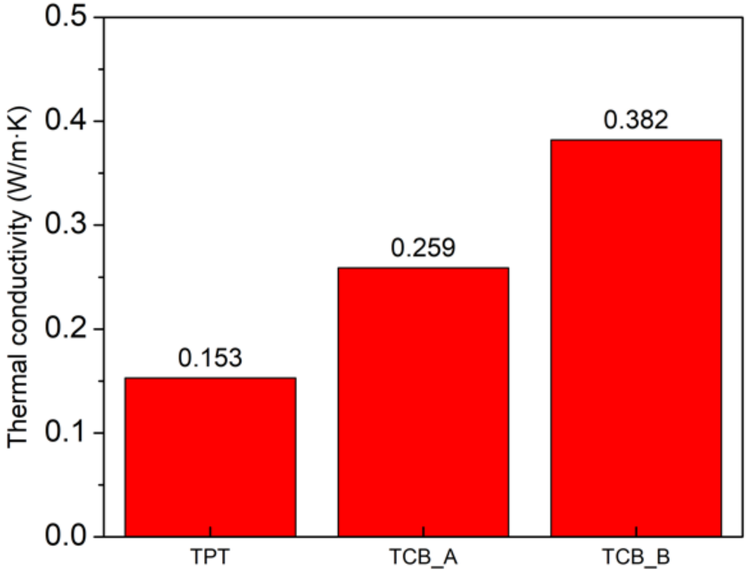
I-V Parameters

Backsheet Type	Isc (A)	Voc (V)	Imp (A)	Vmp (V)	Pmax (W)	FF (%)
TPT	8.902	0.626	8.094	0.4285	3.469	62.2
TCB_A	8.744	0.623	7.995	0.4218	3.372	61.9
TCB_B	8.975	0.625	8.067	0.4269	3.444	61.4

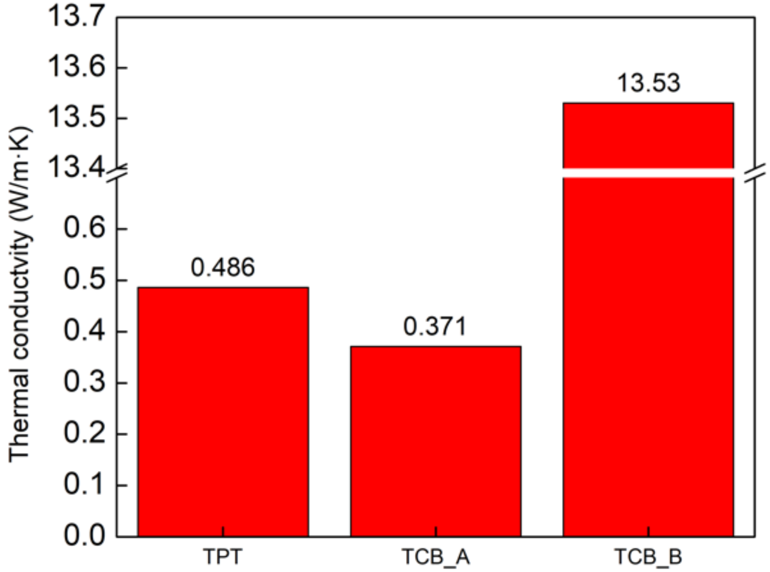


Thermal Conductivity

Axial (through-plane) thermal conductivity



Radial (in-plane) thermal conductivity



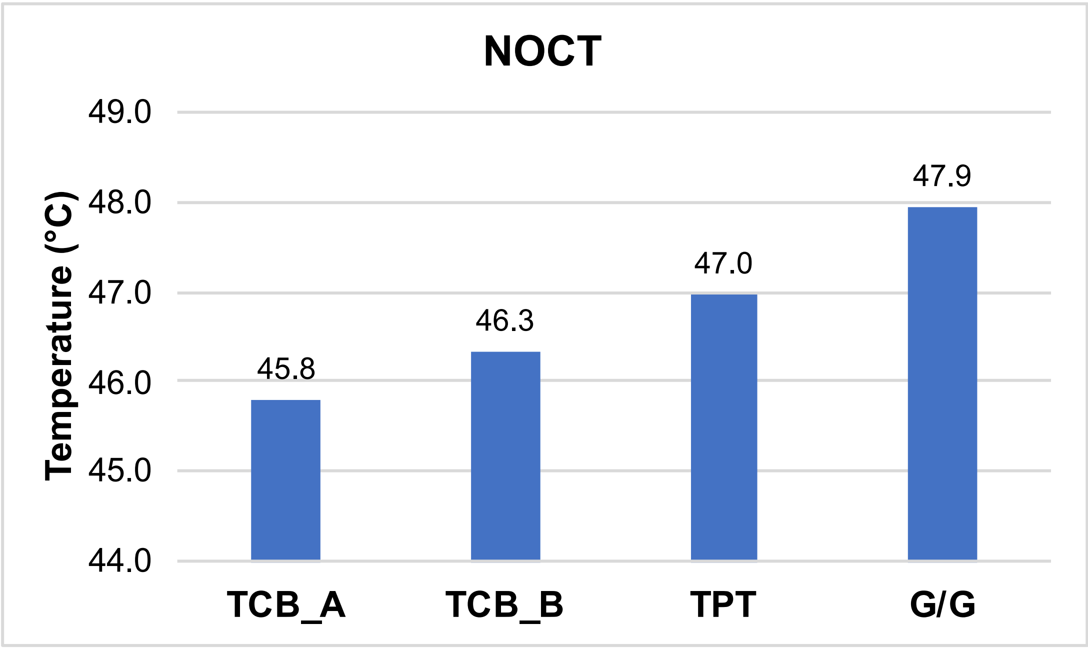
- Both TCBs show higher thermal conductivity than TPT.
- TCB_B has extremely high radial thermal conductivity due the presence of thin aluminum layer.

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/m^2
  - 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

NOCT testing at ASU-PRL

Nominal Operating Cell Temperature (NOCT)

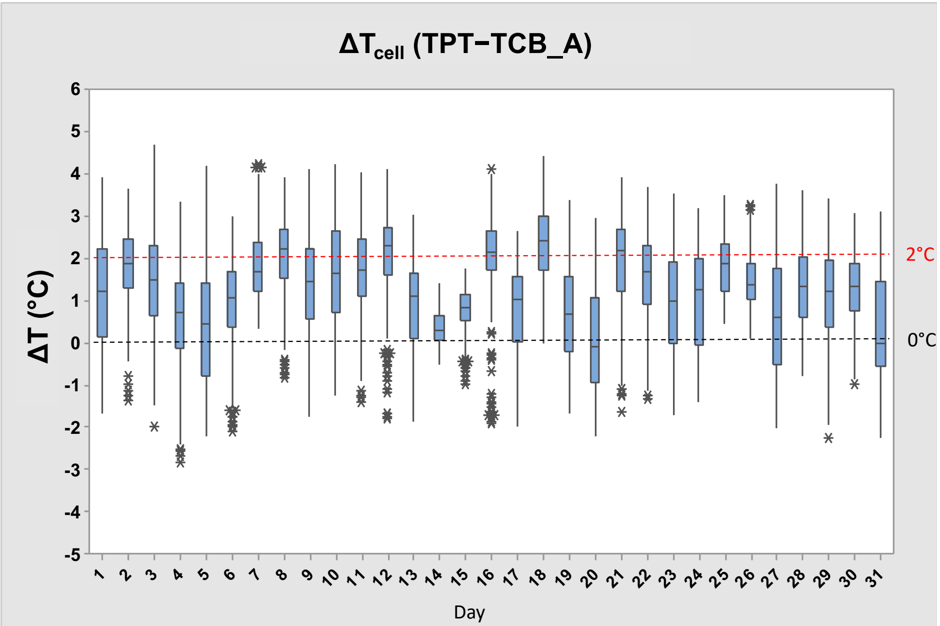


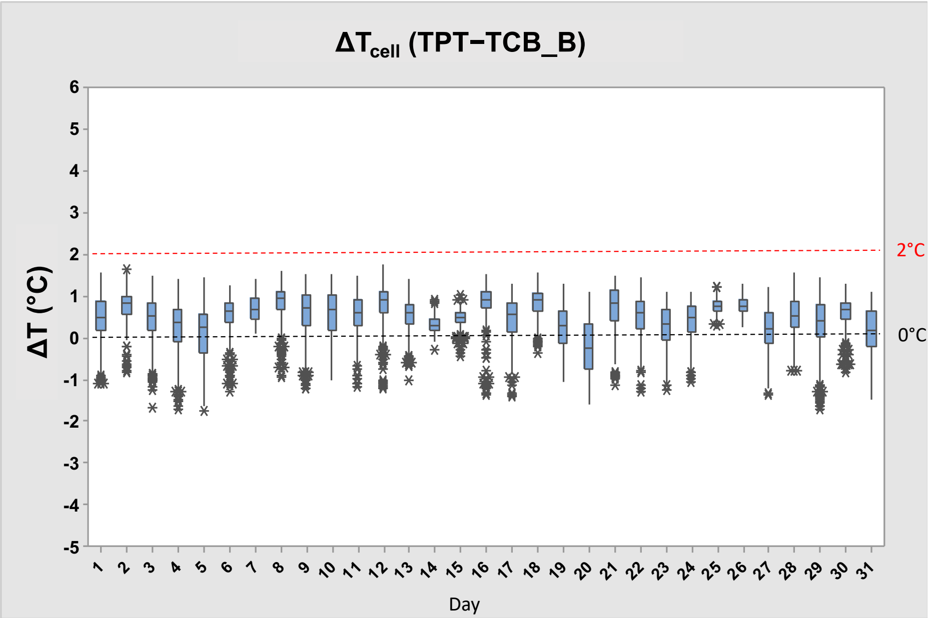
*NOCT value shown here is an average of two coupons per backsheet type

- 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

Daily Operating Temperature

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

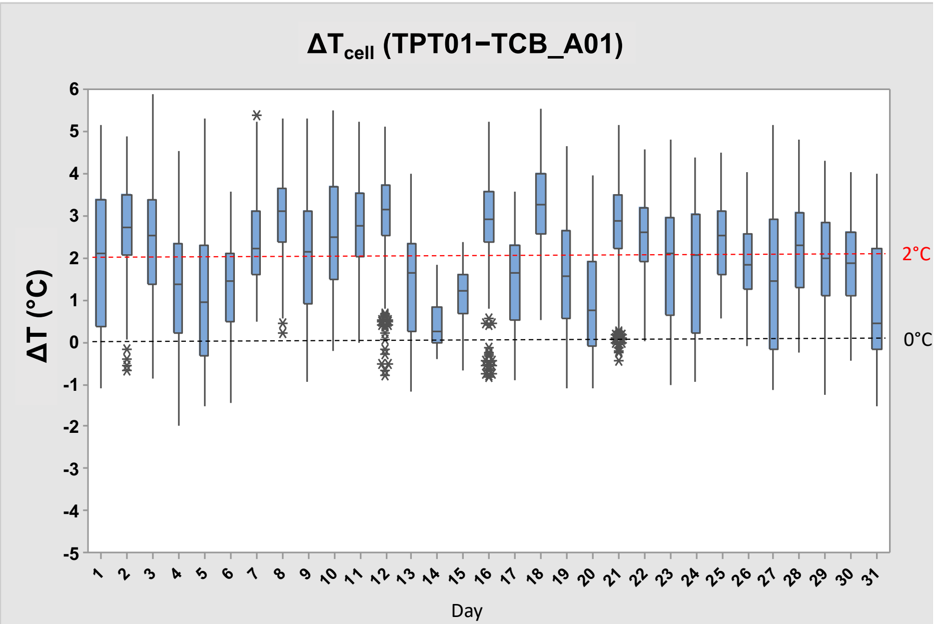




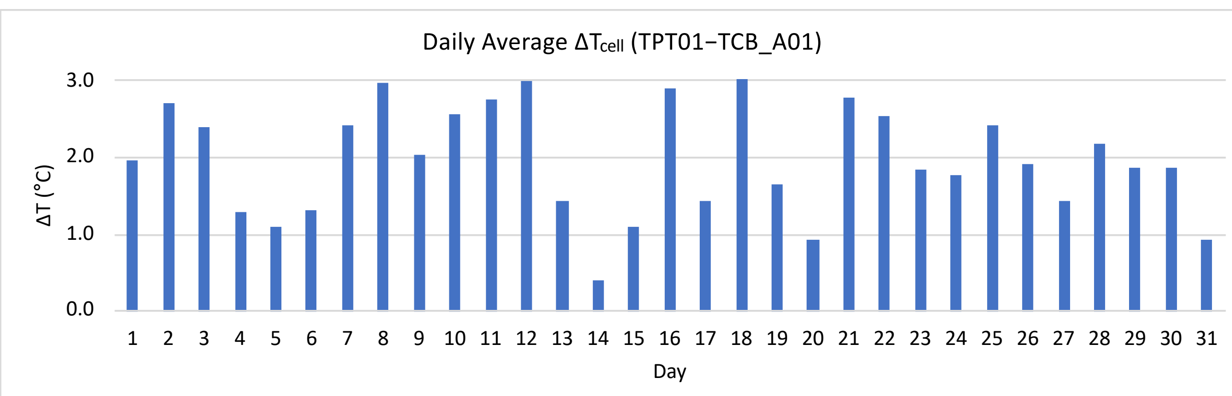
- Overall, TCB_A shows higher ΔT than TCB_B.
- At least one data with ΔT higher than 2°C was observed everyday for the whole month except for two days (May 14 & 15) which were highly cloudy day.
- A daily temperature of >2°C median ΔT is observed for 5 days in a month (May 2017).
- About 0.8°C ΔT observed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

- Data range
  - >400W/m^2 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



- 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

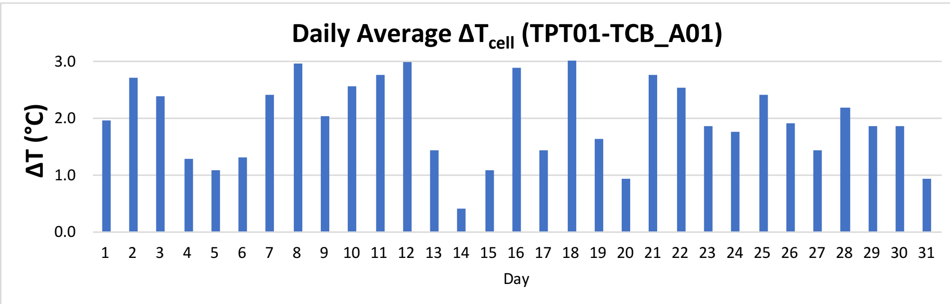


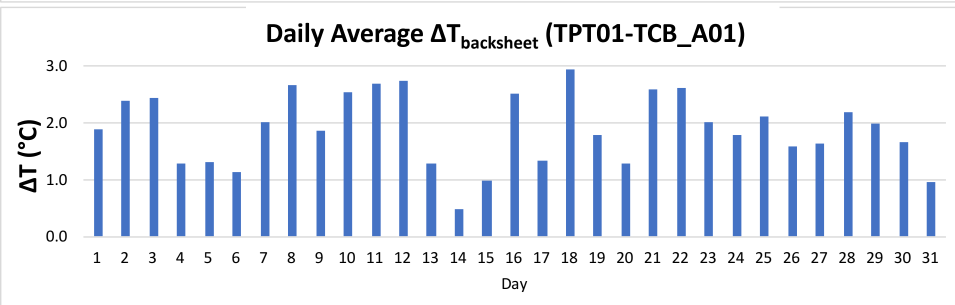
- In May 2017, at least 15 out of 31 days experienced daily average ΔT higher than 2°C.

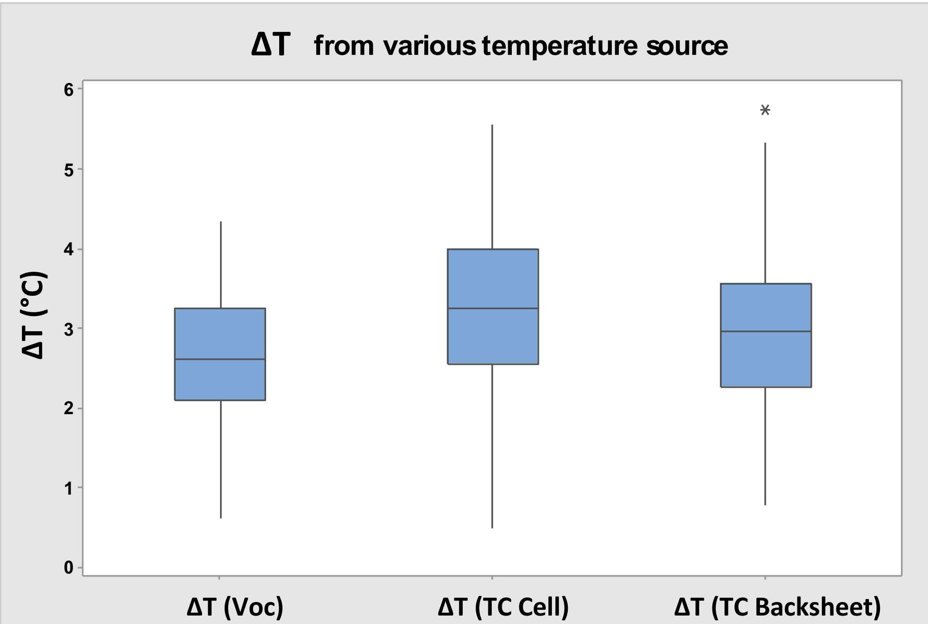
- **The results clearly indicate that TCB_A reduces the operating temperature by at least 2°C as compared to TPT.**

Daily Operating Temperature

T_{Voc} vs. T_{cell} vs. $T_{backsheet}$







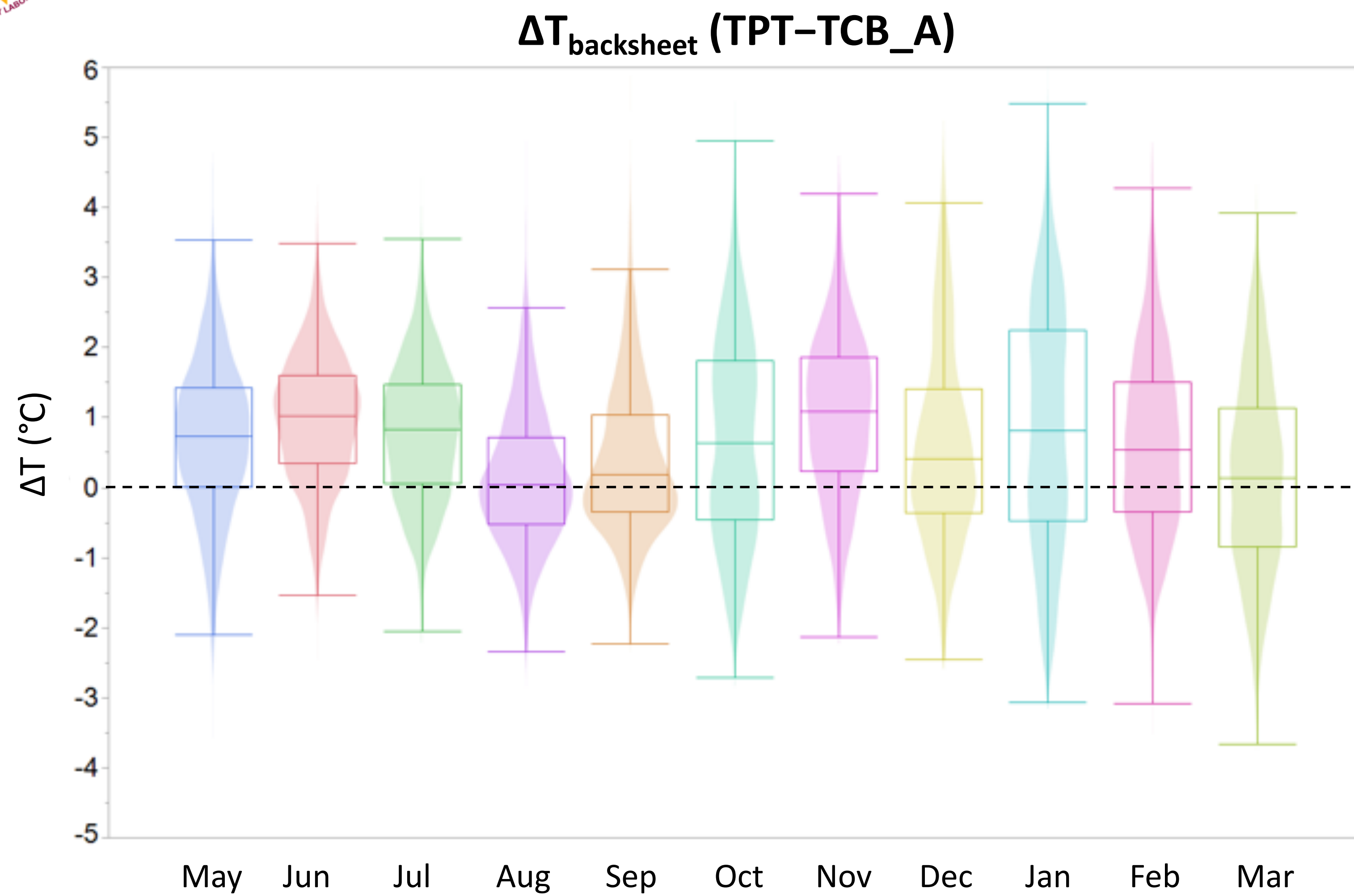
One day data (May 18, 2017)
Maximum irradiance: 933 W/m^2
Maximum ambient temperature: 30°C

- Daily average ΔT_{cell} is higher (0.1-0.3°C) than that of $T_{backsheet}$ for a few days.
- Highest average and median ΔT was observed from ΔT_{cell}

- ΔT_{cell} appears to be slightly better as compared to the one estimated by $\Delta T_{backsheet}$

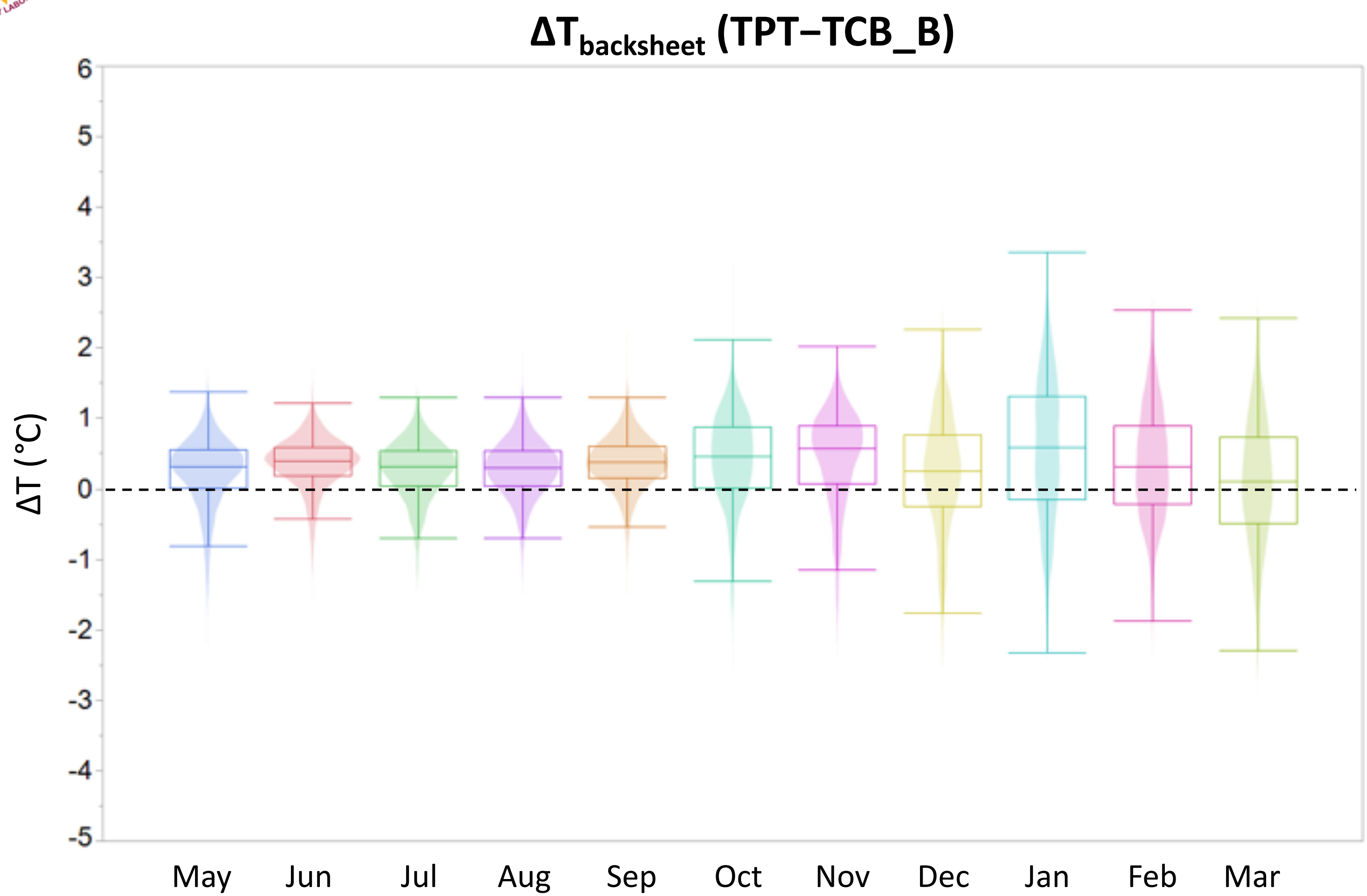
Note: A theoretical Voc temperature coefficient of 2.1 mV/°C is used to calculate delta T (Voc)

Seasonal Effect on TCB Modules



- Monthly variations were observed from TCB_A modules
- Lower thermal performance in August, September, and March
- Overall, TCB_A shows lower temperature than TPT

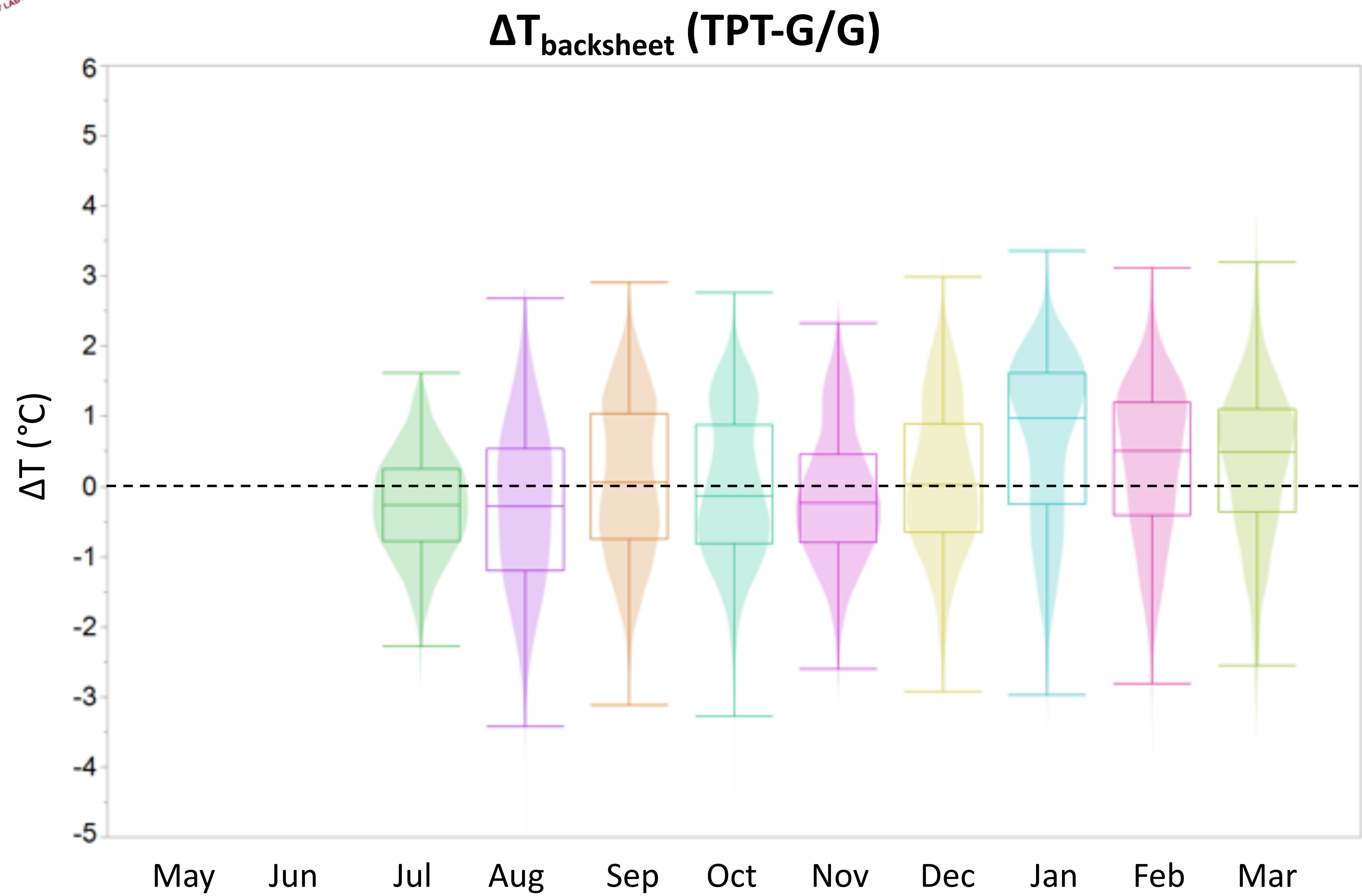
Seasonal Effect on TCB Modules



- Less seasonal influence than TCB_A modules
- Best thermal performance is in January
- 0.5-0.7 °C median ΔT year around

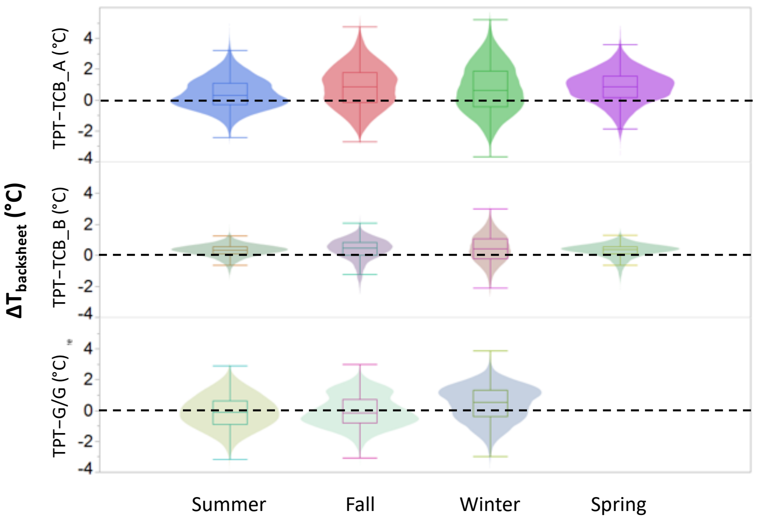
Arizona State University

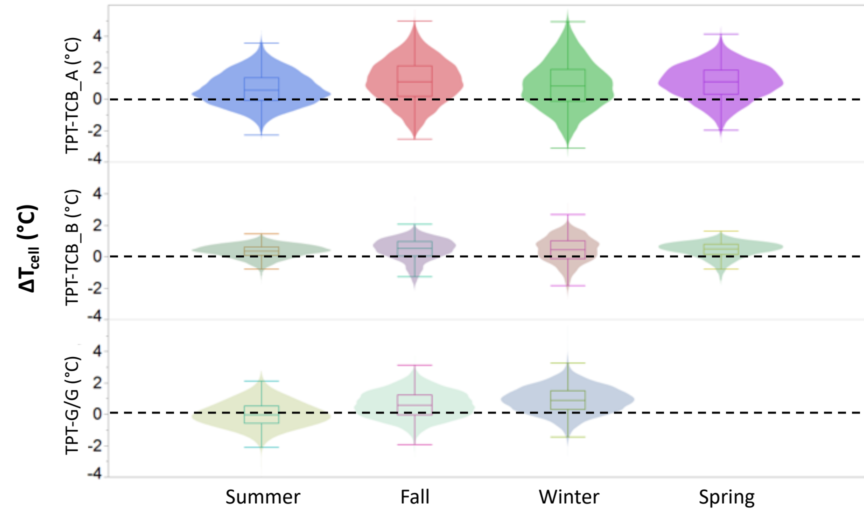
Seasonal Effect on G/G Module



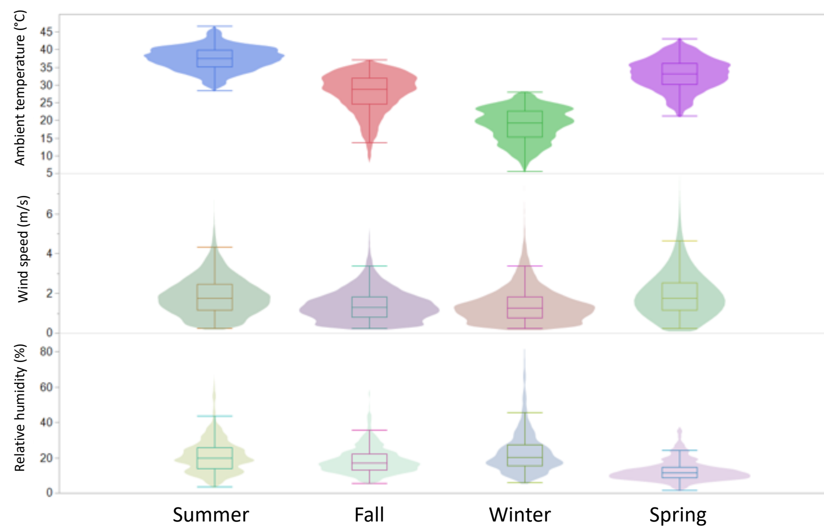
- G/G module showed ~1 °C lower temperature than TPT module in January, February, and March while all other months showed higher temperature than TPT.
- G/G module installation may be a good option for cold region.

Seasonal Effect on TCB modules





Summer: 6/21-9/20
Fall: 9/21-12/20
Winter: 12/21-3/20
Spring: 3/21-6/20



- 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

$$T_{cell} = w_1 \cdot E + w_2 \cdot T_{amb} + w_3 \cdot WS + c$$

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

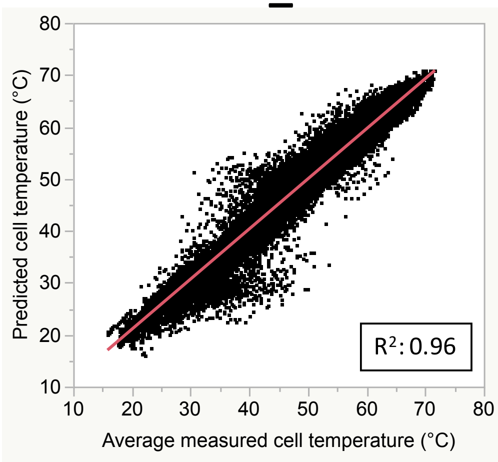
Types	E (w_1)	T_{amb} (W_2)	WS (w_3)	c
TCB_A	0.0300	0.997	−1.484	1.106
TCB_B	0.0312	1.007	−1.439	0.406
TPT	0.0315	1.004	−1.424	0.725
Backsheet Average	0.0309	1.003	−1.449	0.746
G/G	0.0324	1.024	−1.146	−0.265

✓ 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.

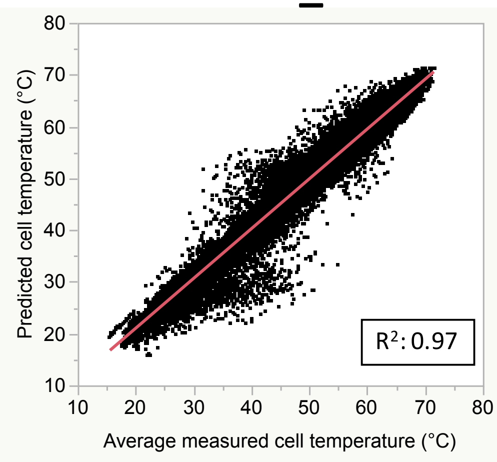
Empirical Thermal Model

TCB_A



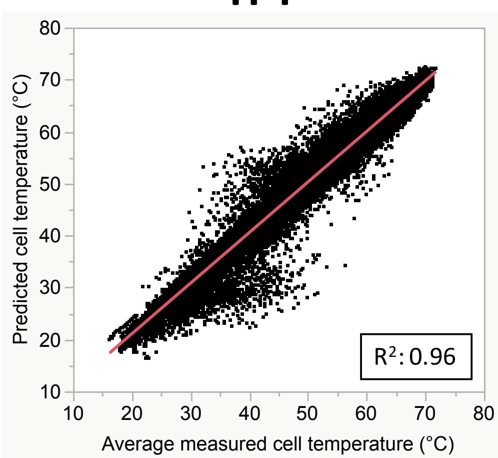
$$T_{cell} = 0.0300 \cdot E + 0.997 \cdot T_{amb} + (-1.484) \cdot WS + 1.106$$

TCB_B



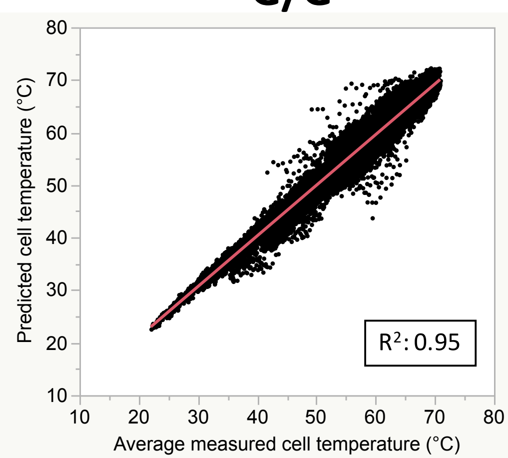
$$T_{cell} = 0.0312 \cdot E + 1.007 \cdot T_{amb} + (-1.439) \cdot WS + 0.406$$

TPT



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

G/G



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

- 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