

Experimental investigation of the temperature distribution in a BIPV façade

Nanna L. Andersen^{*} , Markus Babin , and Sune Thorsteinsson 

Technical University of Denmark, Department of Electrical and Photonics Engineering, Frederiksborgvej 399, 4000 Roskilde, Denmark

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Abstract. This study explores the thermal behavior of Building Integrated Photovoltaics (BIPV) façades, focusing on the impact of different mounting configurations and colored interlayers. Two experimental setups are analyzed to investigate the operating temperatures of PV modules. The first setup consists of single-cell mini-modules including both colored and uncolored modules operating under ventilated and insulated conditions. The Sandia model is utilized to correlate cell temperatures and module backside temperatures, for which new empirical ΔT coefficients are determined for the different configurations and colored interlayers. The second setup consists of a BIPV container with a south-facing 16-module BIPV curtain wall façade. The modules are mounted with different air gap sizes to examine the effects of rear ventilation on module temperature. The results highlight the significant impact of mounting design and display the complicated nature of temperature distribution of BIPV systems. This research aims to contribute to a broader understanding of the influence that BIPV system integration in architecture has on module operating temperatures.

Keywords: BIPV / colored PV / temperature analysis / temperature modelling

1 Introduction and motivation

Building Integrated Photovoltaics (BIPV) consists of photovoltaic materials replacing conventional building materials in parts of the building envelope such as the roof or façades. They serve the dual purpose of providing building element functionality and generating electricity from a renewable source [1,2]. Renewable energy generation is important to reach the goals of reducing reliance on fossil fuels and decreasing greenhouse gas emissions to prevent global climate change. In 2021, buildings represented approximately 37% of global CO₂ emissions [3]. BIPV can be a key factor in reducing CO₂ emissions and assist in working towards a sustainable future.

The dual purpose of BIPV makes it different from conventional PV in a number of ways, such as mounting configuration, orientation, and appearance [4]. These dissimilarities mean that BIPV has different advantages and disadvantages than conventional PV. BIPV can provide more visually appealing solutions as the modules can be designed to blend in with the building’s architecture. Coloration, patterns, and different textures can be used to obtain a certain design [5,6]. This expands the architectural freedom when designing buildings with PV installations [1].

Drawbacks of BIPV are higher costs compared to conventional building materials and traditional PV systems. The higher costs are also linked to lower electrical performance of BIPV due to building orientation, additional shading due to complex building designs and for colored BIPV the addition of colored layers that reflect parts of the incoming light. The non-optimal module orientation, shading, and coloration also affect the operating temperature of the PV modules [7].

Increased operating temperatures decrease the power output of PV systems, mainly due to a decrease in the open-circuit voltage [8,9]. It also negatively impacts long-term reliability due to an acceleration in degradation mechanisms [10]. Operating temperature depends on many factors, including thermal properties of materials, encapsulation, PV cell type, climatic conditions of location, and, most importantly, irradiance, wind, and module mounting configuration [11–14].

Since temperature is an important factor in the performance of PV systems, predicting and monitoring the temperature in PV systems is very relevant. Usually, module temperatures are measured on the surface of the rear side of the module. The actual operating temperature of the PV cell is generally different from this temperature due to cooling of the module surfaces introducing a temperature gradient across its cross-section. Measuring the actual cell temperature requires temperature sensors to

^{*} e-mail: nalan@dtu.dk



Fig. 1. The mini-module setup at Risø, including one clear, two black, one red, one beige, and one terracotta single-cell glass-glass module. This picture was taken in the period when all mini-modules operated in a ventilated condition.

be embedded in the PV laminate, which is difficult to realize in large modules due to a risk of cell breakage and/or moisture ingress along the sensor cables. Only recently have very thin optical sensors been developed, which alleviate many of these problems [15].

Sandia National Laboratories developed a simple model, also known as King's model, which is a commonly chosen method for estimating cell temperature based on the module backside temperature [16]:

$$T_{cell} = T_{bom} + \frac{G_{POA}}{G_0} \cdot \Delta T \quad (1)$$

where T_{cell} is the cell temperature, T_{bom} is the back-of-module temperature, G_{POA} is the plane-of-array irradiance, G_0 is a reference irradiance of 1000 W/m^2 and ΔT is an empirically determined temperature difference.

Introducing colors to a PV laminate alters the module bill of materials. Today there are several options, such as using colored glass, colored interlayers, or colored encapsulants, some with higher maturity than others [6,17]. In [18] it was shown that parasitic absorption in the colorant can contribute to cell heating. When adding a colored material as an interlayer, the thickness and the thermal conductivity of the laminate change, especially since an additional layer of encapsulant is needed as well as the colored interlayer.

Many studies surrounding BIPV have been carried out in recent years, several of which have focused on the temperature of (BI)PV and its impact on performance and reliability. Simulations investigating the effect of differently sized air gaps have been conducted in [19–21]. Smaller scale setups comparing ventilated and insulated BIPV on test buildings or test setups have been investigated experimentally in [7,20,22–24]. Nevertheless, there is a lack in side-by-side comparisons of different BIPV mounting configurations at a larger scale, which may show different effects than small-scale tests. This exposes a need for building-sized test setups with different configurations and spatial temperature analysis of BIPV façades. Validation of the Sandia model and determination of new Sandia ΔT coefficients has been done for open-rack

installations by using different backsheet types [25], but the effect of coloration on the ΔT coefficients has not been explored in literature.

This study aims to validate the Sandia model correlating cell and backside temperature for colored BIPV modules and uncolored BIPV curtain walls for different mounting configurations. This includes validating and improving previously established ΔT coefficients going into the model (for ventilated installations: $\Delta T = 3$; for insulated installations: $\Delta T = 0$ [16]). It also aims to investigate the impact of insulation on the correlation between the cell and back-of-module temperature. Lastly, this study aims to analyze the temperature distribution of a BIPV façade test setup with different mounting configurations.

2 Methodology

2.1 Experimental test setup

This work primarily analyses temperature data from two different outdoor installations. The setups have previously been described in [18,26]. Both are located at DTU Risø campus (55.6958N, 12.1050E) near Roskilde, Denmark.

2.1.1 Colored mini-modules

The first setup consists of six single-cell mini-modules mounted vertically and oriented southwards. Each mini-module is equipped with an integrated thermocouple to measure cell temperature and an externally mounted thermocouple for measuring back-of-module temperature. Both sensors have a nominal uncertainty of $\pm 1.5^\circ\text{C}$ and are connected to the same National Instruments (NI9213) multichannel datalogger with a common cold junction with a nominal typical error of around 1°C . As this error is dominated by the cold-junction compensation accuracy, however, this uncertainty can be reduced to approximately $\pm 0.2^\circ\text{C}$ for temperature differences between two sensors referenced to the same cold-junction [27].

In addition to the integrated temperature sensors, several of the mini-modules include colored interlayers in

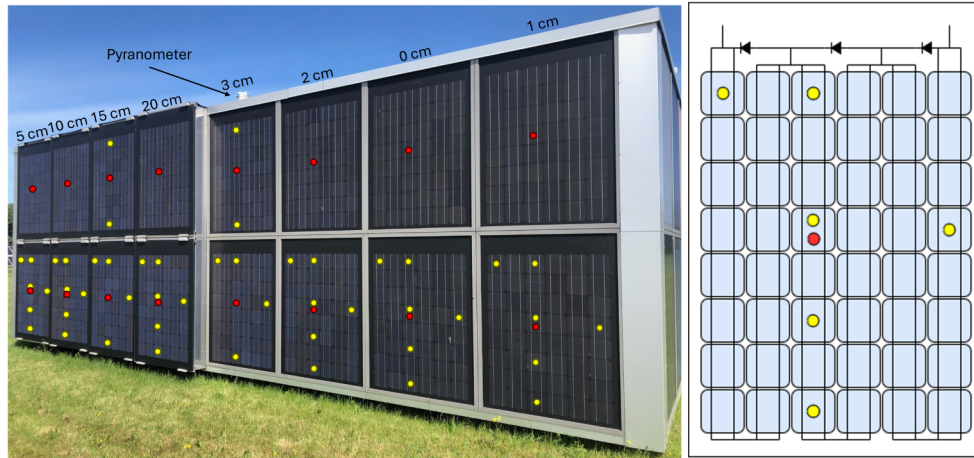


Fig. 2. The south façade of the BIPV container. Eight modules are installed with a small closed cavity between modules and insulation of 0–3 cm (the right part of the façade), the other half is mounted with ventilation at the back of the modules with a gap of 5–20 cm (the left part of the façade). Each colored dot represents a temperature sensor. The red dots are Pt100 sensors while the yellow dots are digital temperature sensors. The figure to the right shows a more detailed illustration of where the sensors are located on the modules.

front of the cells and/or black interlayers behind the cells as seen in Figure 1. As shown in the figure, one mini-module has no interlayers, two samples have black interlayers behind the cells, and three samples contain both black interlayers behind the cells and colored interlayers in front, coloring the mini-module red, beige, or terracotta. The mini-modules are described in detail in [18,28].

For the period from 07-10-2022 to 21-03-2023, the mini-modules were insulated on the backside using 10 cm of mineral wool, while from 28-03-2023 onwards they operated in a condition allowing vertical airflow behind the modules. Mini-module #3 (Black) and #5 (Beige) were operating under open-circuit conditions during the insulated period due to data logging limitations, while the remaining were connected to a shunt resistor operating near short-circuit current (I_{sc}). For the ventilated period, all samples operated near I_{sc} .

2.1.2 BIPV container

A BIPV container is located near the mini-module setup. The container has BIPV curtain wall elements mounted on the east, west, and south façades. This work focuses on the south façade consisting of 16 PV modules. These modules have the same composition as the black reference mini-modules (mini-module #2 and #3) apart from the use of sated glass. In pairs, the 16 modules are mounted in different configurations. Eight of the modules are mounted as rain screens with four differently sized air gaps at the rear to allow for rear ventilation of the modules. The air gaps are 5, 10, 15, and 20 cm. The other half of the modules are mounted without rear ventilation but with a small enclosed cavity between the back of the modules and the wall insulation with cavity sizes of 0, 1, 2, and 3 cm. The setup is shown in Figure 2. The setup is described in greater detail in [18,26].

To map the temperature of the south façade of the BIPV setup, a Pt100 temperature sensor is placed on the back of each module near the center, located directly behind a PV cell. Around 50 one-wire digital temperature sensors (Maxim DS18B20) are also placed at different locations on the backside of the BIPV façade, each measuring back-of-module temperature directly behind a cell. The distribution of the temperature sensors behind the façade is seen in Figure 2. The location of sensors in the bottom row is based on the specification for module temperature measurement in IEC 60891 [29], supplemented with additional sensors along the length of the module. The sensors report temperature measurements every 10 seconds, all Pt100 sensors are of class A and operate in 4-wire mode, and the BIPV façade has been operating since summer 2022. To compare the digital and Pt100 sensors, a digital sensor was placed behind the same cell as the Pt100 sensor on each module. Generally the agreement between the two sensor types is good, however small offsets were seen, possibly due to differences in how the sensors adhere to the modules backside. The digital sensors on the lower modules of the 10 cm and 20 cm air gap have been experiencing problems and are excluded from the analysis.

2.1.3 Additional measurements

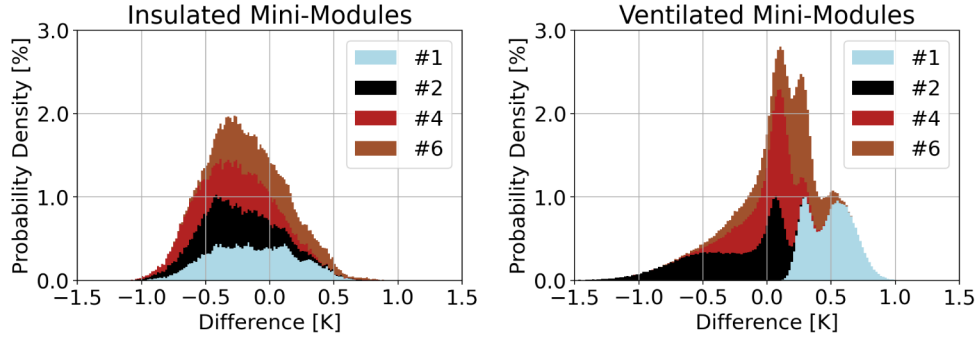
Pyranometers located at the top of each face of the container measure plane-of-array irradiance. Ambient temperature is measured at a nearby weather station on DTU Risø Campus along with wind direction and speed. Infra-red Thermography (IRT) is performed using a FLIR E96 camera to investigate the temperature distribution of the BIPV façade.

2.2 Data filtering

The temperature analysis of the two PV setups mainly consists of clear-sky data. This is chosen because the

Table 1. Number of clear-sky days in each season for each setup.

Setup	Winter	Spring	Summer	Autumn	Total
Mini-module, insulated	5	2	0	1	8
Mini-module, ventilated	0	16	12	3	31
BIPV container façade	1	7	0	0	8

**Fig. 3.** Accumulated probability density of the temperature difference between measured and modeled cell temperature for mini-modules #1 (clear), #2 (black), #4 (red), and #6 (terracotta).**Table 2.** ΔT coefficients for the mini-modules (with effective irradiance corrected plane-of-array irradiance). *Mini-modules #3 and #5 were operating at open-circuit in the insulated configuration.

Module	Insulated ΔT	Ventilated ΔT
#1 Clear	0.65	2.42
#2 Black	0.46	4.21
#3 Black	0.12*	3.1
#4 Red	0.62	3.55
#5 Beige	0.48*	2.65
#6 Terracotta	0.58	3.63
Average	0.49	3.26
Sandia report	0	3

modules experience the largest temperature differences on clear-sky days and the thermal capacitance of the modules makes analysis under rapidly changing conditions difficult. As the setups have been operating at different periods, an overview of the number of clear-sky days in each season the data is based on is shown in Table 1. To avoid including night-time data, any data point with a plane-of-array irradiance lower than 20 W/m^2 is disregarded. The clear-sky days are chosen based on individual assessments of the daily global horizontal irradiance.

3 Results and discussion

3.1 Mini-modules

3.1.1 Validation of the Sandia model

To validate the Sandia cell temperature model for colored BIPV with insulated and ventilated module configurations, the cell temperature of each mini-module is calculated based

on the measured back-of-module temperature using equation (1). The calculated cell temperature is compared to the measured cell temperature and Figure 3 shows histograms of the difference between the calculated and measured cell temperatures for clear-sky days for the ventilated and insulated mini-module setup for mini-modules #1, #2, #4 and #6. Mini-modules #3 and #5 are excluded in this analysis since they operated at open-circuit voltage for the insulated period. For the ventilated period, the cell temperature is calculated using $\Delta T = 3$, which is recommended for open rack systems, while for the insulated period $\Delta T = 0$ is used as the most fitting from [16].

As it can be seen from the figure both for the insulated and ventilated configuration the Sandia model predicts the cell temperature based on the backside temperature within $\pm 1 \text{ K}$ on clear-sky days for this setup. For the insulated configuration, the Sandia model slightly underestimates the cell temperature, while for the ventilated configuration, the model slightly overestimates. Error metrics for the model can be seen in Table 2 in Section 3.1.3. This table also includes validation of the Sandia Model for all weather conditions for 6 months from October to April for both configurations (2022–2023 for the insulated and 2023–2024 for the ventilated configuration).

As seen from Figure 3 for the insulated configuration, the model predicts the cell temperature equally well for all mini-modules, contrary to the ventilated configuration where the distribution of the temperature difference between modeled and measured seems to vary depending on the mini-module. To look further into this difference between modules, the distribution for all six mini-modules can be seen in Figure 4.

From Figure 4, it can be seen that some of the mini-modules show multiple error peaks when applying the Sandia model. The darker part of the plotted data corresponds to the difference between modeled and

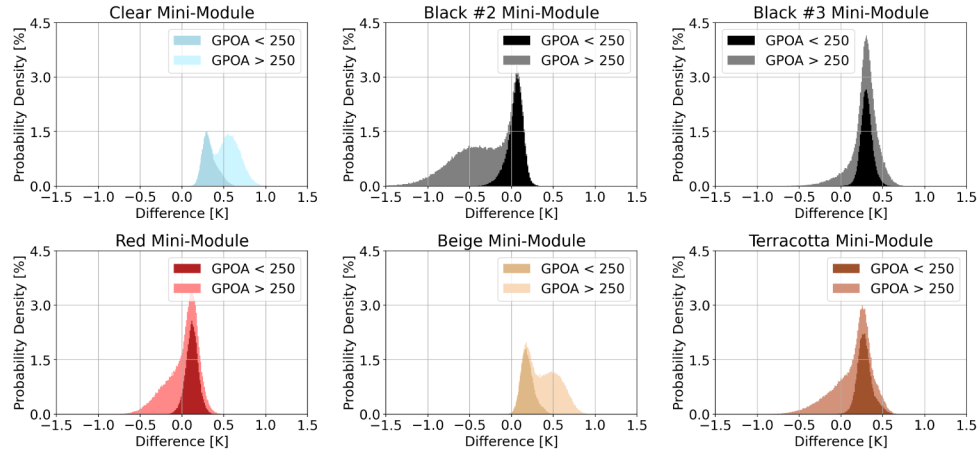


Fig. 4. Histogram of the temperature difference between measured and modeled cell temperature for all mini-modules in the ventilated configuration.

Table 3. Error metrics for the validation of the Sandia model. The validation of the model with the customized ΔT coefficients is only based on clear-sky days.

	Clear-sky	Insulated All	Custom ΔT	Clear-sky	Ventilated All	Custom ΔT
MAE	0.30	0.24	0.24	0.29	0.24	0.27
MBE	0.17	0.04	-0.15	-0.10	-0.10	-0.26
Std	0.33	0.37	0.27	0.36	0.34	0.17

measured temperature for measurements where the plane-of-array irradiance was lower than 250 W/m^2 , while the lighter colored part corresponds to differences measured at times when the plane-of-array irradiance was higher than 250 W/m^2 . The peak for the darker colors (low irradiance) lies between 0 and 0.5 K for all mini-modules. The lighter-colored data (high irradiance) is distributed differently for the different mini-modules.

For the clear and beige module, the model overestimates the high irradiance data more than the low irradiance, as seen by the lighter-colored peak at the right side of the dark peak. This could indicate that the ΔT coefficients for these modules are too high since the coefficient has the most influence on the modeled cell temperature at times with higher irradiance. For the black module #3 the distribution of low and high irradiance temperature differences overlap well, while for the three remaining modules (black #2, red, and terracotta) the model mostly underestimates the cell temperature at times with high irradiance.

The fact that the clear and beige modules experience the same trend with the overestimation of the cell temperature indicates that the light color of the beige module and the missing black interlayer in the clear module result in lower heat absorption around the cell which impacts the relationship between cell and module backside temperature. To further investigate the correlation between cell and module backside temperature in the mini-modules, individual ΔT coefficients were calculated.

3.1.2 Determination of ΔT coefficients

The ΔT coefficients recommended by SNL is determined based on empirical data [16]. Since the model seems to perform differently for the different mini-modules, ΔT coefficients are determined for each of the mini-modules based on the measured cell and backside temperatures, both for the ventilated and insulated configuration. The values found for ΔT for each module can be seen in Table 3.

The coefficients are determined as the slope of the linear fit of the difference between cell and module backside temperature as a function of the plane-of-array irradiance over reference irradiance of 1000 W/m^2 . The plane-of-array irradiance is reflection corrected for the colored modules using the relative effective irradiance described in [18]. This correction is added to account for the loss caused by the reflection from the colorant. Figures 5 and 6 show the linear fit for each mini-module for both the insulated and ventilated configuration respectively. For both configurations data recorded before solar noon on the clear-sky days is a lighter color (labeled ‘Morning’) than data recorded after solar noon (labeled ‘Afternoon’).

As seen from Figure 5, there is a distinct difference between before and after noon for all modules in the insulated configuration, which is not seen for the ventilated configuration in Figure 6. In the figure, it can be seen that before noon (when the irradiance at the module and temperature of the module is increasing) the temperature

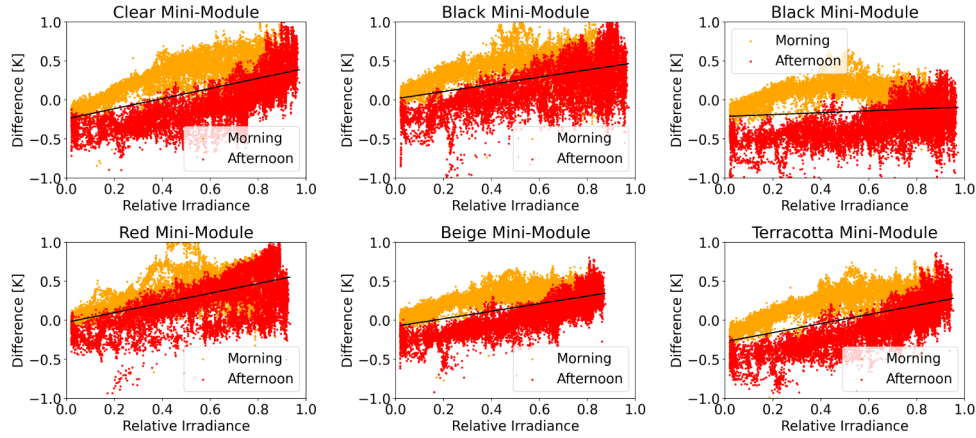


Fig. 5. Difference between cell and backside temperature as a function of relative plane-of-array irradiance for all mini-modules during clear sky days in the insulated configuration.

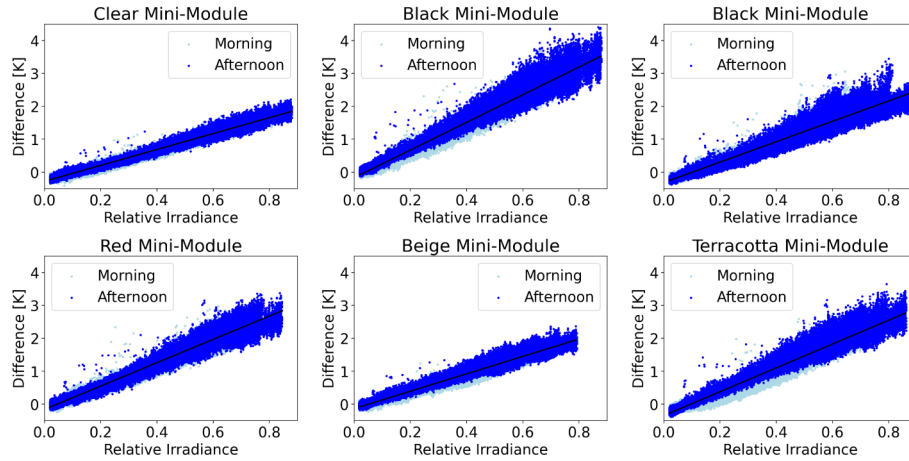


Fig. 6. Difference between cell and backside temperature as a function of relative plane-of-array irradiance for all mini-modules during clear sky days in the ventilated configuration.

difference is positive meaning that the cell temperature is slightly higher than the module backside (0–0.5 K). For the afternoon (when the irradiance at the module and the temperature of the module is decreasing) the difference between the cell and module backside temperature is negative, meaning the cell is cooler than the module backside. Due to the insulated back, the module heat is mostly dissipated from the front side, and the back-of-module temperature is significantly influenced by the thermal diffusion of the complete thermal system. This indicates that the thermal capacitance of the glass-glass PV modules only leads to significant hysteresis in the thermal balance when cooling is restricted through insulation of the module.

This is not the case for the ventilated modules as the backside cooling is not limited. The backside heats up through frontside irradiance delayed by the thermal capacitance. In the afternoon the cooling is not limited like in the insulated case, therefore the backside will always be cooler than the cell.

The difference in plane-of-array irradiance for the two configurations is due to the setups operating at different times of the year. Since the setup is mounted vertically and oriented southwards, in winter when the setup was insulated the Sun is low in the sky leading to high plane-of-array irradiance, while during the summer when the setup was ventilated, the Sun is higher in the sky giving lower plane-of-array irradiance. The variations in plane-of-array irradiance between the modules are due to the effective irradiance correction of the colored modules. Outliers in the plots in Figures 5 and 6 may be due to small variations and imperfections in the irradiance during some of the clear-sky days.

Table 3 lists the slopes of the linear fits from Figures 5 and 6. For both the insulated and ventilated configuration the ΔT coefficients of the clear and beige mini-module are below the averages for the six mini-modules. The lower values for the clear and beige modules are consistent with the tendencies from the previous section where the model overestimated the cell temperature for these modules, especially for the ventilated period.

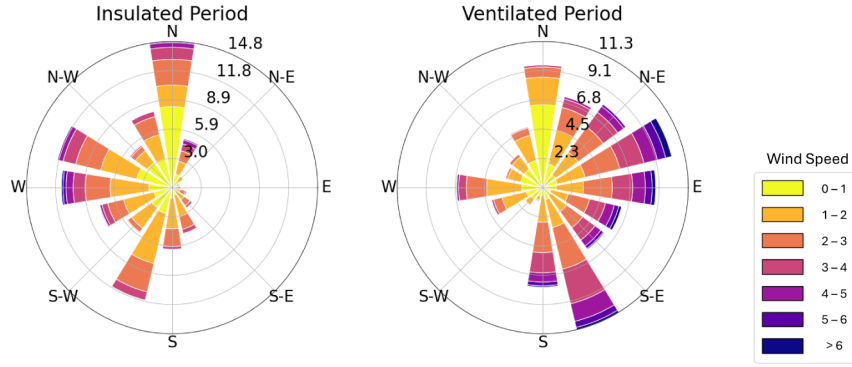


Fig. 7. Distribution of wind on the insulated clear-sky days (left) and the ventilated clear-sky days (right). The r-axis indicates the percentage of the total time that the wind has been in a certain direction and at a certain speed. The wind speeds are measured in m/s.

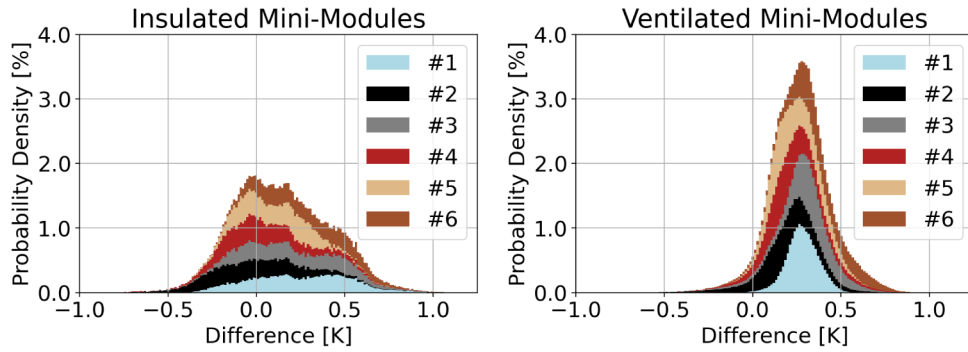


Fig. 8. Accumulated probability density of the temperature difference between measured and modeled cell temperature for mini-modules with the individually determined ΔT values.

The uncertainty of these ΔT coefficients is affected by both measurement uncertainty and the relatively poor fit in the insulated configuration, due to the thermal capacitance of the modules. Nevertheless, the deviations from the standard values in the Sandia Cell Temperature model follow the expectations from Figures 3 and 4.

As can be seen from Table 3 and Figure 4 there is a distinct difference between the two black reference mini-modules despite them having the same composition: Mini-modules #3 and #5 were operating at open-circuit in the insulated configuration whereas the remaining mini-modules were operating near short-circuit current. It is unsure if this had an impact on the difference between cell and module backside temperature of the mini-modules and is marked with a * in Table 3. Since the black reference modules are acting differently for both the insulated and ventilated configuration, the different operating points in the insulated period do not adequately explain the discrepancies. Another possible explanation could be their different positioning on the board, exposing the mini-modules to different wind conditions. The distribution of wind speed and direction on the analyzed clear-sky days can be seen in Figure 7. In the winter period where the mini-modules were insulated, the wind came primarily from the north or west on the clear-sky days, while in the ventilated period during summer, the wind mostly came from the south and east. The wind tends to be stronger on clear-sky days in the summer period. This does not appear to explain

any of the differences seen between the modules but might need further investigation.

3.1.3 Validation of Sandia model using customized ΔT coefficients

The Sandia model with the new ΔT coefficients determined in the previous section is applied to the mini-module setup for clear-sky days and the difference in modeled and measured cell temperature is shown in Figure 8.

Comparing the difference in modeled and measured cell temperature for the Sandia reported and the customized ΔT coefficients (Figs. 3 and 8), it can be seen that the distribution of the difference in the ventilated case becomes narrower and more symmetrical. For the insulated configuration, the customized ΔT coefficients seem to have less of an effect on the shape of the total distribution.

To assess the effect of the individually determined ΔT coefficients error metrics including Mean Absolute Error (MAE), Mean Bias Error (MBE), and the standard deviation (Std), are calculated and shown in Table 2. The error metrics for the custom ΔT coefficients are determined for clear-sky days only and compared to the error metrics when using standard Sandia model coefficients, both for the same clear-sky days as well as for a data set combining all weather conditions for a period from October to April (2022–2023 for the insulated, 2023–2024 for the ventilated case).

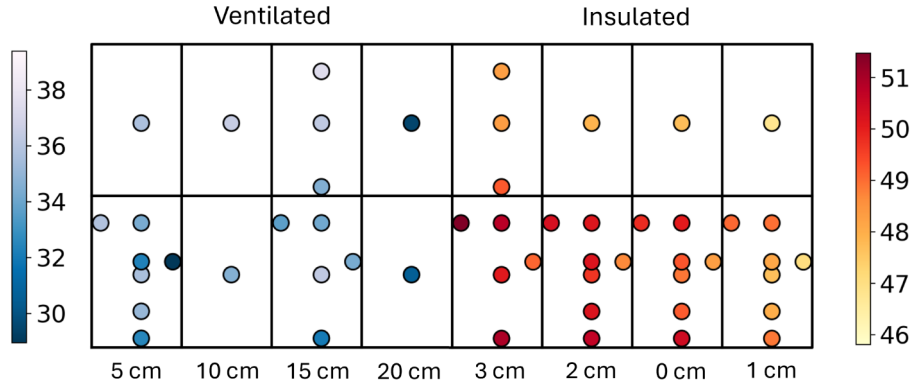


Fig. 9. Average max temperature of clear-sky days during winter and spring 2023. The position of the points represents the physical position of the sensor while the color represents the average max daily temperature in °C.

From the table, it can be seen that for the ventilated configuration the model performs equally well for all weather conditions and clear-sky days only. The MAE is approximately the same for all the cases for the ventilated configuration. The MBE is further from 0 for the customized coefficients, while the std is lower which can also be seen as a narrower distribution shifted lightly towards higher values in Figure 8 compared to Figure 3. This indicates an offset between cell and module backside temperatures that the model is not accounting for. The offset might be due to radiative losses from the PV cells, due to the higher emissivity of Si compared to glass, which leads to consistent temperature differences of around 0.3 K, however further investigation is required.

For the insulated configuration, Table 2 shows roughly the same tendencies with a relatively constant MAE for all cases. Using custom coefficients results in a slightly lower std and an MBE further from 0, at least compared to the case with all weather conditions. That case, however, has an MBE very close to 0, indicating that over time the cell and module backside temperatures average out to almost the same, despite significant deviations shown by the MAE. For the custom ΔT coefficients the distribution of the difference between predicted and measured cell temperature remains relatively wide and flatter, caused by the hysteresis seen for the insulated configuration.

While this analysis has been performed for single-cell PV modules operating close to open-circuit or short-circuit, the general analysis should hold true for larger modules as well. As the sensors were located in the center of the cell, edge effects should have been largely avoided, however the cell-module coverage area will affect the amounts of absorbed irradiance converted to power and heat. In addition, due to mounting structure differences, air flow behind and in front of modules will be affected, thus requiring configuration-specific measurements. At the maximum power point, cells will be operating slightly cooler, as energy is extracted and does not contribute to heating, however this should not significantly effect the difference between cell and back-of-module temperatures.

3.2 BIPV container

From the analysis of the mini-modules, it is clear that the mounting configuration affects the temperature, which is in agreement with literature [30]. The influence of mounting configuration on module temperature is therefore also investigated on the larger setup.

3.2.1 Temperature distribution of BIPV façade

Figure 9 shows the distribution of the average maximum temperature of each temperature sensor on the BIPV container south façade on a selection of clear-sky days. The points in the figure are located at the approximate location of the temperature sensor on the façade.

It shows a clear difference of around 20 K between the hottest and coolest sensors. As expected the coolest parts of the sensors are in the ventilated region, while the hottest are in the insulated. The coolest sensors are located on the right-most row (20 cm column) as expected due to the large air gap of 20 cm. The lower outermost ventilated module (5 cm) also shows a cold sensor on the right side of the module. For the insulated part of the façade, the left-most row (3 cm) shows the highest temperatures despite having the largest closed cavity before insulation. Differences between the individual columns are less pronounced than in the ventilated section, nevertheless, temperatures decrease towards the edge of the setup, likely due to wind effects. The size of the closed cavity between the modules and insulation does not appear to affect the temperature. Based on the modules with multiple sensors, the figure also shows that the modules experience large temperature differences within the module. This is especially true for the lower left ventilated module, experiencing a difference in maximum temperature of approximately 6 K.

To highlight the vertical temperature gradient of the two different configurations, the temperature of six sensors for each configuration located at different heights during a clear-sky day is shown in Figure 10. The color of the lines indicates the height of the sensor: Darker colors refer to sensors near the bottom, lighter colors near the top of the façade.

The figure shows the higher temperatures experienced by the insulated modules in comparison to the ventilated modules on clear-sky days. The temperature span between

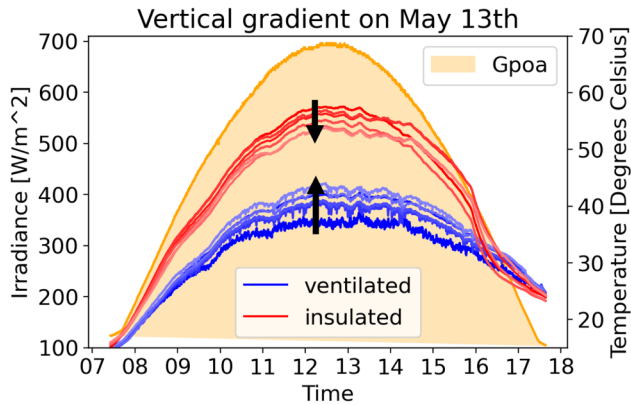


Fig. 10. Example day of May 13th, 2023 – showing data from the 3 cm column (insulated) plus the 20 cm column (rear-ventilated). Showing the temperature development on a clear-sky day for sensors installed at different heights. The lighter the color of the graph, the higher the sensor placement. Arrows point from the lowest-placed sensor to the highest-placed sensor for each mounting configuration.

the hottest and coolest sensors for both mounting conditions is of the same approximate magnitude of 5–10 K. Despite the difference between cell and module backside temperature, this indicates a significant thermal mismatch within the vertical columns of the façade as well as within the modules themselves. In the ventilated part of the façade, the temperature rises with sensor height, while the opposite is true for the insulated section. This is attributed to a chimney effect, where the natural convection is driven by air density differences caused by temperature differences, while the temperature differences in the insulated section can be explained through better ventilation due to stronger wind near the top of the façade.

To further investigate the temperature distribution of the façade the temperature measurements were verified using Infrared Thermography (IRT) on a clear-sky day in June. The result is shown in Figure 11 for the ventilated part of the façade.

Ignoring the fence placed approximately 5 meters in front of the setup and the long grass underneath it, Figure 11 shows the same trends as the temperature sensors in Figure 9 with the coolest part of the façade being the 20 cm column (right-most ventilated column) and the right side of the 5 cm column (left-most column). Apart from having the largest air gap, the cooler temperature of the 20 cm ventilated column could also be influenced by the large gap between the insulated and ventilated modules. Though there is a vertical separator between the sections, the 20 cm column might be cooler since the air hitting it has not been heated by the surrounding modules due to the 20 cm distance to the insulated modules on the right side and the 5 cm gap to the 15 cm column on the left. It could also be due to grass underneath the modules limiting proper airflow behind the modules, the 20 cm being large enough to not be affected by the grass and therefore experiencing more effective circulation behind the module than the other columns. This could suggest that there is a threshold for how large the rear-side air gap has to be in this specific

setup for the grass to not limit airflow at the bottom of the façade. This could be a potential reason that for this setup the rear ventilation appears to not scale linearly with the module temperature.

The left image in Figure 11 shows the lower left-most module, where the right side of the module appears cooler than the rest. This effect could be caused by the vertical separators between the ventilated columns. When the wind is coming from the east or west, it could generate more cooling near these separators. It is also important to note that it is not an effect of shading, as the IRT images were taken in the afternoon. On the contrary, a shading effect can be seen on the left-most part of the insulated modules (3 cm column). This has been observed in the afternoon due to the outwards extended rear-ventilated modules as seen in the left image in Figure 11. This effect is not seen in Figure 9 since it only represents daily maximum temperatures, that on clear-sky days occur around midday.

The analysis of the BIPV façade shows how complicated the temperature distribution of larger façades can be. Many different factors play a role and generalising can be difficult. To get a better understanding of the involved phenomena, further work could include detailed thermal and fluid dynamic simulations.

4 Conclusions

Temperature analysis of two different BIPV setups has been conducted. The setups include a vertically mounted BIPV curtain wall with insulated and rear-ventilated modules with various closed and open cavity sizes along with six vertically mounted colored and uncolored single-cell mini-modules operating with and without allowing rear-ventilation.

The Sandia model correlating cell and module backside temperature was implemented on the mini-module setup. It showed good results predicting the cell temperature within $\pm 1^\circ\text{C}$ for all mini-modules on clear-sky days.

In an attempt to improve the predictions, new ΔT coefficients were calculated for the six mini-modules with averages of 0.5°C for the insulated mounting configuration and 3.3°C for the ventilated, compared to the recommended coefficients of 0°C and 3°C . For the ventilated configuration the determined coefficients improved the precision of the prediction but shifted the predictions towards overestimation, revealing a temperature offset that the model is not accounting for. For the insulated configuration, the customized coefficients had a small impact due to thermal hysteresis behavior during clear-sky days. This is caused by the limited backside cooling and thermal capacitance of the glass-glass modules. This behavior is not seen for the ventilated configuration, due to convective cooling of the backside.

For both configurations, the results indicate that absorptive coloring layers in glass-glass modules affects the relationship between cell and backside temperature. Despite the impact of coloration, the existing coefficients yields fairly accurate cell temperature estimates as long as the irradiance is corrected for reflection losses. The introduction of absorptive coloring layers only has a small

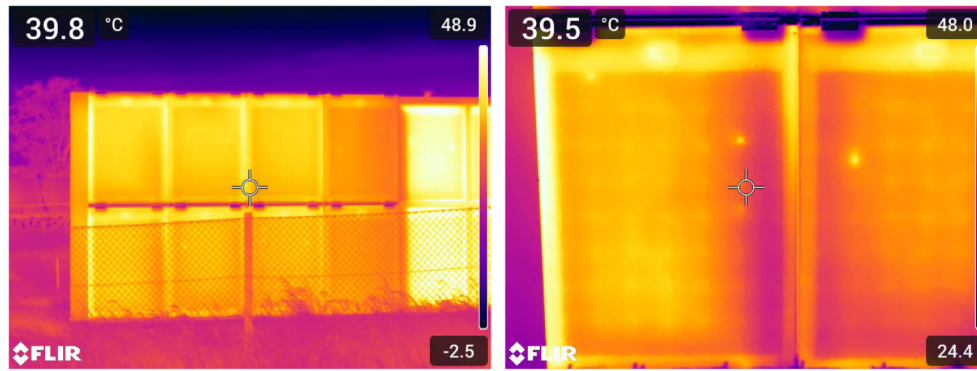


Fig. 11. IR images of ventilated modules on the BIPV façade (left) and the lower left-most module (right). The rear side ventilation on the left image is 5 cm, 10 cm, 15 cm, and 20 cm from the left. This was a relatively windy day, but the same trends were observed on another clear-sky day in June with low wind.

effect on the heat transfer within the module, which is dominated by the module construction (glass-glass) and the mounting configuration. It does however have a significant impact on the thermal balance within the module, with higher fractions of irradiance reflected and/or converted to heat [18].

Analysis of the curtain wall BIPV container façade revealed that the insulated modules experience temperatures up to around 20 K higher than the ventilated modules. For the insulated modules, variations in the size of the closed cavities caused no observable effect. For the ventilated modules, the effect of rear-ventilation significantly lowered the module temperature and the cooling effect was largest for an air-gap size of 20 cm. Variations within modules varied from 2 to 6 K and vertical temperature gradients on the façade were seen for both configurations, varying from 5 to 10 K. The coolest part was seen at the top for the insulated modules, and at the bottom for the ventilated modules. The higher temperatures experienced by the insulated modules can negatively impact the performance and degradation of the modules and provides incentive to install BIPV system in configurations allowing rear ventilation.

The results show the complicated nature of BIPV façade temperature distributions and complex simulations are needed to fully understand the impact of the influencing factors.

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Conflicts of interest

The authors have nothing to disclose.

Data availability statement

The data that support the findings of this study are available from the authors upon reasonable request.

Author contribution statement

N. L. Andersen contributed with the main data processing and analysis. M. Babin contributed to the construction and instrumentation of the façade test site. S. Thorsteinsson contributed to construction and instrumentation of the test sites and is responsible for the overall project supervision. All authors were involved in writing, reviewing and revising of the manuscript.

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