Temperature and Power Study of Adhered and Racked Double Glass Photovoltaic Modules

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Abstract— **Frameless, glass-glass photovoltaic (PV) modules have demonstrated superior durability over conventional framed modules. However, their deployment in the residential market has been hampered by limited mounting options. An efficient and relatively unexplored alternative is the use of adhesives to attach the modules to sloped shingled residential roofs. One concern with adhesive mounting is the impact of temperature on module performance due to a reduction in the module/roof gap. This study compares the temperature and performance of three mounting configurations including adhesive mounting of a glass-glass module on a shingled roof. Results indicate an increase of 10.0-15.6°C and a reduction in power of approximately 15 W for the adhesively mounted (no gap) glass-glass module compared with the same module mounted at a gap of 4 and 7 inches.**

Index Terms— **photovoltaic, temperature, outdoor performance, double glass, adhesive, data analysis.**

I. INTRODUCTION

Innovations continue to drive the growth of solar power. One example is the frameless glass-glass module design which has been gaining attention for several reasons. Without the frame, the modules have no exposed metal and thus, do not need grounding. In addition, the risk of potential induced degradation (PID) is eliminated. By reducing moisture ingress [1], the glass-glass construction enables warranties to be extended to 30 years compared with the typical 25-year warranty associated with conventional framed modules [2]. One barrier to the penetration of glass-glass modules into the residential market is the lack of compatible mounting systems. Compared with conventional systems, there are far fewer mounting options for glass-glass modules, though the options are growing. A potential alternative mounting approach is the use of adhesives to attach the module to the roof. Recently, Honeker et al examined the direct adhesive mounting of a frameless, glassless lightweight c-Si module to a shingled roof [3]. One concern with this approach is the effect of an increase in temperature on module performance due to a reduced roof-to-module gap. To address this concern, we decided to study the effect of gap on performance using the glass-glass modules.

This paper presents a performance study of a glass-glass module mounted at three different gap spacings: no gap (adhesively mounted), a four-inch gap and a seven-inch gap. These systems were installed and monitored in Albuquerque, NM for a period of fourteen months. Since cell temperature impacts system performance [4][5], the reduced ventilation of the adhesively mounted system is expected to result in a yield loss compared to the 4-inch and 7-inch systems.

II. EXPERIMENTAL SETUP

Temperature, power and weather data used in this analysis were collected at the Fraunhofer Outdoor Testing Center in Albuquerque, New Mexico. Monocrystalline double glass modules were mounted on test hut roofs at an angle of 26.6 degrees facing south (6/12 pitch). Two modules were mounted at four and seven inch from a shingled roof using a Orion Solar racking system and a third module was mounted using HelioBond PVA 900HM adhesive pads from Royal Adhesives and Sealants. Care was taken to achieve full contact of the adhesive pads with the test hut roof shingles. The test huts were designed to simulate residential housing. The interior space was kept at 24.5°C by a heater/AC unit and an insulated attic separated the interior space from the roof. Current and voltage measurements were collected at a one minute frequency using individual ET Instrumente GmbH ESL-500 IV curve tracers. A Kipp and Zonen pyranometer was placed near the modules and plane of array (POA) irradiance data was collected at one minute frequency. Last, a nearby weather station collected ambient temperatures at 30 second intervals. Figure 1 shows the two test huts with the mounted modules as well as the pyranometer.

III. RESULTS

A. ECT Calculation

The equivalent cell temperature (ECT) was calculated following IEC 60904-5 with two modifications. First, the effect of shading at sunset from the mounting clips is removed by filtering out all values below 500 W/m^2 irradiance. Second, the standard equation to calculate ECT from Voc and irradiance (equation 1):

$$ECT = T_{stc} + \frac{1}{\beta}\left[\Delta V_{OC} + nV_T N_s ln(\frac{G_{stc}}{G})\right] \tag{1}$$

is modified. Here, T_{stc} and G_{stc} are the standard operating condition (STC) module temperature and irradiance, respectively. β and ΔV_{OC} are the open circuit voltage temperature coefficient and change from V_{OC}, respectively. Finally, n is the ideality factor, N_s is the number of cells in series, V_T is the thermal voltage, and G is the measured irradiance. We simplify (1) to:

$$ECT = T_{stc} + \frac{1}{\beta}\left[\Delta V_{OC}\right], \tag{2}$$

by removing the second term of (1). The second term makes only a small contribution to ECT near irradiance values of 1000 W/m^2. Furthermore, recent studies [6][7] question the validity of this as the ideality factor has been found to be a function of temperature.

Figure 2 presents ECT values over the entire measurement period. The amplitude variation is attributed to diurnal and seasonal weather variations. Dropouts are due to equipment maintenance/troubleshooting as well as filtering. Clearly, the adhered glass-glass module experiences a higher temperature than either the 4-inch or 7-inch mounted modules. The racked modules experience quite similar temperatures.

Fig. 1. The adhesively mounted glass-glass module is attached to the left test hut. The 4-inch and 7-inch mounted glass-glass modules are attached to the right test hut. The plane of array (POA) pyranometer is fixed on the left side of the left test hut.

B. Temperature analysis

Figure 3 plots the hourly averaged ECT vs. the ambient temperature as well as the corresponding linear fits. By comparing the fits, we draw several conclusions. First, the adhered module yields a slope over 10% larger than the racked modules indicating a greater sensitivity to ambient temperature. The intercept of the adhered module is also approximately 10°C higher. The increase in average temperature due to adhesive mounting is thus found to range from 10°C at 0°C ambient to 15.6°C at 35°C ambient. Comparison of the fits for the 4-inch and 7-inch modules shows only a slightly lower temperature for the 7-inch modules at lower ambient temperature. The average difference in temperatures between the 4-inch and 7-inch modules ranges from 1°C at 0°C ambient to approximately 0°C at 35°C ambient. Thus, this analysis suggests that the ECT values at higher ambient temperatures are essentially identical. Note that these comparisons are based on linear fits to the data. Although the fit quality is reasonable, (R^2 values of 0.58, 0.67 and 0.74) there may be subtleties, such as thermal lag, that distinguish these mounting configurations, but are averaged out in the fitting.

C. Power Analysis

A second approach to examining the effect of mounting on module performance is to analyze the power output directly. To eliminate the effect of irradiance we scale the power values to STC conditions:

$$Power_G = Power \times \frac{G_{stc}}{G}. \tag{3}$$

Figure 4 plots the corrected power as a function of ambient temperature. The figure also includes the data frequency distribution to indicate that power values at high ambient temperature have greater statistical significance. In all cases the power values decrease with increasing ambient temper-

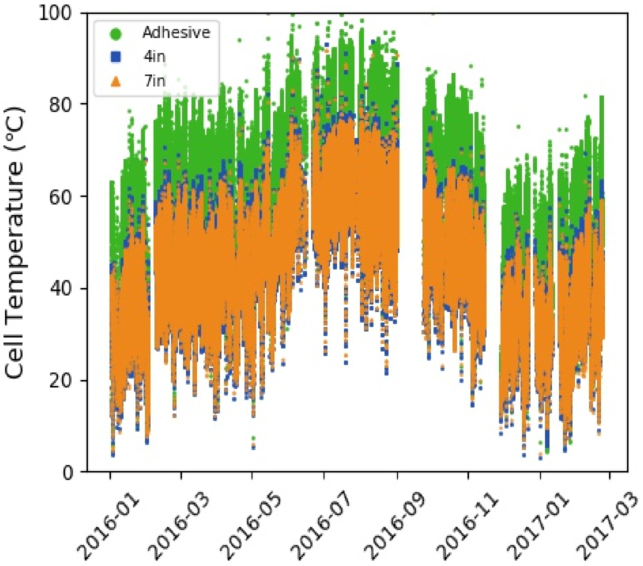

Fig. 2. Cell temperature time series spanning from January 2016 into Feburary 2017. Cell temperature calculated using equation 2.

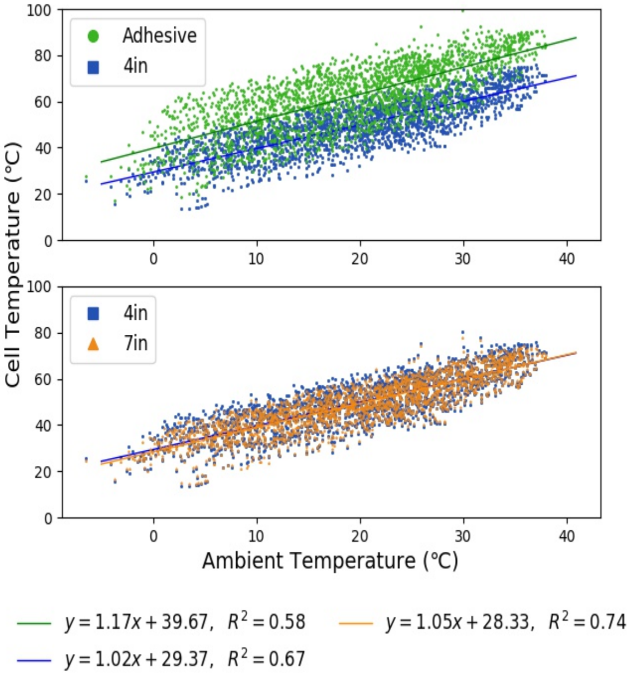

Fig. 3. ECT vs. ambient temperature with corresponding linear fits. Top: Comparison of the adhesively mounted module with the 4-inch racked module. Bottom: Comparison of the 4-inch and 7-inch racked modules.

ature with approximately the same slope. The power drop is consistent with the increase in ECT shown in Figure 3. The power output from the adhesively mounted module is approximately 15 W (5% of nameplate power) lower than from the racked modules at all ambient temperatures.

Figure 4 also shows that the 7-inch module produces slightly more power than the 4-inch module at all ambient temperatures. The average increase in power in the 7-inch module compared with the 4-inch module is 1.3%.

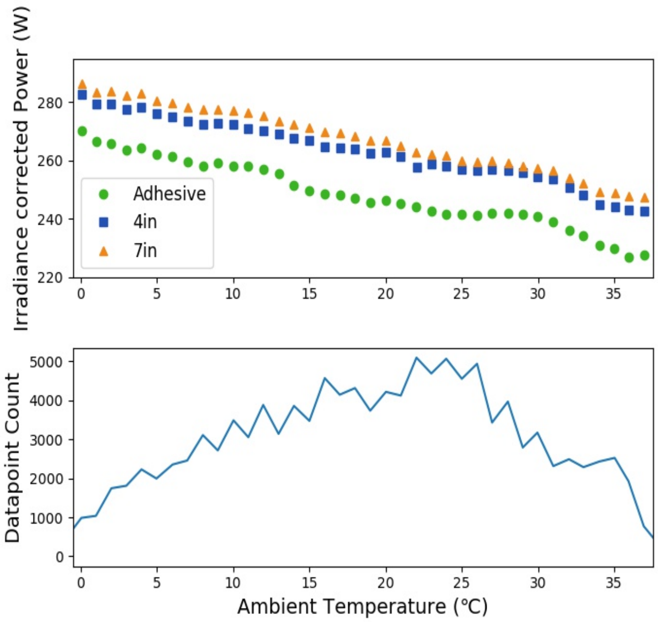

Fig. 4. Top: Irradiance corrected power (ICP) vs ambient temperature for the three mounting configurations. The irradiance correction was performed using equation 3. The data was binned into integer temperature steps. Bottom: Frequency distribution of all the power data

IV. CONCLUSION

The superior performance, durability and aesthetics of glass-glass modules have increased their market appeal. The relatively limited mounting options have lead us to investigate the possibility of adhesive mounting as an alternative. Flush mounting of PV modules to residential roofs is known to increase module temperature reducing module output, however. Here we investigate the magnitude of the temperature increase and corresponding power loss for three gap spacings, no gap (adhesive mounting), 4-inch gap and 7-inch gap for the same glass-glass module in Albuquerque, New Mexico. The effective cell temperature (ECT) was estimated from the open circuit voltage. The adhered module was found to be 10.0-15.6°C higher in temperature than the racked modules. The temperature difference increases with increasing ambient temperature. The 7-inch module was found to be only slightly cooler (1°C) than the 4-inch module at low ambient temperature. A second analysis, in which the irradiance corrected power (ICP) was compared, showed similar results. The adhesively mounted module showed a power loss of 5% of nameplate power compared with the racked modules. In contrast to the temperature analysis this loss is independent of ambient temperature. The power output of the 7-inch module is slightly higher than the 4-inch module.

One previous numerical study found a highly non-linear relationship between module temperature and gap [8]. As gap decreases module temperature was found to increase asymptotically. In light of these results, the 4-inch and 7-inch gaps may reside in the plateau region showing only a weak dependence of temperature on gap. The adhered module would represent the worst-case condition where no significant ventilation is possible.

The increase in temperature and corresponding decrease in power of the adhesively mounted glass-glass module in this study is significant. Note, however, that special effort was made to directly adhere the glass-glass module to the roof resulting in a negligible gap. To enable this, a portion of the roof was cut-away to provide space for the junction box. For practical purposes the adhesive mounting of a glass-glass module would require sufficient space (at least 1.5 inches) for the junction box. In this case, a gap of 1.5 inches (or more) would enable ventilation to substantially reduce module temperature compared to the directly adhered (no gap) case.

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REFERENCES

[1] S. Wang, et al., “Double-glass PV modules with silicone encapsulation“, *in Photovoltaics International*, pp. 2-7, 2016.

[2] P. Peng. *Dual-Glass Modules to See Rising Opportunities in 2016*, [online]. Available: http://pv.energytrend.com/node/print/10265

[3] C. Honeker, et al., “Reducing Installed Costs of Residential Solar by the Use of Adhesive Mounted Lightweight Solar Modules“, *in 43rd IEEE Photovoltaic Specialist Conference*, pp. 95-100, 2016.

[4] N. Umachandran, G. TamizhMani, “Effect of Spatial Temperature Uniformity on Outdoor Photovoltaic Module Performance Characterization“, *in 43rd IEEE Photovoltaic Specialist Conferece*, pp. 2731-2737, 2016.

[5] F. Softić, Z. Bundalo, A. Stjepanović, “Temperature Characteristics and Energy Efficiency of Solar Cells and Solar Modules“, *in 2012 Mediterranean Conference on Embedded Computing*, pp. 288-291, 2012.

[6] G. Yordanov, O. Midtgard, T. Saetre, “Equivalent Cell Temperature Calculation for PV Modules with Variable Ideality Factors“, *in 38th IEEE Photolvoltaic Specialist Conference*, pp. 505-508, 2012.

[7] G. Yordanov, O. Midtgard, T. Saetre, “PV Modules with Variable Ideality Factors“, *in 38th IEEE Photolvoltaic Specialist Conference*, pp. 2362-2367, 2012.

[8] G. Gan, “Effect of air gap on the performance of building-integrated photovoltaics“, *in Energy*, pp. 913-921, 2009.