Convective Cooling of Solar Photovoltaic Modules in Unperturbed Atmospheric Conditions

Jace Davis[1], Marc Calaf[1], Raúl Bayoán Cal[2], Dragan Zajic[3]

[1]University of Utah, Salt Lake City, United States
[2]Portland State University, United States
[3]U.S. Army Dugway Proving Grounds

Laboratory of WIND, ENERGY & TURBULENCE THE UNIVERSITY OF UTAH

Motivation:

Solar photovoltaic (PV) is one of the fastest growing renewable energy sources, and it has great potential for both large scale and residential power production. Several factors affect solar PV's efficiency, limiting its potential benefits. Among them is the effect of rising temperature of the solar PV cells once installed in ambient conditions within solar modules. Investigating the mechanisms to control the solar module's temperature is critical given that even slight improvements in PV efficiency can have significant impacts on the overall energy output at a large scale. At present, several means of cooling PV modules exist, most of which utilize costly engineering approaches, and most times intensive water resources.

In this study we investigate the impact of PV modules' temperature as a function of the local atmospheric conditions. The same way that the wind energy industry realized a few years ago that wind energy harvesting not only depends on the mean wind conditions, it is hypothesized here that solar energy harvesting not only depends on mean solar radiation. Current approaches take into consideration wind speed in convective cooling of solar PV. In this work, we take it a step further by investigating the relevance of other atmospheric forcings, like wind direction, thermal stratification, and relative humidity. Results demonstrate that there is an important relation between the convective heat transfer coefficient and some of these atmospheric parameters. Results suggest that when investigating potential sites for new solar farm deployments, the local atmospheric conditions (beyond wind speed) should also be considered in concert with the standard solar radiation to maximize the overall energy harvesting.

Overall Project Objective:

Investigate the overarching effect of atmospheric conditions on solar photovoltaic module efficiency through experimental data.

Field Experiment Location
U.S. Army Dugway Proving Ground, UT
- Annual Production: 4,079,500 kWh
- 7,000 panels
- 10 acres of land

Figure 1: Geographical location of solar site at Dugway, UT.

Methods:

To measure the effect of atmospheric conditions on a Solar module, equipment was set up and dispersed throughout a solar array wherein several weeks of data was acquired (see right). Five meteorological stations were set up within the solar farm and two were set up outside the perimeter to measure unperturbed conditions.

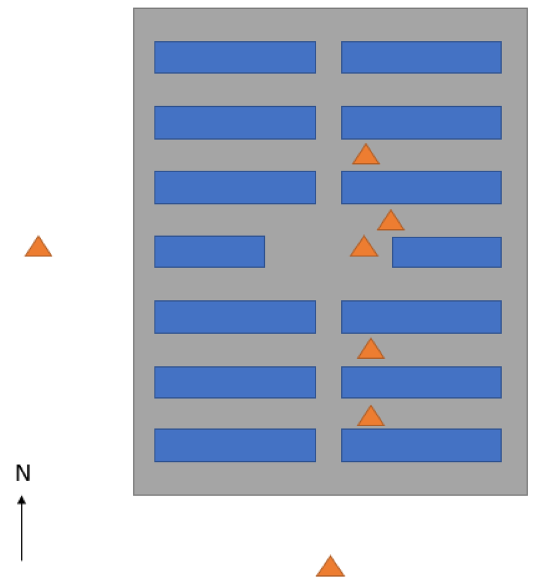

Figure 2: Map of stations at solar site (orange triangles).

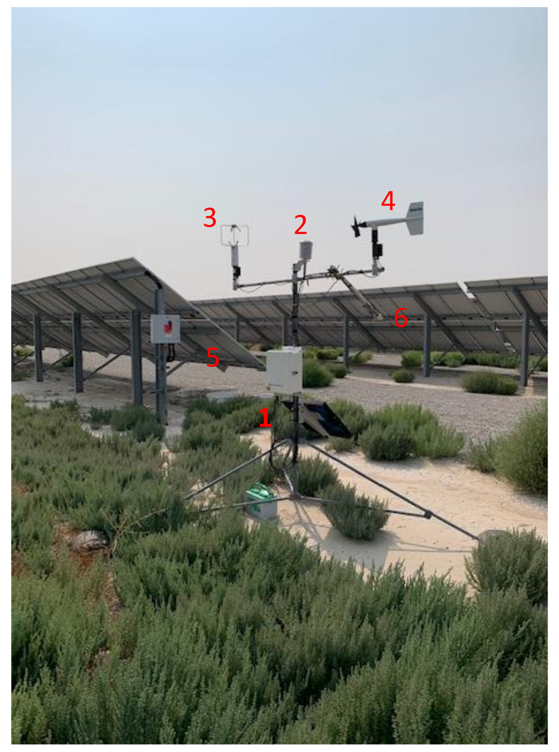

Figure 3: Equipment set up at a station in solar site.

Equipment and Setup:
1. Campbell Scientific CR3000 Datalogger
2. Campbell Scientific HMP45C-L
3. Young 81000 Ultrasonic Anemometer
4. Young 05103L Wind Monitor
5. Omega SA1-T-72-SRTC Surface Thermocouple
6. Apogee Radiometer

Figure 4: Thermal Camera used to collect panel temperature.

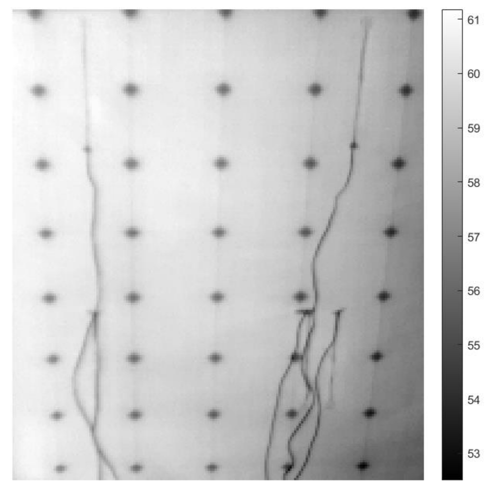

Figure 5: Thermal imaging of panel temperature.

To calculate the convective heat transfer coefficient, an energy budget was considered:

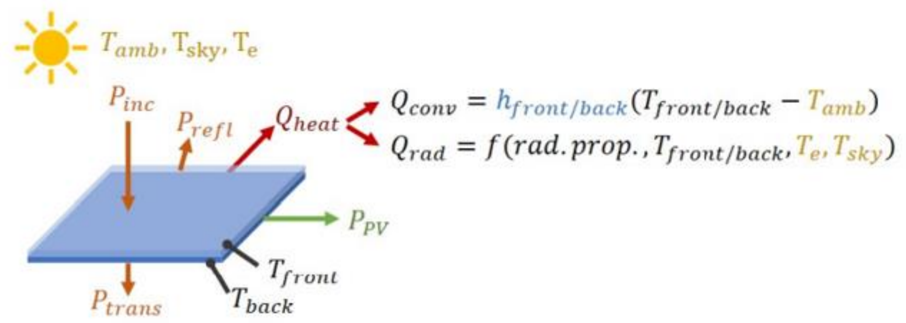

Figure 6: Energy balance on panel.

Newton's law of cooling:
- $q = h(T_s - T_\infty)$

Energy balance on panel:
- $R_{s\downarrow} - R_{s\uparrow} + R_{L\downarrow} - R_{L\uparrow} - q - E_{st} - P_{gen} = 0$

Equation solving for h:
- $h = (R_{s\downarrow} - R_{s\uparrow} + R_{L\downarrow} - R_{L\uparrow} - E_{st} - P_{gen})(T_s - T_\infty)^{-1}$

- $R_{s\downarrow}$: incoming shortwave (solar) radiation
- $R_{L\downarrow}$: incoming longwave (thermal) radiation
- $R_{s\uparrow}$: outgoing shortwave radiation
- $R_{L\uparrow}$: outgoing longwave radiation
- q : convective heat flux
- E_{st} : energy storage
- h : convective heat transfer coefficient
- T_s : surface temperature of the panel
- T_∞ : ambient air temperature around the panel
- P_{gen} : power generated by the panel.

Results:

Using theory and equations[a] wherein high-frequency atmospheric turbulent surface-layer data can be parsed, two months of data were collected including wind speed, wind direction, radiation, ambient temperature, panel temperature, and the Monin-Obukhov length.

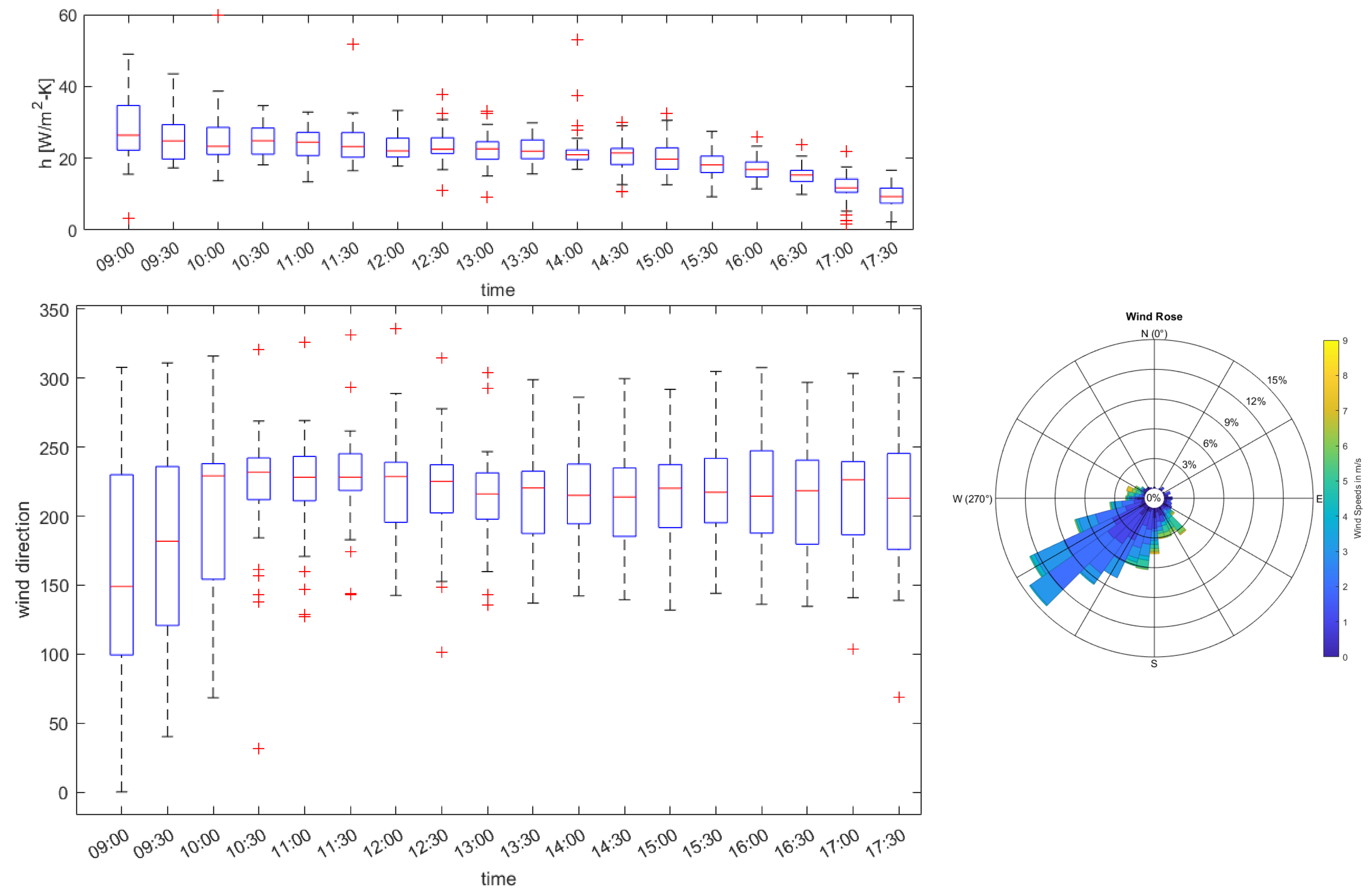

Figure 7: Convective heat transfer coefficient (top), wind direction (bottom left), and wind speed (right) measured over two months.

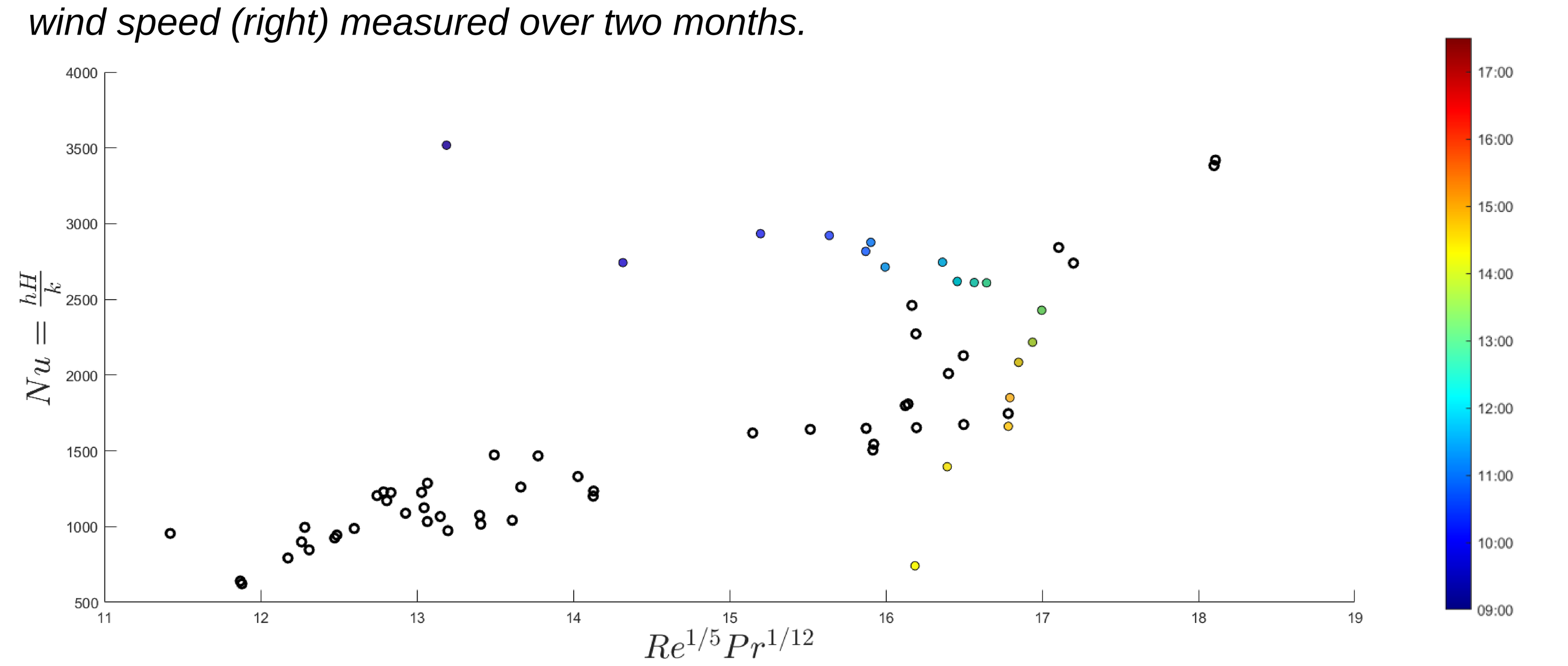

Figure 8: A scaling relation for the convective heat transfer coefficient is explored using the experimental data together with data from numerical simulations[b] and wind tunnel measurements[c]. Field data is colored while simulation and wind tunnel data is hollow points.

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Conclusion:
Successful measurements of the convective heat transfer coefficient at a solar array were acquired along with other atmospheric data. The coefficient seems to be related to a diurnal cycle where the *h* value varies, which suggests the effects of atmospheric data on solar panel efficiency. Further investigation is requisite to gain more insight into the potential of atmospheric effects on solar PV efficiency.

References: [a] Garratt, J. R. (1999). The atmospheric boundary layer. Cambridge University Press.
[b] B. Stanislawski, et al (under review.)
[c] S. Smith et al (under review.)