

Effects of Solar Photovoltaic Panels on Roof Heat Transfer

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Building Heating, Ventilation and Air Conditioning (HVAC) is a major contributor to urban energy use. In single story buildings with large surface area such as warehouses most of the heat enters through the roof. A rooftop 'modification' that has not been examined experimentally is solar photovoltaic (PV) arrays. In California alone, several GW in residential and commercial rooftop PV are approved or in the planning stages. With the PV solar conversion efficiency ranging from 5-20% and a typical installed PV solar reflectance of 16-27%, 53-79% of the solar energy heats the panel. Most of this heat is then either transferred to the atmosphere or the building underneath. Consequently solar PV has indirect effects on roof heat transfer. The effect of rooftop PV systems on the building roof and indoor energy balance as well as their economic impacts on building HVAC costs have not been investigated. Roof calculator models currently do not account for rooftop modifications such as PV arrays.

In this study, we report extensive measurements of a building containing a flush mount and a tilted solar PV array as well as exposed reference roof. Exterior air and surface temperature, wind speed, and solar radiation were measured and thermal infrared (TIR) images of the interior ceiling were taken. We found that in daytime the ceiling surface temperature under the PV arrays was significantly cooler than under the exposed roof. The maximum difference of 2.5°C was observed at around 1800h, close to typical time of peak energy demand. Conversely at night, the ceiling temperature under the PV arrays was warmer, especially for the array mounted flat onto the roof.

A one dimensional conductive heat flux model was used to calculate the temperature profile through the roof. The heat flux into the bottom layer was used as an estimate of the heat flux into the building. The mean daytime heat flux (1200 – 2000 PST) under the exposed roof in the model was 14.0 W m⁻² larger than under the tilted PV array. The maximum downward heat flux was 18.7 W m⁻² for the exposed roof and 7.0 W m⁻² under the tilted PV array, a 63% reduction due to the PV array. This study is unique as the impact of tilted and flush PV arrays could be compared against a typical exposed roof at the same roof for a commercial uninhabited building with exposed ceiling and consisting only of the building envelope. Our results indicate a more comfortable indoor environment in PV covered buildings without HVAC both in hotter and cooler seasons.

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Outline

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- Study Goals
- Experimental setup
 - Building and location
 - Equipment and measurements
- Measurement results
 - Meteorological conditions/typical conditions
 - Measured temperatures
- Simulation of roof cooling load
 - Temperature profile through roof
 - Calculated heat flux
- Next step: building models
- Conclusions

Motivation

- Roof heat flux is a major contributor to total HVAC energy use
- Previous studies have demonstrated the benefits of rooftop and other modifications (high albedo coatings, improved insulation, shade trees)
- Solar photovoltaic (PV) arrays are quickly growing, with several GW approved or in the planning stage in California alone.
- Effects of rooftop PV arrays on building heat transfer improves economics of rooftop installations, but these effects have not been sufficiently quantified.



Images: Sailor 2010

Study Goals

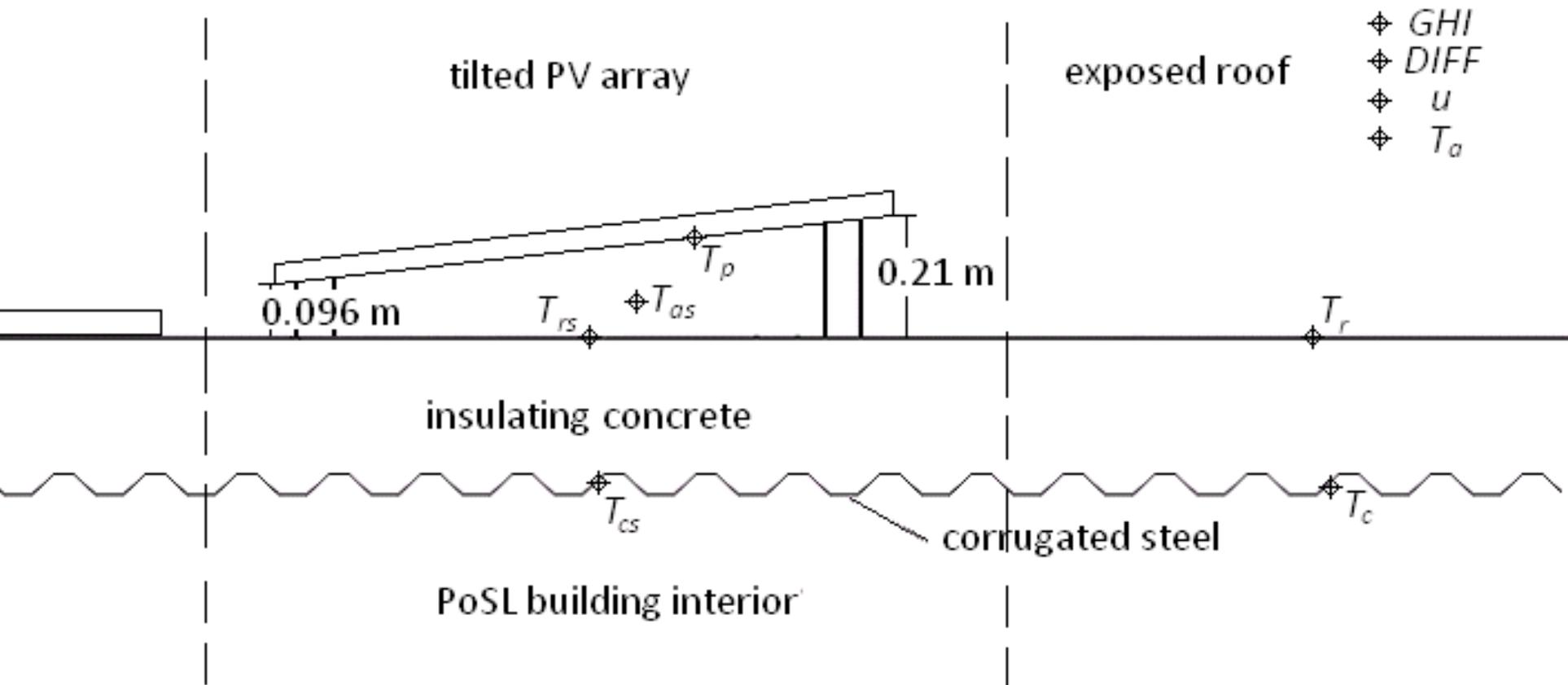
- Examine and quantify the effect of rooftop PV on roof heat flux for an existing, functioning building with an existing PV array
- Develop analysis tools and methods applicable to future general studies
- Use results to motivate:
 - Future research on existing systems
 - Generalized results for energy use models

Study Building

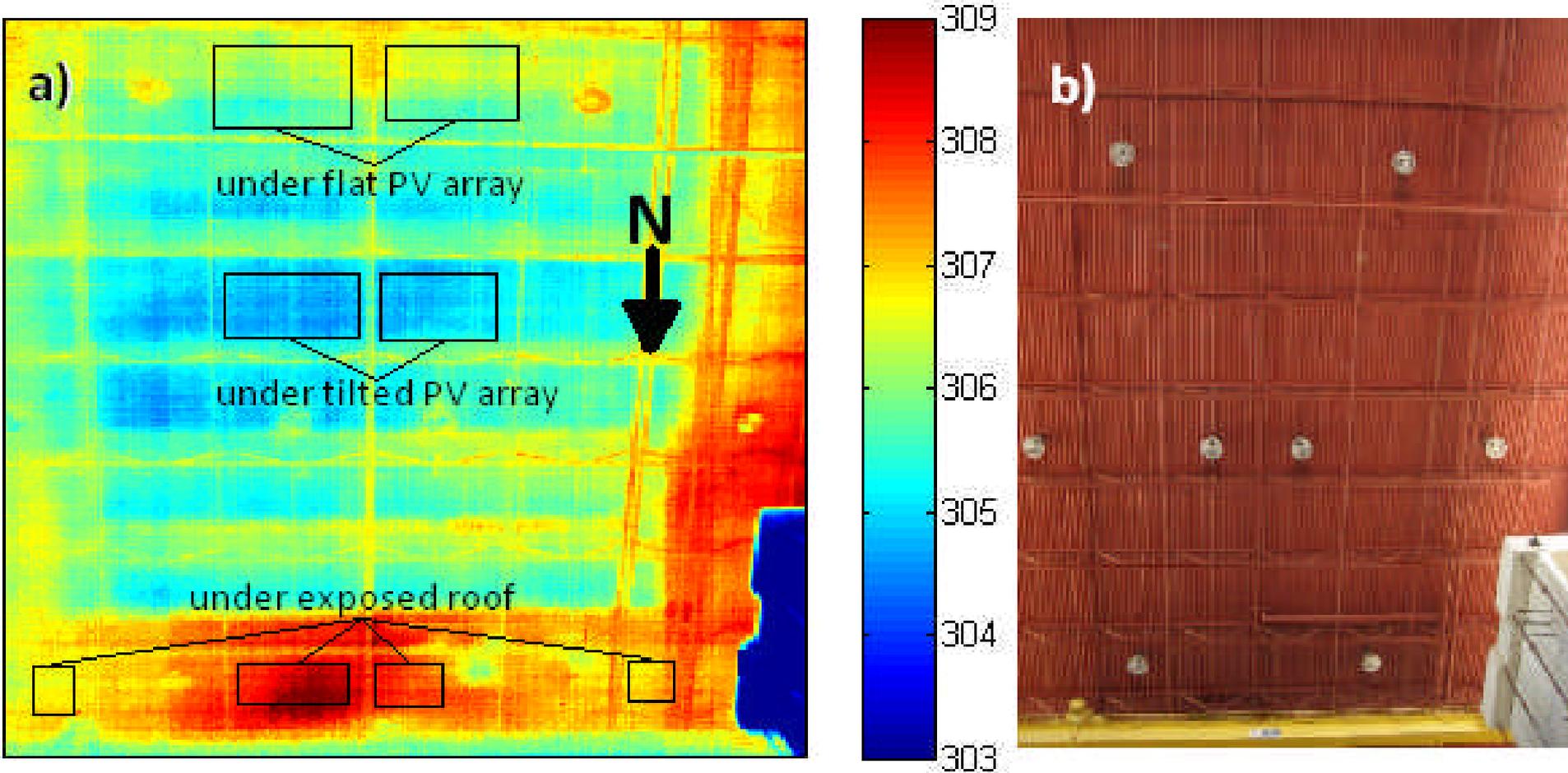
- Powell Structural Laboratory (PoSL) on the UC San Diego campus
- Simple structure (Hollow concrete cube with no HVAC and no ventilation)
- 0.19 rooftop albedo, R3 roof
- Tilted and flat PV arrays totaling 13kW_p



Exterior Measurements



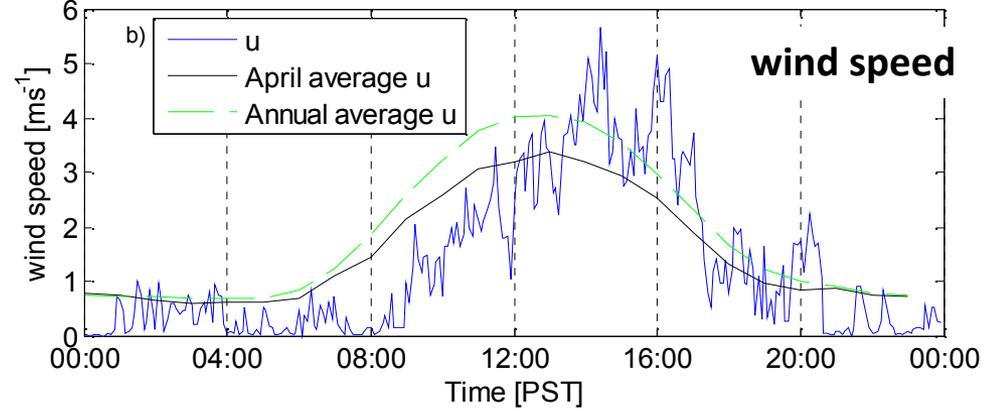
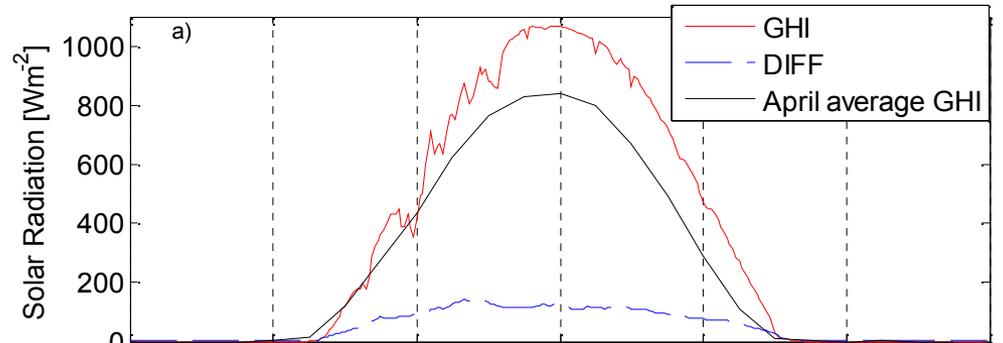
Interior Measurements



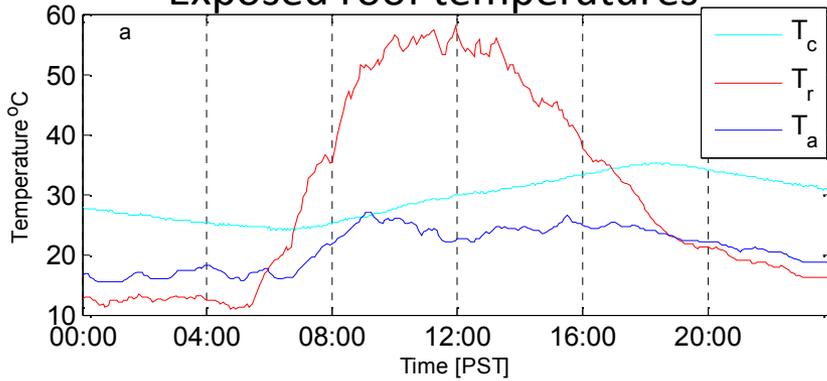
- FLIR A320 TIR camera image of ceiling at 1710 PST on April 19, 2009
- Noted pixel regions averaged for 3 study cases: flat PV array, tilted PV array, and exposed roof

Meteorological Conditions

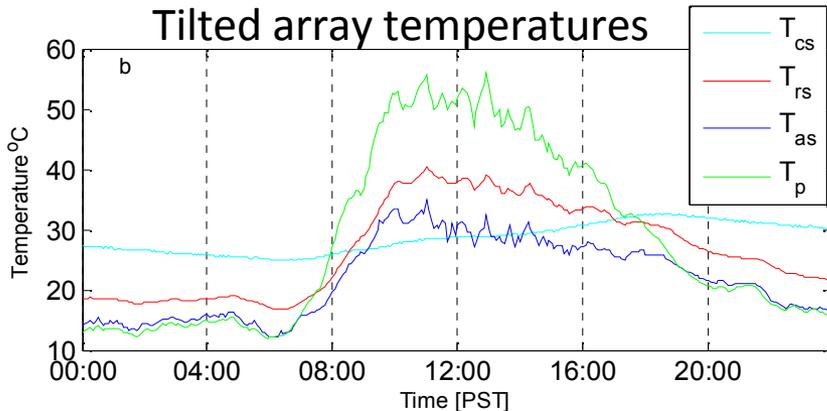
- coastal sea breeze
- clear days



Exposed roof temperatures



Tilted array temperatures

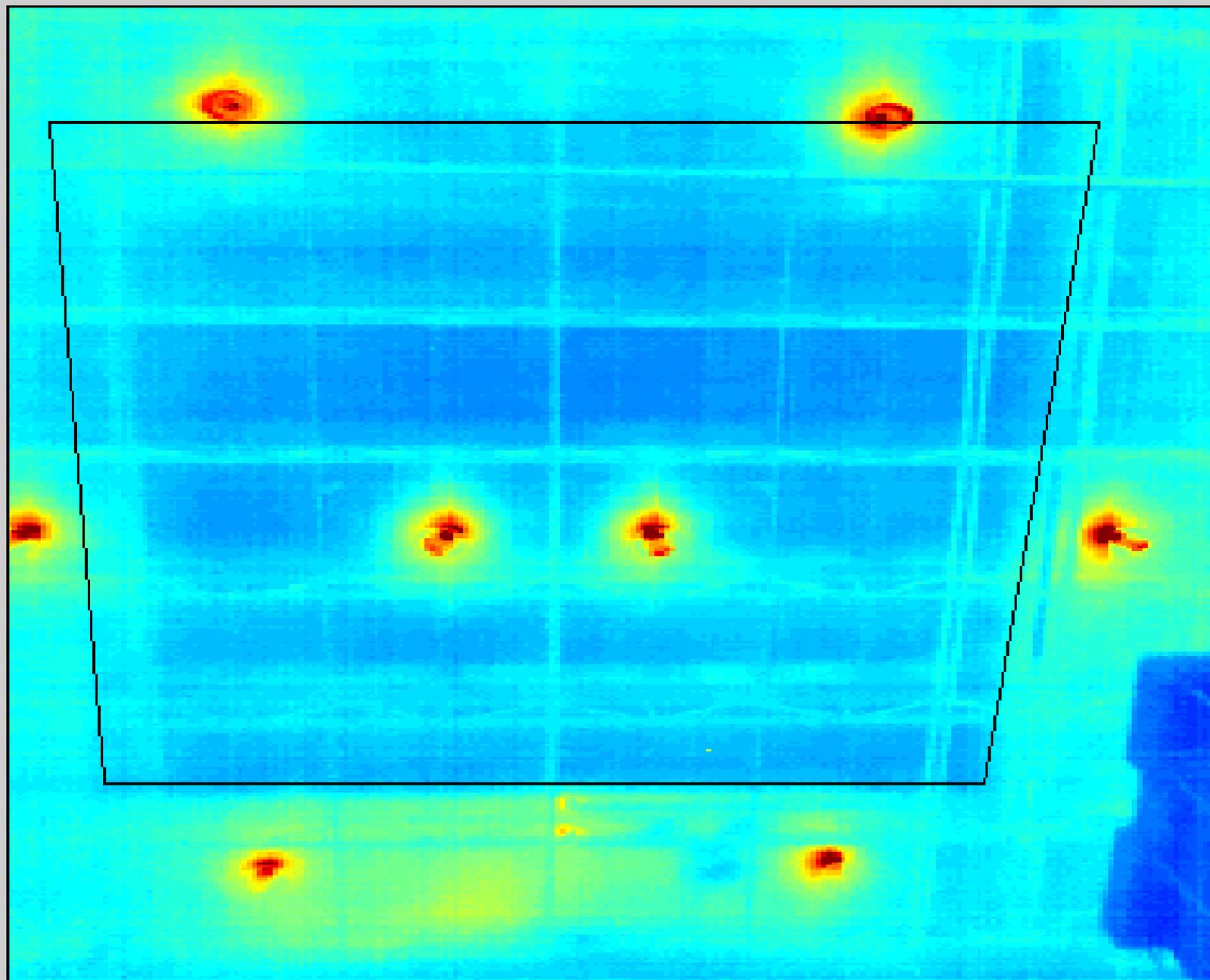


- Ceiling
- Roof surface
- Air gap
- PV panel

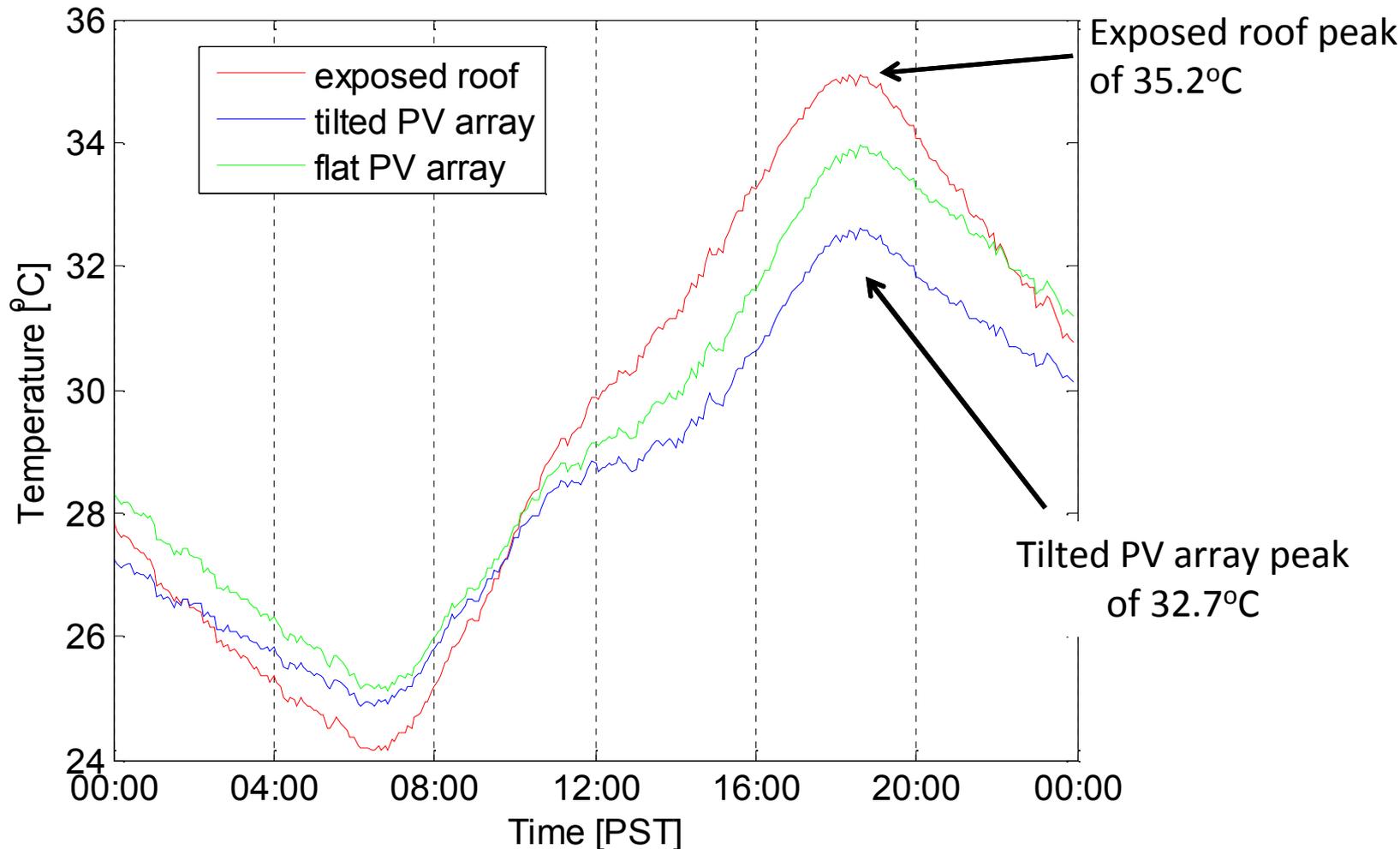
PV array temperatures less than exposed roof case

Temperatures for a) exposed roof, b) tilted PV array

17-Apr-2009 15:27:13



Interior Ceiling Temperatures



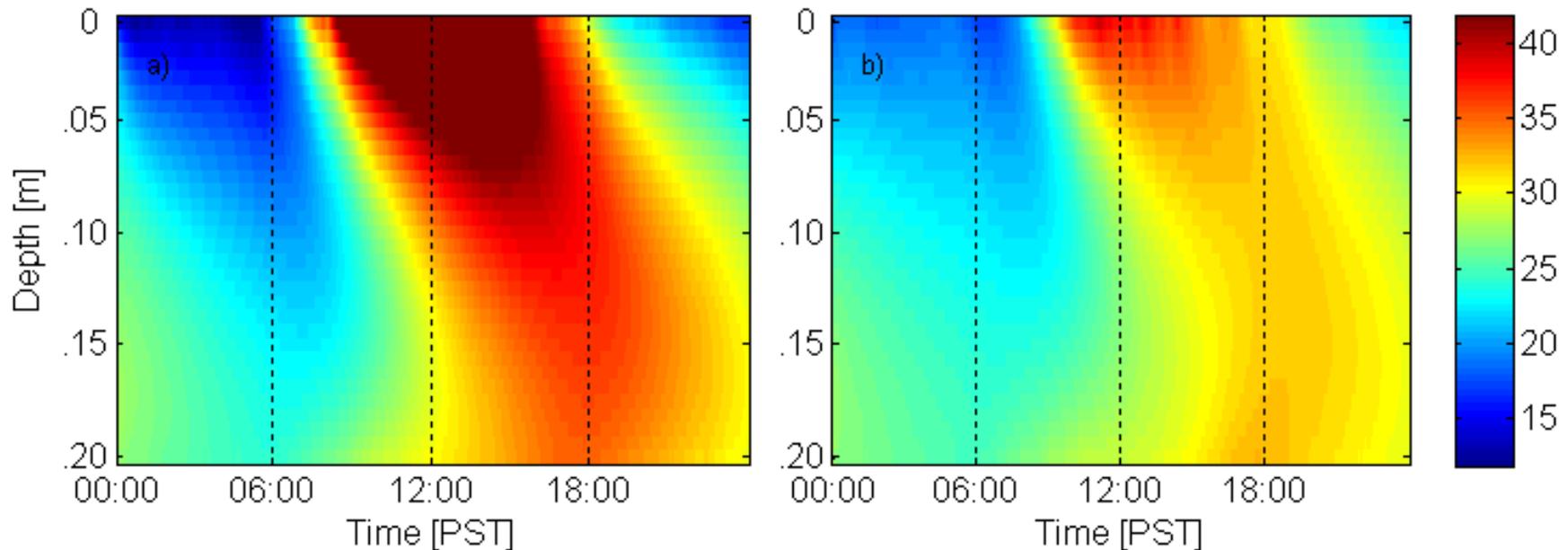
PV acts as insulator.

Flat PV best insulator at night, but warmer than tilted PV during day.

Conduction Model

Modeled using Crank-Nicholson method applied to the 1-d transient heat conduction equation:

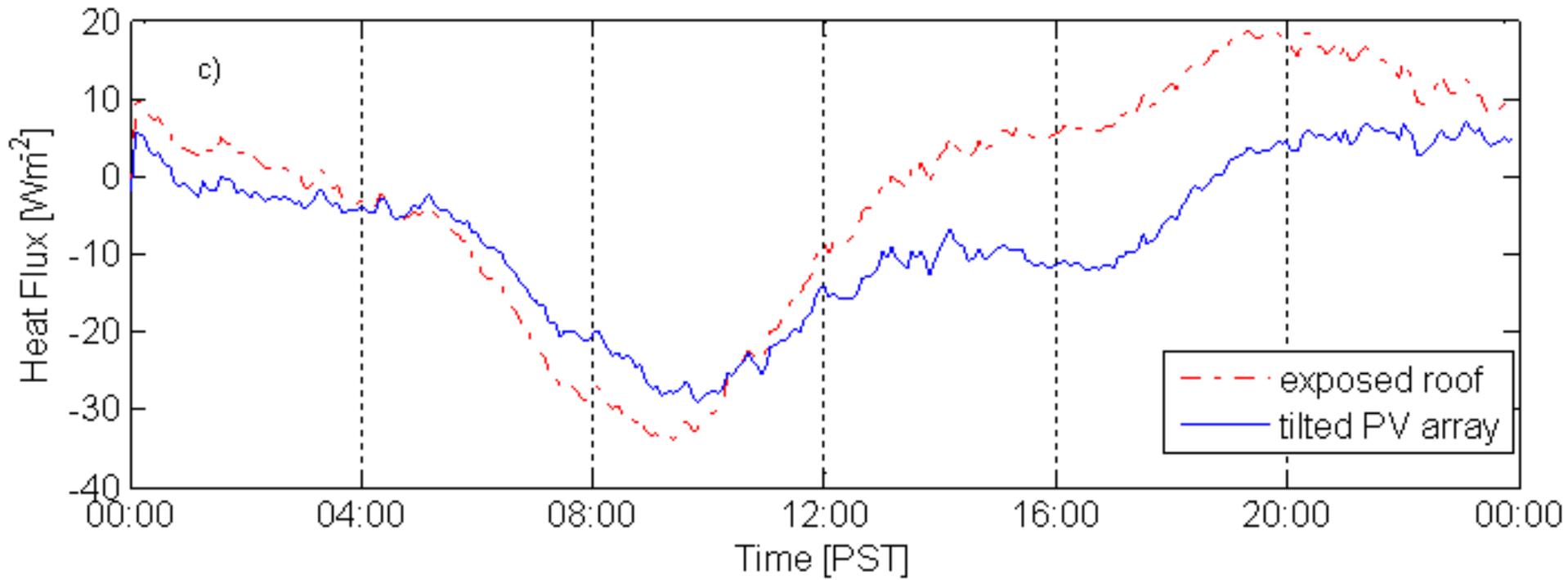
$$\rho c_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$



Temperature profile over 24 hours for exposed roof (a) and PV covered roof (b)

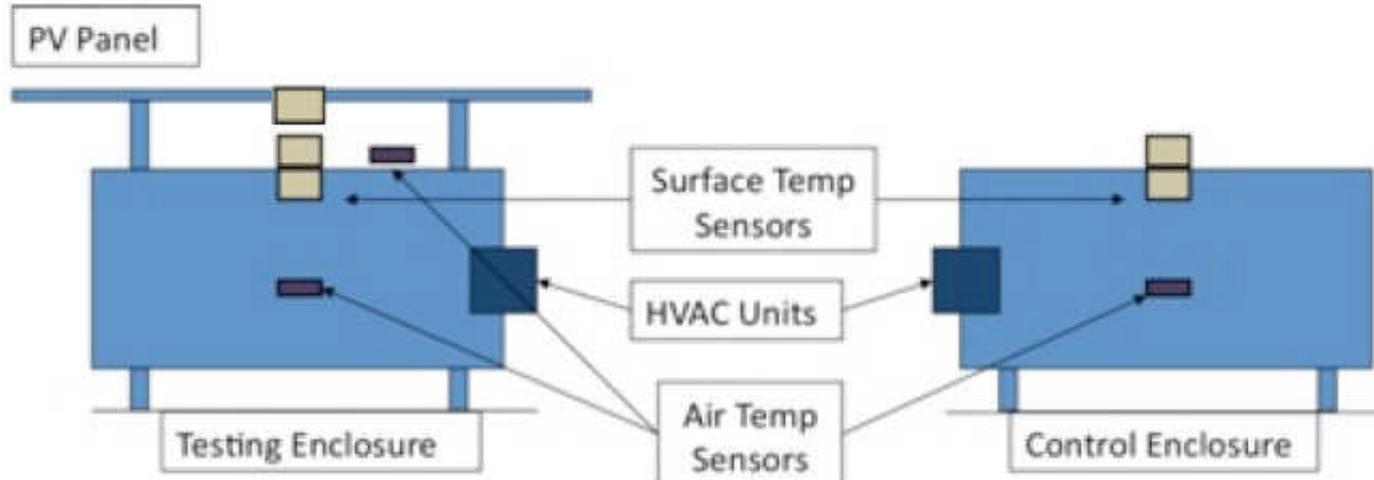
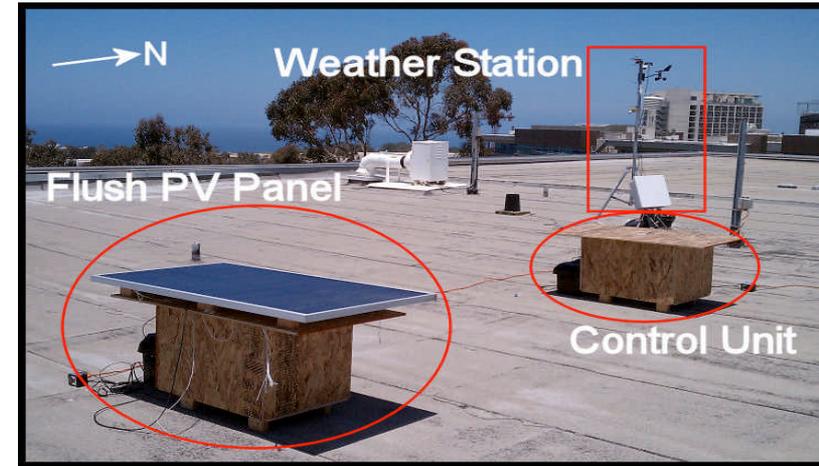
Heat Flux into Building

- The total heat flux into the building air is approximately equal to the conductive heat flux into the bottom discretized roof layer
- The peak heat flux under the PV array is 63% lower than that under the exposed roof, and the mean daytime heat flux under the PV array is 14.0 W m^{-2} less than under the exposed roof.



Continued Studies: Building models

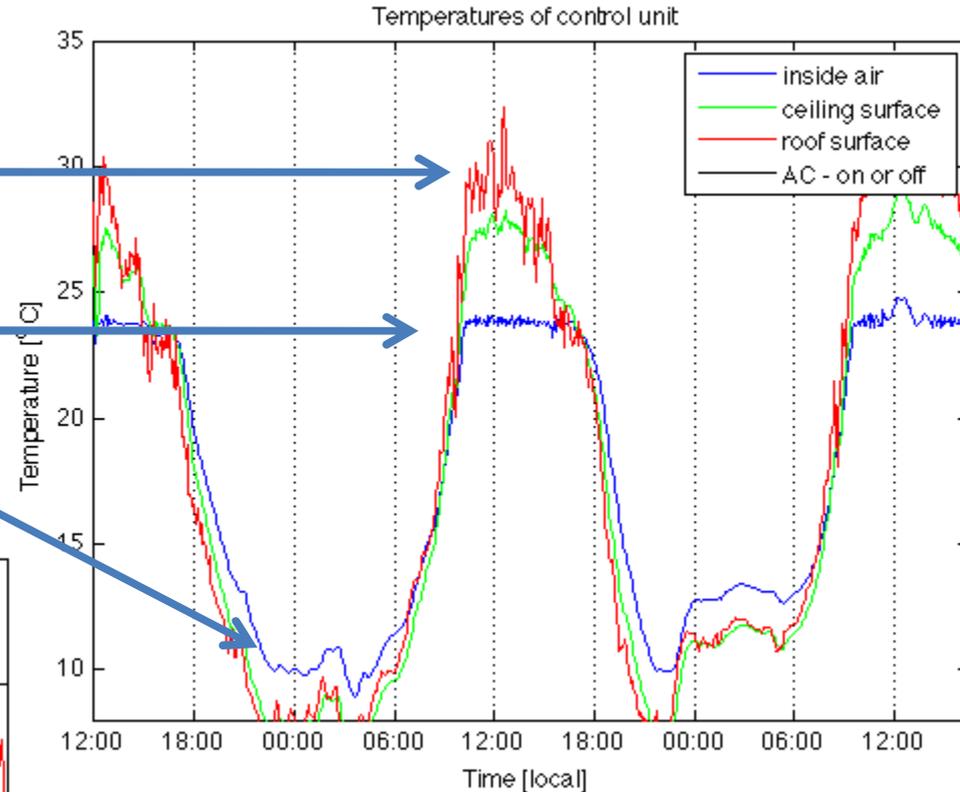
- Models were built to address shortcomings of previous study
 - Insulated walls/floor to minimize heat flux through all surfaces but the roof.
 - Interior air temperature controlled by HVAC units
 - Simple, well known roof construction for more accurate modeling
 - All temperatures measured with contact sensors (no radiative)
 - Separate structures are exposed to same conditions but do not affect each other
- Shortcomings of models
 - Unrealistic roof R-value



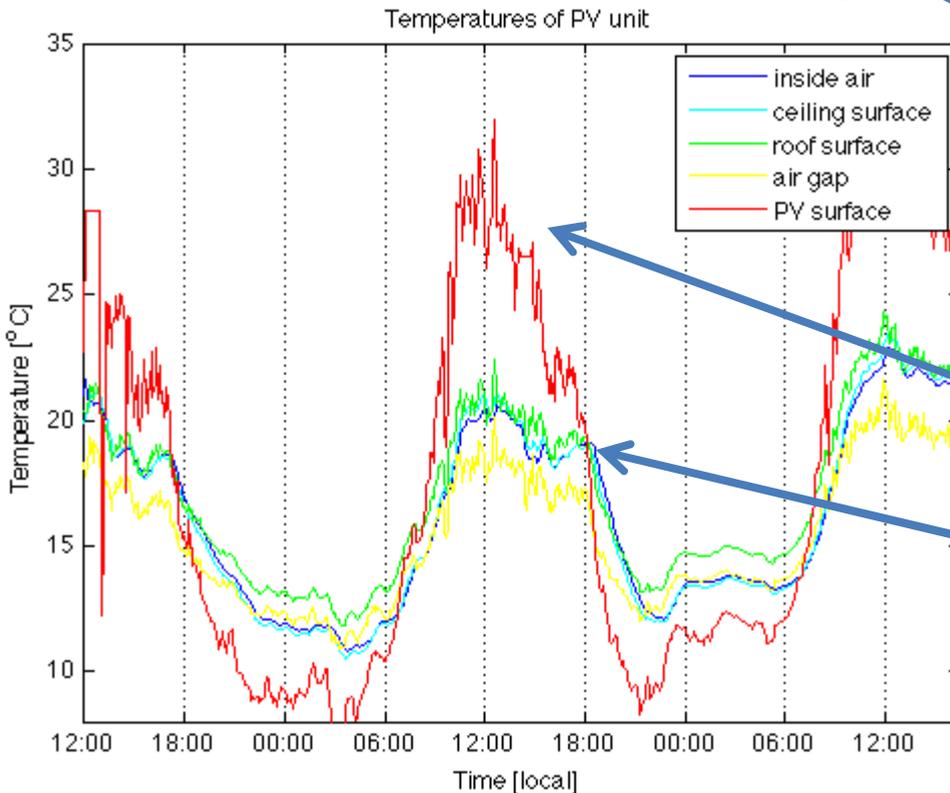
Continued Studies: Initial results

Control Unit

- Inside ceiling surface close to roof surface temperature throughout day
- HVAC unit turned on at 24 °C and off at 23.5 °C utilized from 10:00 am to 4:00 pm to maintain inside air temperature
- Inside air is warmer than roof surface at night



PV Unit



- PV surface temperature nearly the same as roof surface temperature in control unit
- Roof surface, ceiling surface, and inside air temperature all close to each other during day
- HVAC unit never turned on, as inside air temperature never reached setting of 24 °C

Conclusions

- For our particular study building:
 - Interior ceiling surface temperatures are up to 2.5 °C cooler under a tilted PV array than the exposed roof during peak energy use hours.
 - Peak roof heat flux into the building envelope is 63% lower under the tilted PV array.
 - Rooftop PV contributes to a more comfortable environment in this particular non-ventilated building.
- In general:
 - The qualitative results of less roof heat flux in buildings with PV arrays should be easily reproducible.
 - Continued studies with model buildings will allow for the generalization of quantitative results and the ability to incorporate these effects into existing building energy calculators.