Analysis of the Potential for a Heat Island Effect in Large Solar Farms

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***Abstract* — Large-scale solar power plants are being built at a rapid rate, and are setting up to use hundreds of thousands of acres of land surface. The thermal energy flows to the environment related to the operation of such facilities have not, so far, been addressed comprehensively. We are developing rigorous computational fluid dynamics (CFD) simulation capabilities for modeling the air velocity, turbulence, and energy flow fields induced by large solar PV farms to answer questions pertaining to potential impacts of solar farms on local microclimate. Using the CFD codes Ansys CFX and Fluent, we conducted detailed 3-D simulations of a 1 MW section of a solar farm in North America and compared the results with recorded wind and temperature field data from the whole solar farm. Both the field data and the simulations show that the annual average of air temperatures in the center of PV field can reach up to 1.9℃ above the ambient temperature, and that this thermal energy completely dissipates to the environment at heights of 5 to 18 m. The data also show a prompt dissipation of thermal energy with distance from the solar farm, with the air temperatures approaching (within 0.3℃) the ambient at about 300 m away of the perimeter of the solar farm. Analysis of 18 months of detailed data showed that in most days, the solar array was completely cooled at night, and, thus, it is unlikely that a heat island effect could occur. Work is in progress to approximate the flow fields in the solar farm with 2-D simulations and detail the temperature and wind profiles of the whole utility scale PV plant and the surrounding region. The results from these simulations can be extrapolated to assess potential local impacts from a number of solar farms reflecting various scenarios of large PV penetration into regional and global grids.**

***Index Terms* – PV, climate change, heat island, fluid dynamics**

I. INTRODUCTION

Solar farms in the capacity range of 50MW to 500 MW are being proliferating in North America and other parts of the world and those occupy land in the range from 275 to 4000 acres. The environmental impacts from the installation and operation phases of large solar farms deserve comprehensive research and understanding. Turney and Fthenakis [1] investigated 32 categories of impacts from the life-stages of solar farms and were able to categorize such impacts as either beneficial or neutral, with the exception of the "local climate" effects for which they concluded that research and observation are needed. PV panels convert most of the incident solar radiation into heat and can alter the air-flow and temperature profiles near the panels. Such changes, may subsequently affect the thermal environment of near-by populations of humans and other species. Nemet [2] investigated the effect on global climate due to albedo change from widespread installation of solar panels and found this to be small compared to benefits from the reduction in greenhouse gas emissions. However, Nemet did not consider local micro-climates and his analytical results have not been verified with any field data. Donovan [3] assumed that the albedo of ground-mounted PV panels is similar to that of underlying grassland and, using simple calculations, postulated that the heat island effect from installing PV on grassy land would be negligible. Yutaka [4] investigated the potential for large scale of roof-top PV installations in Tokyo to alter the heat island effect of the city and found this to be negligible if PV systems are installed on black roofs.

In our study we aim in comprehensively addressing the issue by modeling the air and energy flows around a solar farm and comparing those with measured wind and temperature data.

II. FIELD DATA DESCRIPTION AND ANALYSIS

Detailed measurements of temperature, wind speed, wind direction, solar irradiance, relative humidity, and rain fall were recorded at a large solar farm in North America. Fig. 1 shows an aerial photograph of the solar farm and the locations where the field measurements are taken.

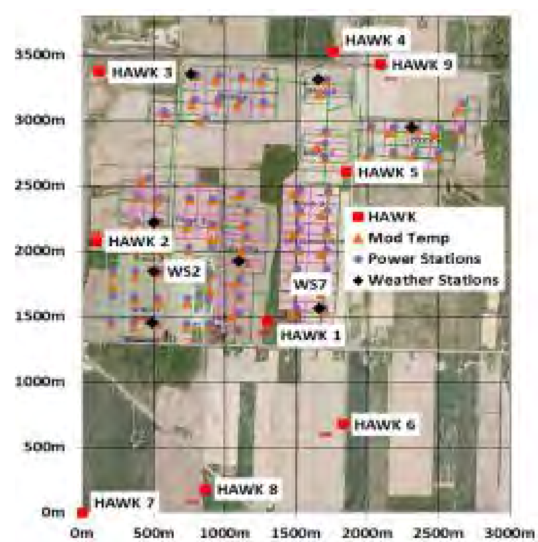


Fig. 1. A picture of the solar farm indicating the locations of the monitoring stations

The field data are obtained from 17 monitoring stations within and around the solar farm, including 8 weather stations (WS) and 9 Hawk stations (HK), all at 2.5 m heights off the ground. There also 80 module temperature (MT) sensors at the back-side of the modules close to each of the corresponding power stations. The WS and MT provide data at 1-min intervals, while the Hawk provides data every 30 minutes. The WS and MT data cover a period of one year from October 2010 to September 2011, while the Hawk data cover a period of 18 months from March 2010 through August 2011.

Hawk stations 3, 6, 7, 8 and 9 are outside the solar farm and were used as reference points indicating ambient conditions. The measurements from Hawk 3, 6, 8 and 9 agree very well confirming that their distances from the perimeter of the solar farm are sufficient for them to be unaffected by the thermal mass of the PV system; Hawk 7 shows higher temperatures likely due to a calibration inaccuracy. In our comparative data analysis we use Hawk 6 as a reference point and, since the prevailing winds are from the south, we selected the section around WS7 as the field for our CFD simulations. Figures 2 to 7 show the difference between the temperatures in Hawk 6 and those in the weather stations WS2 and WS7 within the field, and Hawks 1, 2, 4 and 5 around the solar field.

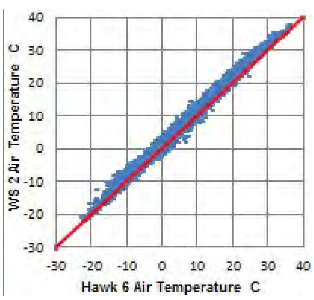


Fig. 2. Air temp WS2 vs. Hawk 6

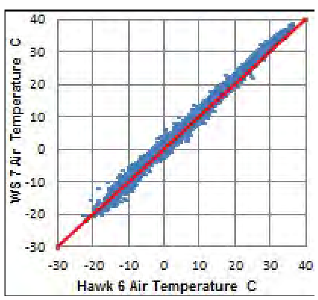


Fig.3. Air temp WS7 vs. Hawk6

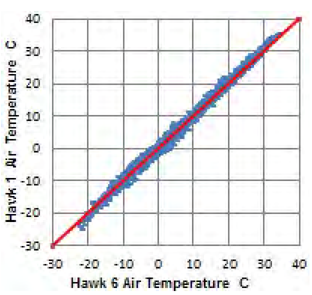


Fig. 4. Air temp Hawk 1 vs. 6

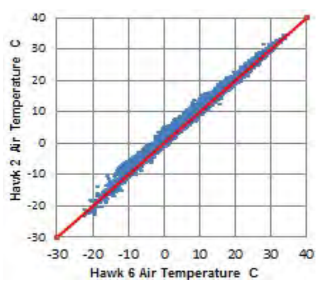


Fig. 5. Air temp Hawk 2 vs. 6

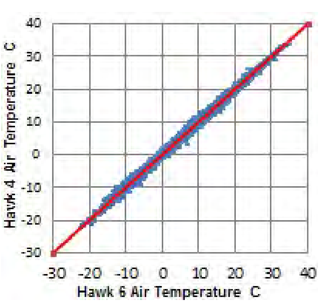


Fig. 6. Air temp Hawk 1 vs. 6

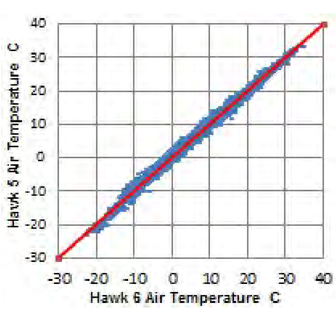


Fig. 7. Air temp Hawk 2 vs. 6

These figures and Table 1 show that with the exception of Hawk 4, the closer the proximity to solar farm the higher the temperature difference from the ambient (indicated by Hawk 6). The relative high temperatures recorded at Hawk 4, and also the relative low temperatures at Hawks 1 and 5 are explained by the prevailing wind direction, which for the time period used in our analysis (8/14/2010-3/14/2011) was Southerly (158°-202°). Hawk 4 is downwind of the solar farm, whereas Hawks 1 and 5 are upwind; the downwind station "feels" more the effect of the heat generated at the solar farm than the ones upwind.

Fig. 8 shows the decline in air temperature as a function of distance to solar farm perimeter. Distances for WS2 and WS7 are negative since they are located inside the solar farm site. WS2 is further into the solar farm and this is reflected in its higher temperature difference than WS7.

TABLE I

DIFFERENCE OF AIR TEMPERATURE (@2.5 M HEIGHTS) BETWEEN THE LISTED WEATHER AND HAWK STATIONS AND THE AMBIENT

Met Station	WS2	WS7	HK1	HK2	HK3	HK4	HK5	HK9
Temp Difference from H6 (^oC)	1.878	1.468	0.488	1.292	0.292	0.609	0.664	0.289
Distance to solar farm perimeter (m)	-440	-100	100	10	450	210	20	300

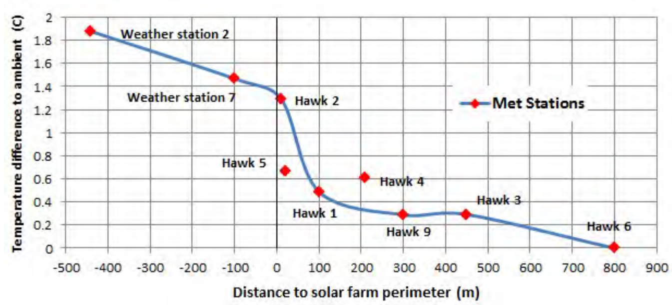


Fig. 8. Air temperature difference as a function of distance from the perimeter of the solar farm. Negative distances indicate locations within the solar farm.

We also examined in detail the temperature differences between the modules and the surrounding air. These vary throughout the year but the module temperatures are consistently higher than those of the surrounding air during the day, whereas at night the modules cool to temperatures below ambient; an example is shown in Fig. 9. Thus, this PV solar farm did not induce a day-after-day increase in ambient temperature, and therefore, adverse micro-climate changes from a potential PV plant are not a concern.

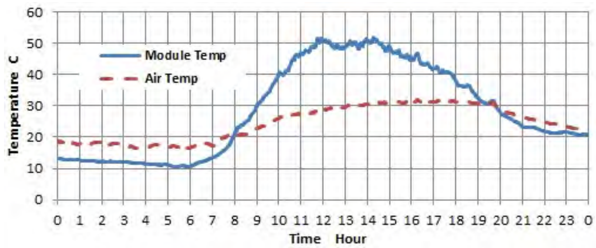


Fig. 9. Comparison of module temperature and air temperature 2.5 m off the ground on a sunny day (July 1, 2011)

III. CFD MODEL DEVELOPMENT

In preliminary simulations we tested the Ansys CFX and FLUENT computational fluid dynamics codes (CFD) and decided to use FLUENT in detailed simulations. FLUENT offers several turbulence schemes including multiple variations of the k-ε models, as well as k-ω models, and Reynolds stress turbulence models. We used the standard, renormalized-group (RNG), and realizable k-ε turbulence closure scheme as it is the most commonly used model in street canyon flow and thermal stratification studies [5]. FLUENT incorporates the P-1 radiation model which affords detailed radiation transfer between the solar arrays, the ground and the ambient air; it also incorporates standard free convection and wind-forced convection models. Our choice of solver was the pressure-based algorithm SIMPLE which uses a relationship between velocity and pressure corrections to enforce mass conservation and obtain the pressure field. We conducted both three-dimensional (3-D) and 2-D simulations.

A 3-D model was built of four fields each covering an area of 93-meters by 73-meters (Fig. 10). Each field contains 23 linear arrays of 73-meter length and 1.8-meter width. Each array has 180 modules of 10.5% rated efficiency, placed facing south at a 25-degree angle from horizontal, with their bottom raised 0.5 m from the ground and their top reaching a height of 1.3 m . Each array was modeled as a single 73 m ×1.8 m × 1 cm rectangular. The arrays are spaced 4 meters apart and the roads between the fields are 8 m. Fig. 10 shows the simulated temperatures on the arrays at 14:00 pm on 7/1/2011, when the irradiance was 966 W/m^2. As shown, the highest average temperatures occur on the last array (array 46). Temperature on the front edge (array 1) is lower than in the center (array 23). Also, temperature on array 24 is lower than array 23, which is apparently caused by the cooling induced by the road space between two fields, and the magnitude of the temperature difference between arrays 24 and 46 is lower than that between arrays 1 and 23, as higher temperature differences from the ambient, result in more efficient cooling.

TABLE II
MODULES TEMPERATURE

Arrays	1	23	24	46
Temperature ℃	46.1	56.4	53.1	57.8

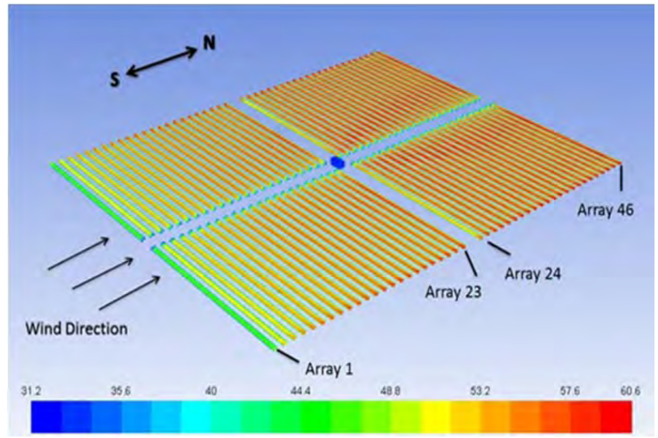
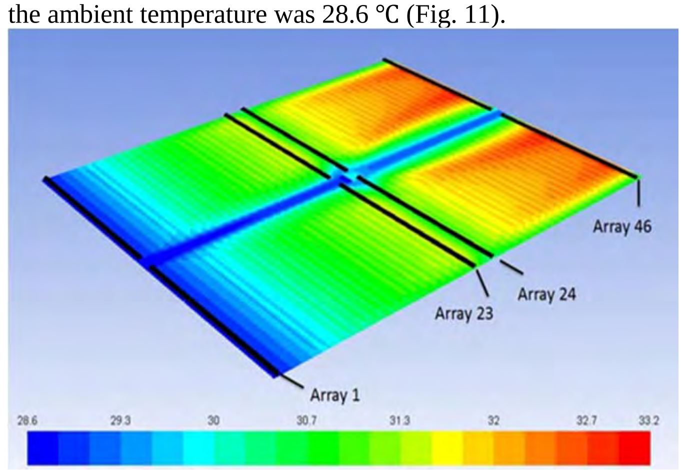
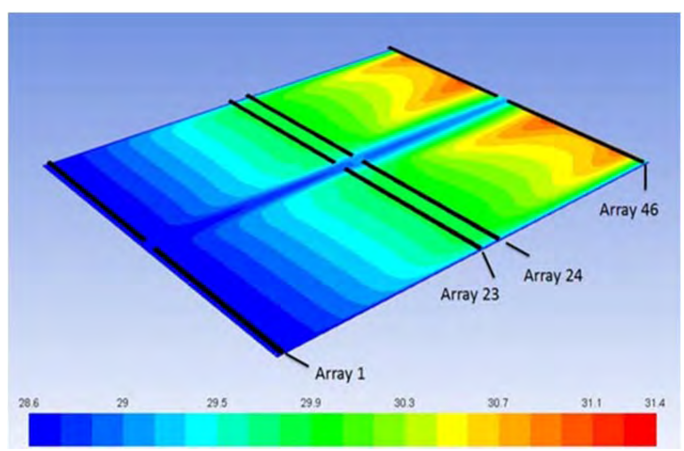


Fig. 10. Module temperatures from 3-D simulations of air flows and thermal exchange during a sunny day

Our simulations also showed that the air temperatures above the arrays at a height of 2.5 m ranged from 28.6 ℃ to 31.1℃; the ambient temperature was 28.6 ℃ (Fig. 11).



(a)



(b)

Fig. 11 Air temperatures from 3-D simulations during a sunny day. a) Air temperatures at a height of 1.5 m; b) air temperatures at a height of 2.5 m.

TABLE III
AIR TEMPERATURE

Temperature	Ambient (℃)	Low (℃)	High (℃)	Average (℃)
2.5m height	28.6	28.6	31.1	30.1
1.5m height	28.6	28.6	33.2	30.8

These simulations show a profound cooling effect with increasing height from the ground. It is shown that the temperatures on the back surface of solar panels is up to 30°C warmer than the ambient temperature, but the air above the arrays is only up to 2.5°C higher than the ambient (i.e., 31.1℃). Also the road between the fields allows for cooling, which is more evident at the temperatures 1.5 m off the ground (Fig. 11a). The simulations show that heat build-up at the power station in the middle of the fields has a negligible effect on the temperature flow fields; it was estimated that a power station adds only about 0.4% to the heat generated by the corresponding modules.

The 3-D model showed that the temperature and air velocity fields within each field of the solar farm were symmetrical along the cross-wind axis; therefore a 2-D model of the downwind and the vertical dimensions was deemed to be sufficiently accurate. A 2-D model reduced the computational requirements and allowed for running simulations for several subsequent days using actual 30-min solar irradiance and wind input data. We tested the numerical results for three layers of different mesh sizes and determined that the following mesh sizes retain sufficient detail for an accurate representation of the field data: a) Top layer: 2m by 1m, b) Middle layer: 1.5m by 0.6m, c) Bottom layer: 1m by 0.4m. According to these mesh specifications, a simulation of 92 arrays (length of 388m, height 9m), required a total of 13600 cells. Figures 12-15 show comparisons of the modeled and measured module and air temperatures.

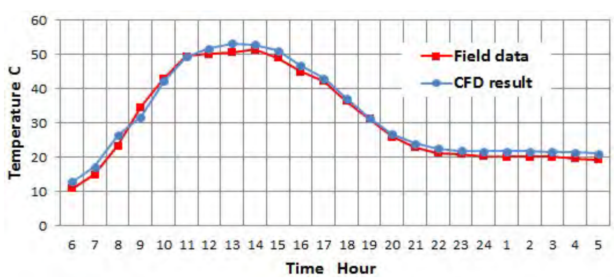


Fig. 12. Comparisons of field and modeled module temperatures; a sunny summer day (7/1/2011); 2-D simulations.

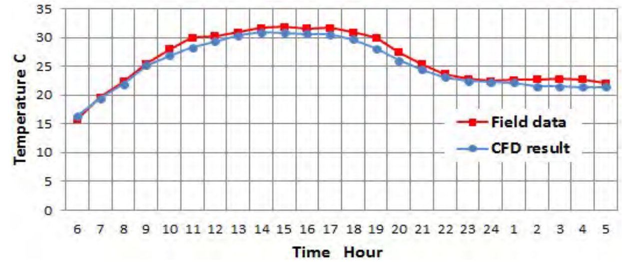


Fig. 13. Comparisons of field and modeled air temperatures at a height of 2.5 m; a sunny summer day (7/1/2011); 2-D simulations.

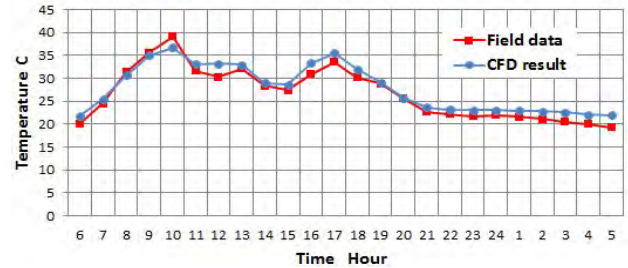


Fig. 14. Comparisons of field and modeled module temperatures; a cloudy summer day (7/11/2011); 2-D simulations.

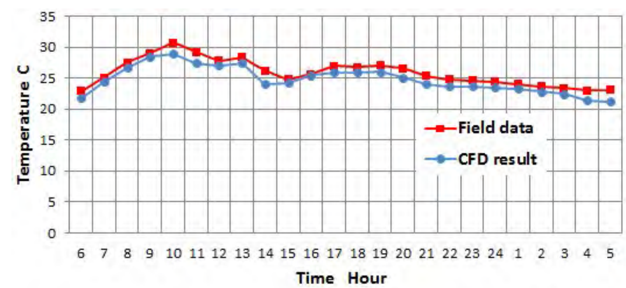
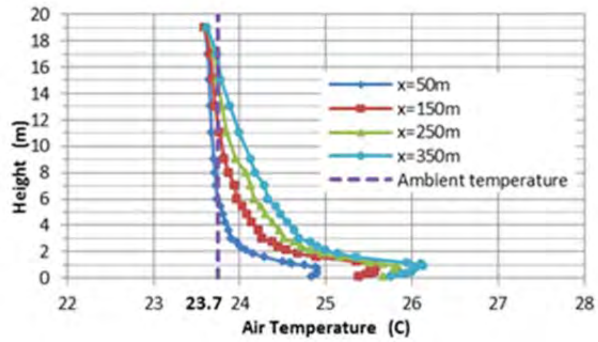
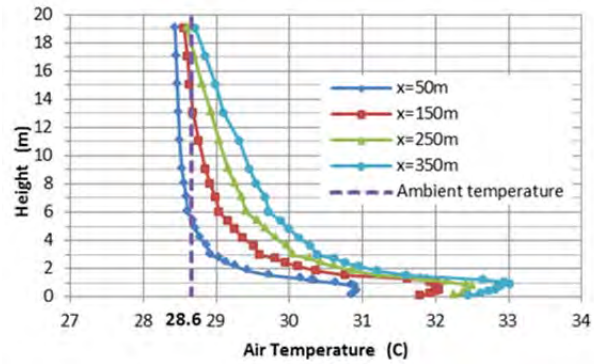


Fig. 15. Comparisons of field and modeled air temperatures at a height of 2.5 m; a cloudy summer day (7/11/2011); 2-D simulations.

Figures 16a and 16b show the air temperature as a function of height at different downwind distances in the morning and afternoon during a sunny summer day. At 9 am (irradiance 500 W/m2, wind speed 1.6 m/s, inlet ambient temperature 23.7℃), the heat from the solar array is dissipated at heights of 5-15m, whereas at 2 pm (irradiance 966 W/m^2, wind speed 2.8m/s, inlet ambient temperature 28.6℃ , the temperature of the panels has reached the daily peak, and the thermal energy takes up to 18 m to dissipate.



(a) 9:00 am



(b) 2:00 pm

Fig. 16 Air temperatures within the solar farm, as a function of height at different downwind distances. From 2-D simulations during a sunny summer day (7/1/2011) at 9 am and 2 pm.

IV. Conclusion

The field data and our simulations show that the annual average of air temperatures at 2.5 m of the ground in the center of simulated solar farm section is 1.9℃ higher than the ambient and that it declines to the ambient temperature at 5 to 18 m heights. The field data also show a clear decline of air temperatures as a function of distance from the perimeter of the solar farm, with the temperatures approaching the ambient temperature (within 0.3°C), at about 300 m away. Analysis of 18 months of detailed data showed that in most days, the solar array was completely cooled at night, and, thus, it is unlikely that a heat island effect could occur.

Our simulations also show that the access roads between solar fields allow for substantial cooling, and therefore, increase of the size of the solar farm may not affect the temperature of the surroundings. Simulations of large (e.g., 1 million m^2) solar fields are needed to test this hypothesis.

Acknowledgement

We are grateful to First Solar for providing data for this study.

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Impacts of a Photovoltaic Power Plant for Possible Heat Island Effect

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***Abstract*—Today, solar energy conversion technologies take a significant place within the efforts of obtaining renewable and sustainable energy around the world, and show a rapid progress. One of the most common technologies is photovoltaic power plants (PVPP) which are built using PV modules that provide electricity directly from sunlight. These plants are qualified as one of the pioneering applications among clean energy production methods. However, as the modules cover large areas and as they are produced by mostly dark-colored *solar cells*, an environmental debate has already been opened via some recent studies in the literature: Do they alter the solar reflectivity (albedo) of the region's surface where they are installed, and in turn affect the typical microclimate characteristics of that region such as the local air temperatures, humidity, pressure and wind speed? Considering also the additional heat that the modules radiate while producing electricity, the main probable result should be expected as Heat Island Effect (HIE). HIE has been particularly discussed for about last 10 years. Basically, this effect defines the day-night and inter-seasonal variations of local temperatures due to artificial changes on the natural land surface. Accordingly, when an urbanized area is compared with the neighboring rural areas, the difference is specifically named as Urban Heat Island (UHI) effect. In the present work, we are conducting a field research with in-situ measurements taken by the two weather monitoring stations inside and outside a PVPP in the district Tavsanlı (Kutahya, Turkey). We also provide the meteorological data of Tavsanlı station from Turkish State Meteorological Service (TSMS), which is the nearest weather monitoring station to the PVPP under inspection. These stations have been collecting the data of air temperature, relative humidity, average wind speed and atmospheric pressure every 10 minutes since October 2017. We used two statistical methods to compare and interpret the first 8-month data of all the three stations. We considered the statistical significance tests for both the first 8 months as a whole and dividing it into two 4 months before and after the PVPP becomes operational. We found that the measurements of the three stations differ significantly for most of the weather parameters. We also carried out pairwise tests and showed that each pair has significant differences for most parameters.**

Keywords— PV power plant, PV module, heat island, albedo, meteorological parameters

I. Introduction

Energy provision has been acquiring various ways in parallel with the integration of reliability, sustainability, stability and affordability since the emergence of the concept "sustainable development (SD)". As in different industries, SD emphasizes the need for a strong balance and collaboration between society, environment and economy for energy sector. For this reason, renewable and clean energy sources have already achieved remarkable utilization rates, and been a substantial alternative to fossil fuels. Not surprisingly, solar energy is one of the leading types with its sub- "photovoltaic (PV)" technology which defines the conversion of sunlight into electricity by PV cells and modules (assembled by the electrical connections of solar PV cells with each other). By installation of these modules, the diverse applications from building-integrated to ground-mounted construction; from transportation to space vehicles/instruments can be seen in many countries of the world. Solar power capacities of the world's many countries like USA, Japan and the ones within BRICS and EU-28, have reached GW-scale in 2017 [1]. Moreover, the popularity of solar electricity is growing day by day with the advantages of increasing employment and decreasing prices.

Renewable energy facilities like solar and wind farms/plants are not only well-known and widely accepted places with their non-depletable side, but also with their clean production feature. Especially in terms of environmental degradation caused by greenhouse gas (GHG) emissions, their environmentally friendly working principles come into prominence by comparison with combustion of fossil fuels. However, there are some concerns related to the operation of these facilities toward green energy. Some previous publications pointed out that utilization from solar energy technologies could bring some negative effects and potential impacts on land-use, microclimate (local climate), ecosystem and biodiversity [2][3][4][5].

This study is intended to understand one of these concerns that have been discussed in some previous field researches and modelling work in the literature [6][7][8] but still more studies are required: Possible Heat Island Effect due to the large-scale deployment of PV modules and arrays.

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The term "heat island" is mostly used with the prefix "urban", because it is generally described for the surface structure and overlying atmospheric layers of big cities and metropolitan areas. Furthermore, UHIs are defined according to its sub-types which are detected by different measuring instruments. Besides, heat islands are categorized by different prefixes depending on the source such as, and for the focus of this study we use PVHI to stand for Photovoltaic Heat Island. At this point, it should be noted that the detection methods of UHIs have already developed a referable basis for other heat island types.

Following this Introduction part, UHIs and PVHI will be explained in detail. Then, our methodology and meteorological data collection-analysis for the first 8-month field data will be given. Finally, the interpretation of the current results and the intention of constructing/implementing a model will be summarized under the title "Discussion, Conclusion and Future Work".

II. Heat Islands: Description, Types and Measurement

A. *Description of Heat Island Effect*

United States Environmental Protection Agency (US EPA) defines the concept of heat island from the point of a city having at least a population of 1 million and surrounded by rural areas [9]. Within its definition, the agency draws attention to the temperature differences occurring in the daytime as 1–3°C and reaching up to 12°C in the evening. US EPA also mentions some adverse consequences of heat islands for the society as human health and comfort problems like heat-related illness; for the environment as GHG emissions, air pollution and water quality impairment; and for the economy as increase in summertime peak energy demand and air conditioning costs.

Gartland [10] expresses this phenomenon by means of hotter air and surface temperatures in an urban or suburban area than its rural surrounding. These higher temperatures mainly show up due to the disturbance in the balance between warming and cooling cycle of a natural surface. Here, the scientific term of solar reflectivity "albedo" is the key element for this cycle because it specifies the ratio of the reflected solar radiation to that of incoming (shortwave). An albedo value of a surface can be given as decimal between 0-1 or as percentage between 0-100 without a unit, and used as a descriptive characteristic of the land surface. If this value is small then the surface lets more sunlight pass into the next/neighboring/bottom layers or absorbs/stores more energy as heat in itself. As sunlight absorption gets bigger from sunrise to sunset, the surface temperature rises as a direct effect. On the other hand, as an indirect effect, that is, the cooling trend of the surface will cause additional heat to atmosphere during the night time via longwave (infrared (IR)) radiation. Considering a large urban topography and a neighbor rural topography covered by different surface types, this altered warming and cooling cycles can cause an unnatural temperature oscillation with rises and falls. In view of the resulting surface and air temperature curves, an island shape is determined as in Fig. 1 so HIE is termed in this direction.

In nature, the untouched formations usually have higher albedo values such as green forests and fields, deserts they have and lower heat release than artificial structures such as the agricultural lands, urban and deforested sites and large

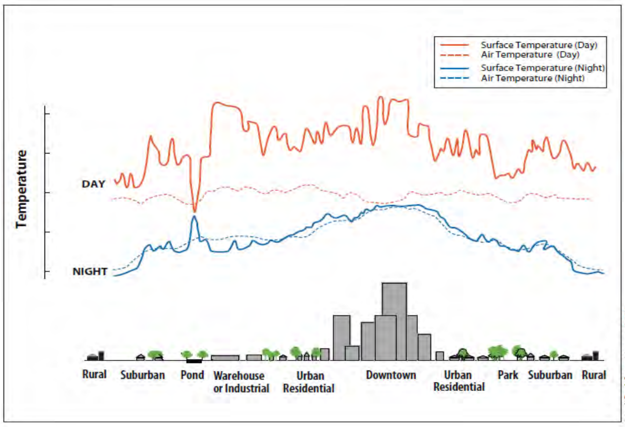

Fig. 1 Temperature curves of day and night time Urban Heat Island Effect from urban to rural areas [9]

area power plants. The natural surface such as snow-covered areas and ice fields (ice caps) etc. have the largest albedo values. The main and effective reasons of UHI are the building density with an inefficient design, rooftops, pavements and asphalt constructed by non-green materials in urbanized areas having low reflectance, resulting in high surface temperatures and more release of extra heat to atmosphere. The thermal interaction of a settlement can be seen in Fig. 1. Growing of a city and its impervious surfaces without allocation of sufficient vegetation can decrease the evapotranspiration and infiltration rates between atmosphere and ground cover, and increase the surface runoff rates. Thus, natural heat transfer paths can be affected from this new land-air interaction and UHIs can be stimulated by this way. In addition to the factors above, GHG emissions from fuel combustion like exhaust gas of vehicles, use of coal etc. contribute to the occurrence of HIE.

B. *Types of Heat Islands and Measurement Methods*

Heat islands have a zonal and vertical classification from the ground to the upper atmosphere of the Earth. Because they are mostly referred for metropolitan areas and densely populated cities, they are categorized into two basic types according to urban environment: Surface Urban Heat Islands (SUHIs) indicate some unusual variations in the surface temperatures of an urban fabric. As for Atmospheric Urban Heat Islands (AUHIs), the layers of a city air towards the upper levels of the atmosphere are taken into consideration. Accordingly, AUHIs are also divided into the two sub-types: Canopy Layer UHIs (CLUHIs) are formed below the rooftops and top of trees where the people reside. Besides, Boundary Layer UHIs (BLUHIs) extend to the higher altitudes where the urban landscape doesn't have an impact on the atmosphere (from surface to 1.5 km). Fig. 2 shows all these types [ref].

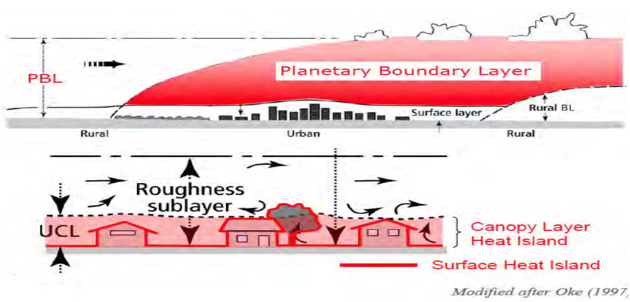

Fig. 2 Types of UHIs and their influence area [11]

Diurnal weather conditions and seasonal climate of an urban region play a fundamental role in the formation of UHIs. As a result, some temporal intensity changes of the concerned UHI can be observed depending on a time interval of the day and the active season. To collect field data and make the relevant observations for the studied UHI type, the researchers use some measuring instruments and identification methods. Table I introduces the UHIs in accordance with a temporal and methodological grouping. A significant distinction between UHI types is the time frame of their emergence during a day and a specific season. A prominent UHI in hot summer day-night times having clear-sky and calm weather conditions arises from higher surface temperatures of urban fabric than air temperatures (compared with rural regions), and known as surface UHI. Conversely, atmospheric UHIs are particularly apparent during cool nights and cold winters because of a slow rate of heat release from a city's infrastructure by cooling, and thus warms the upper layers of urban atmosphere more than nearby rural areas. At the same time, it should be noted that the latitudinal-longitudinal / geographic differences and the prevailing climatic conditions of an urban-rural geography like the demonstration in Fig. 3 (desert, continental etc.) also influence the formation and intensity of UHIs.

Table I summarizes the types of UHI. Atmospheric UHIs are mainly identified by direct measurement methods (e.g. weather monitoring stations and mobile traverses); whereas indirect measurement methods (e.g. remote sensing via satellites) are also used for the identification of surface UHIs. UHI effect from some case studies conducted by direct and indirect measurement methods can be found for several countries/cities in the literature [12][13][14][15]. Benefiting from a variety of the former UHI studies; Deilami, Kamruzzaman and Liu also made a comprehensive review based on spatio-temporal factors, methodology and measurement techniques for the analysis of UHIs [16].

TABLE I. TEMPORAL AND METHODOLOGICAL GROUPING OF UHI TYPES [9][11][17]

Feature	Surface UHI	Atmospheric UHI
Time of day and season	*Presence:* All times of the day and night *Intensity:* During the day and in the summer	*Presence:* Small or absent during the day *Intensity:* At night, before dawn and in the winter
Temperature variation	*Day:* 10 – 15 °C *Night:* 5 – 10 °C	*Day:* -1 – 3 °C *Night:* 7 – 12 °C
Identification method / instrument	*Remote Sensing (3D, 2D and ground):* ➢ Satellites ➢ Aircrafts ➢ Some ground systems	*Fixed weather monitoring stations*: ➢ Ground-mounted versions for CLUHI ➢ Tower-mounted versions for BLUHI *Mobile traverses*: ➢ Automobiles for CLUHI ➢ Aircrafts for BLUHI *Vertical sensing:* ➢ SODAR (Sonic Detection and Ranging) for BLUHI ➢ Tethered balloons for BLUHI
Depiction	Thermal imaging	Isotherm mapping & Temperature graphs

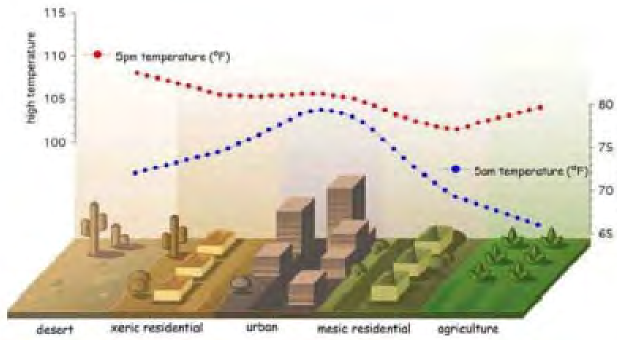

Fig. 3 Time-dependent temperature curves of different geographic regions and landscapes between urban-rural transition [17]

C. Photovoltaic Heat Island Effect (PVHIE)

Cumulative solar PV capacity of the world reached around 350 GW in 2017 [1] and since that time, this value has been growing especially with the new installments of PVPPs. Further increase is expected in the near future worldwide. Thus, an urgent research topic seems PVHIE both conducting field measurements and modellings.

PV modules are produced by the electrical assembly of PV cells which provides electricity generation. The most widely-used and commercial PV cells are manufactured from crystalline silicon (c-Si). Because the final products of these cell and module types have the physical and electrical properties that can bring limited conversion efficiencies (15-30%), dark-colored surfaces, packing density and/or arrays with gaps etc., a possible PVHIE can be induced in a similar way to UHIs. In other words, when PVPPs cover the big and untouched areas involved by a rural environment or natural habitat after a large-scale deployment, their PV arrays in large numbers and the corridors between these arrays may disturb the incoming solar radiation and outgoing IR radiation amounts of the previous land surface by landscape albedo change and alteration. Armstrong, Waldron, Whitaker and Ostle demonstrates a schematic view showing how a ground-mounted solar panel alters the natural radiation and the precipitation amounts between air and land [3]. Figure 4 gives a schematic description of how large area solar modules alter air-land interaction with solar-terrestrial radiation and precipitation.

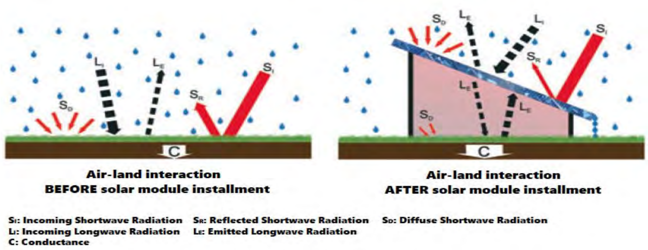

Fig. 4 Air-land Interaction for solar-terrestrial radiation and precipitation amounts BEFORE and AFTER solar module installment *(modified from the source* [3]*)*

III. Methodology, Data Collection and Analysis of the First 8 Months

Present study is based on 8 months of field measurements taken inside and outside of a PVPP. Besides, weather data of a nearby location to the PVPP is also used in the analysis. We started to monitor the data before the PVPP installment and continued to take after the PVPP started to feed the grid. The analysis are carried out mainly using some statistical tools and two former studies [6][18].

A rural region called Sekbandemirli (Tavsanli district of the Kutahya city) is the location of the PVPP, shown in Fig. 5a. The construction of Sekbandemirli PVPP (currently having a total system power of 2.86 MW) started on 25 September 2017 and the plant was being built on a 44000 m^2 field area. The present study is based on the data in the field starting from October, 6th 2017. The two weather monitoring stations were installed on the region, one is inside of the plant and the other is outside on a location between the village and plant as shown in Fig. 5b. The distance between their locations is approximately 180 meters while the elevation difference is 3 meters. The data is collected as 10-minute, hourly, daily and monthly averages of air temperature, relative humidity measurements at 2 meters above ground, average wind speed and direction measurements at 2.5 meters above ground and barometric/atmospheric pressure measurements at 1.5 meters above the ground. These measurements can be numerically and graphically followed by a web interface of an agricultural and meteorological monitoring system, "PlantMet", while tracking some PV output parameters (such as the photovoltaic energy and power) via another web interface, "SunnyPortal" (Fig. 6). The plant started operation on February 5, 2018.

In addition to two weather monitoring stations, the data supplied from Tavsanli station belonging TSMS, which is the nearest station to the PVPP at a distance of 13 km from the plant, and has an elevation difference of less than 50 meters (on a higher topographical location than the stations of the study). We used this data to validate the accuracy of the data taken by the stations of the present research.

The 8-month 10-minute interval data set of four weather parameters for all the three stations were statistically compared by the tools "One-Way Analysis of Variance (ANOVA)" and "Tukey's Honest Significant Difference (HSD) Test". One-Way ANOVA test is to determine if some statistically significant differences exist between the means of three or more independent groups [19]. However, it does not show which specific groups differ from each other. For further clarification of this issue, a Post Hoc Test like Tukey's HSD is required and that should be applied [19]. In the "Appendix" part, Table AI and Table AII present the results of these two methods run from Data Analysis Tools of Microsoft's Office Excel 2016.

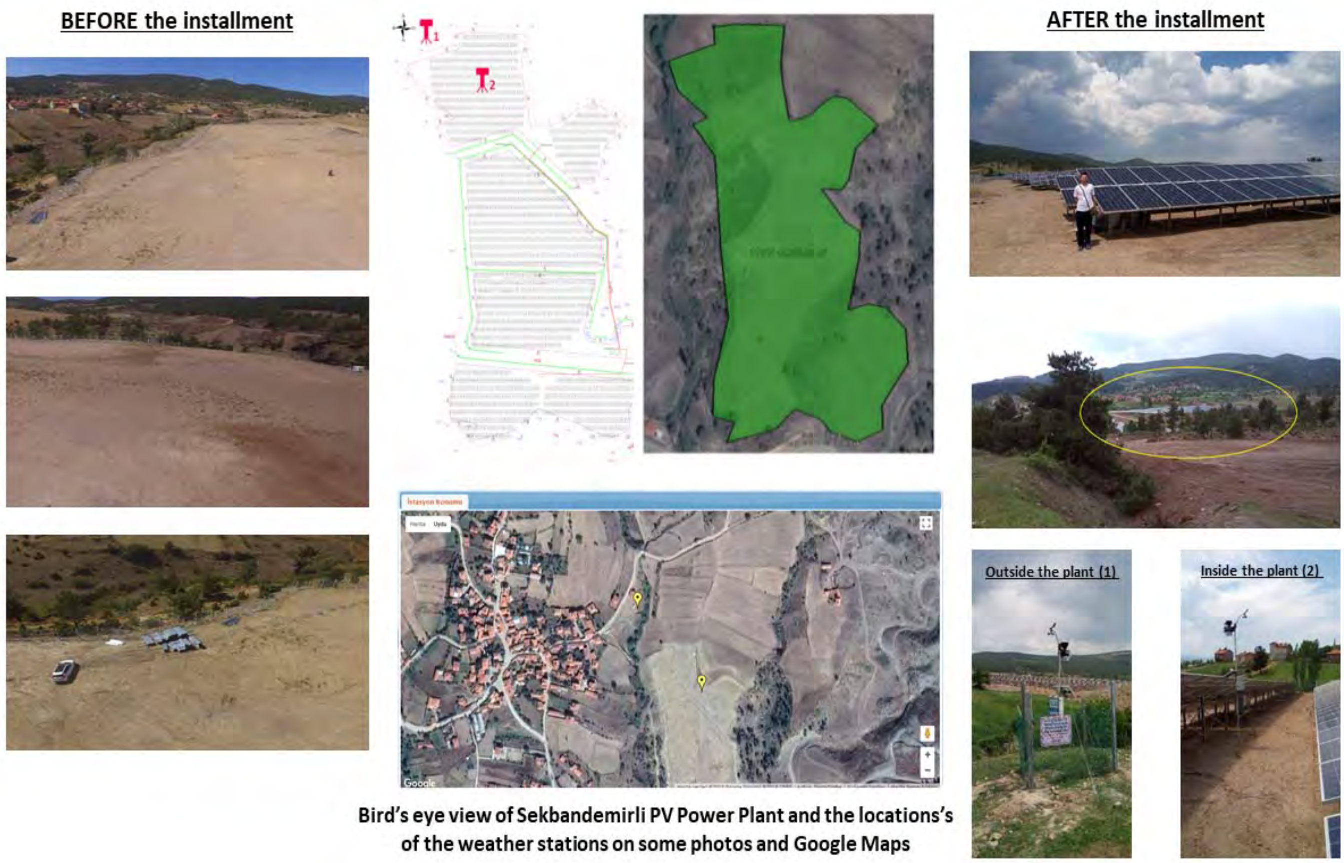

Fig. 5a Sekbandemirli PVPP

Fig. 5b Weather monitoring stations of the study

Fig. 6 Sample pages of data monitoring visual interfaces of the study

IV. Discussion, Conclusion and Future Work

The present preliminary research is to develop a statistical methodology to determine possible PVHIE. Up to now, an 8-month data of air temperature, relative humidity, barometric pressure and wind speed are collected from two different locations from inside and outside of a PVPP at the installation stage. In the first 4 months PVPP was in construction stage while for the last 4 months it started to operate to feed in the grid. We also used the data taken by TSMS from a station 13 km away from the application area. Using two statistical tools to determine if the collected data has significant differences, we reached some preliminary conclusions. One-Way ANOVA tests for the whole 8 months and for the separated 4 months showed significant differences between three set of data for all the four parameters, which is rather expected.

Table AI of Appendix shows the Tukey's test results for four parameters for the whole 8-month period and for the three data sets. As can be observed, for the air temperature there is no significant difference between the data taken from inside and outside of the plants while both of these data set differs from the data of TSMS. This is rather expected considering the length of the data period which is yet short. However, for the other three parameters there are significant differences between each pairs of data sets except one in RH (which is not conclusive).

For the first 4 months we do not expect any statistical difference between the data pair of inside and outside of the application area for all the weather parameters. However, as can be observed from Table AII, except the air temperature, for all the other three parameters there are significant differences for all the pairs. This situation might point out that the air temperature would be the most indicative parameter for a possible PVHIE, but results for the last 4 months, similar situation is still conserved as can be observed. Therefore, we can conclude that either longer time series of data is needed or data of a complete year must be used in such analysis.

Our future plan is to continue collecting data and install new weather stations to other installation sites well before the start of operation of a PVPP. After at least one year of operation, in addition to above mentioned tools we plan to carry out different statistical tests both applied to average values and to the data sets of different time intervals such as hourly, daily and/or monthly. Another future plan is to use the software ENVI-MET [20][21][22] (holistic three-dimensional non-hydrostatic model for the simulation of surface-plant-air interactions [23]) in simulating the considered area and comparing the results with our experimental findings.

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APPENDIX

TABLE AI. STATISTICAL SIGNIFICANCE TEST RESULTS FOR 8 MONTHS

AIR TEMPERATURE	6 Oct -5 Jun
Outside PVPP-Tavsanli	SIGNIFICANT
Inside PVPP-Tavsanli	SIGNIFICANT
Inside PVPP-Outside PVPP	NOT SIGNIFICANT

RELATIVE HUMIDITY	6 Oct -5 Jun
Outside PVPP-Tavsanli	NOT SIGNIFICANT
Inside PVPP-Tavsanli	SIGNIFICANT
Inside PVPP-Outside PVPP	SIGNIFICANT

BAROMETRIC PRESSURE	6 Oct -5 Jun
Outside PVPP-Tavsanli	SIGNIFICANT
Inside PVPP-Tavsanli	SIGNIFICANT
Inside PVPP-Outside PVPP	SIGNIFICANT

WIND SPEED	6 Oct -5 Jun
Outside PVPP-Tavsanli	SIGNIFICANT
Inside PVPP-Tavsanli	SIGNIFICANT
Inside PVPP-Outside PVPP	SIGNIFICANT

TABLE AII. STATISTICAL SIGNIFICANCE TEST RESULTS FOR TWO 4 MOTNHS BEFORE AND AFTER THE START OF OPERATION

AIR TEMPERATURE	6 Oct - 4 Feb BEFORE	6 Feb - 5 Jun AFTER
Outside PVPP-Tavsanli	SIGNIFICANT	SIGNIFICANT
Inside PVPP-Tavsanli	SIGNIFICANT	SIGNIFICANT
Inside PVPP-Outside PVPP	NOT SIGNIFICANT	NOT SIGNIFICANT

RELATIVE HUMIDITY	6 Oct - 4 Feb BEFORE	6 Feb - 5 Jun AFTER
Outside PVPP-Tavsanli	NOT SIGNIFICANT	SIGNIFICANT
Inside PVPP-Tavsanli	SIGNIFICANT	NOT SIGNIFICANT
Inside PVPP-Outside PVPP	SIGNIFICANT	SIGNIFICANT

BAROMETRIC PRESSURE	6 Oct - 4 Feb BEFORE	6 Feb - 5 Jun AFTER
Outside PVPP-Tavsanli	SIGNIFICANT	SIGNIFICANT
Inside PVPP-Tavsanli	SIGNIFICANT	SIGNIFICANT
Inside PVPP-Outside PVPP	SIGNIFICANT	SIGNIFICANT

WIND SPEED	6 Oct - 4 Feb BEFORE	6 Feb - 5 Jun AFTER
Outside PVPP-Tavsanli	SIGNIFICANT	SIGNIFICANT
Inside PVPP-Tavsanli	SIGNIFICANT	NOT SIGNIFICANT
Inside PVPP-Outside PVPP	SIGNIFICANT	SIGNIFICANT

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The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures

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While photovoltaic (PV) renewable energy production has surged, concerns remain about whether or not PV power plants induce a "heat island" (PVHI) effect, much like the increase in ambient temperatures relative to wildlands generates an Urban Heat Island effect in cities. Transitions to PV plants alter the way that incoming energy is reflected back to the atmosphere or absorbed, stored, and reradiated because PV plants change the albedo, vegetation, and structure of the terrain. Prior work on the PVHI has been mostly theoretical or based upon simulated models. Furthermore, past empirical work has been limited in scope to a single biome. Because there are still large uncertainties surrounding the potential for a PHVI effect, we examined the PVHI empirically with experiments that spanned three biomes. We found temperatures over a PV plant were regularly 3–4 °C warmer than wildlands at night, which is in direct contrast to other studies based on models that suggested that PV systems should decrease ambient temperatures. Deducing the underlying cause and scale of the PVHI effect and identifying mitigation strategies are key in supporting decision-making regarding PV development, particularly in semiarid landscapes, which are among the most likely for large-scale PV installations.

Electricity production from large-scale photovoltaic (PV) installations has increased exponentially in recent decades[1–3]. This proliferation in renewable energy portfolios and PV powerplants demonstrate an increase in the acceptance and cost-effectiveness of this technology[4,5]. Corresponding with this upsurge in installation has been an increase in the assessment of the impacts of utility-scale PV[4,6–8], including those on the efficacy of PV to offset energy needs[9,10]. A growing concern that remains understudied is whether or not PV installations cause a "heat island" (PVHI) effect that warms surrounding areas, thereby potentially influencing wildlife habitat, ecosystem function in wildlands, and human health and even home values in residential areas[11]. As with the Urban Heat Island (UHI) effect, large PV power plants induce a landscape change that reduces albedo so that the modified landscape is darker and, therefore, less reflective. Lowering the terrestrial albedo from ~20% in natural deserts[12] to ~5% over PV panels[13] alters the energy balance of absorption, storage, and release of short- and longwave radiation[14,15]. However, several differences between the UHI and potential PVHI effects confound a simple comparison and produce competing hypotheses about whether or not large-scale PV installations will create a heat island effect. These include: (*i*) PV installations shade a portion of the ground and therefore could reduce heat absorption in surface soils[16], (*ii*) PV panels are thin and have little heat capacity per unit area but PV modules emit thermal radiation both up and down, and this is particularly significant during the day when PV modules are often 20 °C warmer than ambient temperatures, (*iii*) vegetation is usually removed from PV power plants, reducing the amount of cooling due to transpiration[14], (*iv*) electric power removes energy from PV power plants, and (*v*) PV panels reflect and absorb upwelling longwave radiation, and thus can prevent the soil from cooling as much as it might under a dark sky at night.

Public concerns over a PVHI effect have, in some cases, led to resistance to large-scale solar development. By some estimates, nearly half of recently proposed energy projects have been delayed or abandoned due to local opposition[11]. Yet, there is a remarkable lack of data as to whether or not the PVHI effect is real or simply an issue

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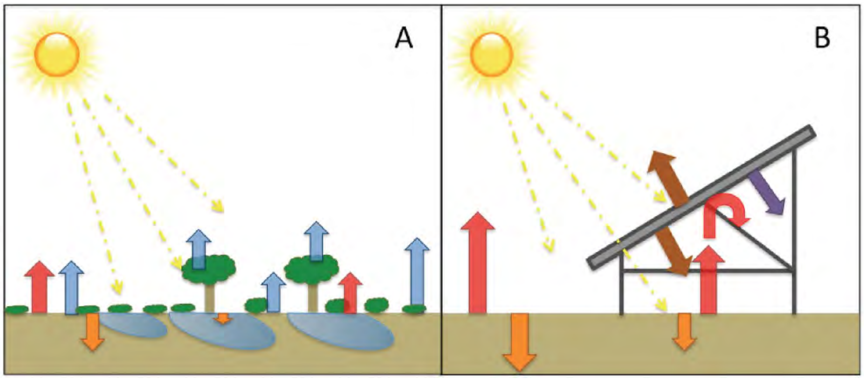

Figure 1. Illustration of midday energy exchange. Assuming equal rates of incoming energy from the sun, a transition from (**A**) a vegetated ecosystem to (**B**) a photovoltaic (PV) power plant installation will significantly alter the energy flux dynamics of the area. Within natural ecosystems, vegetation reduces heat capture and storage in soils (orange arrows), and infiltrated water and vegetation release heat-dissipating latent energy fluxes in the transition of water-to-water vapor to the atmosphere through evapotranspiration (blue arrows). These latent heat fluxes are dramatically reduced in typical PV installations, leading to greater sensible heat fluxes (red arrows). Energy re-radiation from PV panels (brown arrow) and energy transferred to electricity (purple arrow) are also shown.

associated with perceptions of environmental change caused by the installations that lead to "not in my backyard" (NIMBY) thinking. Some models have suggested that PV systems can actually cause a cooling effect on the local environment, depending on the efficiency and placement of the PV panels[17,18]. But these studies are limited in their applicability when evaluating large-scale PV installations because they consider changes in albedo and energy exchange within an urban environment (rather than a natural ecosystem) or in European locations that are not representative of semiarid energy dynamics where large-scale PV installations are concentrated[10,19]. Most previous research, then, is based on untested theory and numerical modeling. Therefore, the potential for a PHVI effect must be examined with empirical data obtained through rigorous experimental terms.

The significance of a PVHI effect depends on energy balance. Incoming solar energy typically is either reflected back to the atmosphere or absorbed, stored, and later re-radiated in the form of latent or sensible heat (Fig. 1)[20,21]. Within natural ecosystems, vegetation reduces heat gain and storage in soils by creating surface shading, though the degree of shading varies among plant types[22]. Energy absorbed by vegetation and surface soils can be released as latent heat in the transition of liquid water to water vapor to the atmosphere through evapotranspiration – the combined water loss from soils (evaporation) and vegetation (transpiration). This heat-dissipating latent energy exchange is dramatically reduced in a typical PV installation (Fig. 1 transition from A-to-B), potentially leading to greater heat absorption by soils in PV installations. This increased absorption, in turn, could increase soil temperatures and lead to greater sensible heat efflux from the soil in the form of radiation and convection. Additionally, PV panel surfaces absorb more solar insolation due to a decreased albedo[13,23,24]. PV panels will re-radiate most of this energy as longwave sensible heat and convert a lesser amount (~20%) of this energy into usable electricity. PV panels also allow some light energy to pass, which, again, in unvegetated soils will lead to greater heat absorption. This increased absorption could lead to greater sensible heat efflux from the soil that may be trapped under the PV panels. A PVHI effect would be the result of a detectable increase in sensible heat flux (atmospheric warming) resulting from an alteration in the balance of incoming and outgoing energy fluxes due to landscape transformation. Developing a full thermal model is challenging[17,18,25], and there are large uncertainties surrounding multiple terms including variations in albedo, cloud cover, seasonality in advection, and panel efficiency, which itself is dynamic and impacted by the local environment. These uncertainties are compounded by the lack of empirical data.

We addressed the paucity of direct quantification of a PVHI effect by simultaneously monitoring three sites that represent a natural desert ecosystem, the traditional built environment (parking lot surrounded by commercial buildings), and a PV power plant. We define a PVHI effect as the difference in ambient air temperature between the PV power plant and the desert landscape. Similarly, UHI is defined as the difference in temperature between the built environment and the desert. We reduced confounding effects of variability in local incoming energy, temperature, and precipitation by utilizing sites contained within a 1 km area.

At each site, we monitored air temperature continuously for over one year using aspirated temperature probes 2.5 m above the soil surface. Average annual temperature was 22.7 + 0.5 °C in the PV installation, while the nearby desert ecosystem was only 20.3 + 0.5 °C, indicating a PVHI effect. Temperature differences between areas varied significantly depending on time of day and month of the year (Fig. 2), but the PV installation was always greater than or equal in temperature to other sites. As is the case with the UHI effect in dryland regions, the PVHI effect delayed the cooling of ambient temperatures in the evening, yielding the most significant difference in overnight temperatures across all seasons. Annual average midnight temperatures were 19.3 + 0.6 °C in the PV installation, while the nearby desert ecosystem was only 15.8 + 0.6 °C. This PVHI effect was more significant in terms of actual degrees of warming (+3.5 °C) in warm months (Spring and Summer; Fig. 3, right).

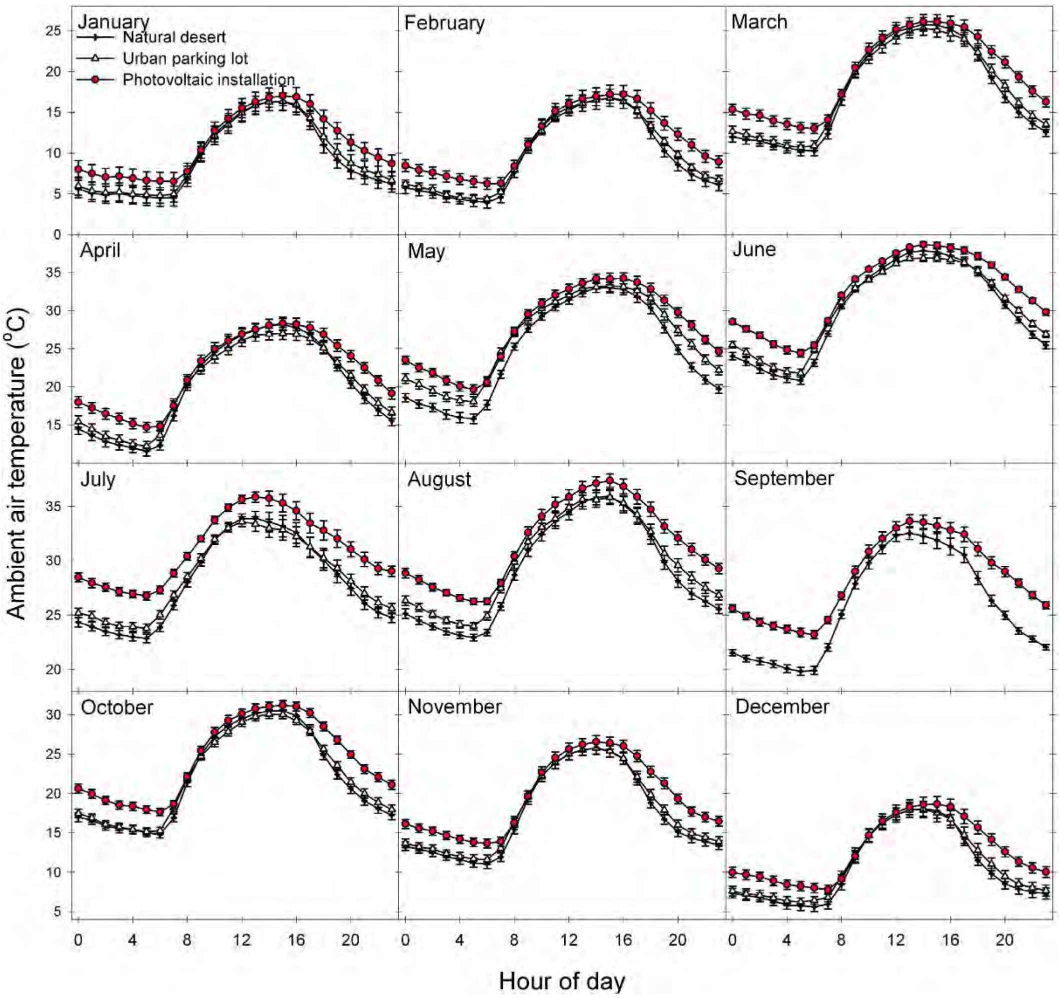

Figure 2. Average monthly ambient temperatures throughout a 24-hour period provide evidence of a photovoltaic heat island (PVHI) effect.

In both PVHI and UHI scenarios, the greater amount of exposed ground surfaces compared to natural systems absorbs a larger proportion of high-energy, shortwave solar radiation during the day. Combined with minimal rates of heat-dissipating transpiration from vegetation, a proportionally higher amount of stored energy is reradiated as longwave radiation during the night in the form of sensible heat (Fig. 1)[15]. Because PV installations introduce shading with a material that, itself, should not store much incoming radiation, one might hypothesize that the effect of a PVHI effect would be lesser than that of a UHI. Here, we found that the difference in evening ambient air temperature was consistently greater between the PV installation and the desert site than between the parking lot (UHI) and the desert site (Fig. 3). The PVHI effect caused ambient temperature to regularly approach or be in excess of 4 °C warmer than the natural desert in the evenings, essentially doubling the temperature increase due to UHI measured here. This more significant warming under the PVHI than the UHI may be due to heat trapping of re-radiated sensible heat flux under PV arrays at night. Daytime differences from the natural ecosystem were similar between the PV installation and urban parking lot areas, with the exception of the Spring and Summer months, when the PVHI effect was significantly greater than UHI in the day. During these warm seasons, average midnight temperatures were 25.5 + 0.5 °C in the PV installation and 23.2 + 0.5 °C in the parking lot, while the nearby desert ecosystem was only 21.4 + 0.5 °C.

The results presented here demonstrate that the PVHI effect is real and can significantly increase temperatures over PV power plant installations relative to nearby wildlands. More detailed measurements of the underlying causes of the PVHI effect, potential mitigation strategies, and the relative influence of PVHI in the context of the intrinsic carbon offsets from the use of this renewable energy are needed. Thus, we raise several new questions and highlight critical unknowns requiring future research.

What is the physical basis of land transformations that might cause a PVHI?

We hypothesize that the PVHI effect results from the effective transition in how energy moves in and out of a PV installation versus a natural ecosystem. However, measuring the individual components of an energy flux model remains a necessary task. These measurements are difficult and expensive but, nevertheless, are indispensable in identifying the relative influence of multiple potential drivers of the PVHI effect found here. Environmental

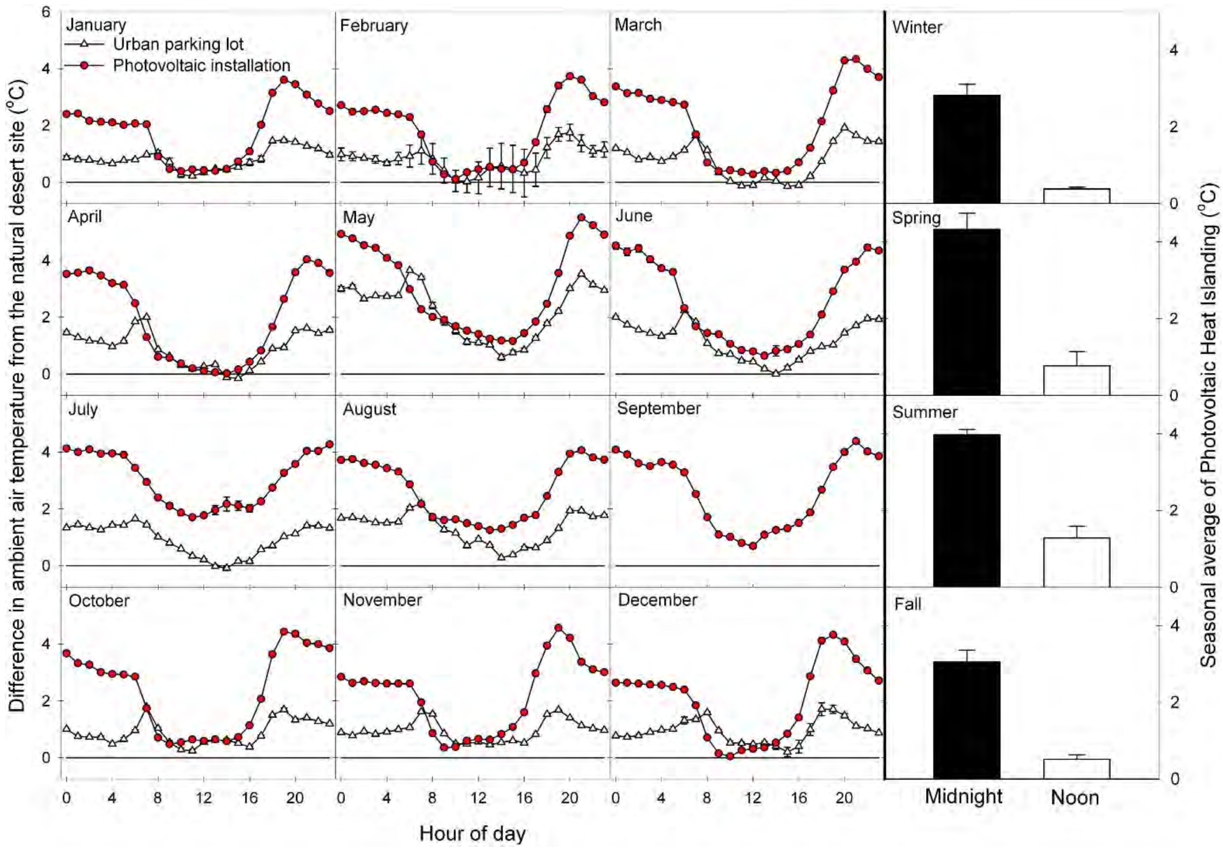

Figure 3. (Left) Average monthly levels of Photovoltaic Heat Islanding (ambient temperature difference between PV installation and desert) and Urban Heat Islanding (ambient temperature difference between the urban parking lot and the desert). (Right) Average night and day temperatures for four seasonal periods, illustrating a significant PVHI effect across all seasons, with the greatest influence on ambient temperatures at night.

conditions that determine patterns of ecosystem carbon, energy, and water dynamics are driven by the means through which incoming energy is reflected or absorbed. Because we lack fundamental knowledge of the changes in surface energy fluxes and microclimates of ecosystems undergoing this land use change, we have little ability to predict the implications in terms of carbon or water cycling[4,8].

What are the physical implications of a PVHI, and how do they vary by region?

The size of an UHI is determined by properties of the city, including total population[26–28], spatial extent, and the geographic location of that city[29–31]. We should, similarly, consider the spatial scale and geographic position of a PV installation when considering the presence and importance of the PVHI effect. Remote sensing could be coupled with ground-based measurements to determine the lateral and vertical extent of the PVHI effect. We could then determine if the size of the PVHI effect scales with some measure of the power plant (for example, panel density or spatial footprint) and whether or not a PVHI effect reaches surrounding areas like wildlands and neighborhoods. Given that different regions around the globe each have distinct background levels of vegetative ground cover and thermodynamic patterns of latent and sensible heat exchange, it is possible that a transition from a natural wildland to a typical PV power plant will have different outcomes than demonstrated here. The paucity in data on the physical effects of this important and growing land use and land cover change warrants more studies from representative ecosystems.

What are the human implications of a PVHI, and how might we mitigate these effects?

With the growing popularity of renewable energy production, the boundaries between residential areas and larger-scale PV installations are decreasing. In fact, closer proximity with residential areas is leading to increased calls for zoning and city planning codes for larger PV installations[32,33], and PVHI-based concerns over potential reductions in real estate value or health issues tied to Human Thermal Comfort (HTC)[34]. Mitigation of a PVHI effect through targeted revegetation could have synergistic effects in easing ecosystem degradation associated with development of a utility scale PV site and increasing the collective ecosystem services associated with an area[4]. But what are the best mitigation measures? What tradeoffs exist in terms of various means of revegetating degraded PV installations? Can other albedo modifications be used to moderate the severity of the PVHI?

Figure 4. Experimental sites. Monitoring a (1) natural semiarid desert ecosystem, (2) solar (PV) photovoltaic installation, and (3) an "urban" parking lot – the typical source of urban heat islanding – within a 1 km^2 area enabled relative control for the incoming solar energy, allowing us to quantify variation in the localized temperature of these three environments over a year-long time period. The Google Earth image shows the University of Arizona's Science and Technology Park's Solar Zone.

To fully contextualize these findings in terms of global warming, one needs to consider the relative significance of the (globally averaged) decrease in albedo due to PV power plants and their associated warming from the PVHI against the carbon dioxide emission reductions associated with PV power plants. The data presented here represents the first experimental and empirical examination of the presence of a heat island effect associated with PV power plants. An integrated approach to the physical and social dimensions of the PVHI is key in supporting decision-making regarding PV development.

Methods

Site Description. We simultaneously monitored a suite of sites that represent the traditional built urban environment (a parking lot) and the transformation from a natural system (undeveloped desert) to a 1 MW PV power plant (Fig. 4; Map data: Google). To minimize confounding effects of variability in local incoming energy, temperature, and precipitation, we identified sites within a 1 km area. All sites were within the boundaries of the University of Arizona Science and Technology Park Solar Zone (32.092150°N, 110.808764°W; elevation: 888 m ASL). Within a 200 m diameter of the semiarid desert site's environmental monitoring station, the area is composed of a sparse mix of semiarid grasses (*Sporobolus wrightii, Eragrostis lehmanniana*, and *Muhlenbergia porteri*), cacti (*Opuntia* spp. and *Ferocactus* spp.), and occasional woody shrubs including creosote bush (*Larrea tridentata*), whitethorn acacia (*Acacia constricta*), and velvet mesquite (*Prosopis velutina*). The remaining area is bare soil. These species commonly co-occur on low elevation desert bajadas, creosote bush flats, and semiarid grasslands. The photovoltaic installation was put in place in early 2011, three full years prior when we initiated monitoring at the site. We maintained the measurement installations for one full year to capture seasonal variation due to sun angle and extremes associated with hot and cold periods. Panels rest on a single-axis tracker system that pivot east-to-west throughout the day. A parking lot with associated building served as our "urban" site and is of comparable spatial scale as our PV site.

Monitoring Equipment & Variables Monitored. Ambient air temperature (°C) was measured with a shaded, aspirated temperature probe 2.5 m above the soil surface (Vaisala HMP60, Vaisala, Helsinki, Finland in the desert and Microdaq U23, Onset, Bourne, MA in the parking lot). Temperature probes were cross-validated for precision (closeness of temperature readings across all probes) at the onset of the experiment. Measurements of temperature were recorded at 30-minute intervals throughout a 24-hour day. Data were recorded on a data-logger (CR1000, Campbell Scientific, Logan, Utah or Microstation, Onset, Bourne, MA). Data from this instrument array is shown for a yearlong period from April 2014 through March 2015. Data from the parking lot was lost for September 2014 because of power supply issues with the datalogger.

Statistical analysis. Monthly averages of hourly (on-the-hour) data were used to compare across the natural semiarid desert, urban, and PV sites. A Photovoltaic Heat Island (PVHI) effect was calculated as differences in these hourly averages between the PV site and the natural desert site, and estimates of Urban Heat Island (UHI) effect was calculated as differences in hourly averages between the urban parking lot site and the natural desert site. We used midnight and noon values to examine maximum and minimum, respectively, differences in temperatures among the three measurement sites and to test for significance of heat islanding at these times. Comparisons among the sites were made using Tukey's honestly significant difference (HSD) test[35]. Standard errors to calculate HSD were made using pooled midnight and noon values across seasonal periods of winter (January-March), spring (April-June), summer (July-September), and fall (October-December). Seasonal analyses allowed us to identify variation throughout a yearlong period and relate patterns of PVHI or UHI effects with seasons of high or low average temperature to examine correlations between background environmental parameters and localized heat islanding.

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Author Contributions
G.A.B.-G., R.L.M. and N.A.A. established research sites and installed monitoring equipment. G.A.B.-G. directed research and R.L.M. conducted most site maintenance. G.A.B.-G., N.A.A., A.D.C. and M.A.P.-Z. led efforts to secure funding for the research. All authors discussed the results and contributed to the manuscript.

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