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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

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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.

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

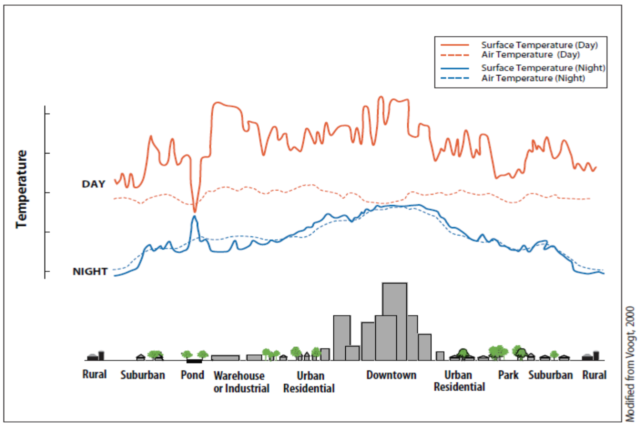


Fig. 1 Temperature curves of day and night time Urban Heat Island Effect from urban to rural areas [9]

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].

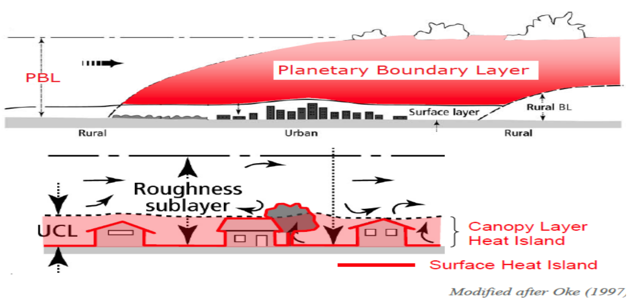


Fig. 2 Types of UHIs and their influence area [11]

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

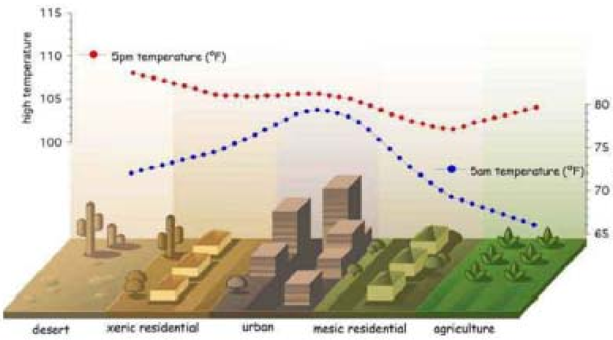


Fig. 3 Time-dependent temperature curves of different geographic regions and landscapes between urban-rural transition [17]

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.

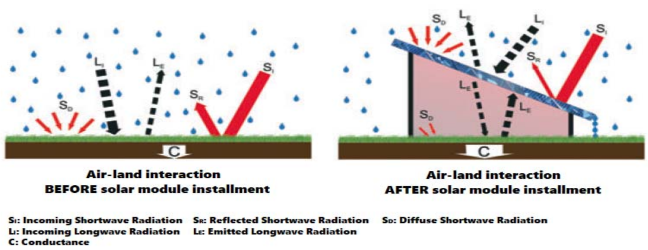


Fig. 4 Air-land Interaction for solar-terrestrial radiation and precipitation amounts BEFORE and AFTER solar module installment *(modified from the source* [3]*)*

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, 6^{th} 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.

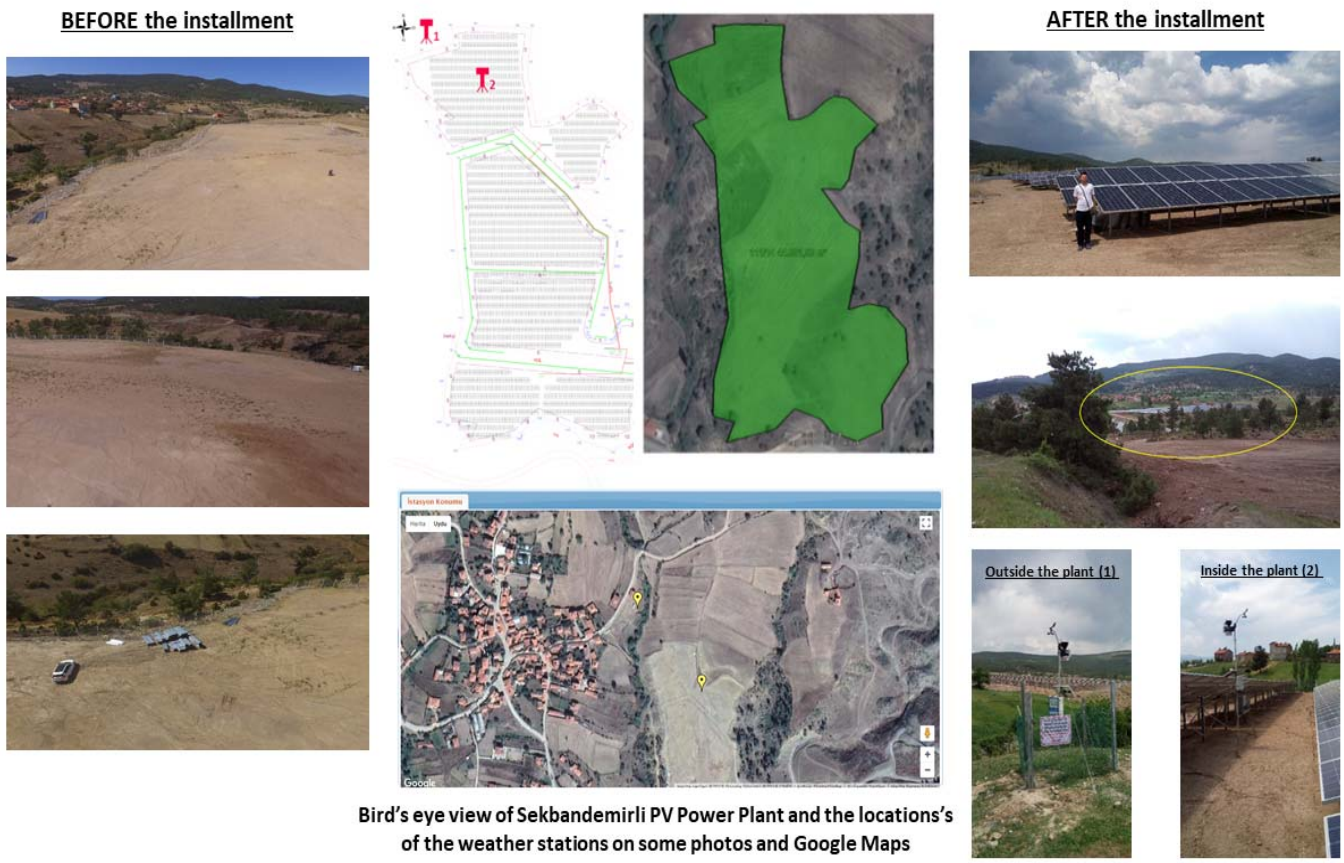
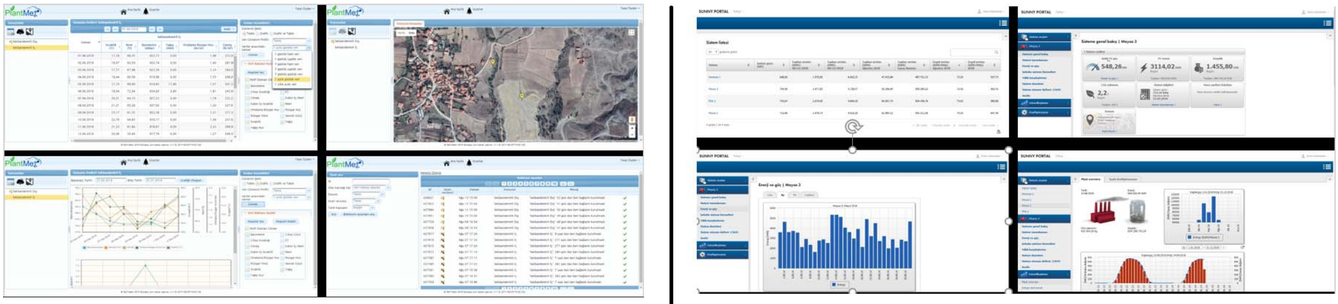


Fig. 5a Sekbandemirli PVPP

Fig. 5b Weather monitoring stations of the study



PlantMET
(http://web.plantmet.com.tr)

Sunny Portal
(https://www.sunnyportal.com/Plants)

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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