Article

Modeling of Stochastic Temperature and Heat Stress directly underneath Agrivoltaic conditions with Orthosiphon Stamineus Crops Cultivation

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Abstract: This paper shares some new information on the ambient temperature profile and the heat stress occurrences directly underneath ground-mounted Solar Photovoltaic (PV) Arrays (monocrystalline-based) focusing on different temperature levels. A common ground for this work lies on the fact that 1^0C increase of PV cell temperature results in reduction of 0.5% energy conversion efficiency thus any means of natural cooling mechanism would gain much benefit especially to the Solar Farm operators. Transpiration process plays an important role in the cooling of green plants where in average it could dissipate around 32.9% of the total solar energy absorbed by the leaf making it a good natural cooling mechanism. This condition is relatively applied for herbs specifically for this project, Orthosiphon Stamineus or generally known as Java Tea are used as the high value crops. The thermal process via convective heat and mass exchange of leaves with the environment is relevant for a better understanding of plant physiological processes in response to environmental conversion factors for a wide range of applications. An important fact for plant heat stress with respect to the Ambient temperature is that the range lies between 10^0C to 15^0C above the surrounding value. This heat stress condition is relatively important and should be modelled in crops-energy integration. Agrivoltaic concept is a system that combines commercial agriculture and photovoltaic electricity generation in the same space. The concept is in line with the Kyoto Protocol and the United Nation Sustainable Development Goals (UN-SDG) which highlights the clean energy and sustainable urban living. The integration of agrivoltaic systems would optimize the yield, improving clean system efficiency and solving the issue of land resource sustainability. The

PV bottom surface temperature are the main source of dissipated heat as shown in the thermal images recorded at 5 minutes interval at 3 sampling time. Statistical analysis shows that the Thermal correlations for transpiration process and heat stress occurrences between PV bottom surface and plant height will be an important finding for large scale plant cultivation in agrivoltaic farms.

Keywords: Transpiration; PV Heat Conversion; Plant Heat Stress; Agrivoltaic system; Sustainable Integration; Thermal Analysis

1. Introduction

The dramatic changes and increasing public interest in solar PV landscape showed the dual beneficial use of land may give better impacts in energy production and future agriculture transdisciplinary design. Some highlights and recent research in solar PV projects by the higher education shows that the solar industry has broaden the stakeholders and interested in the future, reflecting a significant shift in the dynamics of the market [1], [2]. The normal player for large scale solar PV farms is dominated by energy companies but based on the effort above, it is shown that experts in higher education within the research environment has the capabilities to compete amongst the players in Solar PV industry. This trend has been transferred to the ecological efficiency and positive effects, consequently upscaling the number and size of PV installed on the land. Rapidly decreasing price of Photovoltaic (PV) modules in the world market in line with the increasing demand of fresh produce promotes the idea of agro-PV integration or commonly known as Agrivoltaic system.

This type of solar power system, precisely known as Photovoltaic (PV) system is a power generation system that incorporates several parts, namely PV Modules, solar inverter, mounting, cabling and other electrical components which is integrated in Balance of Systems (BOS)[3], [4]. This photovoltaic device absorbs ray from the eternal sunlight and translating it into direct current (DC) via semiconductor materials. Malaysia, a tropical-based country in the South East Asia has given years of commitment on culturing green initiates especially Solar Photovoltaic systems and applications. This statement can be proven based on the increasing quota specifically for Large Scale Solar (LSS) PV system and the commitment by the Ministry of Energy, Science, Technology, Environment and Climate Change (MESTECC), [5] to persistently aims for 20% Energy mix by the year 2025 with initiatives below. Source from: [6]

- Implementing Enhanced Net Energy Metering (NEM) and Solar Leasing
- Implementing Large Scale Solar Programme 3 (LSS3) by March 2019 based on the successful implementation of LSS1 And LSS2 projects
- Implementing Non-Solar RE Projects
- Establishing RE Facilitation Programmes in Sustainable Energy Development Authority Malaysia (SEDA)
- Enabling Greater Access to Renewable Energy Sources

Generally, based on the PV projects in Universiti Putra Malaysia, where the size and ground conditions are put into the factor that generate empty areas under the panels, 1kWp solar PV arrays may occupy roughly 8 to 12 square meters of land [7], [8]. Based on the high demand, solar PV model in the market nowadays are ground-mounted arrays and require a fixed PV panel arrangement. It calls for futuristic features for the market with the application in large-scale areas by enhancing their design yet maintaining cost-effective deployment [9]. Temperature element plays an important factor in DC generation via PV modules. Park et al. [10] in their research under the Building-Integrated PV (BIPV) defines such significant effects of the PV module's thermal characteristics where approximately 0.5 % reduction of energy generated based on 1 °C increase of the module temperature. This statement is supported by Kim et al. [11] with an additional info of the energy efficiency from a common PV module can be increased due to the drop in surface temperature especially on the highest heated portions of PV cell and ribbon.

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The concept of Agrivoltaics or solar farming aspired the creative conversion of agriculture to photovoltaics applied on the same land to maximize the yield [12]. The Agrivoltaic system as shown in Figure 1 contemplate specific plant attributes; height, productivity, water consumption and shading resistance. The figure demonstrates the idea of the Agrivoltaics method employed in several countries by plotting vacant land with various types of crop. This method of farming under the solar panel is an innovation of incorporating green energy into agriculture and it is a part of introducing modern aspect to the agriculture community [13]. Some of the published results relating to Agrivoltaic projects are listed in Table 1.

Table 1. Successful integration of PV Farms with agriculture cultivation.

Author/ Year	Country	Highlights/ Findings
[9]	Italy	The AV system improved environmental efficiency
[12]	France	The AV system promotes effective usage of light and space for concurrent energy and food output.
[13]	USA	AV system will boost the technological capacity for PV and agricultural production conjointly by implementing a hybrid simulation model.
[14]	India	The AV system yielded more crop as compared to the period before the deployment.

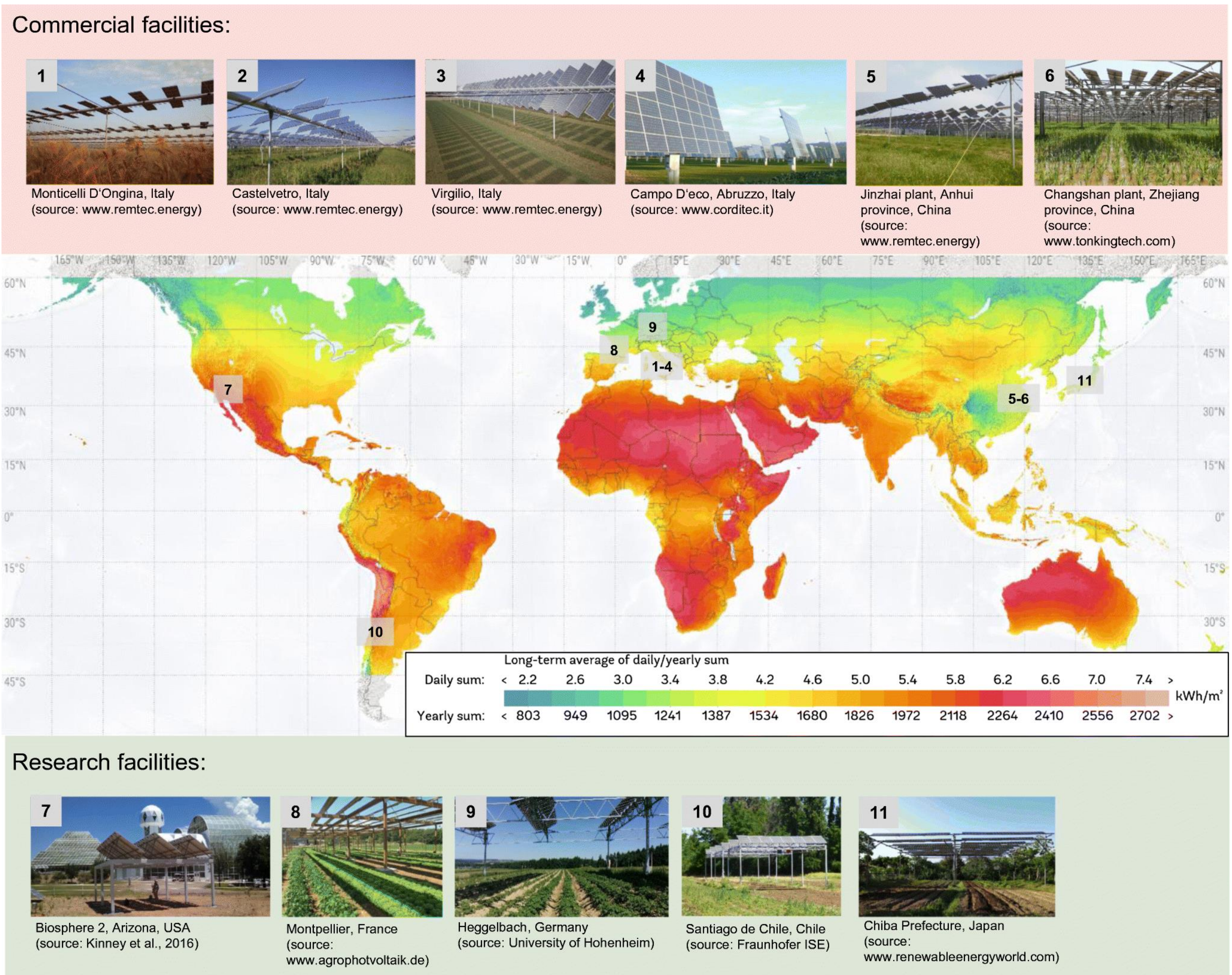

Figure 1. Typical Agrivoltaic research facility worldwide. [15].

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This integrated system will maximise crop production, enhancing the system performance while addressing land management and sustainability issues. The integration of these two resources would optimize the yield, improving clean system efficiency and solving the issue of land resource sustainability. The issue of Agrivoltaic concept implemented in ground-mounted PV system and shading effects by the PV arrays on crop canopy has been discussed by [15] recently.

The group suggested that the density of the PV arrays should be reduced adequately to enable ample amounts of light penetration while also maintaining a respectable production of DC electricity. The concept of Agrivoltaic is in line with the Kyoto Protocol [16] and the United Nation Sustainable Development Goals (UN-SDG) [17], [18] which promotes the clean and affordable energy towards sustainable urban infrastructure furthermore reducing the usage of fossil-fuel.

In Malaysia, most of the planned and retrofitted agrivoltaic facility is based on the existing ground-mounted Solar PV farm infrastructures where the primary activity is to sell the electricity generated to the National Grid. The issue of ground-mounted Photovoltaic system can be explained based on these several factors namely

- The existing solar PV farms do not allow any intervention or disturbance to any wiring, operation, structure or subsurface of PV system.
- There will be difficulty and hazards to farmers working under PV arrays and thus, yields less production.
- Workers had to bend and inspect plants under PV array structure for growth monitoring and harvesting activities (semi-confined working space).
- The need of some tools to ease the process of planting, harvesting, post-harvest and re-planting (most crops yields 4 cycle harvest per annum) under agrivoltaic farming.

1.1. Heat Stress vs Vapour Pressure Density (VPD): Crops natural cooling approach

Heat stress normally occurs when the temperature rises above a certain level for a certain period and bearing deleterious and permanent effects to crop cycle thus affecting yield [19], [20]. Generally, heat stress is set to occur when a transient temperature rises over the average temperature of 10-15°C [20]–[25]. The degree to which it happens in a particular climate zone relies on the frequency and amount of extreme temperatures happening during the day and/or the night. Some general definition of heat tolerance also being discussed which the tendency of a plant to grow and complete its cycle of life under high temperature [20].

Heat stress is often defined as the rise in temperature beyond a threshold level for a period of time sufficient to cause irreversible damage to plant growth and development. In general, a transient elevation in temperature, usually 10-15 °C above ambient, is considered heat shock or heat stress. However, heat stress is a complex function of intensity (temperature in degrees), duration, and specific rate of increase in temperature. Heat stress is defined as a rise in temperature above critical threshold levels for a period of time sufficient to cause irreversible damage to plant growth and development [20], [22], [23]. The extent to which it occurs in specific climatic zones depends on the probability and period of high temperatures occurring during the day and/or the night. Some general definition of heat tolerance also being discussed which the ability of the plant to grow and produce economic yield under high temperatures. Based on this fact, the surrounding temperature underneath the Photovoltaic Panels which occurs within the value of 10^0C – 15^0C above the ambient temperature are considered as base conditions towards plant heat stress.

Transpiration process plays an important role in the cooling of green plants where in average it could dissipate around 32.9% of the total solar energy absorbed by the leaf making it a good natural cooling mechanism [26]–[28]. Increased transpiration level does impact on water stress because the increase in ambient temperature increases the water evaporation from ground soil thus, some plants have the tendency of slow growth or even die at early stage. Orthosiphon Stamineus have been chosen as the herbal plant for the project where based on field evaluation (40 days under tropical

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climate), remarkably, the crop proves growth sustainability [29]. As compared to 4 types of herbal plants in the assessment, Orthosiphon Stamineus shows healthy growth and morphological aspects are enhanced comparable to the normal conditions. The roots and fresh branches show aggressive growth mostly due to soil moisture content thus, it can be harvested in time. The method of cultivation underneath solar PV arrays are using Drip Fertigation System (DFS) directly to polybags to maintain soil moisture level and prevent any disturbances to the electrical cablings and trenches. This method also eases the process of harvesting and replanting under such restricted conditions.

Herbal plants possess the tendency of unexploited bioactive chemical compound reserves with abundance of possible applications in pharmaceutical and agrochemical industries. [30] explains the basic concept of microclimate conditions as a set of climate parameters assessed in a specified area near the surface of the planet, including a variation of temperature, light, wind intensity and humidity factors (RH), are significant measures for habitat selection and other ecological practices. One of the critical elements calculated based on these parameters is the Vapor Pressure Deficit (VPD) which is defined as the discrepancy between the volume of moisture in normal settings with saturated condition (VPD in a greenhouse range of 0.45 kPa to 1.25 kPa with idle of 0.84 kPa) [30]

Leonardi in [31], explains that during daylight hours where high VPD condition is enhanced, the transpiration rates is better for plants grow because VPD exerts a substantial rise of soluble solids, but lowers the fruit fresh weight and internal fluid. Plant's transpiration and the correct VPD under controlled environment can effectively aid to optimize plant's ideal growing and plant health [32], [33]. Hot and dry air under shade surrounding atmosphere can produce high VPD and causes stress to plant. VPD in Kilopascals, kPa can be measured by subtracting the actual vapor pressure of the air with the saturated vapor pressure ($VP_{sat} - VP_{air}$) shown in Eqn. (1).

$$VPD = VP_{sat} - VP_{air} \qquad \text{Eqn. (1)} \qquad (1)$$

Where:
$VP_{sat} = T_a/1000$
$VP_{air} = VP_{sat} \times RH/100$

The value for VPD has also been summarized and simplied by the University of Arizona's College of Agriculture and Life Sciences [34] by using their online VPD calculator where user only insert value for Air Temperature (T_a) and Relative Humidity (% RH). The information related to micro climate for a specified location reflects the ecological process and wildlife behavior covering some elements of plant regeneration and growth which depicted their unique spatial and temporal responses to change [35], [36]. It is also a crucial measure to identify permutations in the local environment for tracking and evaluating the results of various management regimes.

A weather station as shown in Figure 2(a) have been installed at site to measure the environmental factors. The location of the station is near to PV array at 2 meter height to neglect any ground disturbances whilst the PV structure height ranges from 1 to 1.5 meter. Based on 24 hours data monitoring shown in Figure 2(b), the total of 3956 data sample have recorded for temperature value (^{0} C), wind speed (m/s), and Air Humidity (% RH). It is observed that the average wind speed is only 0.098 m/s due to the stagnant condition in most of the time and the location of win sensor under PV array (approx. 4 feet from ground level). The maximum recorded wind speed is at 3.3 m/s. The maximum value of relative humidity (RH) is 80.71% with an average reading of 65.67% throughout three days duration.

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Figure 2(a): Weather station installed at UPM HAVs site

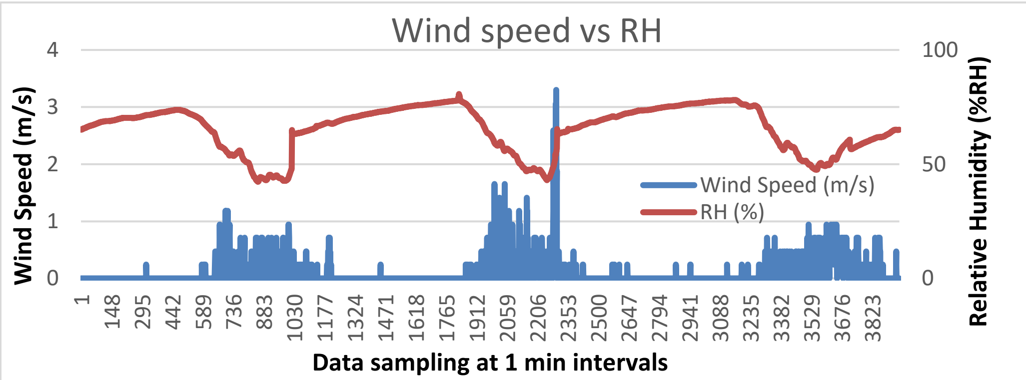

Figure 2(b). Data plots for RH and wind speed for Agrivoltaic plots.

In Agrivoltaic system, plant or crops is one of the crucial element need to be considered. The transpiration process in plant growth takes place when water is biologically released from the aerial parts of the plants in the form of water vapour. During the process of transpiration as illustrated in Figure 3, water molecules are transmitted from roots to stomata, the small pores underneath the leaves, where vaporization stage takes place and the molecules are transpired through the surrounding air. The effect of vaporization increases with the number of plants being deposited under the PV panels which results in increasing the humidity level (RH).

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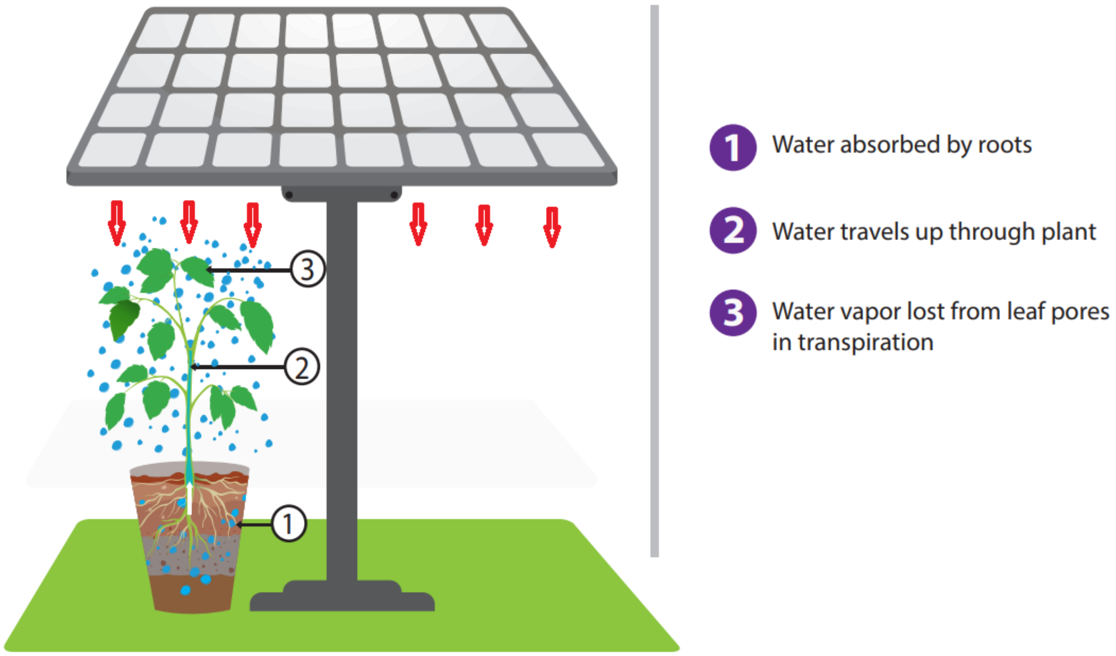

Figure 3. A simple analogy of plant transpiration process directly underneath PV module (heat source). Original source from [37].

Crawford in [38] explains extreme temperature multiplies the risk of plant damaged due to the heat, and simultaneously water shortage, which enhances the plant cooling capability as shown in Figure 4. The leaf temperature with average value of 1^{0}C cooler at 28^{0}C ambient shows that the transpiration process increases in higher surrounding temperature thus proves the plant cooling capacity.

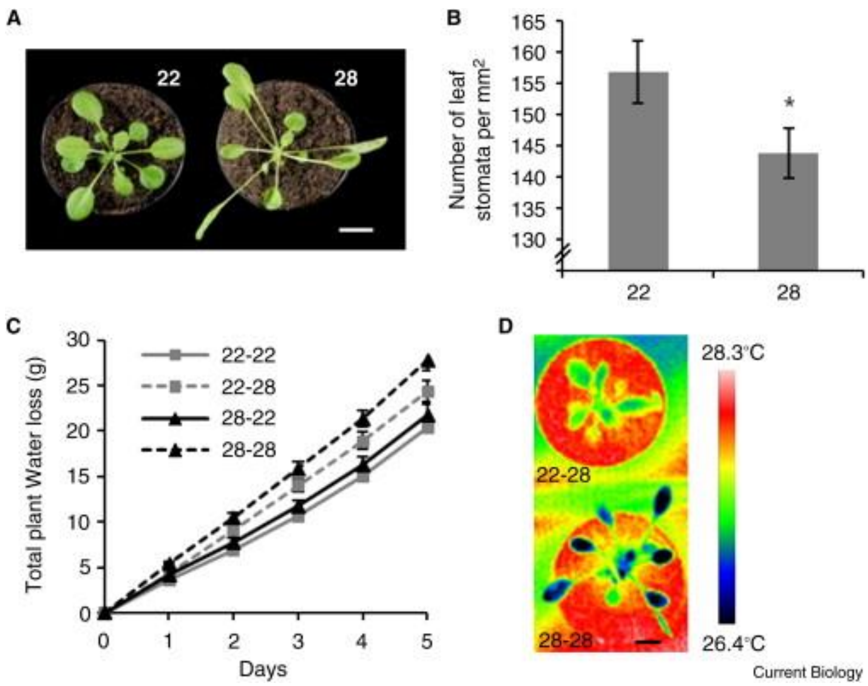

Figure 4. Crops response at high temperature indicates an increased in transpiration and enhanced leaf cooling capacity.

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The transpiration characteristics of plants in different surrounding temperature and relative humidity portrays a significant heat dissipation value (transpirative heat transfer through leaves). In relation to this, a study by [27] in Wuxi, China during summer and winter seasons reflect that 55.8% and 24.3% transpiratory heat flux for each season, accounting the total heat dissipation of the cinnamon.

2. Methodology

The site setup as shown in Figure 5a is located at the Hybrid Agrivoltaic System Showcase (HAVs) at the Faculty of Engineering Universiti Putra Malaysia (https://goo.gl/maps/bMvMGiFNiWQHsja5A).

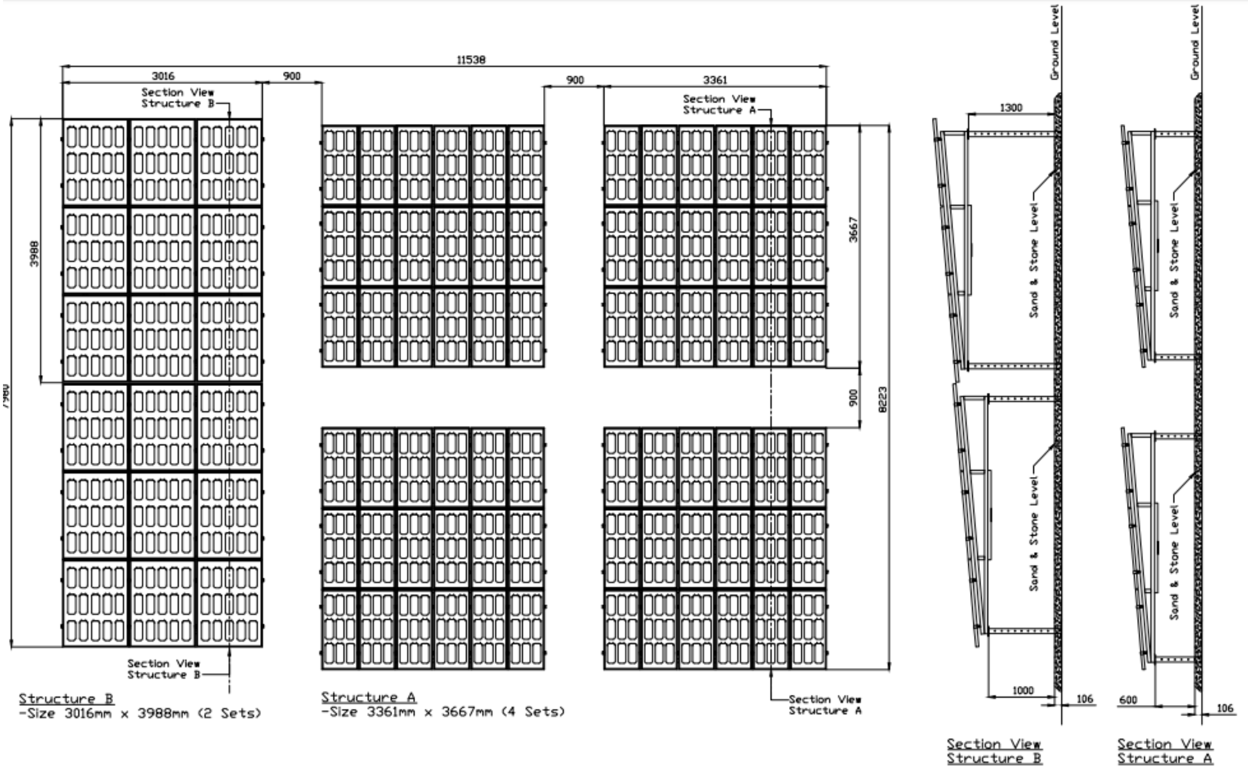

Figure 5. Site setup using 95W CEEG Monocrystalline PV modules.

Ambient Temperature surrounding the plant leaf is the main component to be recorded and analyse in this project. Fluke Thermal Imager is used to record video and images of surrounding temperature and it is located at 2 feet distance from the edge of PV array with infrared lens focusing on the leaves (middle angle) as shown in Figure 5.

Figure 5. Agrivoltaic system with Fluke Thermal Imager c/w tripod for video recording.

The field setup for agrivoltaic system has been installed at the Hybrid Agrivoltaic System Showcase (HAVs) Faculty of Engineering UPM with Thermocouple sensors at various height displacements. Thermal images using Fluke device are shown in Figure 6 where all the thermal images are taken using the same device and the same PV panel arrangements at different time shoot (figure shows thermal condition at 11AM and 3PM). The image shows much higher temperature at Bottom PV with reflect to the surrounding temperature condition and in this scope directly underneath PV panels. The sample clip video of thermal conditions underneath PV array are enclosed with the document.

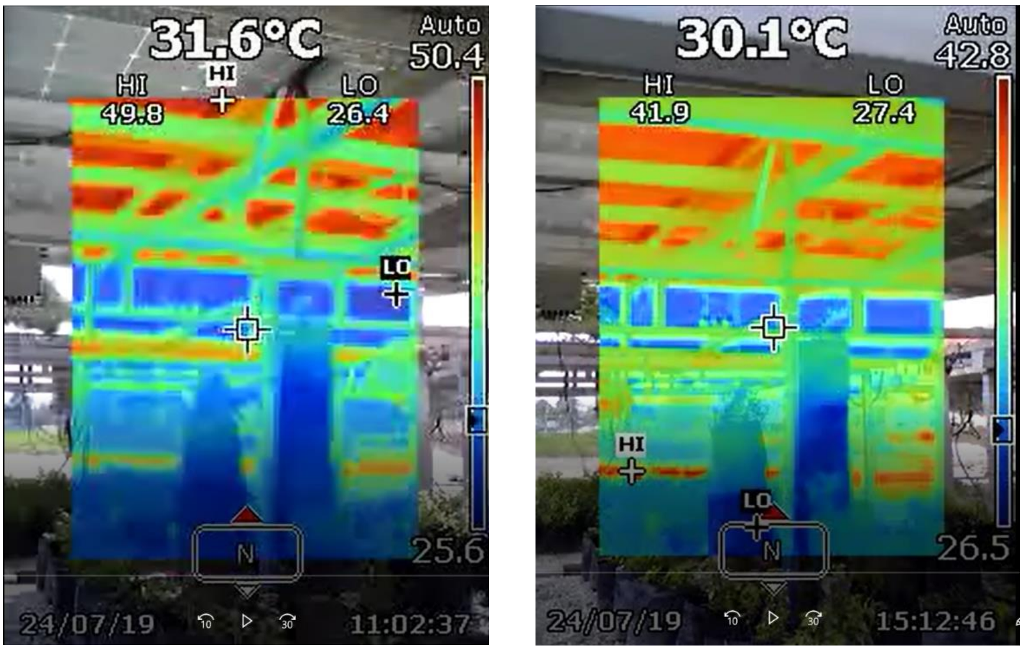

Figure 6. Thermal images of Agrivoltaic conditions for hourly sampling at UPM site.

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Thermal imager provides some insight of the temperature under agrivoltaic conditions although the readings might be not too precise because it shows one spot value at one time. Figure 6 and the attached video show the temperature values at different location i.e Bottom PV panel, surrounding air underneath PV, surrounding air at plant level, leaves, and ground surface temperature taken randomly at different time (5 min each). Assumptions are made for the temperature values in each location and level based on the colour indicator on the right side.

3. Results and Discussion

The main contribution from this work can be shown in the temperature elements plotted in Figure 7 where the actual temperature patern for 6 different height under Agrivoltaic condition is portrayed using 3600 data samples for 5 consecutive days from 7AM until 7PM daily. Each temperature value comes from thermal sensor (Type-K) starting from T_g which is the ground surface temperature up to the PV bottom, ($T_{b,\,pv}$) which is directly glued to the PV bottom surface. The other four temperature location ($T_{1ft,2ft,3ft,4ft}$) is based on reading from hanging sensor to measure the surrounding air. The temperature difference, ΔT is a crucial value to be analyze in Agrivoltaic condition especially the effect of plant height for each growth cycle. [39] explains that heat is one of the prominent elements in Abiotic Stress effect for plant growth where during heat stress, plants open their stomata to cool their leaves by transpiration. If the condition is prolonged or increasing rate, this will eventually create greater detrimental effect on the growth and productivity.

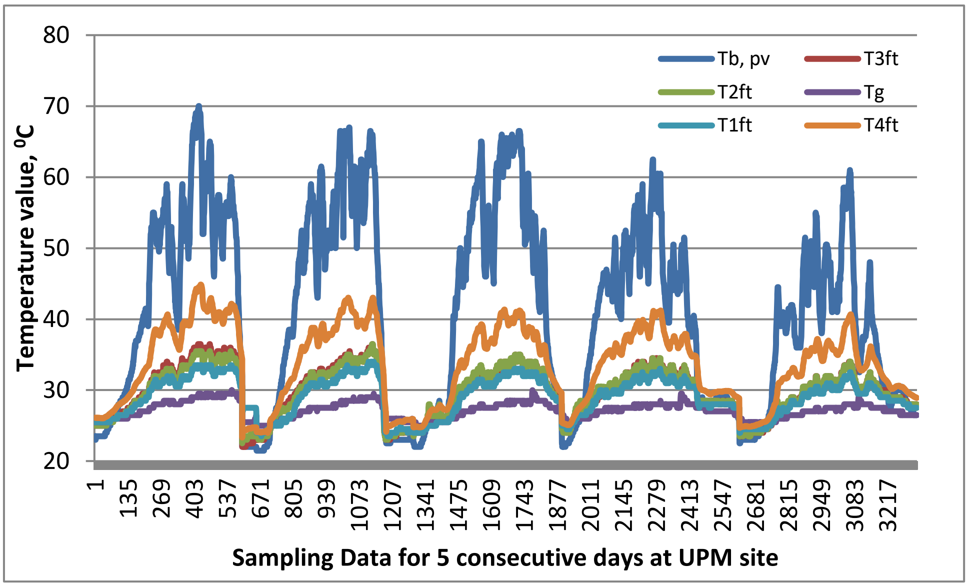

Figure 7. Temperature trend under Agrivoltaic condition with 1 min intervals (12 hours daily)

Based on temperature values in Table 1, the maximum recorded temperature for T_{1ft}, T_{2ft} and T_{3ft} is 34⁰C, 36.5⁰C and 36.5⁰C respectively where at this height, the plant started growing under Agrivoltaic condition. The value for ΔT_{max} is within increasing value with plant height temperature difference (1- 2 feet) ranging below 3 ⁰C. Ground temperature, T_g is considered as the reference value based on the effect towards plant seedling and T_b (bottom surface of PV module) as the maximum plant height. [40] explains that the rate of plant growth and development is heavily dependent on the surrounding temperature (min, max and optimum temperature values) and the temperature annual increment towards Global warming over the next 50 years is likely to reach 1.5°C between 2030 and 2052 [41].

Table 1. Values of temperature difference, ΔT (in ⁰C) based on 1 feet height distribution.

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	T_g	T_{1ft}	T_{2ft}	T_{3ft}	T_{4ft}	$T_{b, pv}$
average	27.14	29.06	29.78	29.83	33.47	40.97
max	30	34	36.5	36.5	44.88	70
min	25	23.5	22.5	22	23.33	21.5
ΔT_{ave}	1.92	2.64	2.69	6.33	13.83	
ΔT_{max}	4	6.5	6.5	14.88	40	
ΔT_{min}	-1.5	-2.5	-3	-1.67	-3.5	

Abbrev: T_g: Ground temperature; $T_{1ft,2ft,3ft,4ft}$: Temperature at 1 feet difference; $T_{b, pv}$: PV Bottom surface temperature

Based on Eqn. (1) and online calculator software, the value for VPD are summarized in Table 2. The value for T_{1ft} is used to represent designated surrounding air temperature (T_a) because the location is at par with the plant at 1 feet height and touching the polybags and soil.

Table 2. VPD calculation based on 1 feet height under Agrivoltaic condition.

Reading	Ta (⁰C)	% RH	SVP (kPa)	VP (kPa)	VPD (kPa)
Average Value	27.24	70.36	3.618	2.546	1.072
Max Value	34	89.7	5.324	4.776	2.005
Min Value	23.5	30.77	2.897	0.891	0.548

The optimum value for VPD under a greenhouse condition ranging from 0.45 kPa to 1.25 kPa, ideally sitting at around 0.85 kPa [31]. For Agrivoltaic condition, the VPD value range between 2.005kPa (max) to 0.548kPa (min) with an average value of 1.072 kPa.

For the temperature analysis, the field data measured are segregated into 5 sampling hours (daily) with different temperature level as shown in Table 3

Table 3. Analysis of temperature distribution based on sampling hours.

		Measure	Early sun	Moderate sun (morning)	Peak sun	Moderate sun (afternoon)	Mild sun (evening)
Time			7:00-8:59	9:00-10:59	11:00-14:59	15:00-16:59	17:00-18:59
Temperature	Tg (°C)	Average	25.5409	26.5125	27.9233	28.2828	26.3924
		Min	25.0000	25.5000	26.5000	25.5000	25.5000
		Max	26.5000	27.5000	29.5000	30.0000	27.5000
	T1ft (°C)	Average	25.1210	27.8650	31.4333	30.7819	26.9340
		Min	23.5000	25.0000	28.0000	24.0000	23.5000
		Max	27.5000	30.5000	33.5000	34.0000	29.0000
	T2ft (°C)	Average	25.2473	28.7383	32.6763	31.6755	26.4902
		Min	23.0000	25.0000	28.5000	23.0000	22.5000
		Max	29.5000	31.5000	35.5000	36.5000	29.5000
	T3ft (°C)	Average	25.0249	28.6808	32.8779	31.8989	26.3888
		Min	23.0000	25.0000	28.5000	23.0000	22.0000
		Max	28.0000	31.5000	36.5000	36.5000	29.5000
	T4ft (°C)	Average	26.0758	32.0005	38.4923	35.7665	27.9299
		Min	24.0000	26.1000	31.9500	26.9100	23.3300
		Max	30.1600	37.6400	44.8800	43.0300	31.1700
	Tb, pv (°C)	Average	24.6806	39.9392	53.6071	42.3635	26.0416
		Min	21.5000	26.0000	35.0000	23.0000	22.0000
		Max	35.5000	55.0000	70.0000	66.5000	30.5000

Abbrev: T_g: Ground temperature; $T_{1ft,2ft,3ft,4ft}$: Temperature at 1 feet difference; $T_{b, pv}$: PV Bottom surface temperature

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Based on this table and R programming, the heat stress contour throughout the 5 sampling hours are then plotted as shown in Figure 8.

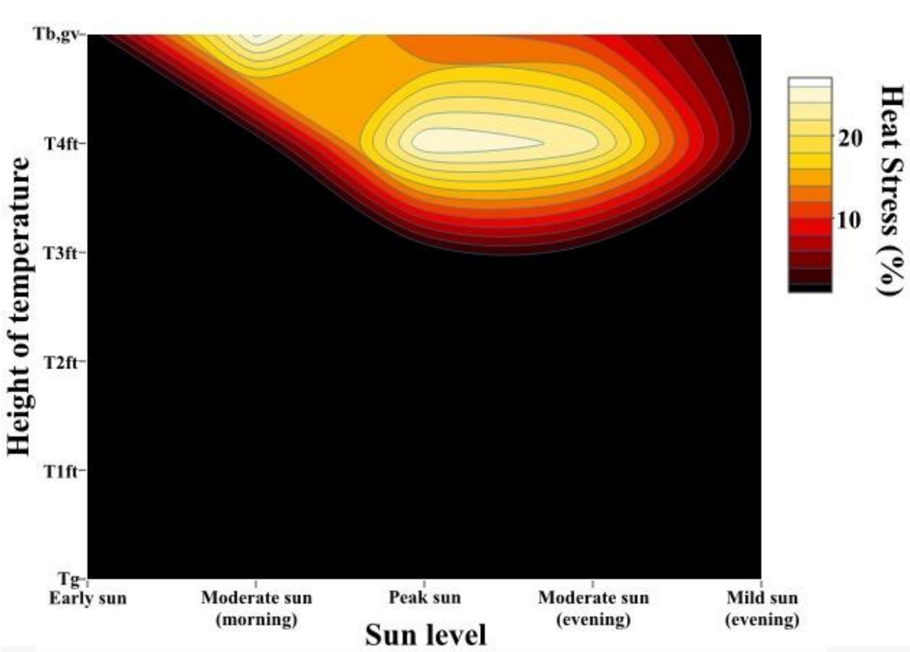

Figure 8: Heat stress contour at 5 sampling sun hours

Illustration of heat stress occurrences with respect to the 1 feet height-temperature level under agrivoltaic condition is shown in Figure 9 where dependencies on bottom PV and 4 feet height can be observed.

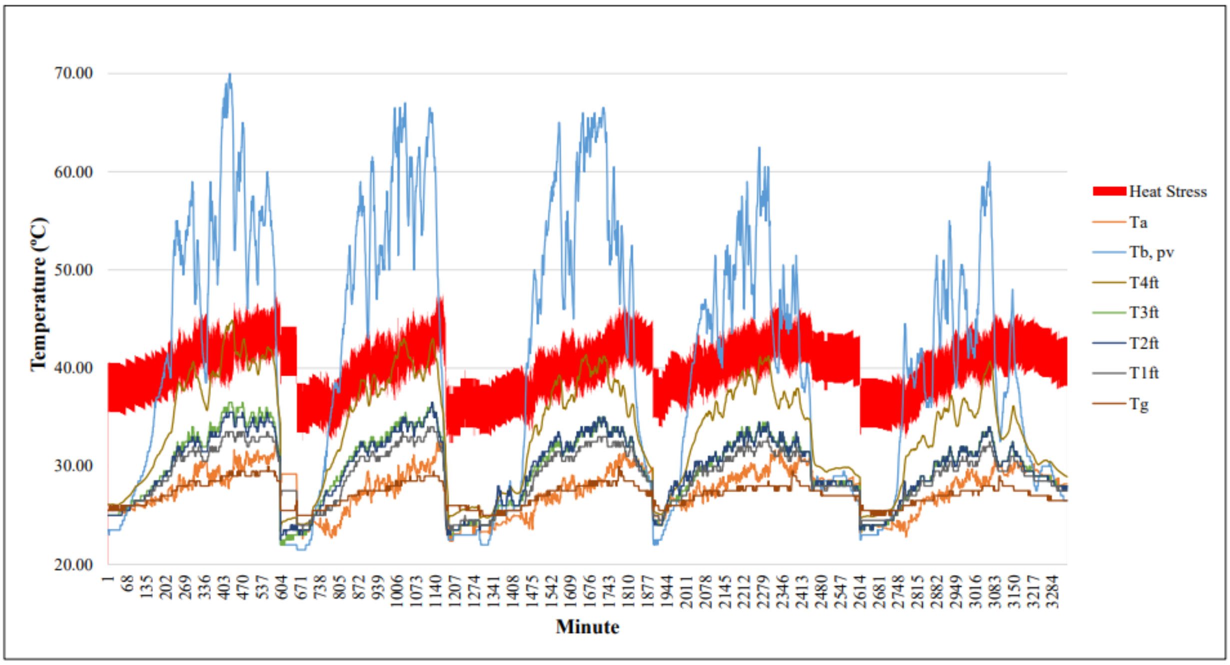

Figure 9. Field observation for Heat stress occurrences directly underneath PV arrays.

Abbrev: T_g: Ground temperature; $T_{1ft,2ft,3ft,4ft}$: Temperature at 1 feet difference; $T_{b,\ pv}$: PV Bottom surface temperature

The percentage of heat stress occurrences shows at what specific time in a day does the plant will possibly experience high surrounding temperature above normal ambient temperature. Based on the data sample, the highest heat stress occurs at 4 feet height during Peak sun and moderate sun (afternoon) with more than 23% heat stress point as shown in Table 4. This is due to the bottom PV produces much higher temperature after the photonic conversion and heat dissipation process. The ground heat effect in this Agrivoltaic condition shows relatively low due to the PV array shading as per temperature values in T_g until T_{2ft} thus, can be assumed no heat stress or neglected.

Table 4. Percentage of heat stress (T_h) occurrence across sun level and height.

	Temperature level	Early sun	Moderate sun (morning)	Peak sun	Moderate sun (afternoon)	Mild sun (evening)
Time		7:00-8:59	9:00-10:59	11:00-14:59	15:00-16:59	17:00-18:59
Percentage of occurrence (%)	Tg	0	0	0	0	0
	T1ft	0	0	0	0	0
	T2ft	0	0	0	0	0
	T3ft	0	0	0	0	0
	T4ft	0	0	25.9167	23.2270	0
	Tb, pv	0	26.5000	10.3333	9.3972	0

Two-samples proportion test and Chi-square test has been used as the statistical approach as shown in Table 5 and 6 respectively.

Table 5. Count of heat stress (T_h) cases across temperature-height levels during peak sun.

		Heat Stress Status		Total
		Heat stress	Non heat stress	
Temperature-height & Sun-level	$T_{4ft\_PeakSun}$	311	889	1200
	$T_{bpv\_PeakSun}$	124	1076	1200

Table 6. Chi-square test for difference in proportions of heat stress (T_h) occurrence during peak sun.

	Value	df	Asymptotic Significance (2-sided)	Asymptotic Significance (1-sided)
Pearson Chi-Square	98.184	1	0.000	0.000

Based on Chi-square test, T_{4ft} has higher percentage of heat stress occurrence than $T_{b,pv}$ during peak sun at 99% of confidence level (p<.00001). The same test has been conducted for height level during moderate sun (afternoon) and the results also proves that T_{4ft} has higher percentage of heat stress occurrence than $T_{b,pv}$ during moderate sun (afternoon) at 99% of confidence level (p<.00001).

Based on the correlations of $T_{b,pv}$ and T_{4ft} towards heat stress (T_h) under agrivoltaic condition, a summary from the findings of both min and maximum value of Heat Stress, $T_{h,min}$ and $T_{h,max}$ is modelled as shown in Table 7. The coefficient of determination (*R Squared*) is 0.739 which indicates that 73.9% of variation in $T_{h,min}$ and $T_{h,max}$ could be explained by the variation in both $T_{b,pv}$ and T_{4ft} and both $T_{h,min}$ and $T_{h,max}$ models are significantly fit at 99% of confidence level (F = 4724.462, *p-value* < 0.001).

Table 7. Regression statistics and Analysis of variance (ANOVA).

Multiple R	0.860
R Square	0.739
Adjusted R Square	0.739
Standard Error	1.205
Observations	3335

	df	*SS*	*MS*	*F*	*P-value*
Regression	2	13722.334	6861.167	4724.462	0.000
Residual	3332	4838.944	1.452		
Total	3334	18561.278			

A t-test on independent variable as shown in Table 8 confirms both $T_{b,pv}$ and T_{4ft} significantly affect the $T_{h,min}$ and and $T_{h,max}$ at 99% of confidence level ($t_{Tb,\ pv}$ = -57.141, t_{T4ft} = 78.155; *p-value* < 0.001). Hence, both are significant predictors of $T_{h,min}$ and and $T_{h,max}$. While, with a unit increase of $T_{b,\ pv}$, $T_{h,min}$ and $T_{h,max}$ would decrease by 0.293 ºC, a unit increase in T_{4ft} would increase $T_{h,min}$ and $T_{h,max}$ by 0.987 ºC.

Table 8. Individual t-test on independent variable.

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	16.553	0.232	71.442	0.000	16.098	17.007
$\mathbf{T_{b,pv}}$	-0.293	0.005	-57.141	0.000	-0.303	-0.283
$\mathbf{T_{4ft}}$	0.987	0.013	78.155	0.000	0.962	1.011

$T_{h,min}$ and $T_{h,max}$ could be expressed by the following new equations:

$$\mathbf{T_{h,min}} = 16.553 - 0.293\mathbf{T_{b,\ pv}} + 0.987\mathbf{T_{4ft}} \quad (2)$$

$$\mathbf{T_{h,max}} = 21.553 - 0.293\mathbf{T_{b,\ pv}} + 0.987\mathbf{T_{4ft}} \quad (3)$$

Or both equations could be simplified into a heat stress temperature model:

$$\mathbf{T_{h}} \text{ (Heat stress temperature)} = [16.553, 21.553] - 0.293\mathbf{T_{b,\ pv}} + 0.987\mathbf{T_{4ft}} \quad (4)$$

4. Conclusion

As a major source of renewable energy, many photovoltaic farms have now been constructed in the world. Agrivoltaic system is a further concept that aims to combine commercial agriculture and photovoltaic electricity generation in the same space, in order to maximise crop production while addressing the land management and sustainability issues.

This paper has presented the field measured data of ambient temperature profile and the heat stress occurring directly underneath Solar Photovoltaic (PV) Arrays (monocrystalline-based) in a tropical climate condition (in Malaysia). The effect of natural cooling mechanism of an Agrivoltaic system installed has been examined and focused with respect to the plant heat stress within 10ºC to 15ºC above the ambient temperature. The percentage of heat stress occurrences was the highest at 4 feet height during peak sun and moderate sun (afternoon) with more than 23% heat stress point. It has also been found that the ground heat effect in this Agrivoltaic condition was relatively low due to the PV array shading. Transpiration dissipated 32.9% of the total solar energy absorbed by the leaf, making it a good natural cooling mechanism while also increasing the conversion efficiency of the solar system.

A heat stress model for ground-mounted Agrivoltaic condition has been developed. It has been found that the coefficient of determination (R Squared) for the model is 0.739, indicating that 73.9% of variation in $T_{h,min}$ and $T_{h,max}$ could be explained by the variations in both T_b, pv and T_{4ft}. Both $T_{h,min}$ and $T_{h,max}$ models are significantly fit at 99% of confidence level. This paper has contributed to the understanding of the plant physiological processes in response to environmental conversion factors. The model developed could also be used for further exploring the integration between crops cultivation and PV energy generation for optimum land use.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "All authors have read and agree to the published version of the manuscript. Conceptualization, X.X. and Y.Y.; methodology, X.X.; software, X.X.; validation, X.X., Y.Y. and Z.Z.; formal analysis, X.X.; investigation, X.X.; resources, X.X.; data curation, X.X.; writing—original draft preparation, X.X.; writing—review and editing, X.X.; visualization, X.X.; supervision, X.X.; project administration, X.X.; funding acquisition, Y.Y.", please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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Appendix

1.1. Findings of $T_{h,min}$ modelling

Regression statistics

Multiple R	0.860
R Square	0.739
Adjusted R Square	0.739
Standard Error	1.205
Observations	3335

Analysis of variance (ANOVA)

	df	*SS*	*MS*	*F*	*P-value*
Regression	2	13722.334	6861.167	4724.462	0.000
Residual	3332	4838.944	1.452		
Total	3334	18561.278			

$T_{h,min}$ could be expressed by the following equation:

$T_{h,min} = 16.553 - 0.293T_{b,\,pv} + 0.987T_{4ft}$

1.2. Findings of $T_{h,max}$ modelling

Regression statistics

Multiple R	0.860
R Square	0.739
Adjusted R Square	0.739
Standard Error	1.205
Observations	3335

Analysis of variance (ANOVA)

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	13722.334	6861.167	4724.462	0.000
Residual	3332	4838.944	1.452		
Total	3334	18561.278			

$T_{h,max}$ could be expressed by the following equation:

$T_{h,max} = 21.553 - 0.293T_{b,\,pv} + 0.987T_{4ft}$

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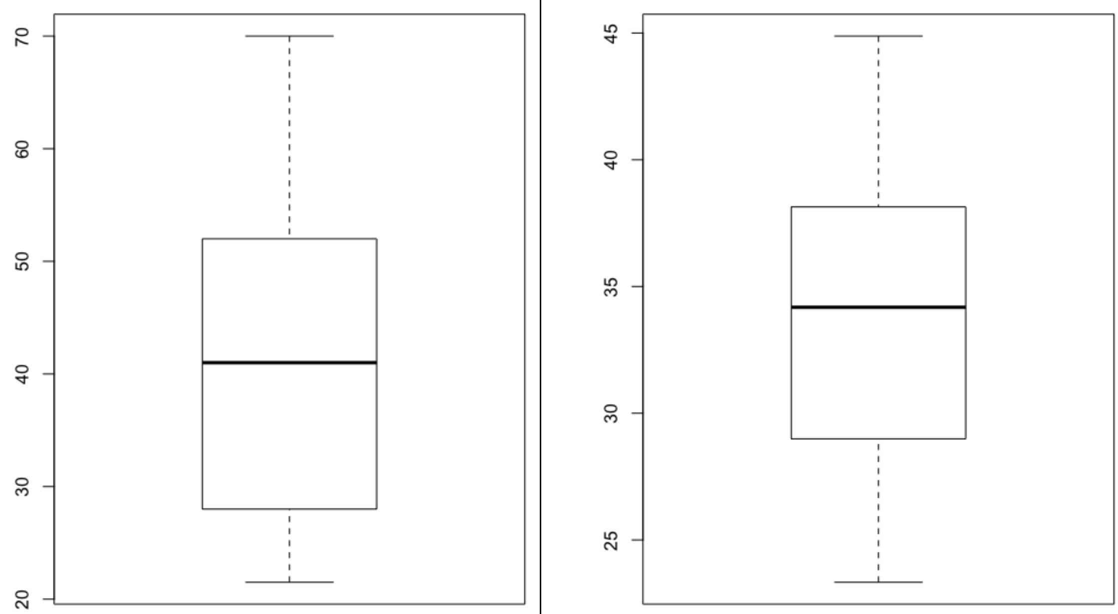
Individual t-test on independent variable

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	21.553	0.232	93.023	0.000	21.098	22.007
Tb, pv	-0.293	0.005	-57.141	0.000	-0.303	-0.283
T4ft	0.987	0.013	78.155	0.000	0.962	1.011

Appendix: Statistical analysis on the Outlier detection

Boxplot was used to detect outliers. Figure 1 (a) to (d) show the boxplot for each independent and dependent variable used. The figures exhibit that no outliers exist in each variable.



(a) Tb,pv (b) T4ft

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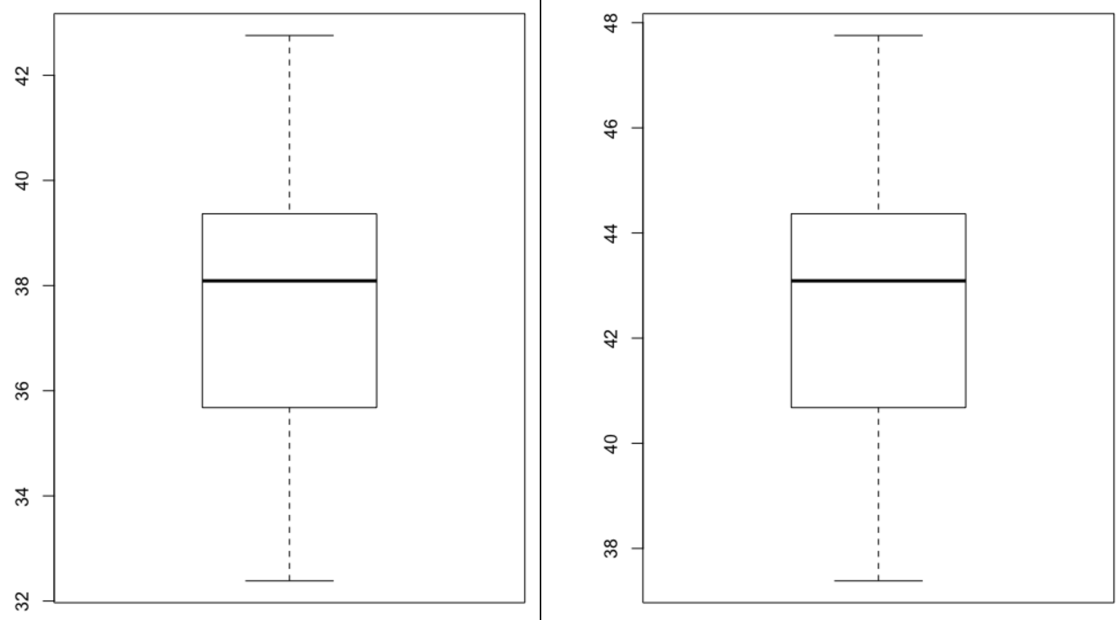


(c) Th,min (d) Th,max

Figure 1. Boxplot for outlier detection.

Some primary assumptions of multiple linear regression modelling include (i) multicollinearity; (ii) linearity of model; (iii) normality of errors; and (iv) homoscedasticity [42], [43].

(i) Multicollinearity.

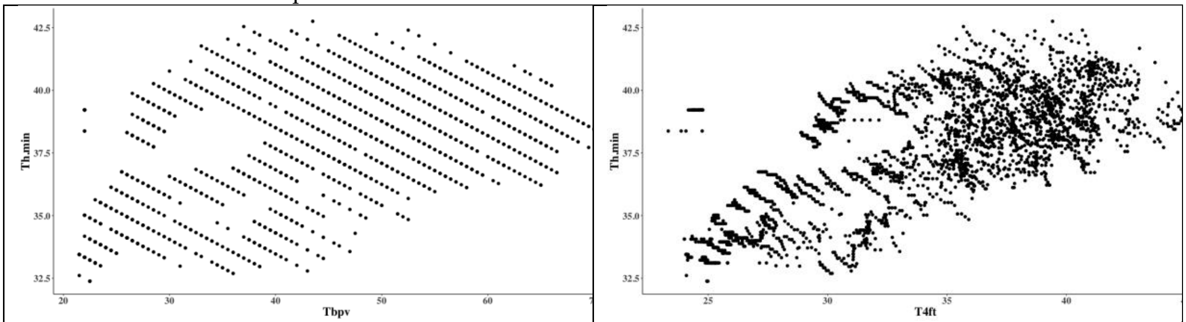
Variance inflation factor (VIF) was used to examine the existence of multicollinearity in the data [44]. Variables with VIF greater than 5.0 should be removed [45]. Table 1 shows that for both heat stress models i.e. minimum and maximum heat stress models have independent variables with VIF greater than 5.0.

Table 1. VIF for all independent variables.

Dependent variable	**Th,min**		**Th,max**	
Independent variable	**Tb,pv**	T4ft	Tb,pv	T4ft
VIF	11.04494	11.04494	11.04494	11.04494

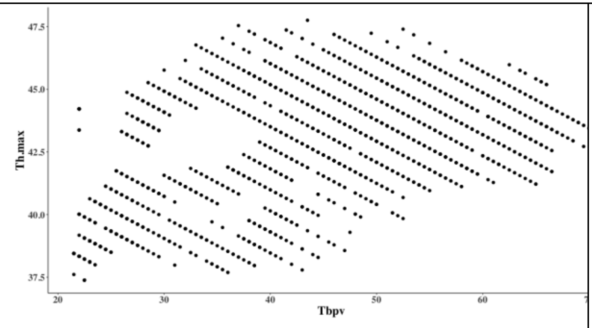
(ii) Linearity.

Scatter plots between dependent and independent variables were constructed and linear pattern of plots are expected to fulfil linearity assumption. Figure 2 (a) to (d) show the plots and linear patterns could be observed from all the plots.

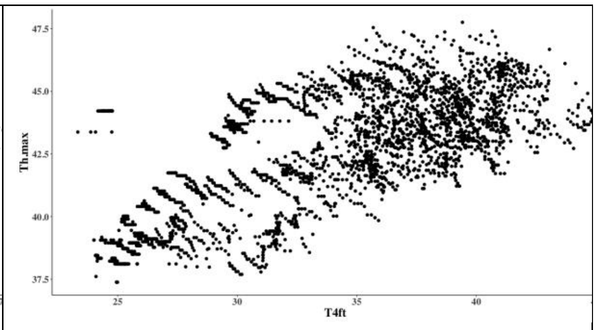


(a) Tb,pv against Th,min (b) T4ft against Th,min

 doi:10.20944/preprints202007.0694.v1



(c) Tb,pv against Th,max

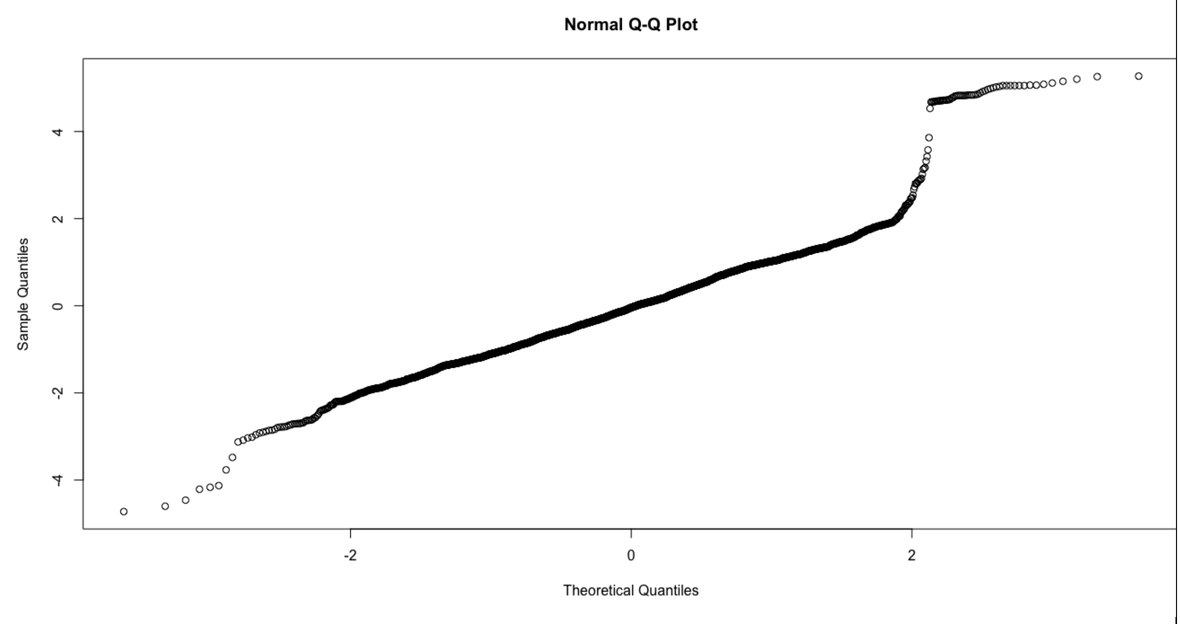


(d) T4ft against Th,max

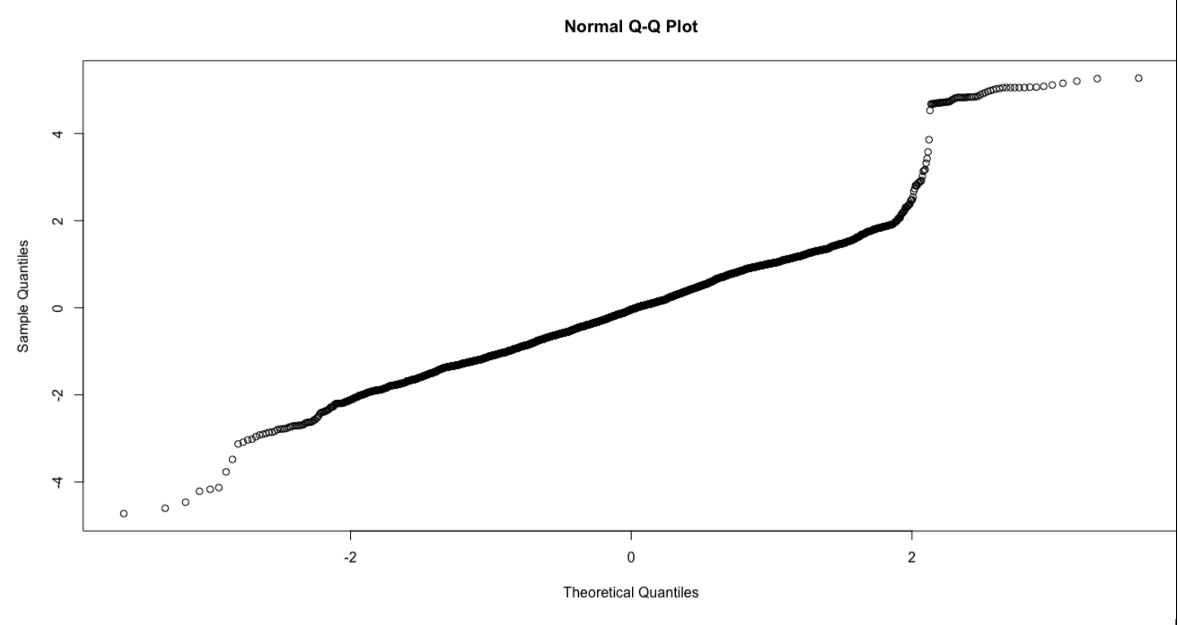
Figure 2. Scatter plot between dependent and independent variables for linearity.

(iii) Normality of errors.

To examine the normality of errors, normal Q-Q plots for the residuals for both Th,min and Th,max models were constructed (as in Figure 3). Figure 3 (a) and (b) show that the errors for both heat stress models were normally distributed.



(a) Th,min model



(b) Th,max model

Figure 3. Normal Q-Q plot for residuals for normality.

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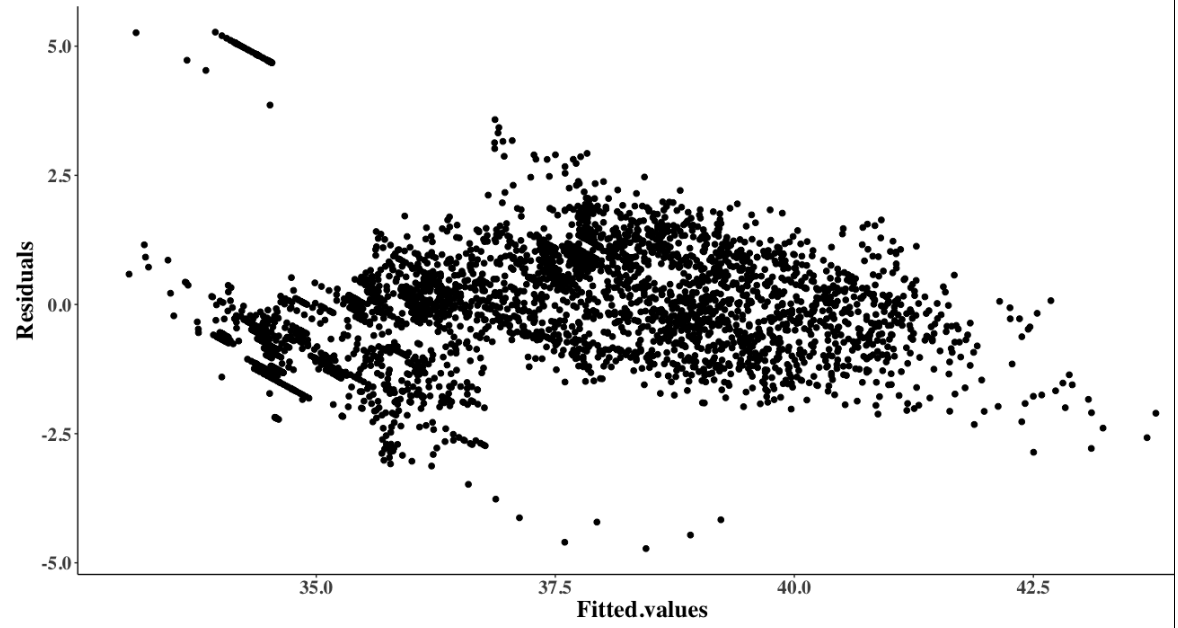
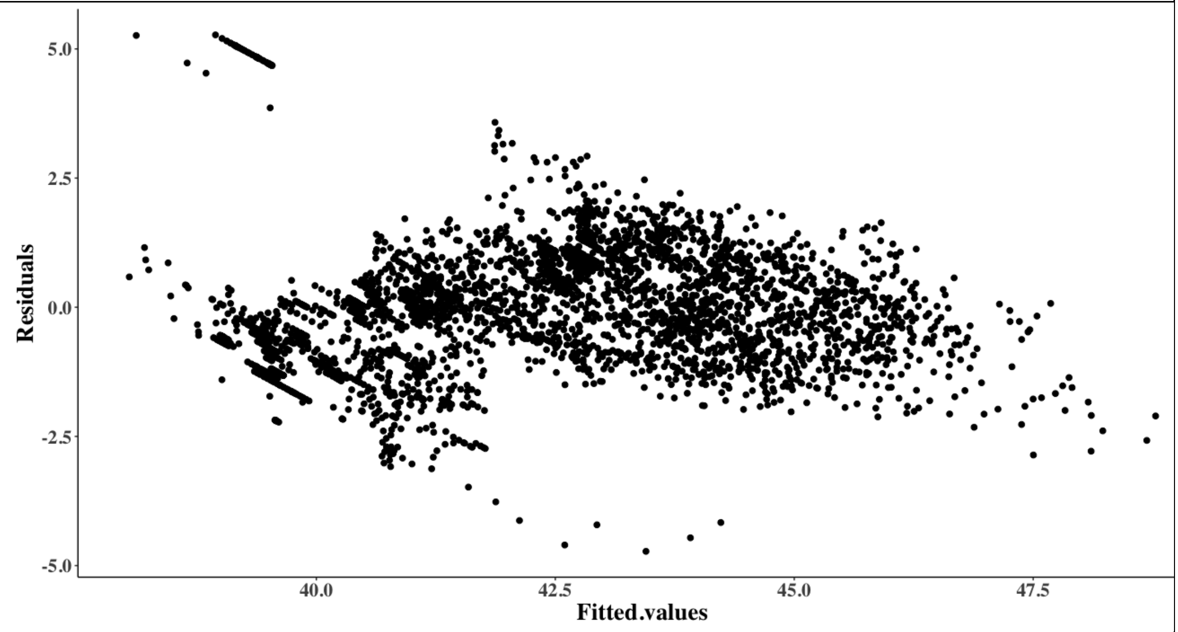
(iv) Homoscedasticity.

Residuals against fitted values plot was constructed to examine the homoscedasticity of errors for each model and evenly scattered points were expected for homoscedastic errors [42]. Figure 4 (a) and (b) show the plots and homoscedasticity of errors were proved to exist.



(a) Th,min model



(b) Th,max model

Figure 4. Residuals against fitted values plots for homoscedasticity.

In conclusion, all four assumptions were fulfilled and data were fit for multiple linear regression.