Effect of evapotranspiration on performance improvement of photovoltaic-green roof integrated system

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Abstract

The purpose of the research is to evaluate performance improvement of photovoltaic (PV) integrated with green roof system due to evapotranspiration from plants. Evapotranspiration rate (ET) has been modeled by regression method to calculate latent heat flux generated which is responsible for reduction of cell temperature and improving efficiency of PV on green roof. ET rates have been generated by using developed regression model and its effect on power output and cell temperature was studied. Experimental results showed that power output of PV-green roof system can be higher than reference PV installed on bare concrete roof by about 8.60% whereas maximum improvement in efficiency can be up to 3%. It is found that ET plays significant role in reducing cell temperature and improving output on days with clear sky and fairly high and constant solar irradiance. However, ET rate may fluctuate on days when irradiance level is low due to which the efficiency and power output improvement of PV-green roof system may be minimal compared to PV on bare concrete roof.

Keywords: *PV output, green roof, PV cell temperature, PV efficiency, evapotranspiration*

1. Introduction

Singapore is moving forward towards sustainability and needs to achieve demanding emission reduction target of 7-11% by 2020 on BAU levels (www.nccs.gov.sg). Therefore development of sustainable technologies is the need of the hour. Considering the inapplicability of renewable energy sources like wind and geothermal in Singapore, solar photovoltaic are one of the most favored technologies that can be applied to meet the needs of the country in a sustainable way.

Photo voltaic cells which use the most abundant solar energy are widely in use as on date. However, currently the efficiency of photovoltaic cells available for public use is less than 20%. One of the significant factors in decreasing the performance of PV panels is its surface temperature. Most of the existing PV panels are mounted on concrete roof and their surface temperatures reach up to 70°C on hot sunny days. Standard operating condition for PV panels is 25°C but most of the time due to changing weather conditions PV Panels do not operate under this ideal operating conditions. Past studies carried out in different parts of the world [1-4, 6] have shown that PV integrated with green roof can help in cooling the solar panels by the process of evapotranspiration and high albedo effect. For example, Scherba et al. [5] reported that by replacing black roof-PV with a green roof-PV, reduction of sensible flux of order of 50% could be achieved. This can help to improve the efficiency of the solar panels during the hot weather condition as the efficiency of solar cells decreases with increase in temperature. Creating a synergy between PV and green roof can achieve more efficient renewable energy generation. A number of modelling and experimental studies on improvement of PV output integrated with green roof has been carried out at several climatic conditions and with different plant types and species. In general in all the researches some improvement in PV output has been reported- varying between 0.08% [2] to 8.3% [1] depending on several factors such as climatic conditions of the place, plant species, reflected radiation from plants, albedo etc.

A study conducted Hui and Chan [1] discussed about the improvement in output by PV-green roof synergy. The study comprised of both modeling and experimental part. Modeling was performed using EnergyPlus for a low rise commercial building and it showed an output improvement of 8.30% However, it should be noted here that PV was mounted with a few inches gap. This resulted in air circulation which can also play a role in reducing PV temperature and increase output. For the experimental part, readings were taken with two PV panels (one on green roof and another on bare roof) between 11 AM and 2 PM. During that time period, the output improvement was 4.30% using the same plant species. Based on the difference between modeling and experimental results, it could be assumed that actual climatic condition and microclimate of the place would affect the output to a great extent. Conditions such as distance between two PV s, soil moisture content etc. play a big role.

Experimental study by Nagengast et al. [3] recorded that PV-green roof produced higher output than a bare roof-PV when temperature was higher than 25^0C and solar radiation higher than 800 W/m^2. Moss was used as the plant for green roof. However, at temperature lower than 25^0C and lower solar radiation, the effect of green roof was not very significant. Therefore, it may be assumed that under high solar radiation and temperature above 25^0C, green roof has significant effect on power generation of PV.Perez et al. [6] investigated several small scale systems including PV-gravel roof and PV-green roof (Sedum species) over small model houses in New York City. For the same month, variability of surface temperature over gravel roof house was 10.69% higher compared to green roof and PV ouput for green roof-PV was 2.56% higher than the gravel-PV for the month of June.

Chemisana and Lamnatou [4] investigated the improvement in PV output when integrated with green roof with two different plant species (Sedum Clavatum and Gazania) compared to PV over gravel roof. Five day average percentage increase of PV output for the two plant species was 3.33% and 1.9% respectively compared to PV-gravel roof. Temperature at 3 cm depth was cooler by 26.1 % for Sedum roof while for Gazania it was 17.5% over a five day period. Sedum species of plants possess thick leaves with high water content and thus improved the effective irradiance on the module by 1.43% compared to Gazania.

It is clear that temperature reduction by employing green roof plays a vital rolein improving output and efficiency of PV. Evapotranspiration (ET) of plants is the underlying mechanism that affects microclimate around PVs and reduces temperature by converting sensible heat into latent heat. Therefore, it is important to understand the underlying mechanism of ET for a given green roof to estimate the cooling of PV cell temperature in a tropical region like Singapore. There are established ET models like Penman-Monteith model and Priestley-Taylor model but it is often difficult to measure the parameters needed to correctly estimate the ET rate from these models. Alternatively it is possible to frame ET model in terms of climatic variables including solar radiation, wind, vapor pressure gradient, humidity and ambient temperature [7, 8]. Thus, the aim of the study is to conduct experiments to compare the improvement of PV module efficiency over green roof compared to that over bare concrete roof and develop an ET model in terms of the climatic factors to study the influence of ET on cooling of PV cell temperature. In other words, the ET model would predict the amount of latent heat generated by the plants of a particular species in Singapore climatic condition and therefore help in making decisions on choosing an optimal location for PV installation.

2. Materials and methods

Two mono-crystalline PV s were installed - one over green roof (area about 50 m^2) and another over bare concrete roof. The PV module as per manufacturer's rating has maximum power output of 30 W. The experimental measurements were designed to collect data to frame evapotranspiration model which include climatic variables such as air temperature, humidity, solar irradiance, air velocity and soil surface temperature. PV cell temperature is also measured to enumerate the cooling effect of green roof. PV voltage and current are also measured to obtain PV output and PV efficiency. The green roof under study has soil depth of 13 cm. The plant species in green roof is Complayatrilobataor Weedelia. Gausman and Allen [9], leaf thickness for such species is 0.82 mm and water content is 94.9%. The leaf area index of the plants as measured by LAI analyzer is around 3.2 which translates into shading coefficient of 0.08 using the equation[10]

$$SC = -0.2277\ X\ LAI + 0.8175 \quad (1)$$

Where,

SC = shading coefficient

LAI = leaf area index

This means fairly dense vegetation which allows only 8% solar radiation to reach the surface. There was no rainfall during the measurement period and therefore it was assumed that there was no latent heat through evaporation generated from concrete roof surface.

Field measurement

PV panel over green roof was placed about 30 cm above the canopy of the plants at 10^0 to the surface. Same height and angle were maintained for PV panel over the concrete surface. For PV-Green and PV-Concrete the experiment was conducted over 3 days from 9.00 AM to 5.00 PM at 5 minute interval. Voltage and current generated by PV was measured using data logger. A weather station with anemometer, humidity and temperature sensor was installed to measure the microclimatic condition. The solar irradiance was measured by CM 6B pyranometer at 5 min intervals from 9.00 AM to 5.00 PM. Temperature and humidity were measured at 12 cm from the canopy which is near the PV. HOBO H8 pro temperature and humidity sensor were used to record temperature and humidity at 5 minute interval. The surface temperature of the green roof was measured by thermocouples.

Due to relatively small size of green roof and effects of micro-climatic parameters, the boundary conditions needs to be defined for the experimental set-up. Vertical boundary was considered to be at 2m from the plant canopy. To measure the climatic parameters temperature and humidity sensors were attached at 2m above the canopy as shown in Fig.1.

Bowen ratio energy balance (BREB) equation was chosen to calculate the ET rate. The measures of temperature and humidity at upper level (at 120 mm) were used. The temperature and humidity data for developing the ET model proposed in the study were taken at height of 60 mm from the canopy. At height 60 mm and 120 mm from the canopy between green roof and PV the conditions are considered to be homogeneous. Only those data with advection index less than 1 and Bowen-ratio less than 1 are selected. This is to maintain the assumption of closed system in BREB. Advection index less than 1 means that there is not significant heat transfer from outside by the flowing wind over green roof. Bowen ratio less than 1 is considered which means that mostly latent heat is transferred into the air. Experimental set up for PV over green roof and concrete roof are shown in Fig. 1.

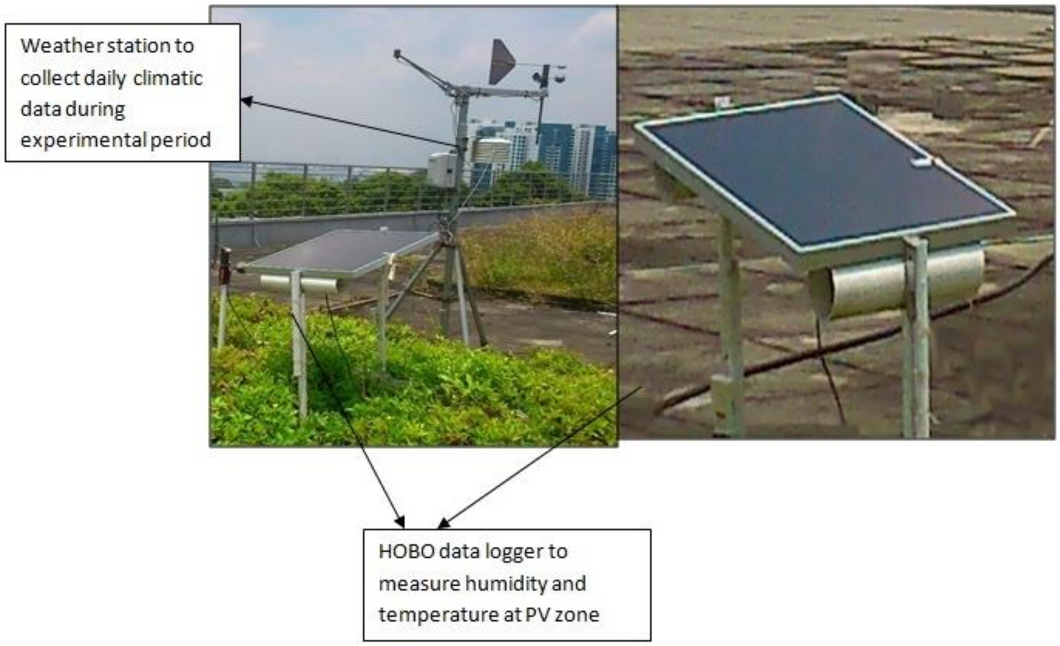


Figure 1 Experimental set up over green roof and bare concrete roof

3. Results and analysis

3.1 Analysis of difference in power output of PV panel over green roof and concrete roof

From Fig.2, it is observed that power output in case of PV integrated with green roof is higher compared to that of PV on bare concrete roof. Based on three days average PV integrated with green roof produced about 8.60% more power output than the PV panel installed on bare concrete roof. This is in line with Hui and Chan [1] that highercell temperature can decrease PV panel productivity by up to 25%. The green roof cools ambient temperatures around PV cells through evapotranspiration from soil and plantation, allowing the PV Cells to stay cooler and perform better.

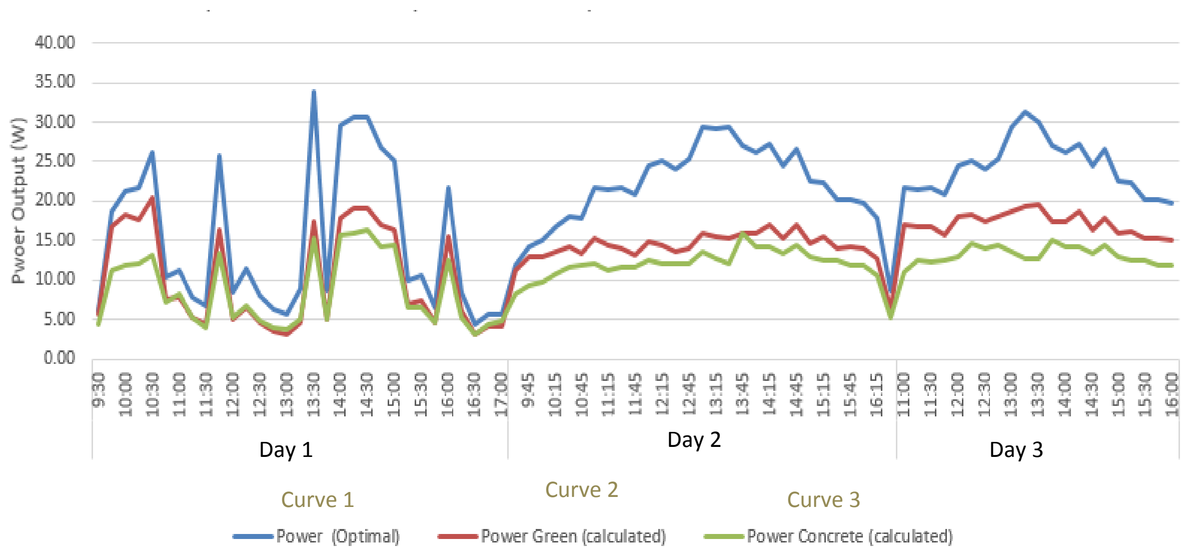


Figure 2 Comparison of PV cell power outputs (on concrete roof and green roof) compared to best operating conditions

Curve 1 (Power (Optimal) has been plotted assuming the most optimal conditions for the performance of PV cells, i.e., maintaining the cell temperature at 25°C while the radiation levels and weather conditions remain as per actual site conditions. It can be seen that Curve 2 (power output for PV over green roof) imitates the trend of Curve 1, maintaining the output trend even during noon. The net cooling effect by green roof on micro-climate could be a possible reason. Curve 3 which represents power output from PV installed on concrete roof shows lower power output compared to PV on green roof. It can be observed that on day 1, the difference in power output for PV on concrete roof and green roof is not very prominent owing to high fluctuation in irradiance and lower level of irradiance altogether. This may be due to lower heat buildup over concrete roof and lower vapor pressure deficit due to low and varying radiation.

Fig.3 shows the curves plotted for cell efficiency for both the PV systems during the measurement time. It can be seen from the graph that with time of day cell efficiency for both systems decreases with increase in irradiance level. However, the maximum efficiency is observed during early morning hours for both the systems where efficiency of PV on green roof is significantly higher than that on bare concrete roof. This could be attributed to early morning watering of the plantation around 08:00 A.M. Overall, efficiency for PV integrated with green roof is higher than PV over concrete roof, also shown in Fig. 4. Maximum improvement in efficiency is about 2.90% and three day average improvement was by about 2.30%

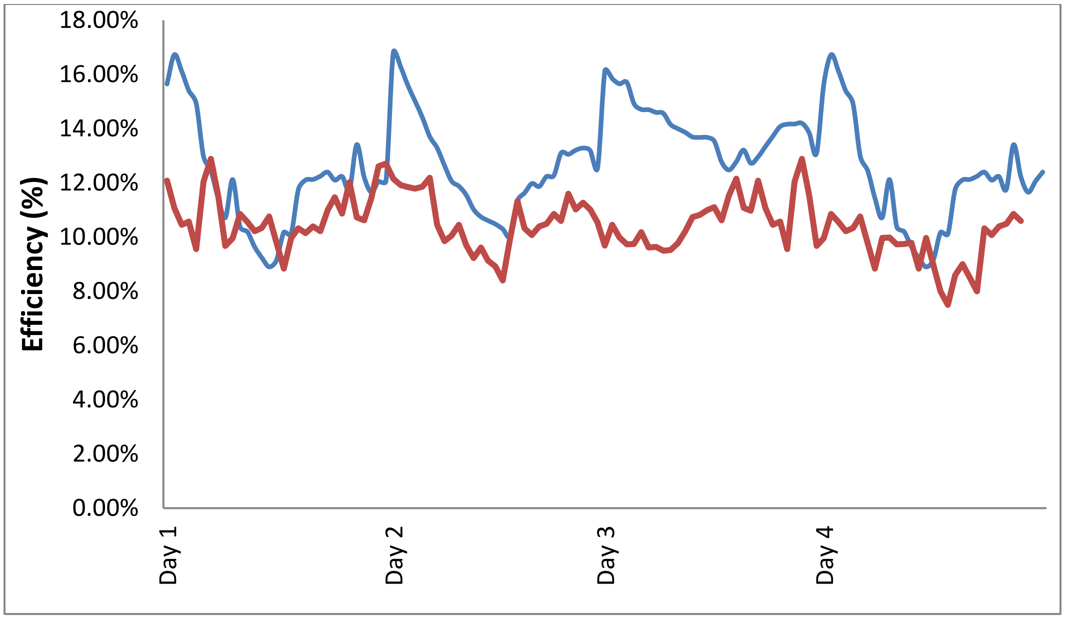


Figure 3 Efficiency profile of PV on green roof and concrete roof on different measurement days

On Day 1, there is little difference in efficiency between PV-green and PV-concrete which may be due to low evapotranspiration because of lower and fluctuating irradiance and consequent lower vapor pressure deficit.

It was also observed that wind velocity had a role to play in influencing cell temperature. Considerable decrease in cell temperature could be observed with rise in wind speed which helped to attain higher efficiency at those points in time. The effect of wind is more prominent in case of PV over concrete roof perhaps due to the reason that wind could flow unobstructed between the panel and the roof whereas for green roof, the effective velocities were lower due to obstruction by plants. Higher wind velocity aids in efficient heat removal thereby inducing a cooling effect of PV cell. However, this behavior is highly dynamic because of constantly changing wind direction and speed. Nevertheless, researchers think that wind plays a crucial role in influencing PV cell operative temperature and should be considered in the analysis [11].

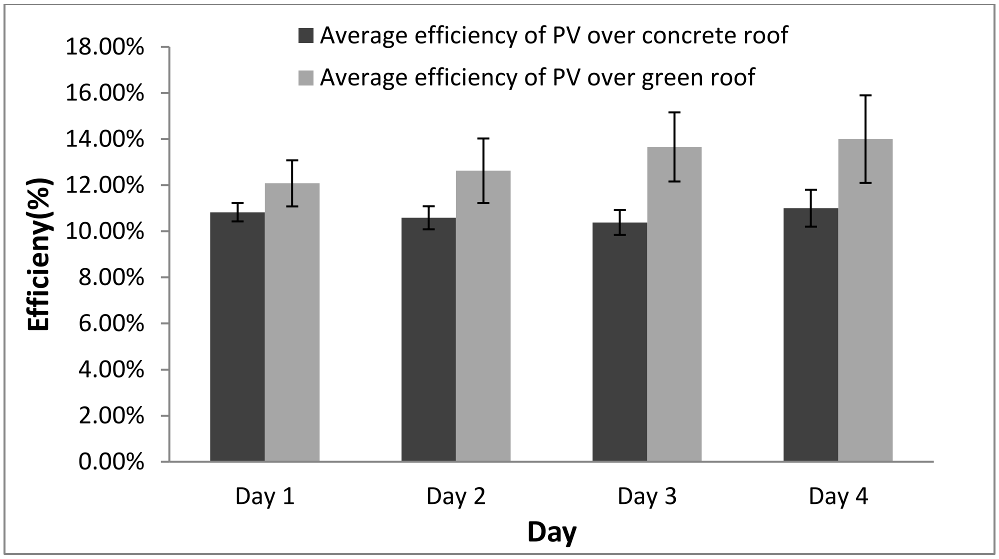


Figure 4 Comparison of efficiency of PV over concrete and Green roof

Efficiency of PV over concrete and green roofs is plotted with respective uncertainties in Fig. 4. Although the average efficiency of PV installed over green roof is consistently higher than PV on concrete roof**,** the error bar is wider in case of PV integrated with green roof .It may be attributed to more number of variables which affect efficiency of PV over green roof including evapotranspiration from soil and plants, albedo effect of plants and effect of plantation on micro-climate around the PV panel.

*3**.**2 Statistical development of proposed equation*

Statistical analysis for verification and validation of the proposed model was performed using Toolpak provided in Excel. Each independent variable was correlated with the dependent variable i.e ET to check the strength of influence. The independent variables having correlation coefficient less than 0.60 were eliminated and would not be further considered for the regression and the ANOVA analysis.

The dependent variable in this study is evapotranspiration rate (ET), while the independent variables are the residual of net radiation and soil heat flux (*Rn-G*), PV zone temperature (T_a), absolute humidity (or humidity) (*H*), wind speed (V_w) and air temperature (T_{air}).Absolute humidity (moisture content) was considered instead of relative humidity to eliminate multicollinearity effect which may arise since relative humidity is actually dependent on air temperature.

In BREB, The leaf absorbance value α_{leaf} is taken as 0.64 for the plant species under consideration [9]. In BREB equation$T_{sky}$is the cold sky temperature and considered as a function of air temperature. In the study, air temperature data at the upper boundary (2 m from the canopy) has been used to generate values of T_{sky}. It is assumed that at the boundary, air temperature is not significantly affected by ground parameters.

Correlation analysis:

Table1 Correlation analysis results of each independent variable against ET

Variables	**ET rate (*ET*)**	**R-sq**
Air temperature	0.50	0.26
PV zone temperature	0.89	0.81
Humidity	-0.87	0.76
Net radiant	0.99	0.99
Air velocity	0.71	0.60

The results of correlation analysis are shown in Table 1. As seen from the correlation analysis, ET rate is weakly influenced by air temperature which is measured at upper boundary layer which is 2m above canopy (R^2 = 0.26). Air velocity also has low correlation among the selected variables probably because of the dynamic behavior wind in terms of direction and pattern over a roof surrounded by buildings on one side and open on other three sides. Therefore, this factor i.e. air temperature is eliminated from analysis for regression and ANOVA. Negative value for humidity suggests that increase in humidity near the canopy decrease ET, an effect which is also observed in regression analysis and discussed later in the study.

ANOVA and regression analysis:

ANOVA performed for statistical significance suggest that all the variables have statistically significant effect on ET, shown in Table 2.

Table 2 ANOVA analysis for significance

Sources	F-value calculated	*P*-value	F-value tabulated	Remarks
Net radiant	50	0.0005		
PV zone temperature	8.52	0.025	3.10	Statistically significant
Air velocity	5.25	0.043		
Humidity	30.49	0.008		

Regression analysis is performed to generate equation to express ET as a function of independent variables. R-square for analysis is 99%, shown Table 3. Regression results are shown in Table 4 where the coefficients for final model development can be obtained.

Table 3 Regression statistic

R Square	0.99
Standard Error	1.97E-06
Observations	90

Table 4 Regression analysis result

	Coefficients	**Standard Error**	***P*-value**
Intercept	2.31E-05	2.03E-05	0.027
PV zone temperature	-4.90E-07	4.41E-07	0.028
Humidity	-1.8E-04	1.23E-07	0.032
Net radiant	4.12E-07	5.90E-09	3.15E-29
Air velocity	3.87E-07	1.03E-06	0.018

Thus, based on the regression analysis, the developed model can be stated as

$$ET = 2.31x10^{-5} - 4.90x10^{-7}T_a - 1.8x10^{-4}H + 4.12x10^{-7}(Rn - G) + 3.87x10^{-7}V_w$$

As observed from the *ET* rate model, *ET* is positively related with net radiant which means that with increase in net radiant,*ET* increases. Net radiant is broadly a function of solar radiation, air temperature and soil temperature. Sun is the source of energy for heat required to convert water into vapor. With increase in radiation, the soil surface and the surrounding air is heated thus increasing the temperature over evaporative surfaces. This results in faster evapotranspiration. Moreover, higher radiation causes higher vapor pressure deficit which also enhances evapotranspiration.

ET increases with decrease in moisture content of air. The difference between the water vapor pressure at the evapotranspiring surface and the surrounding air is the determining factor for the vapor removal. Therefore, in humid microclimatic situation, evapotranspiration decreases because higher moisture content in air would mean that there is no space to hold excess moisture from evapotranspiration.

ET increases with increase in wind speed. The process of removing water vapor from evapotranspiring surfaces depends to a large extent on wind and the turbulence created which moves large quantities of air over the evaporating surface. As evapotranspiration occurs, the air above the surface becomes more saturated with water vapor and therefore the deficit tends to be lower. This saturated air has to be removed continuously by dry air, which is made possible by higher wind velocity over the surface. This helps *ET* to increase with replacement of moist air. In tropical region, rise in temperature around PV zone may cause stomata closure [12, 13] which probably explain decrease in *ET* with rise in temperature in PV zone as observed from the *ET* rate model.

The proposed model takes into account climatic factors which are easily measurable at any location. Thus, the model is able to predict ET with respect to weather conditions of a location in the tropics. However, the model has been developed for an extensive green roof system and thus its application may not be extended to intensive roof system (with bigger trees and wide variety of plants).

A comparison of ET values on steady days and fluctuating days (varying irradiance and other climatic factors) was performed. This is shown in box plot in Fig. 5.

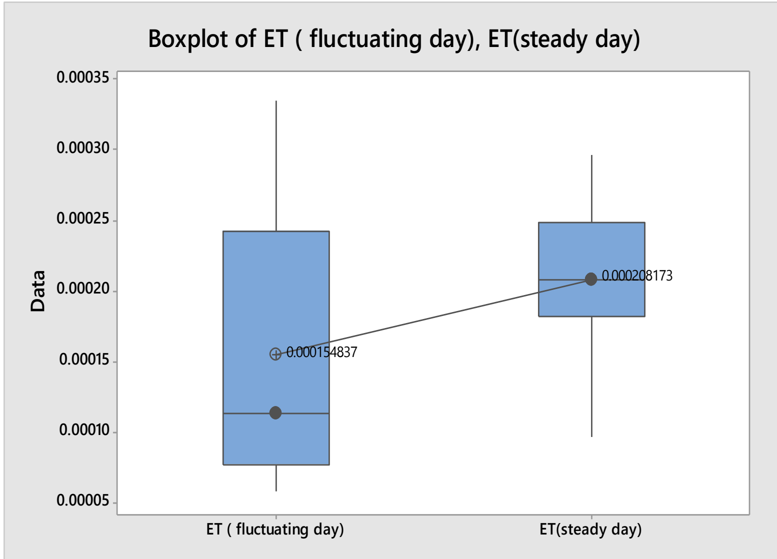


Figure 5 Box plot of ET on steady day and fluctuating day

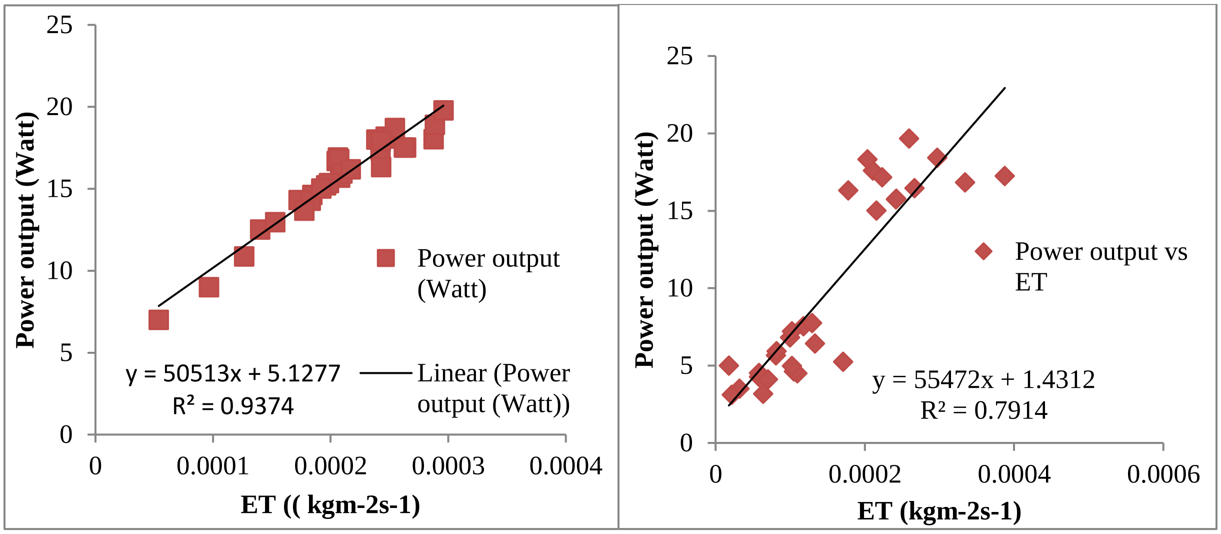
For example, a fluctuating day was marked by highly fluctuating solar radiation trend and lower average air velocity - recorded average of 0.80m/s compared to about 1.30 m/s on a steady day or clear day. Moreover the coefficient of variation of solar irradiance calculated was close to 60% compared to 25 % on a steady day. Average solar irradiance was also low compared to that on a steady day. A maximum of 25 % reduction in ET rate was recorded on a fluctuating day compared to steady day values.

Such difference could be explained by reduced vapor pressure deficit caused by low and fluctuating solar radiation. This cause reduced moisture elimination from the air which slows down evapotranspiration. Wind speed was lower which was insufficient to increase ET owing to higher moisture content in air in absence of consistent solar radiation. This finding is also supported by Hendarti [14] which suggested that solar irradiance is in good correlation with the reduction of water vapor in the atmospheric layer.

3.3 Effect of evapotranspiration on power output under different day conditions

Effect of evapotranspiration rate on power output of the solar panels was studied under different day conditions - steady day condition as shown in Fig.6 (a) and fluctuating condition shown in Fig.6 (b). Power output is governed by voltage which reduces with rise in cell temperature. Evapotranspiration reduces cell temperature and enhance power output.

It is observed from Fig 6(a) and (b) that there was a drop in R^2 for the fluctuating day condition compared to clear sky condition. Clear sky days are associated with fairly steady irradiance and higher evapotranspiration due to higher vapor pressure deficit. Thus the output is in good agreement with evapotranspiration rate as irradiance plays an important role for both. However, in case of fluctuating day condition, irradiance variation is high along with relatively higher humidity. As the solar radiation becomes higher after a period of low radiation, power output increases instantaneously while ET is still at a lower level because it takes some time before the high radiation dries up the moist air and create sufficient vapor pressure deficit for ET to increase. In other words, there is a lag between the increase in power output and recovery in ET rate. The scattered points are mostly the points when there was a transition from a period of low solar radiation to higher radiation or vice-versa.



(a) **(b)**

Figure 6 Correlation between ET and Power output in **(a)** steady sky condition and **(b)** fluctuating condition

3.4 Influence of evapotranspiration on cell temperature

Sensible heat flux, ET and cell temperature have been plotted in Fig.7 to study effect of ET on cell temperature. Sensible heat flux plotted has been calculated using Bowen ratio (ratio between sensible and latent flux). ET is plotted which is actually product of latent heat flux and latent heat of vaporization of water (assumed to be constant). Therefore the trend of the curve would be same as that of latent flux. As highlighted by red dot boxes, it is observed that whenever there is a peak in ET a drop in sensible heat flux and cell temperature as well can be observed. Thus it may be argued that increase in ET keep in control the sensible flux which is responsible for rise in cell temperature. Evapotranspiration is plays more important role till late afternoon when sensible heat buildup is high. From late afternoon onwards, the influence of ET is diminished and decrease in cell temperature reduces primarily due to decrease in solar radiation and irradiance.

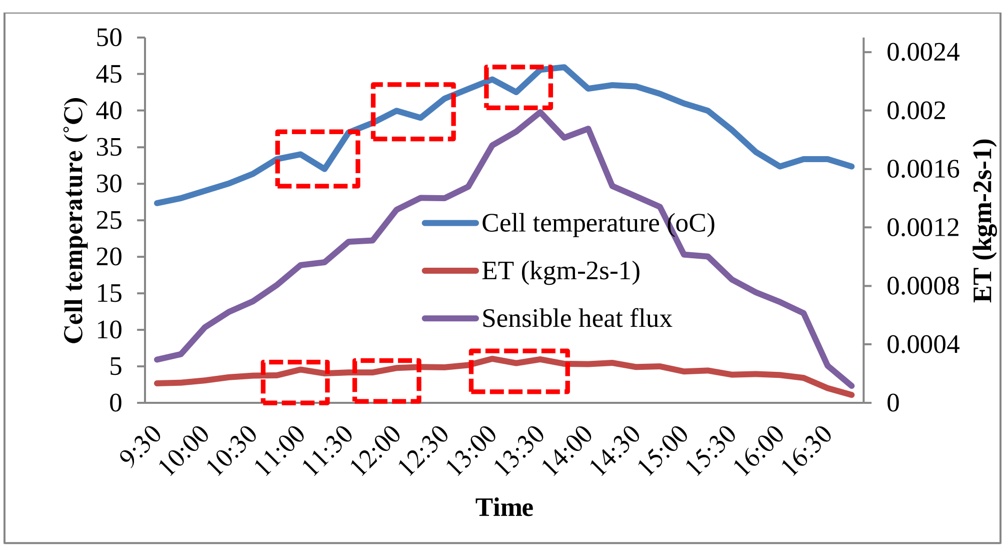


Figure 7 Plot of sensible and ET (indirectly latent flux) with Cell temperature

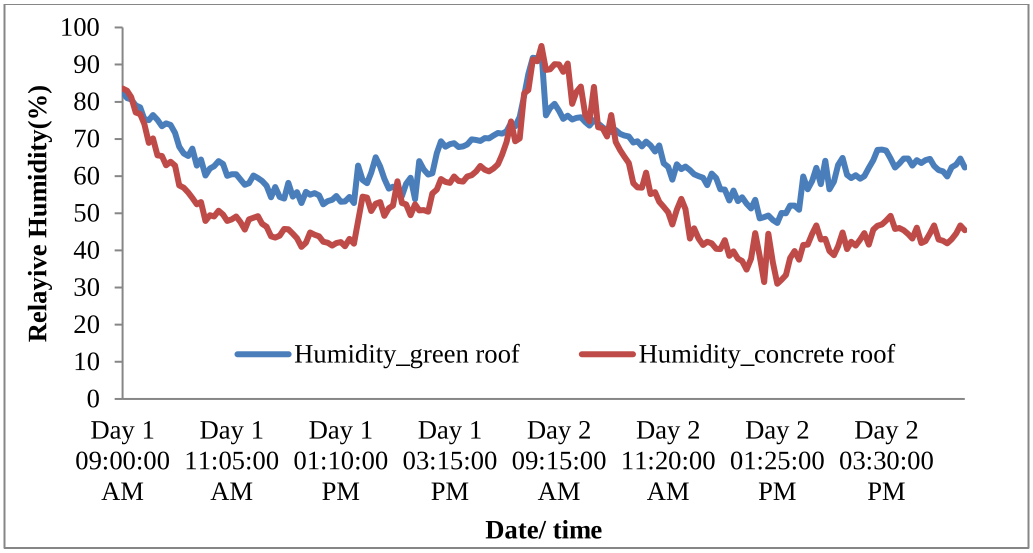


Figure 8 Humidity profiling as result of ET on green roof vs. humidity on concrete roof

The effect of ET could be more realized from the measurement of humidity over greenery and concrete roof at the same height (0.3 m in this case). Humidity measurements on green and concrete roof on two days have been shown in Fig.8. More latent heat flux created as a result of evapotranspiration keeps the humidity over green roof consistently higher than that of on concrete roof at same height. This moisture content is responsible for evaporative cooling of cell temperature and thus aid in generation of more power and increase in efficiency compared to that installed on bare concrete surface. The peak difference is created at around 2 PM (afternoon) just around the time ET reaches its peak and introduces more moisture in the air. During evening or early in the morning when ET is low there is little difference between humidity on green and concrete roof.

4. Conclusion

It is observed from this research that PV integrated with green roof performs significantly better then PV over concrete surfaces. Power output and efficiency have been reported to have been improved by 8.60% and 2.30 %. Improvement in performance becomes significant when there is abundant solar radiation and clear sky. The percentage improvement may not seem very high because of relatively small scale of the experiment. Significant energy efficiency may be realized when such system is implemented in proper building scale. Latent heat generated by green roof is directly linked to cooling of PV panels and improving its output. The ET model proposed here can be used by building managers and designers to estimate the latent heat generated by a green roof in the tropics and chose an optimal location for PV integration with green roof. However, day conditions play significant part on the contribution of green roof to cooling of panels. Solar radiation plays the most important role in determining ET rate and therefore on a day with low and varied radiation, ET rate may decrease by as much as 25% as reported in this research. The research also finds that other factor such as air movement is necessary to cool down PV panel and enhance ET rate. Therefore, it is recommended that PV s must be placed at a certain height from the plant canopy. However, panel placed too high above the canopy may not realize the benefits of evapotranspiration. Therefore, more research is needed to arrive at an optimal mounting height of PV for different dimensions of green roof.

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