A SIMULATION STUDY OF THERMAL IMPACTS OF GREENERY ON A PV ROOFTOP

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1. Introduction

A tropical city like Singapore, with no distinct seasons, is able to harvest high solar radiation throughout the year. However, high solar radiation could also increase PV cell temperature above 25 °C, the standard testing temperature at which PV modules are tested. Eventually, the electricity generation is reduced due to high cell temperature. To overcome this obstacle, one of the solutions is to provide a cooler surrounding environment for PV modules, so that the surface temperature can be reduced.

Greenery is usually used for better thermal insulation for rooftops. It also helps to reduce the ambient temperature, due to its evapotranspiration process. In the evapotranspiration process, solar radiation is absorbed by plants and used as energy to convert water into vapor without temperature changes. This energy transfer is known as latent heat. Onmura et al. (2001) reported that the ambient air temperature of a rooftop could be reduced by 10-30 °C due to the evaporative cooling effect.

This paper presents a preliminary study of an integrated PV rooftop system with greenery in the Ttropics. The study investigates the PV module orientation and the thermal impact of the green roof on the PV module performance. An energy simulation program, EnergyPlus, was employed to investigate the thermal impact of green roof. Heat flux analysis was performed to identify the cooling effect of the green roof and its impact on the PV module performance.

2. PV module orientation

Weather Tool from Autodesk was used to study the optimum solar module position in Singapore. Singapore weather file from EnergyPlus was imported to simulate the solar path over Singapore. The outcome showed that the solar path circulate above Singapore from 08.00 am to 19.00 pm. According to that solar path pattern and the three hottest and coolest months in Singapore, the optimum PV module orientation is 75° clockwise from the North, where PV module expose to the maximum solar radiation.

The three hottest and coolest months in Singapore, based on the National Environment Agency (NEA) Singapore, are respectively March, April, May, and November, December, January.

3. EnergyPlus Simulation to study the thermal impact of green roof to the PV module

3.1. Location of study

The 3-storied SDE 2 building which is located at the School of Design and Environment, National University of Singapore, was examined for the suitability of conducting this study. To facilitate the study, the existing metal roof was replaced and simulated with two scenarios which will be described in the following section.

3.2. Modelling method

EnergyPlus is a building simulation program, released by the U.S. Department of Energy (DOE). It is constructed with the features of BLAST and DOE-2, and also designed for modeling buildings with associated heating, cooling, lighting, ventilating and other energy flows.

The simulation was conducted in the EnergyPlus version 5.0 environment and the Equivalent One-Diode method in EnergyPlus was used for this study for a period of one year based on the EnergyPlus given Singapore weather data. The Equivalent One-Diode model simulates a PV module with an equivalent circuit consisting of a direct-current source, diode, and one or two resistors. The strength of the current source is dependent on incident solar radiation. The current-voltage characteristics of the diode depend on the temperature of the solar cells. The hotter the module, the lower its electical output. The model determines current as a function of load voltage.

The geometry of the building was constructed in Google Sketchup with the assistance of Openstudio software which enables the geometry be used for EnergyPlus simulation (Fig. 1). The terrain is city with latitude and longitude of 1.3667 and 103.8 respectively. Two roof scenarios were simulated, namely scenario one: is a PV panel over a concrete roof, and scenario two PV panel over a green roof.

The building and PV modules were simulated in two separated thermal zones in EnergyPlus. The building orientation is 21° clockwise from the North and the PV module faces 75° clockwise from the North. The PV module orientation is based on the result from the Weather tools to ensure the maximum of solar radiation.

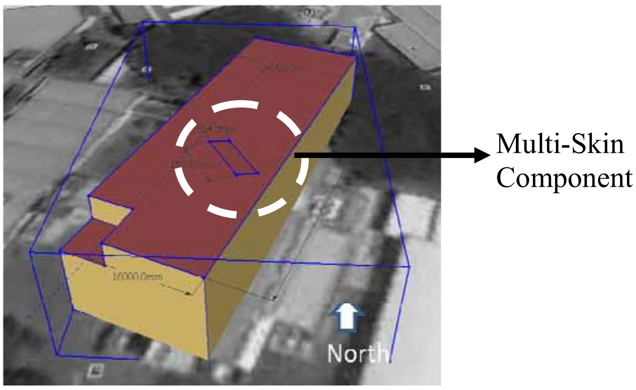

Fig. 1: The geometry of building and PV array in the Open Studio

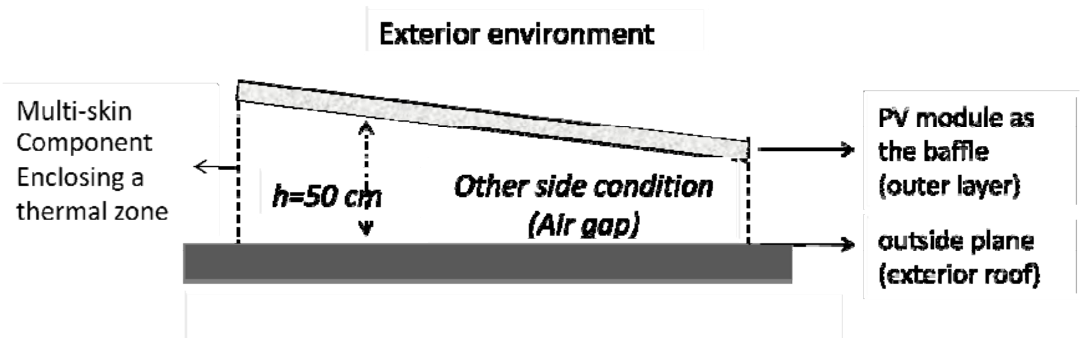

Fig. 2: Schematic drawing of thermal zone 'ventilated cavity' for EnergyPlus, named 'Other side condition'. The cavity between the PV rooftop and exterior roof (h) is 50 cm.

Some general assumptions were made in terms of building model construction in order to focus on the thermal effect of the exterior roof type to the PV rooftop and it describes as follows:

- Simplification of the building form, such as ignoring the presence of windows and canopies.
- Disregard the presence of the surrounding greenery and landscape, such as trees and lawn.
- Disregard the presence of the surrounding building.

The selected PV module is monocrystalline Si based with the dimension of 530x1188 mm^2. Its nominal efficiency is 11.9%, nominal power rating is 75 W, temperature coefficient of short circuit current is 0.00065 A/K and the temperature coefficient of open circuit voltage is -0.08 V/K. The PV system comprises of a 3x20 module array. The total area is 37.78 m^2 with the capacity of 60x75 W. The cavity between PV rooftop and the exterior roof for both scenarios was 50 cm.

"Exterior vented cavity" in EnergyPlus is used as the heat transfer mode for simulation. This object is applied to model a "Multi-Skin Component" exterior heat transfer surface and the outside face, referred to as the baffle which forming a naturally ventilated cavity (Fig. 2). Therefore, the cell temperature is obtained from the exterior baffle temperature in the naturally ventilated exterior cavity model. The input for each scenario is shown in Table 1.

Tab. 1: Key Input Data File

Input Data File	**PV over concrete roof**	**PV over green roof**
Material: Exterior roof	Heavy concrete roof Conductivity: 1.95 W/mK^{-1} Specific heat: 900 J/kgK^{-1}	Plants with LAI (Leaf Area Index) of 5 Conductivity of dry soil: 0.4 W/mK^{-1} Specific heat: 1100 J/kgK^{-1}
Building Surface: Detailed	Roof top: PV module Solar absorbtivity: 0.92 Boundary condition: Other side condition model. Exterior roof: concrete roof Boundary condition: Outdoor.	Roof top: PV module Solar absorbtivity: 0.92 Boundary condition: Other side condition model Exterior roof: concrete roof Boundary condition: Outdoor
Other Side Condition Model	PV Roof Paver system.	PV Roof Paver system
Exterior Natural Vented Cavity	PV Roof Paver Ext Vent Cav1	PV Roof Paver Ext Vent Cav1
Heat Transfer Integration Mode	Integrated Exterior Vented Cavity	Integrated Exterior Vented Cavity
Photovoltaic Performance	Equivalent One-Diode	Equivalent One-Diode

4. The model of Energy Balance

4.1. Literature Review

Energy balance is the total gains of incoming energy and all losses of outgoing energy. The energy difference is expressed by the level of temperature in two bodies (Smithson, 2001). According to Jones and Underwood (2001), the energy balance in the PV module mechanism are in the form of conduction, convection and radiation respectively. Another factor is the electrical energy generated (Fig. 3).

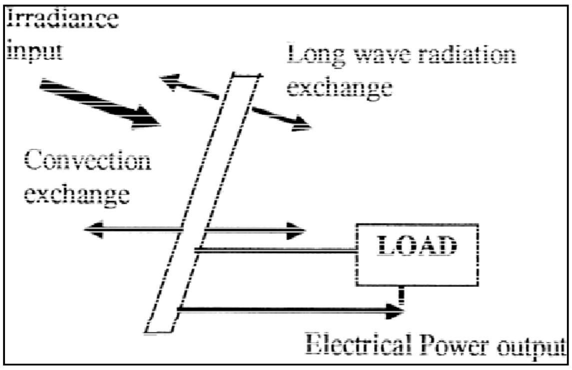

Fig. 3: Heat transfer energy exchange at PV module
Source: Jones, A.D. and Underwood, C.P (2001).

The change of temperature resulting from the energy balance mechanism may be expressed as the sum of the contributions:

$$C_{PV}\frac{dT}{dt} = qlw + qsw + qconv - Pout$$

(eq. 1)

The convection and radiation heat transfer are from the front and back surfaces of the module and are considered significant. On the other hand, the conduction heat transfer from the array can be considered negligible when the contact point area is small.

In terms of the energy balance in the evapotranspiraiton process, Jones, H.G. (1992) described as the following equation:

$$\phi_n = C + \lambda E + M + S$$

(eq. 2)

where ϕ_n is the net heat gain from radiation (shortwave plus longwave), C is the net sensible heat loss, λET is the net latent heat loss, M is the net heat storage in biochemical reaction and S is the net physical storage. The unit for all these heat are expressed in Watt per meter square (Wm^{-2}). The sensible heat loss is the sum of all heat loss to the surrounding by conduction and convection. The latent heat flux is the rate of heat loss by evapotranspiration. The storage ($M + S$) represents the process of photosynthesis and respiration and the energy used in heating the plant material to raise the temperature of the air. These heat storage is small except for massive leaves and forests.

4.2. The concept of Energy Balance in the integration of PV and greenery

Based on the literature review above, the propose mechanism of heat balance for the integration of PV and green roof is illustrated in the following schematic:

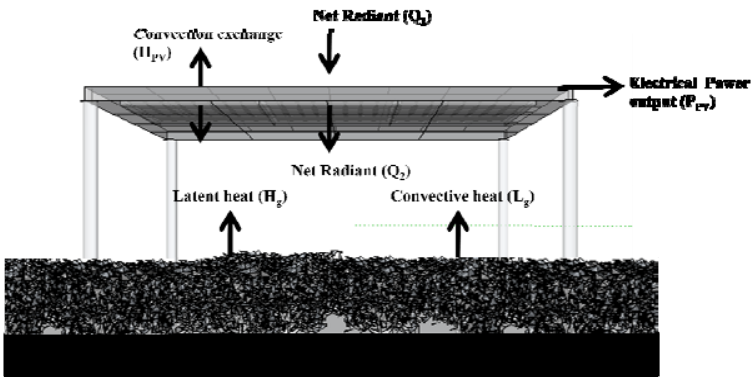

Fig. 4: The mechanism of heat balance

The mechanism is also developed from the first law of Thermodynamic theory, which defines the internal energy as equal to the difference of the heat transfer into a system and the work done by the system. Therefore, the proposed equation is described as follow:

$$\phi_1 = H_{PV} + \frac{P_{PV}}{A_{PV}} + \phi_2$$

(eq. 3)

$$\phi_2 = H_g + L_g$$ (eq. 4)

$$\phi_1 = H_{PV} + \frac{P_{PV}}{A_{PV}} + H_g + L_g$$

(eq. 5)

ϕ_1 is the net radiant coming from above the PV panel which is the sum solar radiation and longwave radiation absorbed by the PV module. H_{PV} is the net sensible loss at the front and back of the PV surface. P_{PV} is the electrical generated. A_{PV} is the area of PV module. ϕ_2 is the net radiant absorbed by the plants which is the sum of the remaining and reflected solar radiation and longwave radiation. H_g is the net sensible loss at the green roof surface underneath the PV module. L_g is the net latent heat loss from the greenroof.

Regarding to the results provided by EnergyPlus, the analyses for the energy balance in these two scenarios can only use the convective heat flux which is derived from multiplying the temperature differences of surface temperature and the convective heat coefficient given by the EnergyPlus results. Therefore, the analysis is modified into:

$$\phi = H_{PVo} + H_{PVb} + \frac{P_{PV}}{A_{PV}} + H_R + H_L$$

(eq. 6)

ϕ is the net radiant coming from above the PV panel which is the sum of solar radiation and longwave radiation absorbed by the PV panel. H_{PVo} is the net sensible loss at the front PV surface. H_{PVb} is the net sensible loss at the back PV surface. P_{PV} is the heat that used for the electrical power output. A_{PV} is the area of PV module. H_R is the net sensible loss at the exterior roof surface underneath the PV module. H_L is the remaining heat loss which is the remaining heat flux from the equation. The analysis applied at 14.00 pm as an example and the results are shown in Table 2. Subsequently the zone air balance surface convective rates were compared in order to identify thermal effect of the greenery on the performance of a PV module.

5. Results and discussion

5.1. PV module performance and temperature

Fig. 5 compares the average monthly PV cell temperatures during the daytime. The PV cell temperature could be reduced by 2.9 °C in January whilst in April and November only by 1 °C. In average, the daytime PV cell temperature could be reduced by 1.7 °C.

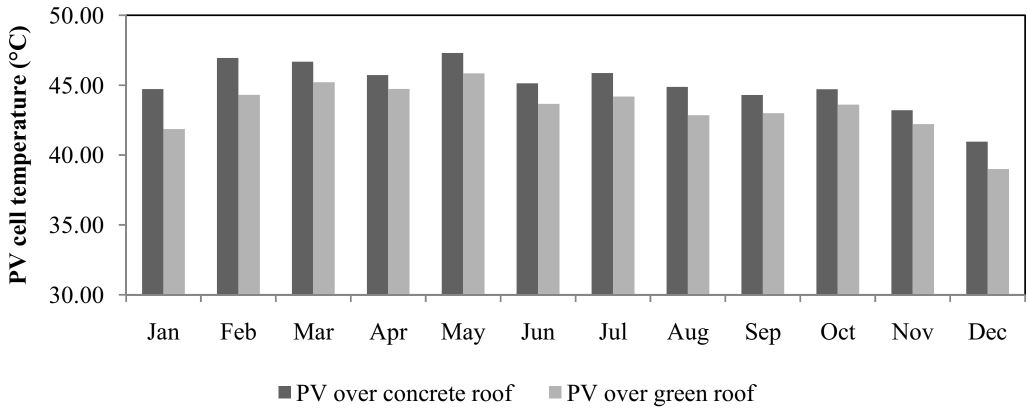

Fig. 5: Monthly PV cell temperature of different roof top system.

Fig. 6 shows that by comparison of the two scenarios, the results indicate that the electrical production of PV module over green roof excelled the one of PV module over concrete roof. The highest difference occurred in January at 2.9% while the least was in April and November at 1%. In average, the PV electrical production could be improved by 1.6% within a year. Additionally, the highest efficiency of the PV module was reached at 11.6% at 27.3 °C, while the lowest efficiency was 9% at 64.8 °C.

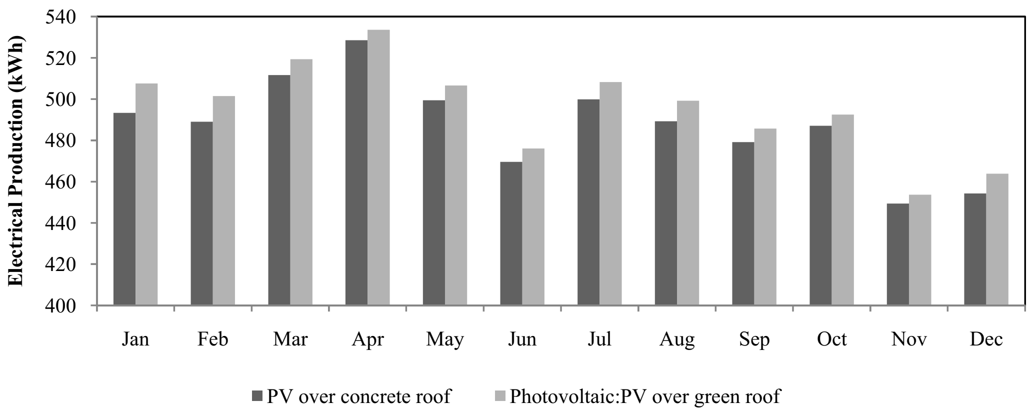

Fig. 6: Monthly Electricity Production of different roof top system.

The results have shown that the electrical production increases due to the reduction of the PV cell temperature. The thermal impact of greenery is more apparent with the improvement of the average of PV array efficiency by 1.15%.

5.2. Heat flux analysis

The simulation results are substituted into the eq. 6 and summarized in Table 2. From the table, it can be seen that at 14.00 pm, the green surface can reduce the convective heat flux at the front and the back surface of PV module by 54% and 53% respectively. The heat flux at above the green surface is lower 73% than the heat flux at above the concrete surface. On the other hand, the heat flux of PV power generated increases by 3% as well as the remaining heat flux increases by 22%. The increase of the remaining heat flux may be identified as the released energy of latent heat flux due to the evapotranspiration process of plants. Subsequently the total air balance reduces by 78% in the PV module over green roof for the whole day (Table 3).

Tab. 2: The heat fluxes

Heat flux	PV over concrete roof (Wm^{-2})	PV over green roof (Wm^{-2})	Difference (%)
Q	898	898	-
H_{PVo}	24	11	(-) 54
H_{PVb}	19	9	(-) 53
P_{PV}/A_{PV}	65	67	(+) 3
H_R	163	44	(-) 73
H_L	627	767	(+) 22

Tab. 3: The total air balance convection rate

	PV over concrete roof (W)	PV over green roof (W)	Reduction (%)
Outside roof surface	26,894	5,684	78

Those reduction results at the scenario of PV module over green roof may identify that the latent heat flux plays important roles as the outcome of evapotranspiration process of the plants. That process could be observed by the emerging low temperature and high humidity on the green roof surface (Fig. 7 and Fig. 8).

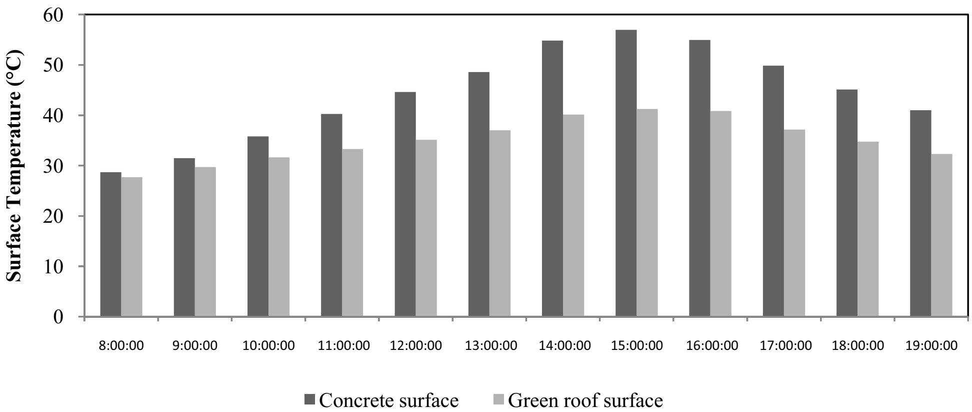

Fig. 7: Surface temperature during day time

The surface temperature difference can be as high as 15.7 °C. At 13.00 hours the green surface temperature was only at 37 °C, but the concrete surface reached up to 48.5 °C. In April, the hottest month, the concrete surface can reach up to 56.9 °C at 15.00 hours time. This result is in accordance with a previous research that was also conducted in Singapore by Hien et al. (2003). It was reported that during afternoon the hard surface could reach around 57 °C by field measurement. However, the highest temperature for green surface, the result from EnergyPlus was 41.2 °C, while from Hien et al. (2003) report was only 36 °C.

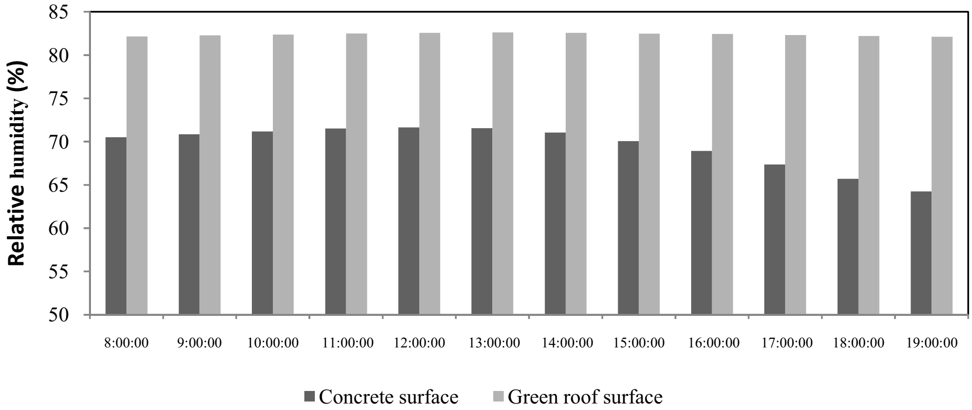

Fig. 8: Relative Humidity during day time

The figure above shows that the relative humidity over green roof was around 30% higher than over the concrete surface. The higher humidity could be attributed to the evapotranspiration process by greenery. Additionally, the relative humidity over green roof showed relatively constant. This might be due to "smart schedule" used for Roof irrigation schedule in the simulation. "Smart schedule" is the irrigation schedule that allows the precipitation schedule to be overridden if the current moisture state of the soil is greater than 30% saturated.

6. Conclusion

The simulation in EnergyPlus by using the Exterior Vented Cavity as the heat transfer mode has shown that green roof potentially provide better thermal impact to the PV roof top. Based on the results, in the Tropics, like Singapore, the PV cell temperature reduction for the arrangement of a 3x20 module array ranged from 1°C (in April and November) to 2.9°C (in January) and the PV electrical generation increased in a range of 1% to 3% over a year.

Although the average of PV performance only improves by 1.6% per year and the electrical energy generation improve by 3% at noon, the zone air balance convective rates can be decreased nearly by 80%. The high reduction of the air balance convective rates may reduce the heat penetration to the building and reduce the use of energy consumption of the building especially for air conditioning, and thus the use PV solar panel can be more effective.

In addition to the above, those reductions of heat flux around PV module may prove that greenery has used some amount of solar radiation as the energy to their biological function, such as evapotranspiration and photosynthesis. Therefore, the thermal condition around the PV module can be improved and consequently increase the PV performance.

7. Acknowledgment

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8. References

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