Wind Effect in Enhancing PV Performance

Analysis of Wind Speed, Direction, and Convective Heat Transfer on Inclined PV Module at Tennant Creek, Australia

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Abstract

Aligning with the Paris agreement to combat climate change, the world is moving towards increasing renewable energy share in the energy mix. The utilization of large scale - Photovoltaic (PV) solar farms has grown significantly throughout the last decade making meteorological data analysis of the area become more crucial than ever in PV solar farm design. PV output is not only decided by solar irradiance but also other important factors such as cell temperature, because high temperature means lower PV efficiency and lifetime. For predicting cell temperature more accurately, analysis of both natural and forced convection are necessary. Studying wind both speed and direction will enrich analytical data for PV yield. Tennant Creek, Australia, is being chosen for this master thesis case location because the area is abundant in solar resources, has plenty of land availability, flat terrain, high ambient temperature and suitable wind data.
This master thesis is presenting PV convection analysis related to solar irradiance, inclination angle, wind speed and wind direction by summarizing from various previous research papers in regard to convection modelling: natural and forced convection. The model factoring frontside and backside of the PV, up-wind or down-wind, flow condition: laminar, turbulent or mixed, and PV characteristic length to determine the convection coefficient. Lastly, calculation of efficiency which results in having higher efficiency of 0.83% compared if wind direction is disregarded and also utility scale PV solar farm design is proposed for case location.

Key words: Free convection, Wind direction, Forced convection, Convection coefficient, PV convection model.

1. Introduction

Over the last decade, solar photovoltaic (PV) technology showed significant development in increasing its efficiency and cheaper price. These conditions align with world leaders' commitment to the Paris agreement in increasing their renewable energy shares to their country's energy mix for combating climate change, which made utility scale PV solar farm installation grow rapidly with close to 107 GW addition in 2020 and more than 700 GW total installed capacity globally (iea, 2021). A utility scale PV solar farm is a solar farm capable of generating more than 1 MW (Seia, 2021). For a solar farm to generate 1 MW a land about 20,000 m2 is needed. PV cell performance (efficiency and lifetime) is affected by its operating temperature which decreases along with the increase of temperature. Typical PV efficiency is 15% - 20% means that only that much of solar irradiation is converted into electric power while the rest is converted into heat. 1% increases or decreases in efficiency can be considered significant for above 1 MW solar farms. Thus, predicting PV temperature becomes more important than ever.

Many PV solar farms are being built either on barren lands, with plenty of wind as heat transfer medium for cooling down PV surfaces. Optimizing wind speed and direction for reducing heat on a PV module can be important factors to increase PV performance. Although the study of natural convection from plate with arbitrary inclination angle is dated back to 1972 (Fujii & Imura, 1972) and forced convection 1977 (Sparrow, 1977), current widely used “bankable” modelling softwares only accommodate wind speed but not wind direction in their model. The purpose of this research is to propose a utility scale solar farm design factoring natural wind flow to improve PV performance through convective heat transfer. The impact of wind flow parameters such as wind velocity, temperature, direction, turbulence on PV module structure and tilt angle and orientation will be analyzed to model the solar farm output better. An experiment for the similar topic has been conducted (Glick & Ali, 2020) but not yet implemented in a model where optimum output solution can be derived. Tennant Creek, Australia, is chosen as a case study because it has plenty of land availability, flat terrain, high ambient temperature and suitable wind data.

Developing the model, the author collaborated with Sun Cable Pte Ltd which planned to construct a 13 GW solar farm in Australia to provide 20% of Singapore Electricity, which mostly comes from natural gas, via HVDC (High Voltage Direct Current) submarine cable which will provide adequate information regarding solar irradiance and wind parameters data.

2. Research goals & limitation

This research goals are analyzing convective heat transfer for PV model by factoring solar irradiance, wind speed and direction. This research only limited to ground fixed north/south faced PV solar farms. The study will be performed only by simulation using software, which is Microsoft Excel and Helioscope

3. PV Temperature Effect

Standard test (STC) for measuring PV I-V characteristic is inside a lab with irradiance of 1000 W/m2, air mass 1.5 spectrum (AM 1.5) and cell temperature of 25o C. PV power output is a combination of its voltage and current. Current is more affected by solar Irradiance with almost linear relation $G_1/G_2 \approx I_2/I_1$ Where G_1 & G_2 are different value of Irradiance (W/m2) and I_1 & I_2 are the corresponding electrical currents (A). PV voltage output is highly determined by the cell operating temperature. The nominal operating cell temperature (NOCT) for PV is measured by open circuiting the cell under Irradiance of 800 W/m2, air temperature of 20o C and 1 m/s wind velocity. For the same irradiance PV output can vary depending on its operating temperature. The PV I-V curve in the following figure shows the change of the curve when cell temperature increases while receiving the same solar irradiance. See Figure 1

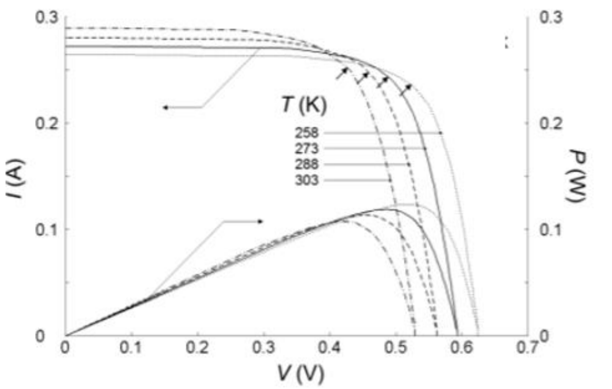


Figure 1 I-V curve for different temperature adapted from (Libra & Poulek, 2017)

4. Faiman model

PV modules often operate more than its rated NOCT especially in locations where ambient temperature is high and from experiments higher irradiance translates to higher PV temperature. Since predicting PV temperature becomes the first task for predicting PV output accurately, a model which correlates PV temperature, ambient temperature, plane of array irradiance (POA) is being proposed by Faiman (Faiman, 2008).

$$T_{pv} = T_{amb} + \frac{H}{U'_0 + U'_1 \times v_w} \qquad \text{(Eq. 1)}$$

Where T_{pv} and T_{amb} are PV and ambient temperature, H is total irradiance incident to PV surface during measurement, U'_0 and U'_1 are constants, and the value can vary between PV type and manufacturer from experiments.

5. Convection model

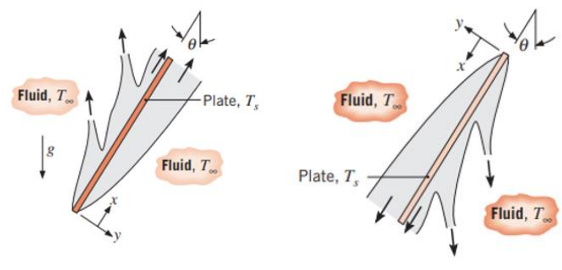
5.1. Free convection

Free convection happens when a different temperature of a surface interacts with fluid under gravity and in the absence of external force. One important constant in convection heat transfer is Nusselt number (N_u) which relates convection coefficient with fluid thermal conductivity (k) and surface characteristic length (L) in this general expression $N_u \equiv h \cdot L/k$. Nusselt number have correlation with free convection (h) and Nusselt number also related with Rayleigh number.

$$Ra_L = \frac{g \cdot \beta \cdot (T_{pv} - T_{amb}) \cdot cos\theta \cdot L^3}{\alpha \cdot v} \qquad \text{(Eq. 2)}$$

Where g is gravity acceleration β is fluid volumetric expansion coefficient or $2/(T_{pv} + T_{amb})$ and the temperature unit is in Kelvin. Rayleigh number also parameter check for labelling the convection flow with $Ra_L \leq {}_CRa$ (critical Rayleigh number) the flow considered laminar otherwise it's turbulent. In free convection model critical Rayleigh number for $0 \leq \theta < 60°$ is 10^9 for higher θ (Mittag & Vogt, 2019) suggest $Ra_c = 10^{8.9-0.00178*\theta^{1.82}}$.

There are two modes of PV operation: cold plate ($T_{pv} < T_{amb}$) and hot plate ($T_{pv} > T_{amb}$)



a b

Figure 2 PV as hot plate (a) & cold plate (b) by (Bergman, 2011)

Equations related to average Nusselt for the PV front side as a hot plate:

Table 1 Free convection frontside equations

Frontside	Average Nusselt Number $(\overline{Nu_{L\_fs}})$	Eq.
$Ra_L \leq Ra_C$	$0.56\ {Ra_L}^{1/4}$	3
$Ra_L > Ra_C$ & $\theta \geq 60°$	$0.13\ {Ra_L}^{1/3}$	4
$Ra_L > Ra_C$ & $\theta < 60°$	$0.13 \cdot \left[\left(\frac{Ra_L}{cos\theta}\right)^{1/3} - {Ra_C}^{1/3}\right] + 0.56 \cdot (Ra_C \cdot cos\theta)^{1/4}$	5

Reference for (Eq. 3,4,5) (Fujii & Imura, 1972)

And equations for the backside:

Table 2 Free convection backside equations

Backside	Average Nusselt Number $(\overline{Nu_{L\_bs}})$	Eq.
$Ra_L \leq 10^9$ & $0 \leq \theta < 60°$	$0.68 + \frac{0.670{Ra_L}^{1/4}}{[1 + (0.492/Pr)^{9/16}]^{4/9}}$	6.a

$Ra_L > 10^9$ & $0 \le \theta < 60°$	$\left\{0.825 + \frac{0.387 Ra_L^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right\}^2$	6.b
$10^5 \le Ra_L \le 10^{11}$ & $60° \le \theta < 88°$	$0.56\ Ra_L^{1/4}$	7
$10^6 \le \frac{Ra_L}{cos\theta} \le 10^{11}$ & $88° \le \theta < 90°$	$0.56\ \left(\frac{Ra_L}{cos\theta}\right)^{1/5}$	8

Reference for (Eq. 6.a, 6.b) (Bergman, 2011)
Reference for (Eq. 7 & 8) (Fujii & Imura, 1972)
For PV operating as a cold plate equation the equation is the opposite. Frontside PV hot plate wil be used for backside PV cold plate

5.2 Forced convection

Forced convection happens when there is an external force driving the fluid flow, for PV case is the wind. Similar with free convection, one important constant in forced convection is Reynolds number as fluid's ratio of the inertia and viscous force (Bergman, 2011).

$$Re_L = \frac{\rho \cdot v_\infty \cdot L}{\mu} \qquad \text{(Eq. 9)}$$

Where ρ, v_∞, and μ are fluid density, velocity, and viscosity. L is the characteristic length of the surface that is in contact with the fluid flow. For upwind surface characteristic length represents the distance between from leading edge to trailing edge. If we consider γ as the angle difference between PV azimuth and wind direction where 0º represents North and act as reference. Characteristic length for PV surfaces when upwind and $|\gamma| \le 45°$ is the PV height and when $|\gamma| > 45°$ the characteristic length is the PV width.

For downwind PV surface since wind speed and orientation is not relevant the characteristic length is $L = 4 \cdot A/S$ where A is PV module area and S is its perimeter (Kaplani & Kaplanis, 2014). The relation between γ and L is in the following table.

Table 3 Forced convection characteristic length

Υ (degree)	Frontside	Backside
$0 \le \gamma \le 45$ Or $315 \le \gamma \le 360$	L = PV Height	$L = 4 \cdot A/S$
$45 < \gamma \le 90$ Or $270 \le \gamma < 315$	L = PV Width	$L = 4 \cdot A/S$
$90 < \gamma < 135$ Or $225 < \gamma < 270$	$L = 4 \cdot A/S$	L = PV Width
$135 \le \gamma \le 225$	$L = 4 \cdot A/S$	L = PV Height

Synonymous with Rayleigh number to determine flow condition in natural convection, Reynolds number is used to determine the flow condition in forced convection. By using the ratio between critical length and characteristic length the condition can be predicted whether it's a laminar, turbulent, or mixed. Rearranging Eq. 9 we can have $x_c = Re_{x,c} \cdot \upsilon / v_w$ where x_c is critical length, $Re_{x,c}$ is critical Reynolds number or 4 x 10^5, $\upsilon\ and\ v_w$ are air kinematic viscosity and speed. From (Sartori, 2006) if $x_c \ll L$ it is considered the flow is fully turbulent and if $x_c \ge 0.95\ L$ indicating that the flow is laminar and if $x_c < 0.95\ L$ the flow is in transition from laminar to turbulence or a mixed flow condition.

Another equation to estimate forced convection is proposed by (Kendoush, 2009) by accommodating wind speed and direction incidence to the PV surface. Based on (Kaplani & Kaplanis, 2014) experiment, (Kendoush, 2009) general equation provides more accurate result for upwind PV surface and (Sartori, 2006) is being used for downwind and backside PV surface. The wind incidence angle (α_w) is calculated from $\alpha_w = cos\ (\gamma) * \cos\ (90 - \beta)$

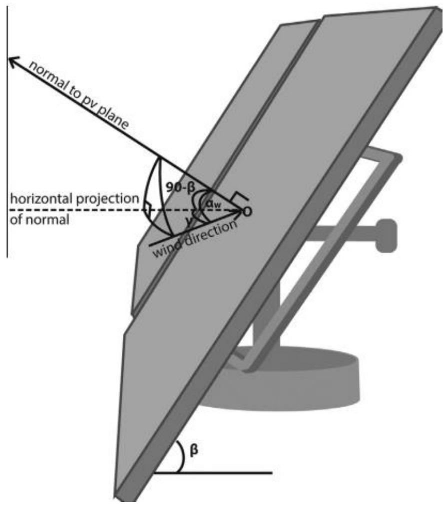


Figure 3 Wind incidence angle by ϒ and β by (Kaplani & Kaplanis, 2014)

Table 4 Forced convection coefficient for PV frontside

Frontside	Forced convection coefficient (h_{forced_fs})	Eq
$0 \le \gamma \le 90$ Or $270 \le \gamma \le 360$	$0.848 \cdot k \cdot (\cos(\alpha_w) \cdot v_w \cdot Pr/v)^{0.5} \cdot (0.5 \cdot L)^{-0.5}$	10
$90 < \gamma < 270$ & $\frac{x_c}{L} \ge 0.95$	$3.83 \cdot {v_w}^{0.5} \cdot L^{-0.5}$	11
$90 < \gamma < 270$ & $0.05 < \frac{x_c}{L} < 0.95$	$5.74 \cdot {v_w}^{0.8} \cdot L^{-0.2} - 16.46 * L^{-1}$	12
$90 < \gamma < 270$ & $\frac{x_c}{L} \le 0.05$	$5.74 \cdot {v_w}^{0.8} \cdot L^{-0.2}$	13

Reference for (Eq. 10) (Kendoush, 2009)
Reference for (Eq. 11,12,13) (Sartori, 2006)

Table 4 and Table 5 are PV forced convection coefficient equations where v_w is wind speed (m/s) and Pr is Prandtl number.

If the ratio $x_c/L \ge 0.95$ the flow is considered laminar, if $x_c/L \le 0.05$ the flow is fully turbulent and $0.05 < x_c/L < 0.95$ the flow is considered mixed. All wind velocity from backside PV $|\gamma| > 45°$ flowing on PV width with speed greater than 3 m/s will be considered turbulent regardless the ratio of x_c/L. Flow condition will determine the equation for calculating forced convection coefficient (h_{forced}).

Table 5 Forced convection coefficient for PV backside

Backside	Forced convection coefficient (h_{forced_bs})	Eq
$0 \le \gamma \le 90$ Or $270 \le \gamma \le 360$ & $\frac{x_c}{L} \ge 0.95$	$3.83 \cdot {v_w}^{0.5} \cdot L^{-0.5}$	11
$0 \le \gamma \le 90$ Or $270 \le \gamma \le 360$ & $0.05 < \frac{x_c}{L} < 0.95$	$5.74 \cdot {v_w}^{0.8} \cdot L^{-0.2} - 16.46 * L^{-1}$	12
$0 \le \gamma \le 90$ Or $270 \le \gamma \le 360$ & $\frac{x_c}{L} \le 0.05$	$5.74 \cdot {v_w}^{0.8} \cdot L^{-0.2}$	13
$90 < \gamma < 270$ & $v_w \ge 3m/s$	$5.74 \cdot {v_w}^{0.8} \cdot L^{-0.2}$	13

Reference for (Eq. 11,12,13) (Sartori, 2006)

5.3 Combining free and forced convection

Combining both free and forced convection coefficient to get total convection coefficient is not a simple addition. Since both free and forced convective heat transfer happen at the same time, the ratio of the surface Grashof number (Gr_L) and

Reynolds number (Re_L) need to be estimated (Bergman, 2011). Grashof number is related to free convection as Rayleigh number multiplied by Prandtl number in the following equation

$$Gr_L = \frac{Ra_L}{Pr} = \frac{g \cdot cos\theta \cdot \beta \cdot (T_{pv} - T_{amb}) \cdot L^3}{v^2} \quad \text{(Eq. 14)}$$

Grashof number is related to free convection like Reynolds number is to forced convection. If $Gr_L/{Re_L}^2 \ll 1$ the free convection effect may be neglected and conversely, when $Gr_L/{Re_L}^2 \gg 1$ the free convection effect can be neglected. Combining the free and forced convection can be considered when $0.01 < Gr_L/{Re_L}^2 \leq 100$ (White, 1988) as cited in (Kaplani & Kaplanis, 2014).

To combine the free and forced convection coefficient (h_{c_total}) by following the expression from (McAdams, 1942) as cited in (Churchill, 1977) experiment regarding the correlation between the combined average Nusselt number from forced convection and natural or free convection : $Nu^n = {Nu_F}^n + {Nu_N}^n$ with n = 3 for assisting or opposing fluid flow it can be derived that ${h_{c\_total}}^3 = {h_{free}}^3 + {h_{forced}}^3$ since Nusselt number directly related to convection coefficient in general expression of $h \equiv Nu \cdot k/L$. Since convective heat transfer happen for both PV surfaces at the same time, separate calculations for total convection coefficient are needed. Convection coefficient for PV surfaces can be written in this following table.

Table 6 Total convection coefficient equations

PV frontside	${h_{c\_fs}}^3 = {h_{free\_fs}}^3 \pm {h_{forced\_fs}}^3$	(Eq. 15.a)
PV backside	${h_{c\_bs}}^3 = {h_{free\_bs}}^3 \pm {h_{forced\_bs}}^3$	(Eq. 15.b)
PV average	$h_{c\_pv} = \frac{h_{c\_fs} + h_{c\_bs}}{2}$	(Eq. 16)

The plus / minus ($\pm$) sign depends on whether the forced convection is assisting or opposing the natural free convection. Meaning that if the forced convection flow is assisting the free convection flow the sign is positive (+) and if the forced convection is opposing the free convection flow the sign is negative (-). The sign considers PV orientation vs wind direction (γ) upwind or downwind, and PV operating state whether as a hot plate or cold plate. Blue arrow is upwind and green arrow is downwind, left side is PV frontside and right side is PV backside.

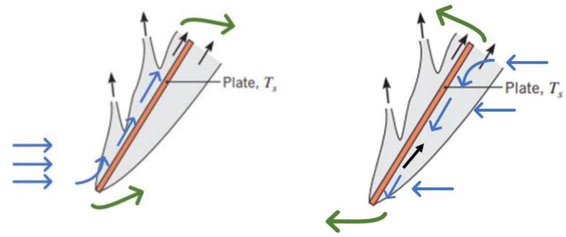


Figure 4 Combining free and forced convection

6. Analysis

PV farm location, roughness length = 0.03 (open flat terrain with few obstacle).

Figure 5 Proposed PV location

Average wind speed at PV height (2.5m) is 3.63 m/s with dominant wind direction from southeast and east-southeast

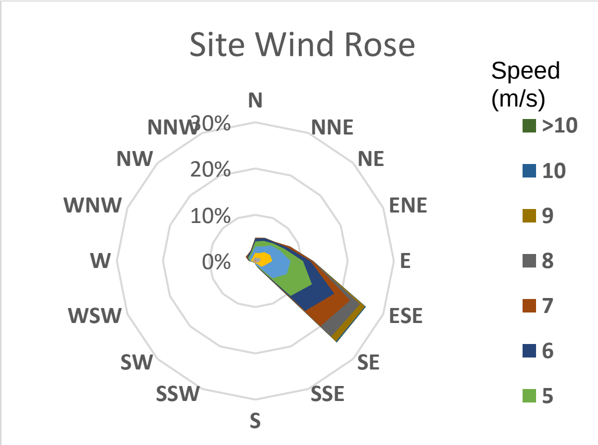


Figure 6 Wind rose diagram of the PV farm

Solar irradiation profile

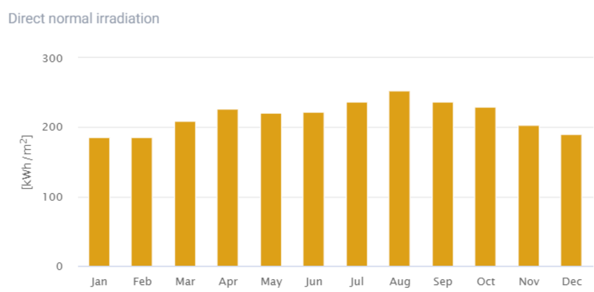


Figure 7 DNI profile by (globalsolaratlas, 2021).

Annual DNI solar potential of 2.49 MWh/m2 and GHI is 2.28 MWh/m2. With a ratio of GHI/DNI ≈ 0.92, it suggests that the location is suitable for lower PV inclination angle (β) < 30o. As mentioned before, the minimum β that will be considered in this thesis is 2º this is to combat soiling and increase PV self-cleaning. Optimum *β* is calculated by sensitivity analysis. $B_{optimum}$ = 22º

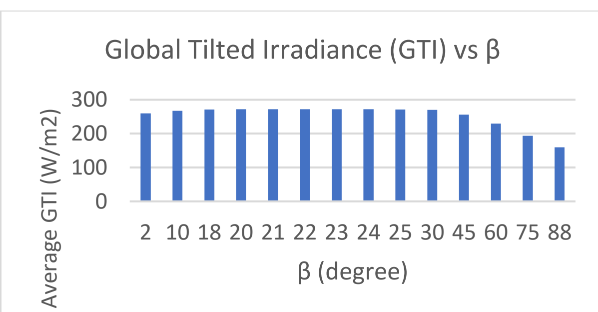


Figure 8 Sensitivity analysis of GTI vs PV inclination angle (β)

7. Convection coefficient analaysis

8.1 Convection coefficient vs PV Inclination angle

Series of sensitivity analysis being conducted with the main goal is to get the relation between overall convection coefficient (h_c) with *β* and *γ* in Figure 12. Convection coefficient increases as *β* increases since both forced and free convection coefficients also increase. This model shows a relation that total convection coefficient $h_c \approx h_{forced} - h_{free.}$ This is because mostly PV is operating as a hot plate and PV backside is upwind since dominant wind comes from the backside.

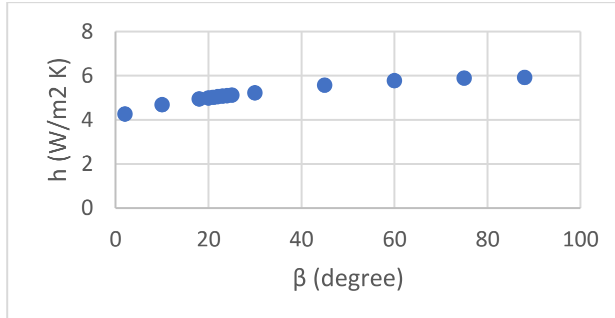


Figure 9 Average convection coefficient

The average convection coefficient for optimum *β* is 5.1 W/m² K

8.2 The effect of wind direction to convection coefficient

This sensitivity analysis, comparing h_c vs *γ*, is being conducted by grouping the wind direction into a certain degree but keeping other parameters constant. From the chart the lowest h_c is 2.8 W/m²K, happens when the wind is blowing in a small angle from west or east of the PV surface. This is possibly because the wind flow is not obstructed or tends to be laminar and has a smaller Nusselt number by having a short characteristic length (*L*). The highest average hc is 7.5 W/m²K obtained if all the wind comes from south (180 degree) or upwind PV backside. With the same wind speed h_c can increase to almost 50% if the direction changes to the most optimum.

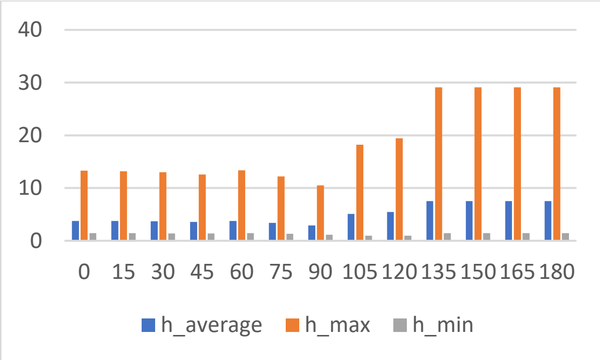


Figure 10 Wind direction vs convection coefficient

8.3 Wind velocity and convection coefficient

Another important parameter is the wind speed. The chart signals that the wind speed also affects convection coefficient significantly since the forced convection equation depends on wind speed. Below is the relation of wind speed and h_c if the wind speed is changed while keeping other parameters constant h_c will also increase almost exponentially especially when temperature is high.

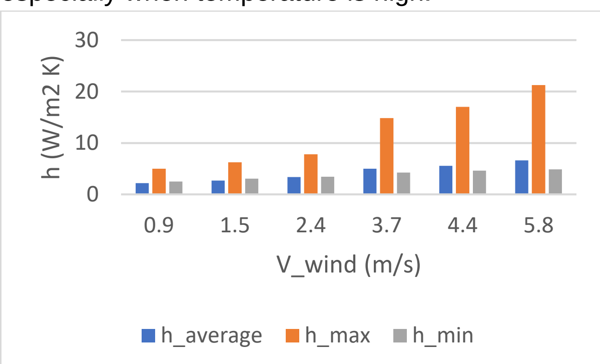


Figure 11 Wind speed vs convection coefficient

From series of sensitivity analysis and by using newton general expression on heat transfer (cooling) $Q = h \cdot (T_{PV} - T_{\infty})$

8. PV solar farm layout recommendation

Passive convection cooling should be taken advantage of to design PV solar farm, by considering wind direction, without sacrificing optimum azimuth and tilt angle. Based on (Glick & Ali, 2020) experiment regarding PV arrangement, to maximize the wind direction that converges started from 8 – 9th row, an example of 1 MWp PV solar farm layout recommendation and designed by using Helioscope as follows.

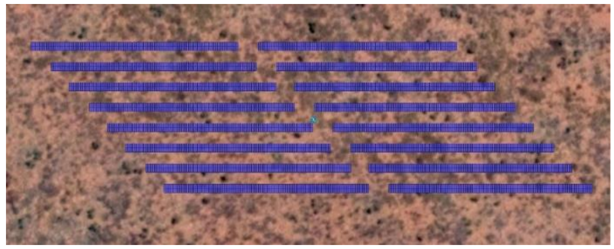


Figure 12 Proposed 1 MWp solar farm layout

compared PV temperature difference between this thesis PV convection model with the same but disregarding the wind direction, the temperature difference estimated to be 2.37°C and if assumed PV module is JAM72S10 400 PR which has temperature coefficient for P_{max} is -0.35%/°C this temperature difference translates to 0.83% difference in efficiency. The solar farm consists of approximately 2888 PV modules, 1 MWp solar inverter, with maximum capacity of 1,1 MWp. If -2% soiling is considered, the annual energy yield at irradiation level forecasted to be 2,590 MWh.

9. Economical & environmental impact

The 0.83% difference in efficiency will be calculated to estimate PV solar farm output at cell temperature. If wind convection is disregarded the temperature will cost -7.7% from energy yield. By accommodating this model, the loss can be cut up to -6.87% or save 21.45 MWh. On a global scale, a typical household with standard appliances consumes 1,250 kWh annually (iea, 2020) this means the saved energy can potentially provide for 17 households. Since Sun Cable will sell the electricity to Singapore with selling price of 0.086 Euro / kWh (globalpetrolprices, 2021) the cost saving can up to 1,845 Euro and environmentally reducing 10.5 tonCO_2eq. This will scale up with solar farm capacity.

With 2GWp capacity, the energy saving now will be more than 42,900 MWh, equal to almost 3.7 million Euro and can provide for more than 34,000 households also potentially reduced 20,934 kiloton CO_2eq annually. If the social cost of carbon, a measure of socio-economic harm because of damages from one ton carbon dioxide emission, is 50 USD or 43 Euro per ton (EDF, 2015) the annual social cost of carbon that can be avoided will be more than 900,000 Euro.

10. Conclusion & Future Work

The study of wind effect: speed and orientation in enhancing PV performance can be considered as an additional value in forecasting PV solar farms output. In terms of convection coefficient (hc), a location with higher hc means higher heat exchange from PV surface to the fluid (air), this resulting less temperature difference between PV temperature and ambient temperature thus, lower PV temperature and results in higher electrical power output. Optimum PV tilt angle against solar irradiance and convection heat transfer need to be considered to obtain maximum energy yield. Prioritizing optimum PV tilt angle and azimuth is needed for obtaining best possible solar irradiance. Finding a solar farm with good wind speed and dominant wind direction from PV backside is preferred to get better PV performance.

This convection model can benefit for PV solar farm developers in giving a more complete analysis compared to the traditional model especially in a farm located in high latitude which will have higher optimum inclination angle and strong wind. A small increase of efficiency and lower PV temperature in a utility-scale solar farm means a large additional electrical energy and longer PV lifespan thus, can reduce capital expenditure for deploying a lesser number of PV and reducing operational expenditure for operation and maintenance cost. For 1 MWp PV farm in this location annually can save to 21.45 MWh equal to 1,845 Euro and can avoid 10,467 kg of CO_2eq and 450 Euro social carbon cost and it scales up with solar farm capacity.

It is for humanity best interest that this “extra efficiency” not only be viewed as monetary and LCOE profit but also for environmental impact. The saved energy from PV solar farms can replace that comes from more potentially harmful to the environment power plants. This environmental benefit comes from reducing pollution and greenhouse gasses emission, combating climate change, lowering the social cost of carbon and many more.

For future work, a complete thermal heat transfer can provide even better accuracy thus, the model not only considers convective heat transfer but also conductive and radiative heat transfer. Implementation of the model in other racking systems will be interesting such as East – West racking system, one axis or two axis racking system where PV angles can be adjusted.

Onsite PV array testing can greatly improve this model. Because getting a complete data set of PV specification, electrical output, with corresponding meteorological data such as wind speed and wind direction are not easy to acquire. By conducting onsite testing, investors can benefit from different PV array arrangement and onsite measuring of the convection and then to be compared with the model. A deep study for utility scale PV solar farm business models can be an interesting topic as how optimizing and better model accuracy can impact the whole solar farm industry.

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