Evaluating the nature and significance of ambient wind regimes on solar photovoltaic system performance

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Abstract

Commercially available photovoltaic (PV) systems are predominantly silicon-based and their performances vary depending on inherent material properties, installation geometry and environmental factors. Ambient parameters vary from location to location, and can include the insolation level, ambient temperature, precipitation levels, dust regimes and local wind conditions. While the noticeable impact of the ambient temperature and dust settlement on PV efficiency has been recognized, the extent of influence attributed to wind patterns remains unclear. High wind speeds have the potential to enhance cell efficiencies by lowering the cell operating temperatures. Numerous correlations appear in literature that relate the cell temperature to the local wind speed, with a quoted efficiency gain of 0.7% for a 1 km hour^{-1} rise in wind speed. Such a gain is significant considering the relatively low maximum efficiencies possible with present material technology and the large scale of PV installations. The applicability of the empirical correlations for wind flow over PV surfaces has been validated by wind tunnel experiments, particularly for wind movements parallel to the PV panels. However, wind speed and its direction rarely remain constant over time and terrain, and traditional heat transfer models inadequately account for these variations. The current study adopts a comprehensive approach to structure the nature of wind patterns for their direct or indirect influence on PV system performance.

This paper investigates the effect of wind related heat transfer on the performance of roof-mounted photovoltaic panels in tropical regions, where operating temperatures tend to be higher. The investigations are based on real-time monitoring of a Building-Integrated Photovoltaic roof combined with the development of simulation models. This paper reviews the current status of research in this domain. Further, attempts are made to provide guidelines for the appropriate geometry for installation of roof-mounted PV panels taking into account prevalent wind regimes at the site.

1. Introduction

The use of building-integrated photovoltaic (BIPV) surfaces as building envelopes is on the rise. Silicon photovoltaic cells that are generally deployed in BIPVs have been reported to achieve a maximum solar energy conversion efficiency of 25% in laboratory testing (Green et al., 2011). Continuous exposure to intense solar radiation and an increase in the ambient temperature lead to a rise in the cell temperature. The direct effect of the cell temperature on the electrical conversion efficiency of the cell can be seen from the traditional linear expression for PV efficiency, Eq. (1) (Evans and Florschuetz, 1977)

$$\eta_c = \eta_{ref}[1 - \beta_{ref}(T_c - T_{ref})] \quad (1)$$

where η_{ref} is the electrical efficiency of the cell at the reference temperature, T_{ref} = 25°C and at an insolation of 1000 Wm^{-2}, and η_c is the cell efficiency at the cell operating temperature T_c. The temperature coefficient β_{ref} is a material property having a value of 0.0045 K^{-1} for monocrystalline silicon (Notton et al., 2005). A single degree Celsius rise in cell temperature above 25°C would therefore result in a percentage efficiency loss equal in magnitude to β_{ref}, which is 0.45% in this case. This may seem small, but considering that most commercially available modules today have operating efficiencies between 12-18% and cell operating temperatures can rise by as much as 42°C above the ambient during operation (Radziemska and Klugmann, 2006) characteristic of

PV installations in tropical regions, the associated drop in efficiency becomes significant. It is evident then that the PV cell operating temperature plays a central role in the photovoltaic conversion process.

As described by Mani and Pillai (2010), natural wind movements affect PV performance and installation geometries by effecting the accumulation or clearing of dust from PV surfaces. Natural wind movements may have the beneficial effect of lowering the PV cell temperature by carrying away some part of the surface heat through forced convective heat transfer. It is of interest, hence, to understand the nature and significance of the interactions of ambient wind regimes on solar photovoltaic system performance.

The value of the reference efficiency η_{ref} of a cell varies with the material used for fabrication and is generally furnished by the respective manufacturers. Considering a typical value of 15%, and substituting the values of the reference temperature and the reference efficiency, Eq. (1) can be written as

$$\eta_c = 0.15[1 - 0.0045(T_c - 25)] \quad (2)$$

2. Effect of wind speed on photo-voltaic performance

As previously stated, high wind speeds have the effect of lowering the cell operating temperature, thereby resulting in a potential gain in efficiency. It is possible to predict this gain in operating efficiency for a given set of weather conditions by estimating the corresponding operating temperature of the PV cell under those conditions. Applying the principle of energy conservation for a PV cell, its operating temperature can be derived, *ab initio* either as, an implicit function of the insolation level, the ambient temperature and the wind speed, or as an explicit function of the wind speed alone.

Consider the generic case of an unglazed PV cell (Figure 1) of unit area tilted at an angle θ (here 0°) to the horizontal, over which wind flows parallel to its surface and with a uniform speed V_w. A part of the insolation, G incident on the cell surface is converted into electric power W_p depending on the instantaneous efficiency η_c of the cell. The remaining energy is converted into heat and is either accumulated within the cell, raising the cell temperature, or is dissipated to the environment through convective and radiative heat losses. The energy balance for the system can be written as

$$\alpha G = W_p + Q_{\text{free conv}} + Q_{\text{wind}} + Q_{\text{rad}} + \rho\delta C \frac{dT}{dt}\frac{dT}{dt} \quad (3)$$

To compute the instantaneous cell temperature at known values of weather variables that include the insolation, the ambient temperature and the wind speed, we shall analyse the heat exchange at steady state where the rate of change of thermal energy contained within the cell is zero, and the cell is at an equilibrium temperature T_c.

The cell temperature can be estimated by solving Eq. (3), using appropriate relations for the convective and radiative heat transfer components. This comprises the implicit methodology for the estimation of T_c,

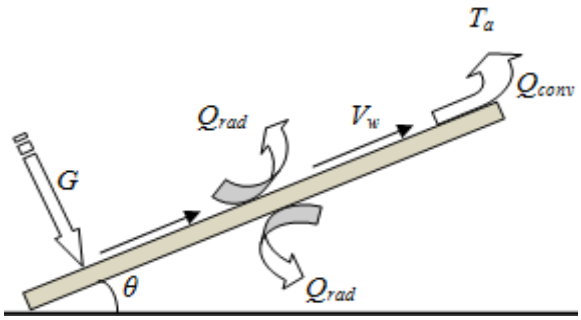

Fig. 1 – Heat exchanges in an unglazed PV cell

2.1 Implicit method for cell temperature estimation

The free and wind-induced convection components and the radiation heat transfer in Eq. (3) can be evaluated from the basic theory of heat transfer and from equations derived in previous studies.

The free convective heat transfer from the cell surfaces can be calculated as

$$Q_{\text{free conv}} = (h_f + h_b)(T_c - T_a) \quad (4)$$

where h_f and h_b are the coefficients of heat transfer for the front and back surfaces of the PV cell, and T_a is the ambient temperature. Approximations for the turbulent free-convective heat-transfer coefficients for the front and back surfaces tilted upward at an angle θ from the horizontal are shown in Eqs. (5) and (6) respectively (Raithby and Hollands, 1975).

$$h_f = 1.52[(T_c - T_a)\cos\theta]^{1/3} \quad (5)$$

$$h_b = 1.31[(T_c - T_a)\sin\theta]^{1/3} \quad (6)$$

The radiative heat loss per unit area of the PV surface can be approximated by Eq. (7)

$$Q_{rad} = F\varepsilon_f\sigma(T_c^4 - T_{sky}^4) + F\varepsilon_b\sigma(T_c^4 - T_a^4) \quad (7)$$

where ε_f and ε_b are the front and back surface emittances and can be taken as 0.9. The ground temperature can be assumed to be equal to the ambient temperature. The view factor F is unity for both surfaces (Armstrong and Hurley, 2010).

The sky temperature T_{sky} (Ware, 1974) is given as

$$T_{sky} = 0.914T_a \text{ (in K)} \quad (8)$$

The forced convective heat transfer induced by wind flowing over the PV cell surface can be calculated by

$$Q_{wind} = H(T_c - T_a) \quad (9)$$

where H is the forced-convective heat transfer coefficient, $Wm^{-2}K^{-1}$

Using these relations, Eq. (3) can be rewritten as

$$\alpha G = G \times 0.15[1 - 0.0045(T_c - 25)] + \{1.52[(T_c - T_a)\cos\theta]^{1/3} + 1.31[(T_c - T_a)\sin\theta]^{1/3}\} \cdot (T_c - T_a) + H(T_c - T_a) + \varepsilon_f\sigma(T_c^4 - T_{sky}^4) + \varepsilon_b\sigma(T_c^4 - T_a^4) \quad (10)$$

For a known set of values of the insolation, ambient temperature and wind speed, the calculation of the cell efficiency at a particular wind speed, can hence be determined by estimating the wind-induced convective heat transfer coefficient.

Numerous empirical formulae are available from heat transfer theory that correlate the convective heat transfer with the wind speed for the simple case of parallel flow over a surface. The earliest equation for wind-driven heat transfer was developed by Nusselt and Jürges (1922). In its traditional form, the Nusselt-Jürges correlation is expressed as

$$H = 5.678\{a + b[(\frac{29426}{T_a})V_w / 0.3048]^n\} \quad (11)$$

where a, b and n are empirical constants that depend on the surface texture and the wind speed. T_a is in K.

The Nusselt-Jürges correlation in SI units takes the simplified form

$$H = 5.8 + 3.95V_w \quad (12)$$

This equation is still popular and is widely used for calculations and simulations. Palyvos (2008) points out that this dimensional equation includes radiation loss in addition to the convective heat loss and further, that the conditions in which the equation was derived differ widely from real life situations.

Over the years, several researchers have carried out experiments to correlate the wind heat transfer coefficient with the wind speed. It was found that linear regression equations of the form $H = a + bV_w$ were effective in fitting the test results obtained. Prominent among these are the equations published by McAdams (1954) and Lunde (1980) in their respective texts on convective heat transfer. Watmuff et al. (1977) developed a linear equation based on wind tunnel tests. A few other linear equations have been developed by Ito et al. (1972), Test et al. (1980), Cole and Sturrock (1977), and Sharples and Charlesworth (1998) based on field measurements. It should be noted that these equations include the effect of natural convection, thereby giving non-zero convection coefficients even for null wind speeds. An appraisal of these equations is given in Table 1.

As fundamental heat transfer theory supports a power relation between convective heat transfer coefficients and wind speed, many researchers such as McAdams (1954) and Loveday and Taki (1996) developed relations that were of the form $H = a + bV^n$. For steady-state parallel airflow over a plate, relations (13) and (14) for the wind heat transfer are found to be consistent with experimental measurements (McAdams, 1954), (Stultz and Wen, 1981)

$$H = 3.8V_w; \quad V_w \le 5ms^{-1} \quad (13)$$

$$H = 7.13V_w^{0.78}; \quad V_w > 5ms^{-1} \quad (14)$$

These formulae were developed through laboratory tests with air blowing over the front surfaces of PV modules by means of a fan. The coefficients so derived include the free convection heat transfer component. However, natural wind movement being more complicated than fan-induced flows, these formulae may not be directly used for natural wind impinging on PV cell surfaces since wind is transient.

Kimura et al. (1975) derived the power-law equation

$$H = 18.63V_w^{0.605} \quad (15)$$

authors	correlations	comments
Nusselt, Jürges (1922)	$H = 5.8 + 3.95V_{\mathrm{w}}$ $H = 7.13V_w^{\,0.78}$	Includes the radiation loss
McAdams (1954)	$H = 5.7 + 3.8V_{\mathrm{w}}$	May include free convection and radiation losses
Kimura et al. (1975)	$H = 18.63V_w^{\,0.605}$	From field measurements
Cole, Sturrock (1977)	$H = 11.4 + 5.7V_{\mathrm{w}}$	Applies to windward flow
Watmuff et al. (1977)	$H = 2.8 + 3.0V_{\mathrm{w}}$	Exclusive of free convection and radiation losses
Lunde (1980)	$H = 4.5 + 2.9V_{\mathrm{w}}$	Applies to smooth surfaces
Test et al. (1980)	$H = 8.55 + 2.56V_{\mathrm{w}}$	V_w measured 1m above surface
Sparrow, Lau (1981)	$Nu = 0.86\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}$	From wind-tunnel testing
Schott (1985)	$H = 7.0 + 2.1V_{\mathrm{w}}$ $H = 5.79V_w^{\,4/5}L^{-1/5}$	$\forall 1.0 \le V_{\mathrm{w}} \le 1.5ms^{-1}$ $\forall V_{\mathrm{w}} \ge 0.3ms^{-1}$
Loveday, Taki (1996)	$H = 8.91 + 2.0V_{\mathrm{F}}$ $H = 4.93 + 1.77V_{\mathrm{F}}$	Windward flow Leeward flow
ASHRAE (1997)	$H = 5.62 + 3.9V_{\mathrm{w}}$	Proposed by ASHRAE
Sharples, Charlesworth (1998)	$H = 6.5 + 3.3V_{\mathrm{w}}$ $H = 8.3 + 2.2V_{\mathrm{w}}$	Windward flow Leeward flow
Furushima et al. (2006)	$H = 5.5 + 2.2V_{\mathrm{w}}$	Measurements on PV modules
Sartori (2006)	$H = 5.74V_w^{\,4/5}L^{-1/5}$	Applies to fully turbulent flow
Palyvos (2008)	$H = 7.4 + 4.0V_{\mathrm{F}}$	Averaged over 30 correlations

Table 1 – Wind heat transfer coefficient correlations

Davies (2004) has more recently found that linear equations are as effective as power-law equations in predicting the heat transfer coefficient from the wind speed. ASHRAE has accepted one such linear correlation, with the values of the constants *a* and *b* as a = 5.62 and b = 3.9 (ASHRAE, 1997).

It is cumbersome to measure the component of wind velocity parallel to the PV surface. With a view to resolve this difficulty, Ito et al. (1972) correlated this component with the free stream velocity, V_F at a height 10 metres above the surface as:

$$V_w = 0.25V_f; \qquad V_F > 2ms^{-1} \tag{16}$$

$$V_w = 0.5ms^{-1}; \qquad V_F \le 2ms^{-1} \tag{17}$$

The above listed correlations estimate the wind-induced heat transfer for only the front side of PV modules which is the case relevant for BIPVs in the windward direction. Through field measurements of the free stream wind speed Loveday and Taki (1996) developed relations for heat transfer from windward and leeward surfaces separately (see Table 1).

On the basis of data generated by thirty such linear correlations, Palyvos has derived purely empirical 'average' correlations for windward surfaces of the form of Eq. (18) and for leeward surfaces as Eq. (19):

$$H = 7.4 + 4.0V_{\mathrm{F}} \tag{18}$$

$$H = 4.2 + 3.5V_{\mathrm{F}} \tag{19}$$

A number of correlations have been developed that take into account the decrease of the wind convection coefficient in the direction of wind flow along the surface. They have the general form $H = aV^bL^c$. For instance, for fully turbulent airflows over flat surfaces, the equation is (Sartori, 2006)

$$H = 5.74V_w^{\,4/5}L^{-1/5} \tag{20}$$

The theory of thermal boundary layers has led to the development of correlations for the Nusselt number *Nu* in terms of the Reynolds number *Re* which depends on the wind speed, and the Prandtl number *Pr*. Through their findings on heat transfer from wind tunnel experiments on naphthalene plates, Sparrow et al. (1979) proposed a global correlation for angles of wind incidence between 90° and 25° from the horizontal with a maximum error of ±10% leading to

$$Nu = 0.86\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3};\ 20{,}000 < \mathrm{Re} < 90{,}000 \tag{21}$$

The aforementioned correlations have been collated in Table 1. Using an iterative procedure, the cell efficiency at the cell operating temperature has been plotted over a range of wind speed for a few of these correlations for quantitative comparison, in Figure 2.

2.2 Explicit method for cell temperature estimation

The cell operating temperature can be arrived at by employing any of several equations expressing the cell temperature as an explicit function of the wind speed and the ambient temperature. Ross (1976) gave the earliest explicit equation for the PV cell operating temperature, in terms of the G and T_c as

$$T_c = T_a + kG \qquad (22)$$

where *k* is known as the Ross coefficient. However, this equation only holds under zero wind conditions.

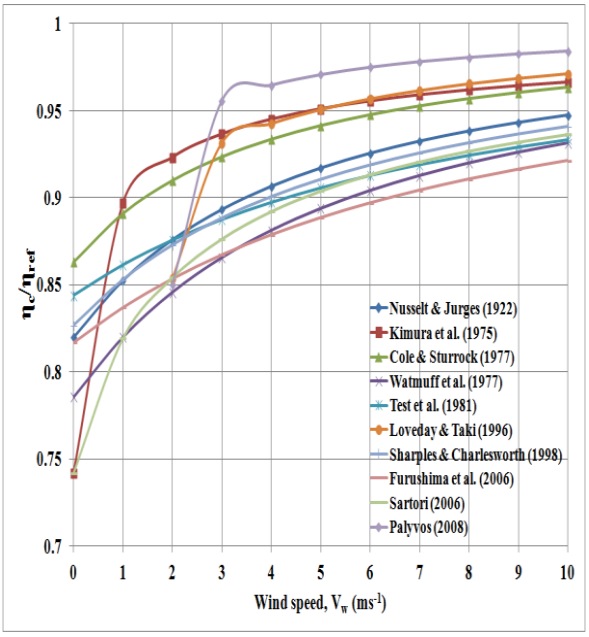

Fig. 2 – Comparison of ηc/ηref as a function of wind speed as predicted by implicit correlations in Table 1 (G = 800 Wm-2, Ta = 25°C, α = 0.9, ηref =15%)

An explicit methodology to estimate the effect of wind speed on the cell temperature T_c involves the use of the Nominal Operating Cell Temperature (NOCT). This quantity is specified by the module manufacturer, and is defined as the mean PV cell junction temperature in an open-rack mounted open-circuited module, tilted normal to the solar noon Sun in the so called Nominal Terrestrial Environment (NTE) conditions: insolation level of 800 Wm^{-2}, ambient temperature of 20°C and an average wind speed of 1ms^{-1} (Stultz and Wen, 1981).

With the NOCT, the Ross approximation can be used to estimate T_c as (Ross, 1980)

$$T_c = T_a + \frac{G}{G_{NOCT}}(T_{NOCT} - T_{a,NOCT}) \qquad (23)$$

This approximation assumes that the overall heat transfer coefficient for the module remains constant. Skoplaki et al. (2008) have derived semi-empirical relations for PV cells, substituting typical values for NOCT and reference variables, and making use of the linear correlations for the wind heat transfer coefficient proposed by Loveday-Taki and Nusselt-Jürges, as Eqs. (24) and (25) respectively:

$$T_c = T_a + \left(\frac{0.32}{8.91 + 2.0V_F}\right)G \qquad (24)$$

$$T_c = T_a + \left(\frac{0.25}{5.70 + 3.8V_w}\right)G \qquad (25)$$

These equations are limited to use for free-standing PV modules, but can be extended to other mounting geometries using the mounting coefficient ω (see Table 2) (Ross, 1976) which is the ratio of the value of the Ross parameter for the mounting geometry in question to the Ross parameter for free-standing modules. T_c is expressed in terms of ω as

$$T_c = T_a + \omega\left(\frac{0.32}{8.91 + 2.0V_F}\right)G \qquad (26)$$

Mounting situation	Ω
Free standing	1.000
Flat roof	1.238
Sloped roof (well cooled)	0.952
Façade integrated	2.667

Table 2 – Values of the mounting coefficient, ω employed in Eq. (26)

The NOCT methodology should be avoided for use in BIPV applications, since the under side of a building-integrated PV module experiences different ambient temperatures and wind conditions than the upper side. Moreover, the NOCT approach assumes that the overall heat transfer coefficient for the module remains constant over time, which is not valid under variable wind conditions. Davis et al. (2001) state

that the NOCT method can under-estimate PV cell operating temperatures by as much as 20°C below the actual temperatures.

In order to circumvent the limitations of the NOCT model, King et al. (2004) propose an empirical relation that incorporates the effect of the wind speed as well as the configuration of the installation as

$$T_c = T_a + Ge^{\{a+bV_w\}} \quad (27)$$

authors	correlations	comments
Ross (1980)	$T_c = T_a + \frac{G}{800}(T_{NOCT} - 20)$	Independent of the wind speed
Risser, Fuentes (1983)	$T_c = 3.12 + 0.025G + 0.899T_a - 1.3V_w$ $T_c = 3.81 + 0.028G + 1.31T_a - 1.65V_w$	18 kW DC output to UPS 104 kW array with MPPT
King (1997)	$T_c = T_a + \frac{G}{800}[0.071V_w^2 - 2.41V_w + 32.96]$	c-Si in open rack mount, $V_w < 18$ ms^{-1}
King et al. (2004)	$T_c = T_a + Ge^{\{a+bV_w\}}$	Wind speed measured at a height of 10 m
Chenni et al. (2007)	$T_c = 0.943T_a + 0.028G - 1.528V_w + 4.3$	T is in °C
Skoplaki et al. (2008)	$T_c = T_a + \omega(\frac{0.25}{5.70 + 3.8V_w})G$	Using the Nusselt - Jürges relation in SI units

Table 3 - Correlations for Tc explicit in the wind speed

It should be noted that in Eq. (27) the index $a + bV_w$ is constant for a given wind speed. This model can estimate the cell temperature under more diverse conditions than the NOCT model.

A few other explicit correlations have been proposed by Risser and Fuentes (1983), King (1997), King et al. (2004) and Chenni et al. (2007) as illustrated in Table 3. The PV cell efficiency at the operating temperature predicted by these correlations are plotted over a range of wind speed in Figure 3.

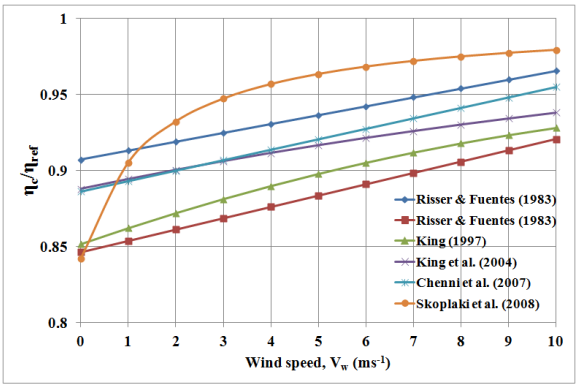

Fig. 3 – Comparison of ηc/ηref as a function of wind speed as predicted by explicit correlations in Table 3. (G = 800 Wm-2, Ta = 25°C, α = 0.9, ηref =15%)

The plots in Figures 2 and 3 indicate that the PV cell efficiency η_c increases by amounts of 5 to 14% of the reference cell efficiency η_{ref} as incident wind speed increases from a standstill 0ms^{-1} to a speed of 10ms^{-1}. This corresponds to an absolute increase in cell efficiency η_c of up to 2% which is significant for silicon-based PV systems. Also, it is seen that power-law relations predict higher cell efficiencies than other implicit correlations and thus may not precisely model the effect of wind on PV cell temperatures.

3. Effect of wind flow direction on photovoltaic performance

From the previous discussion, it is evident that the wind speed has a significant influence on the PV cell efficiency. The results were based on the simple case of parallel wind flow over flat surfaces. It is of interest to appreciate the effect of variation in wind flow direction on PV efficiency, which is closer to real world mounting geometries of BIPV arrays on different roof slopes. Conventionally, PV arrays are tilted to the horizontal at an inclination equal to the geographic latitude of the site and oriented facing due South (in the Northern hemisphere).

Most literature suggests that altering the tilt angles of PV arrays to accommodate for prevalent wind flow direction may not result in significant gains in

cell efficiencies. Through studies conducted on wind flow over inclined plates, Rowley and Eckley (1932) have found that the wind heat transfer coefficient for convection from an inclined plate reduced only slightly as the angle between the plate and the air stream is increased from 15° to 90°. They concluded that this reduction is insignificant and that the results obtained in the case of parallel air flow should be satisfactory for all design considerations.

Sparrow and Tien (1977) carried out tests to determine the average heat transfer coefficients for forced convection due to air flow over inclined plates. They employed the so-called j-factor to estimate heat transfer coefficient where *j* is given as

$$j = Nu / \mathrm{Re} \cdot \mathrm{Pr}^{1/3} \qquad (28)$$

It is seen from their findings that the j-factor is insensitive to the angle of incidence, for the flow Reynolds numbers between 20,000 and 100,000. They report that the j-factor decreases by only 5% as the angle of incidence varies from 90° to 25°, which does not produce a significant change in wind heat transfer coefficient over the range of wind incidence.

The insensitivity of the wind heat transfer coefficient to the wind flow direction was validated by Karava et al. (2012) through two-dimensional steady Reynolds Averaged Navier Stokes (RANS) simulations of forced convective heat transfer from inclined roofs. Their results indicate that the slope of the roof has a less than 5% effect on Nusselt number, for Reynolds numbers up to 6.7×10^5. The array tilt angle hence, has little role to play in enhancing PV cell efficiency.

As reported by Wen (1982) using results of field testing conducted at the Jet Propulsion Laboratory, the value of the coefficient of heat transfer is affected by wind direction. Incidence directions of 90 to 120° correspond to the highest values of wind heat transfer coefficient (see Figure 4) with a gain in the coefficient value of close to 25% with a 90° wind direction at a speed of $2 ms^{-1}$, over a 150° directional flow. This value shows a dramatic 40% increase at a wind speed of $3 ms^{-1}$. This implies that convective heat transfer is maximized when wind impinges on the PV cells in a plane perpendicular to the array.

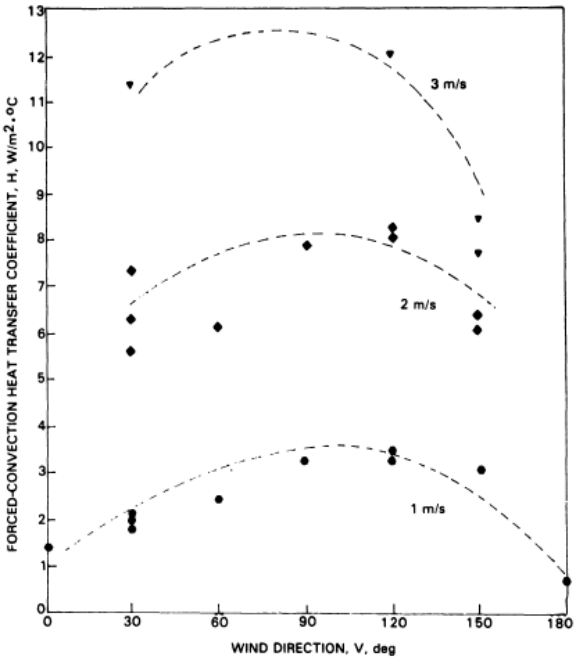

Fig. 4 – Convection heat transfer coefficient versus wind direction (Wen, 1982)

A study by Mondol et al. (2007) reveals that the variation of annual PV efficiency with respect to the orientation is insignificant for lower tilt angles. For tilt angles of 15-30°, the cell efficiency remains fairly constant for inclinations up to 45° east or west of due south. These findings can be used to optimize the orientation of PV panels taking into account the seasonal prevalent wind regimes, to allow for a more normal incidence of wind on the PV installation.

The city of Bangalore lies in a tropical region. In order to study the effect of ambient wind regimes on the performance of building envelope integrated PVs, instantaneous wind regimes were measured on the BIPV roof of the Centre for Sustainable Technologies at the Indian Institute of Science (IISc), Bangalore at five minute intervals throughout 2011. The BIPVs were installed as a joint collaboration between the Bharat Heavy Electricals Limited Electronics Division (BHEL EDN) and the Indian Institute of Science. It was observed that the wind speed striking the BIPV panels is under $1 ms^{-1}$ in all seasons. Also, the wind direction varies between 157.5° (SSE) and 225° (SW) (see Figure 5).

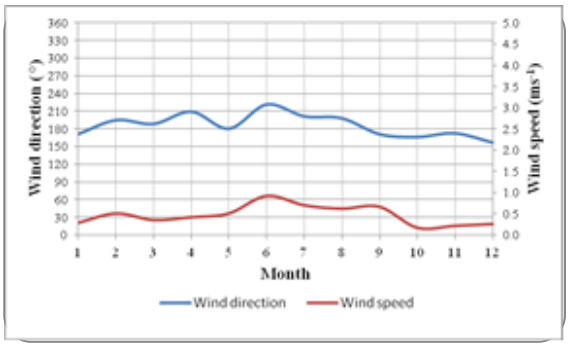

Fig. 5 – Prevalent wind regimes in different months at the IISc campus in Bangalore

Since the BIPV roof is tilted by 15° facing south i.e. 180°, the southerly wind regime on the roof rarely impinges on the surface of the PV panels. It is clear then that altering the orientation of the panels to accommodate a normal impinging of wind is not recommended for the roof as this would result in a significant drop in PV cell efficiency. However, the measured wind regime on the roof may be due to a local channel effect induced by trees around our Centre, as this differs from weather data published by the Indian Meteorological Department (IMD). Here, we demonstrate our results for the two extreme weather conditions experienced in Bangalore i.e. in May (summer) and December (winter). The average ambient temperature in May and December are 27°C and 21.1°C while the global insolations received are 900 Wm^{-2} and 650 Wm^{-2} respectively. The monthly average wind speed is 2.5ms^{-1} in both months.

Considering these values, the BIPV cell temperature is estimated using Chenni et al.'s relation (ref. Table 3). The BIPV cell efficiency for the corresponding cell temperatures is computed based on Eq. (2). The cell operating efficiencies obtained for the summer and winter seasons under three different wind regimes are listed in Table 4. It may be seen that the PV cell efficiency under the free stream wind regime, recorded by the IMD, increases by an absolute 0.26% over the case of zero wind and by an absolute 0.21% to 0.23% over the lower wind speeds measured on our roof in both months. These are significant gains in cell efficiencies achieved by the impingement of natural wind on the PV surfaces. BIPV envelopes are thus seen to operate at their most efficient when local wind regimes impinge the panels without obstruction.

wind regime	may	dec
Zero wind movement	12.98%	13.83%
Wind regimes measured on our BIPV roof	13.03%	13.86%
Meteorological wind records	13.24%	14.09%

Table 4 – BIPV cell efficiencies in two seasons under three different wind regimes (G – May: 900 Wm-2, Dec: 650 Wm-2; Ta – May: 27°C, Dec: 21.1°C)

4. Conclusion

The current status of research in wind convective heat transfer from building envelopes and its effect on building-integrated PV systems indicates that BIPV performance is markedly affected by ambient wind regimes. A graphical representation of PV cell efficiencies predicted by several empirical relations appearing in literature reveals that a wind of 5ms^{-1} striking a PV array can lead to a 1% gain in cell efficiency. This translates to a higher electrical output for a given insolation received at a site. Also, the percentage gain in PV cell efficiency is higher as the wind speed increases from a standstill to 5ms^{-1}, than with increases in the wind speed beyond 5ms^{-1}.

The cell efficiency is largely insensitive to the angle of incidence of wind on the PV surface. However, the orientation of the array, with respect to the prevalent wind direction at the site, has a significant effect on the performance of the array, with maximum cooling effect obtained when wind is incident normally on the PV surface. An installation geometry for normal wind incidence is especially beneficial for BIPVs in the tropics where cell temperatures tend to be higher.

Ambient wind regimes are therefore an important factor that must be considered for the performance of PV surfaces and of BIPV envelopes in particular.

5. Nomenclature

Symbols

a, b, c, n	constants in empirical relations
C	specific heat capacity ($Jkg^{-1}K^{-1}$)
G	solar insolation (Wm^{-2})
h	free convection coefficient ($Wm^{-2}K^{-1}$)
H	wind convection coefficient ($Wm^{-2}K^{-1}$)
k	Ross coefficient
L	surface length in wind direction (m)
NOCT	nominal operating cell temperature
Nu	(°C)
Pr	Nusselt number
$Q_{free\ conv.}$	Prandtl number
$Q_{rad.}$	free convective heat transfer (Wm^{-2})
Q_{wind}	radiative heat transfer (Wm^{-2})
Re	wind convective heat transfer (Wm^{-2})
t	Reynolds number
T	time (s)
T_a	temperature (K)
T_c	ambient temperature (°C)
V, V_w	cell operating temperature (°C)
V_f	wind velocity (ms^{-1})
W_p	free stream velocity (ms^{-1})
α	power output (Wm^{-2})
β_{ref}	solar absorptance
δ	temperature coefficient (K^{-1})
ε	thickness of PV cell (m)
η	emissivity
θ	efficiency
ϱ	tilt angle
σ	density (kgm^{-3})
ω	Stefan-Boltzmann constant ($Wm^{-2}K^{-4}$)
	mounting coefficient

Subscripts

a	ambient
b	back side
c	of the cell
f	front side
F	free stream
NOCT	at NOCT conditions
ref	at reference conditions
sky	of the sky
w	of the wind

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