Power output evaluation of a wind–solar farm considering the influence parameters

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Abstract
Power generation from a hybrid wind–solar farm depends on several parameters such as farm location (solar radiation, wind direction, wind speed), layout of farm, shadowing effect and ambient temperature. Based on the location, the hourly uncertain wind speeds and solar radiation are estimated using Kernel density estimation. An irregular crossed wind farm layout is considered for study as it reduces the effective wake effect, produced due to upstream wind turbines. Further solar panels are also fitted onto the wind farm in order to increase the power output using the same land. In this work, the wake analysis includes single as well as multi-wake model. The output of the solar farm is affected by many parameters like irradiance, wind speed, atmospheric temperature, self-shadowing of consecutive photovoltaic (PV) panels and turbine shadowing on PV panels. The power output from solar is calculated considering the temperature effect on PV cell, effect of wind speed on solar panel, self-shadowing of PV panel and shadowing effect of wind turbine on solar panel.

1 | INTRODUCTION

Wind and solar are the most prudent and sustainable sources of renewable energy to supply an ever-increasing energy demand [1]. These solar and wind energies are occupied in most of the applications of power industry for being the fastest growing power source [2, 3]. A hybrid solar and wind power generating system produces electrical energy same as that of a thermal power plant. As a matter of fact, solar power generation is high during the summer days while the wind power generation is significant during the colder days. The combined solar–wind farm maintains the balance of energy production and keeps it more stable throughout the year as well as saves the land cost [4–7].

The wind farm (WF) consists of few wind turbines, those can be placed in a regular grid-like structure or irregular cross structure. The vacant lands of the wind farm have the potential to generate solar power with PV panel installation [8]. Hybrid wind–solar results in higher power generation utilizing same land [9]. Wind farm developer should leave some space between turbines in a cross manner as per the National Institute of Wind Energy (NIWE) guidelines [10]. In papers [11, 12], some irregular arrangements of WTs have been done and used for the further respective study. The pattern of wind turbine placement decides the quantity of energy loss because of the wake effect on wind speed produced by the upstream turbines.

The wake effect carries both single and multiple wake effect. Single wake considers only wake radius and multi wake considers wake radius as well as shadow area of wind turbines on layout of WF. There are several methods for analysing the effects and calculating the wind speed after considering the wake effect for individual turbines. The upstream wind turbines affect the downstream wind turbines by shadowing the common area [13]. There is a significant solar power loss due to the shadowing effect on solar panels. The shadowing includes both self-shadowing and wind turbine tower shadowing. The losses caused because of the adjacent shadowing are eliminated by keeping some standard gap between the panels [14], but the shadowing caused by turbine towers on solar panels cannot be removed. The tower shadow affects the solar panels up to a larger distance and hence the losses cannot be neglected in case of a small-scale DG application. In paper [15], the analysis
concludes that 7% of the PV farm is completely getting shadowed and the generation is just doubled with the solar farm installation. A study shows that shading conditions cast by wind turbine towers cause about 1% of solar power loss [16].

The output of solar panel highly depends on weather condition such as atmospheric temperature, wind speed and irradiance [17, 18]. Solar modules are designed under Standard Test Conditions (STC) but when they are in domestic use, the parameters like daily radiation, temperature, wind speed and installation cost affect the emerging power output [18, 19]. Methods have been adopted to determine the cell temperature at any ambient condition [20]. Wind effect acts as a cooling constraint to the solar panels and improves the panel efficiency, as increase in panel temperature lowers the power output [21–23]. To estimate the solar cell temperature, there are different methods developed according to the type of materials used in the PV technologies. The onsite data are compared with the system performance and few methods are accepted for their better performance. Polycrystalline solar PV cell uses a different method to determine the cell temperature [24].

In this work, an irregular WF layout is considered with an optimum land with more wind power generation and less wake loss. The location of wind turbine is determined with a modified irregular pattern. This placement is decided after the single as well as multiple wake analysis. Solar panels are fitted to increase power generation and to make the dual use of land. The wind–solar farm has wind speed and solar radiation as the input parameters which are highly uncertain. To generate the wind speed and solar radiation data samples, a non-parametric method as Kernel density estimation is implemented. The wind–solar farm power output depends on many parameters such as weather condition, design of layouts and location. The location depends on the availability of wind speed and solar irradiation. In this work, effect of different weather parameters on wind and solar power output is analysed. Wake effect of upstream turbines on downstream turbines is analysed using wake models. Effect of temperature and wind speed with temperature on solar output is carried out. Also, a combined wind–solar farm layout is designed. The temperature model is implemented in solar power generation for the new farm layout. The wind effect is included with a combined model of temperature effect and solar astronomical effect. The turbine towers also shade the solar panels with different shadow length and shadow angle throughout the day. The number of shadowed panels lowers the effective power obtained from the photovoltaic cells. This work also includes the self-shading of solar panels as well as the wind turbine’s shadowing effect on solar panels. The shadowing loss due to turbine tower is found using graphical modelling which is hardly mentioned in any literature. Power generation from all the wind turbines after wake effects and solar panels after shadowing effect are determined, respectively. The effective power generation of the farm-layout is improved with the wind effect. The system is studied without ambient temperature, with ambient temperature, and with ambient temperature along with wind as a coolant. The combined implementation of all the influence parameters to a wind–solar farm power production is the novelty of the work.

2 | DIFFERENT WIND FARM LAYOUTS

In this work, wind farm with 10 wind turbines is studied for wake analysis. Micro-siting of wind turbines is incorporated in the wind farm in order to mitigate the wake losses. To design a layout of a farm, the vertical distance of the wind farm as well as between two wind turbines is assumed to be constant ($2B_R$). The inter turbine horizontal distance are varied with $B_R$ (WF-I:3$B_R \times 2B_R$), 2$B_R$ (WF-II:6$B_R \times 2B_R$), 3$B_R$ (WF-III:9$B_R \times 2B_R$) and 4$B_R$ (WF-IV:12$B_R \times 2B_R$), respectively. The wake losses are calculated and wind speeds for all the wind turbines are examined for all the farm layouts. A modified wind farm (WF-V:10$B_R \times 2B_R$) with turbine spacing of 3$B_R$ as well as 4$B_R$ is considered in order to further decrease the wake effect with minimum land cost as compared to other layouts [26].

2.1 | Single wake and multi wake model

The wake effect causes the efficiency of downstream wind turbines to be significantly decreased because of the upstream wind turbine placed ahead of it. To analyse the model, a simple Jensen Wake model [12] is used to find the wake speed of all the turbines. In a wind farm, one turbine is not only affected by the wind wake of the turbine ahead of it but also gets affected by the crosswind turbines. This combined effect is known as multiple wake effect [11–13]. The crosswind turbine effects consider partially shadowed region between turbines. Using the formulae [26], in any irregular crossed wind farm, wind speed for any WT for any horizontal distance can be determined. The wake effect has no effect is assumed to be negligible for a distance of eight times the diameter of the wind turbine generator [12, 26]. The speeds with wind wakes are determined for all different wind farm layouts.

3 | PV PANEL INSTALLATION

Solar panels are installed on the same land for more power generation with the same land cost. The uncertainties in ambient temperature, self-shadowing effect of solar panels and wind turbine shadowing effect on the solar panel are considered on solar power output. In this section, the effects of all these above parameters are described.

3.1 | Effect of ambient temperature and wind speed

Temperature of PV module affects the solar power generation significantly. When the wind flow is not introduced in the panel temperature calculation, the widely used formula [20] to determine the temperature of the module is given by Equation (1):

$$T_{CL} = T_{amb} + \left( \frac{T_{CLNOCT} - T_{ambNOCT}}{I_{NOCT}} \right) \times I_p.$$

(1)
Here, the values of $T_{\text{CLNOCT}}$, $T_{\text{ambNOCT}}$, $I_{\text{NOCT}}$ are considered to be 44°C, 20°C and 800 W/m², respectively [34]. Apart from this, there are different models to determine the temperature of PV cell with the speed of wind. It carries many meteorological parameters like incoming global irradiance, atmospheric temperature, wind speed and its direction. Mattei methods are mostly used for Silicon Polycrystalline technologies considering the numerical weather data [25]. Hence, the cell temperature can be determined using the formula given in Equation (2) considering wind speed as one of the input parameters [25].

$$T_{\text{CL}} = \frac{V_{\text{PV}}(S) T_{\text{amb}} + I \{ \chi \times \alpha - \psi_{\text{STC}} (1 - \eta_{\text{STC}} \times T_{\text{STC}}) \}}{V_{\text{PV}}(S) + (\eta_{\text{STC}} \times \psi_{\text{STC}} \times I)}.$$  \hspace{1cm} (2)

Here, the $\chi \alpha$ value is considered as 0.81. The parameterisation used in this work [25], is defined in Equation (3).

$$V_{\text{PV}}(S) = 24.1 + 2.9 \times S_r,$$  \hspace{1cm} (3)

$$\frac{V_{\text{PV}}(S)}{V_{\text{PVref}}} = \left( \frac{Z_{\text{PV}}}{Z_{\text{PVref}}} \right)^q,$$  \hspace{1cm} (4)

where,

$$q = \frac{0.37 - 0.0881 \times \ln(V_{\text{PVref}})}{1 - 0.0881 \times \ln\left(\frac{Z_{\text{PVref}}}{10}\right)}.$$  \hspace{1cm} (5)

Wind speed at a certain height (solar mounting height and turbine tower height) is found by using Equation (4) [35]. In this work, $Z_{\text{PVref}}$ and $V_{\text{PVref}}$ are the turbine tower height and wind speed at reference height of 10 m [28]. The hourly wind speeds are obtained from any meteorological website (visibility is 10 m) [28].

$$P_{\text{PWW}} = T_{\text{PV}} \times F_{\text{PV}} \times \left( \frac{I}{I_{\text{STC}}} \right) \times \gamma,$$  \hspace{1cm} (6)

where,

$$\gamma = 1 + \eta_{\text{STC}} \times \left( T_{\text{CLSTC}} - T_{\text{CLNOCT}} \right).$$  \hspace{1cm} (7)

The PV array power [34] can be found using Equations (6) and (7). Here, $T_{\text{CLSTC}}$, $F_{\text{PV}}$, and $I_{\text{STC}}$ values are taken as 25 °C and 0.8 and 1000 W/m², respectively [25, 33].

### 3.2 Shadowing of solar panels and turbine tower

This section gives an idea regarding the power losses due to the shadow effect of solar panels and wind turbine tower on power generation by solar panels fitted into the wind farm. As the wind turbine tower is having a similar look like a vertical pole, the shadow magnitude along with shadow angle for different solar hours of the day is mentioned in this section. The calculations for self-shadowing and tower shadowing are mentioned individually to get a complete idea.

To avoid the self-shadowing of consecutive panels, inter-row spacing is determined and is given in Figure 1(a). The panel’s uppermost edge and lowermost edge are calculated to be 3 and 2.168 m, respectively [14]. Now the inter spacing between the consecutive panel rows (dl) is found by using Equations (14)–(17) [14]:

$$dl = L_a \times \cos(\alpha)$$  \hspace{1cm} (8)

$$L_a = \frac{3}{\tan(\text{ang})}$$  \hspace{1cm} (9)

$$\sin(\text{ang}) = \cos(L_a) \times \cos(del) \times \cos(H) + \sin(L_a) \times \sin(del)$$  \hspace{1cm} (10)

$$a = \cos(del) \times \sin(wr) \times \cos(wr).$$  \hspace{1cm} (11)

For a 30-degree angle panel elevation (ang = 30°), the respective length is 1.44 m [27, 31]. After self-shading effect, the spacing can be of 4.14 m. The overall layout is given in Figure 1(b). Here, C1 to C44 represents the column number of the solar panels and R1 to R50 represents the number of solar panel rows. The effective inter spacing distance is found to be 5.581 m or nearly 5.6 m. With the farm layout of area 50 m × 250 m (XBR × YBQ), the number of solar lines on length side will be 44. Similarly, the number of solar panel lines on breadth side is calculated to be 50 as the small side of the solar panel is 0.998 m, which is nearly equal to 1 m. The total number of panels can

![Free Standing Consecutive PV panels](image_url)
be fit onto the wind farm is 2200 after the self-shadowing clear-

ances.

### 3.2.2 Shadow component of a vertical pole

The wind turbine is having a pole height of \( H \) as shown in Figure 2. The sun position can be defined with an altitude, solar hour angle and azimuth, and the relations among these are given in Equation (12). The shadow length and corresponding angle for the pole can be evaluated using Equations (12)–(21):

\[
\sin(a) = \sin(L_a) \times \sin(\delta l) + \cos(L_a) \times \cos(\delta l) \times \cos(w) \tag{12}
\]

The east-west and north-south shadow components are given by Equations (13) and (14), respectively [15, 36].

\[
F_x = H \times \frac{\cos(\delta l) \times \sin(w)}{\sin(L_a) \times \sin(\delta l) + \cos(L_a) \times \cos(\delta l) \times \cos(w)} \tag{13}
\]

\[
F_y = H \times \frac{\cos(\delta l) \times \sin(L_a) \times \cos(w) - \cos(L_a) \times \sin(\delta l)}{\sin(L_a) \times \sin(\delta l) + \cos(L_a) \times \cos(\delta l) \times \cos(w)} \tag{14}
\]

\[
\tan(S_s) = \frac{F_y}{F_x}
\]

\[
S_s = \tan^{-1} \left( \frac{1}{\sqrt{\frac{\cos^2(L_a)}{\tan^2(\delta l)} - \sin^2(L_a)}} \right) \tag{16}
\]

Equations (13) and (14) give the pole shadow components as a function of time and the location. Equation (15) gives the shadow angle for all the solar hours and since the shadow angle has some limits during sunrise and sunset, the modified angle can be found using Equation (16) [36, 37].

### 3.2.3 Shadowing of a turbine tower

A wind turbine’s tower resembles a vertical pole with some width that shadows the ground in a day as shown in Figure 3. Assuming the turbine rotor radius to be \( b_0 \), the height of the turbine tower can be between 1.5\( b_0 \) and 2.5\( b_0 \) and the tower plus blade height can be between 80 and 150 m and above depending on specific turbine power. A WF with vertical spacing of 2\( B_R \) in the N-S direction and horizontal spacing of 10\( B_R \) in the E-W direction is shown in Figure 4. The height and average width of turbine tower are considered to be 2.5\( B_R \) and \( B_R/16 \), respectively [36].

The wind turbine tower shadow falls on the solar panel resulting in relatively lower solar power output. Due to the motion of the sun throughout the day, it produces different shadow angles as well as different shadow length. From the Figure 4, it can
be observed that the shadow of the wind tower is falling over the solar panels and the number of the panels affected with the shadow is determined through graphical approach. The wind turbine shadow analysis for WT-6 on solar panels is given in Figure 4.

The affected solar panels due to the tower shadow can be shown in the Figure 5. Similarly, the shadowed panels can be found for all other wind turbines. These values are given in Table 1.

4 | ANALYSIS OF ENERGY PRODUCTION

4.1 | Site description

The site for the wind-solar farm installation is in Surat, Gujarat, India (21.1702° N, 72.8311° E). From the historical wind speed data, the wind rose is obtained using Hydrognomon software [25]. From the wind rose diagram, the turbine facing is decided to be in West direction and hence the best direction to face solar panels is East.

4.2 | Kernel density estimation and Monte Carlo simulation

Due to the uncertainty in meteorological parameter, the daily solar irradiance and wind speed values are obtained with Kernel density estimation [26, 27, 29]. The Probability Density Function (PDF) for irradiance is generated considering the 20 years of renewable energy data [30]. Here, the wind speeds are generated considering the wind speed data during 2010 to 2017 from any meteorological site [28]. For Kernel estimation, a Kernel function and a smoothing parameter are established. Let \( R_{i1}, \ldots, R_{in} \) be the number of samples of a random variable \( R \) having PDF of \( PDF_{H} (R_a) \). Then, kernel density estimator is given in Equation (17) [26, 27].

\[
PDF_{H} (R_a) = \frac{1}{\rho \rho'} \sum_{i = 1}^{J} KDE \left( \frac{R_a - R_{ai}}{\rho} \right) \tag{17}
\]

The Cumulative Distribution Function (CDF) enables generating random irradiance samples and wind speed samples that are required for MCS [26, 27].

4.3 | Solar irradiance astronomical model

Astronomical modelling gives the effective solar radiation from global solar radiation. It considers many factors like latitude, longitude, year, day, time, solar declination angle and panel tilt angle [1, 29]. In this work, \( d' \) is assumed to be 144th day of the year. The effective solar radiation calculation can be done using Equation (18) [29].

\[
I_i (wr, d') = I_{sun} (wr, d') \times \cos \theta (wr, d') \tag{18}
\]
TABLE 2 Wind turbine specification [32]

| Rated Power | 100 kW |
|-------------|--------|
| Rated wind speed | 10 m/s |
| Cut-in wind speed | 2.7 m/s |
| Cut-out wind speed | 25 m/s |
| Rotor diameter | 25 m |
| Hub height | 45.7 m |
| Operational speed | 50 RPM |

TABLE 3 Solar panel specification [33]

| Rated power | 250 W |
|-------------|--------|
| Open circuit voltage-VOC | 38 V |
| Short circuit current-ISC | 9.28 A |
| Maximum power point efficiency at STC (n_{mppt}) | 16.4% |
| Solar cell | Multicrystalline (156.75 × 156.75 mm [6 inches]) |
| Cell orientation | 60 cells (6 × 10) |
| Module dimensions | 1658 × 992 × 6 mm (65.3 × 39.1 × 0.236 inches) |

A threshold value of irradiance is chosen for the higher state (state-1) or lower state (state-0) identification. This value can be determined as, \( I_{th} = I_{max}/50 \) [27, 29]. Lower irradiance states are neglected as they produce very less amount of power.

5 | RESULT ANALYSIS AND DISCUSSION

This paper proposed a modified wind–solar farm layout to find out power output considering wake effect on wind turbine and self-shadow effect, ambient temperature and wind speed effect on solar power output. This section deals with the hourly power generation from solar panel after considering all the losses, wind turbine power generation and total power generation from the farm. Considering the wake losses, the power generation for all the wind turbines are calculated on hourly basis. Similarly, after considering the shadowing loss, the power generated by the solar panels is taken in order to obtain the total power from the dual purposed wind and solar farm.

The specifications for both the wind turbine and solar panel are given in Tables 2 and 3, respectively. The specifications are chosen in such a way that it can be connected to a distribution system as Distributed Generation (DG). The power generation is determined in terms of watt in order to get the exact figure of generation and loss. The calculation process for the entire wind-solar farm power generation is given in Figure 6.

5.1 | Shadowing power loss by wind turbines

Power calculation with turbine shadowing effect is obtained using graphical approach of vertical pole shadowing concept. The wind-solar farm is scaled with solar panel rows and wind turbine positions using an extra-long graph sheet (25 m × 5 m). The vertical wind turbine shadow represents length as well as angle of shadow with the motion of the sun. The number of solar panels getting affected from the turbine shadowing is determined and one and half of the solar panel is found to be covered by turbine shadow. The graphical modelling for WT-6 at 12.00 PM is shown in Figure 7. From Figure 7, it can be observed that seven solar panels on column-1(C1) got shadowed by the turbine. Similarly, the number of solar panels shaded can be found for other hours of the day and the shadowing for rest of the turbines is determined using this approach. One unit on X-axis and Y-axis scales are considered to be 1 m for simplified calculation.

The unshaded portion of the solar panel will generate the solar power depending upon the radiation value at that time. The solar irradiance values calculated from Monte Carlo simulation have undergone solar astronomical model and corresponding power losses obtained due to the shading effect is given in Table 4.

This Table 4 gives the hourly power losses caused due to the shadow effect of individual wind turbines. It can be observed...
that the total power loss due to shadowing of turbine tower in a day is 78.9 kW.

5.2 Solar power generation

The solar power generation with temperature effect and wind effect is given in Table 4. Table 4 gives the information for ambient temperature, solar PV cell temperature and wind speed at 45.7 m height and 3 m height. Solar power per panel for ideal case (no temperature involved), with temperature effect and with temperature as well as wind effect is calculated as given in Table 5.

5.3 Wind–solar power generation

The gross solar and wind power from the wind farm is calculated and given in Table 6. The total wind generated power for all the turbines are mentioned in Table 6 for modified
TABLE 5  Effect of temperature and wind on solar power generation of WF-V layout

| Time       | Ambient temp ($T_{amb}$ in °C) | Wind speed at 45.7 m height (m/s) | PV cell temp ($T_{CL}$) at 3 m height (°C) | Generated solar power (W) per panel |
|------------|-------------------------------|-----------------------------------|------------------------------------------|----------------------------------|
|            |                               | Without wind                      | With wind                                | Ideal case                       |
|            |                               |                                   | With temperature effect                 | With temperature and wind effect |
| 7:00 AM    | 30                            | 4.54                              | 32.31                                    | 31.35                            | 15.4                             | 14.9384                         | 14.999 |
| 8:00 AM    | 32                            | 3.88                              | 39.17                                    | 36.39                            | 47.8                             | 45.023                          | 45.5663 |
| 9:00 AM    | 33                            | 6.45                              | 46.47                                    | 41.11                            | 89.8                             | 81.8952                         | 83.8666 |
| 10:00 AM   | 34                            | 7.07                              | 53.05                                    | 43.75                            | 127                             | 112.3944                        | 117.2336 |
| 11:00 AM   | 35                            | 8.75                              | 57.65                                    | 45.65                            | 151                             | 130.7864                        | 138.2104 |
| 12:00 PM   | 37                            | 7.68                              | 60.19                                    | 48.35                            | 154.6                           | 132.2945                        | 139.6679 |
| 1:00 PM    | 38                            | 6.70                              | 60.5                                     | 49.82                            | 150                             | 128.1675                        | 134.7303 |
| 2:00 PM    | 39                            | 5.57                              | 60.87                                    | 51.27                            | 145.8                           | 124.3576                        | 130.0953 |
| 3:00 PM    | 40                            | 6.08                              | 58.09                                    | 49.84                            | 120.6                           | 104.2383                        | 108.3147 |
| 4:00 PM    | 41                            | 7.43                              | 53.3                                     | 47.19                            | 82                              | 72.4855                         | 74.5365 |
| 5:00 PM    | 41                            | 6.70                              | 47.36                                    | 44.32                            | 42.4                            | 38.5129                         | 39.0406 |
| 6:00 PM    | 40                            | 5.32                              | 41.95                                    | 41.09                            | 13                              | 12.0966                         | 12.1419 |

Wind farm WF-V layout. The hourly power output from wind farm is calculated incorporating wake model and is given in Table 6.

The solar power during the daytime is generated with ideal case, with temperature effect and with both temperature and wind effect. The cumulative power for the solar hours after the solar panels fitted onto the wind farm has been increased.

The effect of wind and ambient temperature on total wind and solar power output can be observed from Table 7. The overall power gets improved with the wind effect. The percentage increase in total power generation after the temperature effect and after wind effect is mentioned in Table 7 during the solar hours.

6  CONCLUSION

In this work, hybrid wind-solar farm layout is planned considering wake effect on wind speed, temperature effect on solar power output and shadowing effect of solar panel as well as wind turbine on solar power output. Using wake effect, temperature effect and shadowing effect, it is seen from the results that, the total hourly power generation from the wind–solar farm has been increased significantly. To reduce the wake losses, the wind farm is redesigned with an irregular modified turbine placement. This forms a new wind farm with more output power having same land cost. Solar panels are placed in the wind farm considering the self-shadowing effect forming toward a wind-solar farm. The panels are affected by the shadowing of wind turbine tower. The power losses for individual turbines are calculated for the shadowing effect on solar panel on an hourly basis. The ambient temperature effect on the solar PV cell lowers the solar power generation. Since the solar panels are placed in the wind direction, it results in cooling effect on solar panel. This further increases the power output from PV panel by decreasing the power losses caused by temperature effect. From the results it is noted that with temperature effect the power generation is decreased to 3.03% and with temperature effect and wind effect, the power generation is decreased to 2.15%. Moreover, the overall power generation of the system is improved to 0.91% due to the wind effect. Further, this work can be extended with additional effects of wind shear, turbine shadow and wind shadow implementation. The wind–solar farm can be investigated with all these influence parameters with consideration of individual effects, and the power generation performance can be examined with these effects.

Nomenclature

- $\theta$  Incidence angle
- $a$  Solar altitude angle
- $\text{Ang}$  Solar panel elevation
- $b_0$  Turbine rotor radius
- $R_R$  Rotor diameter
- $d'$  Day of the year
- $\text{del}$  Solar declination angle
- $dl$  Horizontal spacing b/w consecutive solar panels
- $F_{PV}$  Derating factor of solar panel
- $F_x$  East–West shadow component
- $F_y$  North–South shadow component
- $H$  Hub height of wind turbine
- $I_e$  Effective solar irradiance
- $I_{STC}$  Solar irradiance at STC
## TABLE 6 Hourly solar and wind power generation

| Time    | Generated wind power (W) | Generated solar power (W) | Turbine shadowing loss (W) | Generated solar power (W) |
|---------|--------------------------|---------------------------|---------------------------|----------------------------|
|         |                          | Ideal case                | With temperature and without wind effect | With temperature and with wind effect |
| 1:00 AM | 480347                   | 0                         | 0                         | 0                          |
| 2:00 AM | 371506                   | 0                         | 0                         | 0                          |
| 3:00 AM | 175832                   | 0                         | 0                         | 0                          |
| 4:00 AM | 140254                   | 0                         | 0                         | 0                          |
| 5:00 AM | 83263.9                  | 0                         | 0                         | 0                          |
| 6:00 AM | 262448                   | 0                         | 0                         | 0                          |
| 7:00 AM | 109486                   | 33880                     | 289                       | 33591                      |
| 8:00 AM | 68170.1                  | 105160                    | 770.56                    | 104389.44                  |
| 9:00 AM | 313981                   | 197560                    | 976.72                    | 196583.28                  |
| 10:00 AM| 412855                   | 279400                    | 833.35                    | 278566.65                  |
| 11:00 AM| 784101                   | 332200                    | 871.8                     | 331328.2                   |
| 12:00 PM| 528872                   | 340120                    | 376.84                    | 339743.16                  |
| 1:00 PM | 351545                   | 330000                    | 646.99                    | 329353.01                  |
| 2:00 PM | 202354                   | 227670                    | 683.5                     | 26551.26                   |
| 3:00 PM | 351545                   | 92820                     | 628.05                    | 84100.33                   |
| 4:00 PM | 262448                   | 28600                     | 214.72                    | 250852.28                  |
| 5:00 PM | 175832                   | 28600                     | 214.72                    | 250852.28                  |
| 6:00 PM | 54891.9                  | 0                         | 0                         | 0                          |
| 7:00 PM | 140254                   | 0                         | 0                         | 0                          |
| 8:00 PM | 246519                   | 0                         | 0                         | 0                          |
| 9:00 PM | 246519                   | 0                         | 0                         | 0                          |
| 10:00 PM| 412855                   | 0                         | 0                         | 0                          |
| 11:00 PM| 607135                   | 0                         | 0                         | 0                          |
| 12:00 AM| 784101                   | 0                         | 0                         | 0                          |
| Total   | 7800743                  | 2506680                   | 7890.79                   | 249789.2                   |

### Symbols

- \( I_{\text{NOCT}} \): Solar irradiance at NOCT
- \( I_{\text{max}} \): Maximum irradiance value
- \( I_{\text{sun}} \): Global solar irradiance
- \( I_{\text{th}} \): Threshold irradiance value
- \( \text{KDE} \): Kernel density estimation
- \( L_s \): Length of the shadow
- \( \text{MCS} \): Monte Carlo simulation
- \( \text{NOCT} \): Nominal operating cell temperature
- \( \text{PDF}_H \): Probability density function
- \( P_{\text{PV,W}} \): Power generated from PV module
- \( R_n \): Random number
- \( S_s \): Wind speed
- \( S_{\theta} \): Shadow angle
- \( \text{STC} \): Standard test condition (STC)
- \( T_{\text{amb}} \): Ambient temperature
- \( T_{\text{ambNOCT}} \): Ambient temperature at NOCT
- \( T_{\text{CL}} \): Cell temperature
- \( T_{\text{CLNOCT}} \): Cell temperature at NOCT
- \( T_{\text{CL,W}} \): Cell temperature with wind
- \( T_{\text{CLWSTC}} \): Cell temperature with wind at STC
- \( T_{\text{STC}} \): Temperature at STC
- \( V_{\text{PV}} \): Heat exchange coefficient
- \( V_{\text{PV,ref}} \): Wind speed at reference height
- \( \text{WF} \): Wind farm
- \( \text{wr} \): Hour of the day
- \( \text{WT} \): Wind turbine
- \( Z_{\text{PV}} \): Unknown height
- \( A \): Absorption coefficient
- \( \eta_{\text{STC}} \): Temperature coefficient at STC
- \( \chi \): Transmittance of system
- \( \psi_{\text{STC}} \): Panel efficiency at STC
### TABLE 7

| Time  | Total power generation (W) | Total solar and wind power generation (W) | Percentage decrease in power generation | With temperature and with wind effect (W) | Total solar and wind power generation (W) | Percentage decrease in power generation | Overall percentage increase in total generated power due to wind |
|-------|---------------------------|------------------------------------------|----------------------------------------|------------------------------------------|-------------------------------------------|----------------------------------------|---------------------------------------------------------------|
| 7:00 AM | 143077                    | 142061.5                                 | 0.709772                               | 142194.7                                 | 0.616633                                   | 0.093804                               |
| 8:00 AM | 172559.54                | 166450.1                                 | 3.540459                               | 167645.3                                 | 2.847829                                   | 0.718053                               |
| 9:00 AM | 510564.28               | 493173.7                                 | 3.406153                               | 497510.9                                 | 2.556661                                   | 0.879447                               |
| 10:00 AM | 691421.65               | 659289.4                                 | 4.64728                                 | 669356.6                                 | 3.107525                                   | 1.614799                               |
| 11:00 AM | 1115429.2              | 107095.9                                 | 3.986797                               | 1087292                                  | 2.522536                                   | 1.525063                               |
| 12:00 PM | 868615.16              | 819543.1                                 | 5.649464                               | 835764.7                                 | 3.78194                                   | 1.979347                               |
| 1:00 PM  | 680898.01               | 632866.5                                 | 7.05414                                | 647304.6                                 | 4.93369                                    | 2.281382                               |
| 2:00 PM  | 522430.5               | 475257.2                                 | 9.029584                               | 487880.3                                 | 6.613358                                   | 2.650657                               |
| 3:00 PM  | 526999.26              | 491003.6                                 | 6.830133                               | 499971.6                                 | 5.128603                                   | 1.826463                               |
| 4:00 PM  | 659916.48              | 638984.6                                 | 3.171901                               | 643496.7                                 | 2.488163                                   | 0.706136                               |
| 5:00 PM  | 444196.95              | 435645.3                                 | 2.656057                               | 436806.2                                 | 1.663854                                   | 0.266462                               |
| 6:00 PM  | 204217.28              | 202229.8                                 | 0.973218                               | 202329.5                                 | 0.924408                                   | 0.049292                               |

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