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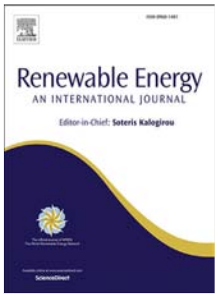

Design study on the parameters influencing the performance of floating solar PV

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Graphical Abstract

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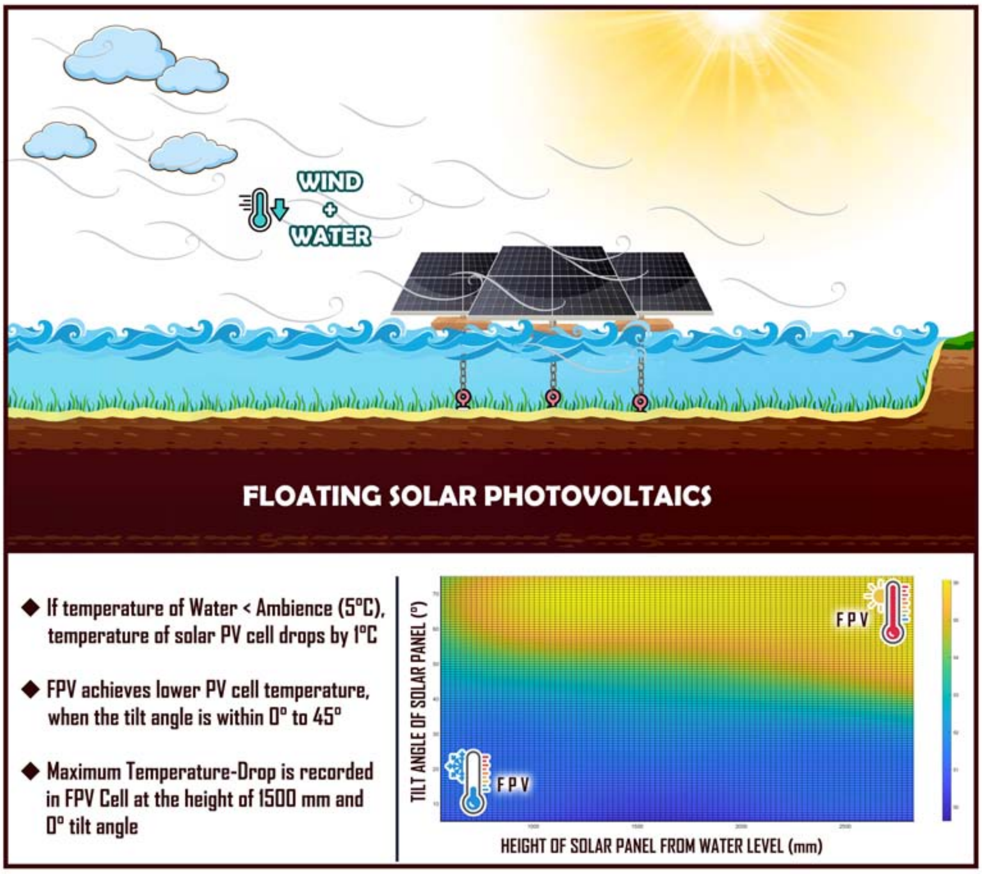

Highlights

Design Study on the Parameters Influencing the Performance of Floating Solar PV

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- FPV provides maximum cooling effect for 0° tilt angle at a height of 1500 mm.
- Water should be 5°C lower than wind to get 1°C reduction in PV cell temperature.
- FPV is highly suitable for a tilt angle less than 45° irrespective of height.

Design Study on the Parameters Influencing the Performance of Floating Solar PV

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Abstract

Floating solar PV, or FPV, refers to the installation of solar PV panels on floating platforms over water bodies for power generation. This technology offers higher efficiency and superior power generation by minimising the solar PV cell temperature. The parameters affecting the performance of floating solar PV (FPV) and its design differ from that of the conventional solar PV system. To ensure successful implementation of this technology, a thorough understanding of its design configuration and proper installation in different geographical locations is crucial. The current study aims at evaluating the impact of wind, ambient temperature, water temperature, height and tilt angle in a FPV. The effect of these parameters on the temperature drop in a FPV cell due to the combination of wind and water is compared with a free-standing photovoltaic module allies with the NOCT condition (NOCT PV) where the source of cooling is only wind. With respect to it, CFD simulation was carried for a 2D solar PV module using finite volume approach. Multiple simulations were performed by changing different combinations of parameters to optimize the design of FPV. It is found that, a minimum of 5°C temperature difference between wind and water is required for heat transfer enhancement in FPV. The lower height and tilt angle favors FPV in reducing

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the temperature of solar PV cell. At higher height and tilt angle, the heat transfer only by wind in the NOCT PV is better than that in the FPV. For a tilt angle less than 45°, irrespective of height, FPV performs well. For a tilt angle greater than 55°, the solar PV cell temperature of NOCT PV is lower than that of FPV. This variation is observed to be the impact of high wind velocity in NOCT PV compared to FPV. Further, the simulation result revealed that FPV provides maximum cooling to the PV cell at 0° tilt with a height of 1500 mm.

Keywords: Floating solar PV, Parametric study, Thermal Analysis, CFD simulation

1. Introduction

The increase in the usage of solar energy for power generation is one of the important reasons behind global decarbonization in recent years [1]. Considering it, the effort to improve the efficiency of conventional solar photovoltaic systems led to the invention of floating solar photovoltaics (FPV), which offers an improvement in performance. FPV is estimated to promote eight Sustainable Development Goals (SDG) of the United Nations (UN) in straightforward [2]. The apex of FPV is that it has improved efficiency, saves land and minimizes the water evaporation [3]. The heat associated with solar radiation decreases the power production of the solar panel [4]. On average, the power production and the efficiency of a solar PV decreases by 0.4% to 0.5% for a degree Celsius increase in the temperature [5]. In a conventional solar PV panel, the temperature is reduced by the influence of natural convective heat transfer supplied by the wind [6]. Unlike these systems, the water at the bottom in a FPV provides additional cooling effect to the solar panel along with the flow of wind [7]. This is reflected in the decrease in cell temperature between 2% to 11% that contribute to 8% to 35.9% higher energy yield compared to land solar PV [8]. The design, structure and environmental parameters for the specific geographical location influence the performance of FPV [9]. Direct solar radiation is high at higher altitudes and solar panels at these heights increase the power output [10]. On the contrary, the pole height of the solar panel in land solar PV has no significant impact and the power gain is infinitesimal [11, 12]. Moreover, the importance of solar PV tilt angle is to absorb maximum solar radiation [13]. In the case of FPV, Nisar et al. [8] found that the lower height and tilt angle achieve higher cooling as the solar panel is close to the vicinity of the water body. Thus, the parameters affecting the performance of FPV and its design differs from the conventional solar PV systems. This creates a research gap to understand the impact of these parameters on FPV technology.

In order to save research's cost, time, and materials, the computational fluid dynamic (CFD) approach [14] is preferred in research and development. The CFD investigation found that the integration of thermosiphon tube for water circulation in a FPV increased the heat transfer rate of the PV panel [15]. CFD investigation on the structural analysis of FPV found that the impact of water current force is more effective than the wind [16]. Similar CFD study stated that the floating structure decreased the wind load on the FPV [17]. Another research found that solar radiation and ambient temperature have no significant impact on the thermal transmittance of the FPV panel [18]. As a progress, this novel work is set with an objective to perform a CFD analysis of FPV to understand the impact of height, tilt angle, wind, ambient temperature and water temperature in order to find the optimal parameters. The findings are also compared with a free standing solar PV panel in air subject to the condition of nominal operating cell temperature (NOCT PV). This benchmark system which is an independent solar panel in the air under NOCT condition or the 'NOCT PV' used in this study has the same cooling effect as in the conventional solar PVs.

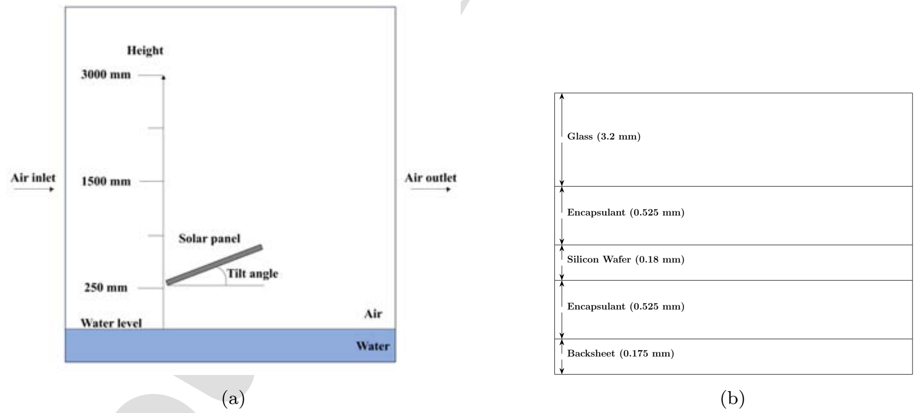


Figure 1: Domain design of the FPV for the present CFD simulation (a) Computational domain, (b) Solar PV cell.

2. Materials and Methodology

The CFD analysis was carried out by Ansys Fluent 2020 R2 software. The approach for the parametric study of FPV in this article follows the domain creation, modeling and boundary conditions as defined by Lindholm et al. [18] in their study. To reduce the efforts of CFD simulation, the author considered the three-dimensional FPV model to be in symmetric condition. In the present research work, a two-dimensional CFD model of the FPV fits the purpose of this parametric study.

2.1. Numerical Modeling

The solver is pressure based and the fluid is observed to be a steady state flow with standard k-epsilon viscous model. In order to calculate the heat transfer, energy equation and the discrete ordinates radiation model were turned on. The computational domain consists of a single solar PV panel initially tilted at an angle of 15° at a height of 250 mm from the base. For the FPV, a 200 mm depth water body was considered at the base. The 2D domain representing the change in height and tilt angle was created as in Figure 1a. Each single layer of the solar PV cell with its thickness was designed as in the Figure 1b. The geometrical parameters of these domains and the solar PV cells are listed in Table 1. The material properties of the air, water and solar PV cell are defined in the CFD solver as in Table 2 [18, 19]. The following Eq. (1) to Eq. (6) are used by CFD solver to perform the calculation [20].

Table 1: Geometrical parameters of the 2D CFD model for NOCT PV and FPV.

Characteristic	**Magnitude (mm)**
Air body height	2000
Air body width	4000
Air body height (FPV)	4000
Water body depth (FPV)	200
Solar panel thickness	4.6
Solar panel length	992

Table 2: Material properties.

Material	Density (kg/m^3)	Specific heat C$_p$ (J/kgK)	Thermal conductivity (W/mK)	Viscosity (kg/ms)
Air	1.225	1006.43	0.0242	1.79 x 10^{-5}
Water	998.2	4182.00	0.6000	1.01 x 10^{-3}
Glass	3000	500	2.00	-
Encapsulant	960	2090	0.35	-
Silicon wafer	2330	677	148	-
Backsheet	1200	1250	0.20	-

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0, \tag{1}$$

Momentum equation:

$$\frac{\partial(\rho V)}{\partial t} + \nabla \cdot (\rho V \cdot V) = -\nabla P + \nabla \cdot \tau + \rho \mathbf{g} + F, \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial t}\left(\rho\left(e + \frac{\mathbf{v}^2}{2}\right)\right) + \nabla \cdot \left(\rho \mathbf{v}\left(h + \frac{\mathbf{v}^2}{2}\right)\right) = \nabla \cdot (k_{\text{eff}} \nabla T) - \sum_j \left(h_j J_j + \tau_{eff} \mathbf{v}\right) + S_h, \tag{3}$$

Discrete Ordinates (DO) radiation equation:

$$\nabla \cdot (I(\mathbf{r}, \mathbf{s})\mathbf{s}) + (a + \sigma_s) I(\mathbf{r}, \mathbf{s}) = a \cdot n^2 \cdot \frac{\sigma \cdot T^4}{\pi} + \sigma_s \cdot \frac{1}{4\pi} \int_0^{4\pi} I(\mathbf{r}, \mathbf{s}') \Phi(\mathbf{s} \cdot \mathbf{s}')\, d\Omega' \ , \tag{4}$$

Turbulent kinetic energy (k):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho \varepsilon - Y_m + S_k \ , \tag{5}$$

Turbulence dissipation (ϵ):

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \ . \tag{6}$$

2.2. Boundary Condition

As in common for both FPV and NOCT PV, the boundary condition takes the consideration of the inlet of wind flow velocity (m/s) and its temperature (°C) variation. To explore the cooling effect, a given heat flux (W/m^2) represents the part of the fixed solar irradiance for the silicon wafer layer as shown in Figure 1b. The pressure and velocity was coupled with second order discretization for better results as the mesh was unstructured. As contrast, FPV obtains varied temperature of the water body at the bottom for this parametric study. Considering the far distance of the sky and the temperature gradient is null for the height of 3000 mm, the sky surface at the top was neglected [21]. The absorption coefficient (1/m) of the glass and encapsulant are 0.02 and 0.03 respectively. In addition, the scattering coefficient (1/m) and the refractive index of the glass were set to 0.01 and

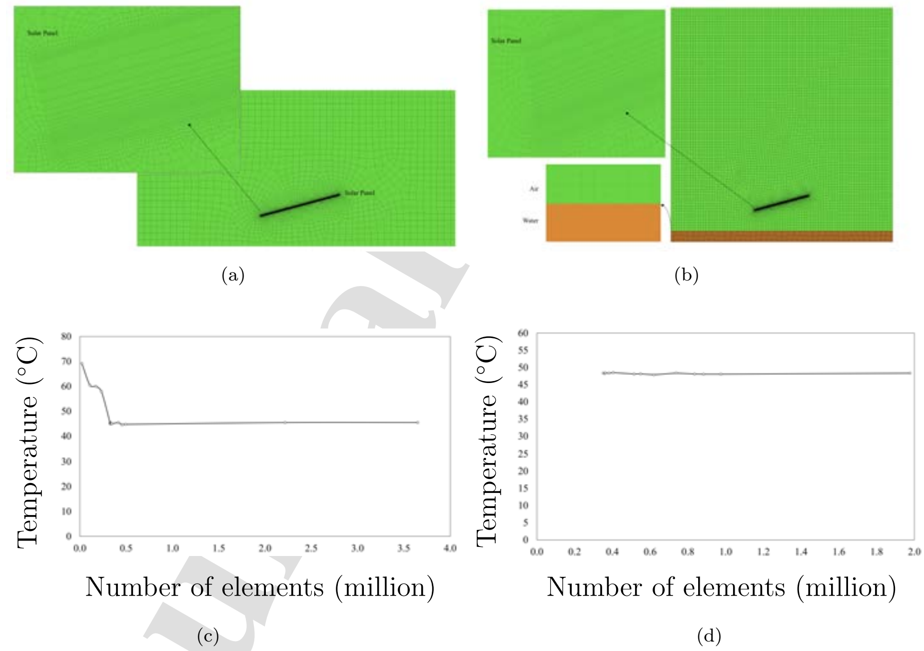


Figure 2: Mesh image and grid independence study for the changing number of mesh elements against the observed solar PV cell temperature (a) NOCT PV mesh view, (b) FPV mesh view, (c) NOCT PV GIT, (d) FPV GIT.

1.6. The emissivity of the water and glass are 0.96 and 0.91 respectively.

2.3. Grid Independence Study

The number of mesh elements in CFD is essential in simulating an PV model with precise result in shorter time. An optimal resolution of the mesh is required to set for the NOCT PV and FPV models. In this case, a hexahedral type of mesh is applied in the simulation for higher resolution as illustrated in Figure 2a and 2b. The number of mesh elements of NOCT PV is varied at a range of 0.02 million to 3.7 million. On the other hand, the number of mesh elements of FPV is increased from 0.35 million to 2 million. As the focus of the research is on the temperature of solar PV cell, the average cell temperature is plotted against the number of mesh elements as in Figures 2c and 2d. It is observed that, the temperature of the solar cell in the NOCT PV was steady after 0.33 million mesh elements. In the case of FPV, from the starting range of 0.35 million to the increasing number of mesh elements, the temperature of the solar cell was linear. Based on the observation of graph, 0.33 million mesh elements and 0.4 million mesh elements were implemented for NOCT PV and FPV simulations, respectively.

3. Results and discussion

To determine the concurrence of the 2D model in the present study with the real case scenario, validation was performed. Initially, the support-free solar PV module in the air is tested at nominal operating cell temperature (NOCT PV) condition as performed by Lindholm et al. [18]. Following it, the FPV model is compared with two scenarios reported in the literature.

3.1. Validation of NOCT PV

The validation of the independent solar PV module in the air was performed at NOCT condition, where the wind velocity is 1 m/s with a temperature of 20°C, under the plane of array solar irradiance of 800 W/m^2. The expected temperature of the open circuit solar PV cell at this condition is 45±2°C, commonly given by most of the solar panel manufacturers [22]. The simulation of the two-dimensional model used in the present study resulted a value of 45.39°C subject to the same NOCT condition. This obtained solar PV cell temperature value is within the range of the nominal operating cell temperature (NOCT). Further, with reference to the NOCT, by varying the solar irradiance and ambient temperature, the solar PV cell temperature [22] can also be calculated as follows,

$$T_{\mathrm{PV}} = T_a + (\mathrm{NOCT} - 20) \cdot \frac{I_T}{800}, \quad (7)$$

where, T_{PV} is solar PV cell temperature, T_a is the surrounding temperature, NOCT is the solar PV cell temperature given by the manufacturer and I_T is the solar irradiance.

In Eq. (7), the cell temperature was calculated for 5 intervals between 800 W/m^2 to 1200 W/m^2 under three different ambient temperatures 20°C, 25°C and 30°C. Similarly, the same input was given as a boundary condition and the solar PV cell temperature was found through simulation. The obtained solar PV cell temperature through Eq. (7) and simulation is plotted and compared as shown in Figure 3. The similarity in the result between the derived values and the simulation result can be observed in Figure 3. In

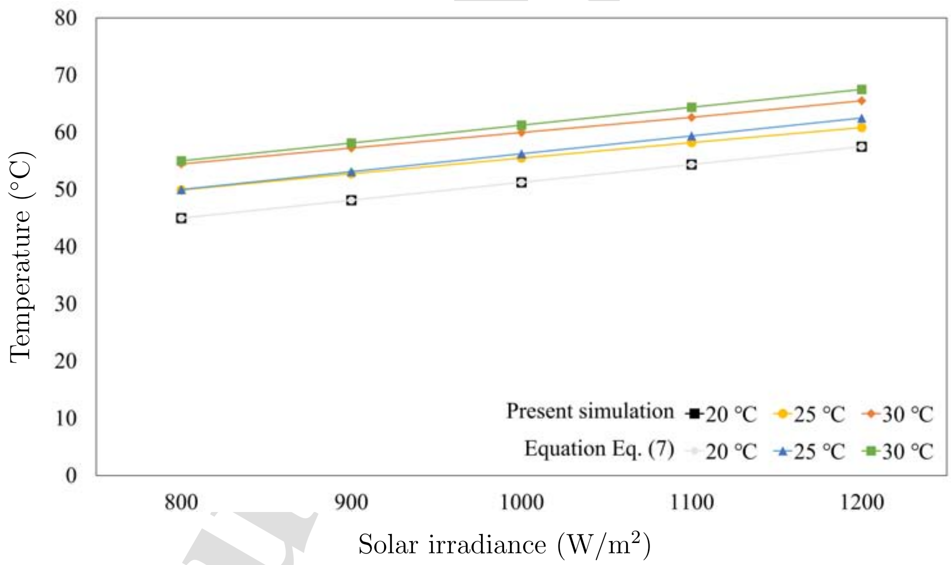


Figure 3: Validation of the independent solar PV module in the air under NOCT condition where X axis is solar irradiance and Y axis is solar PV cell temperature at constant wind velocity of 1 m/s. The legend represents the ambient temperature used in the equation Eq. (7) and in the present simulation.

Table 3: Boundary condition and panel temperature from Nisar et al. [8].

Ambient temperature	35 °C
Water temperature	28 °C
Wind speed	2.9 m/s
Solar irradiance	600 W/m^2
Panel temperature (front)	41 °C
Panel temperature (back)	44 °C

addition, the mismatch between the simulation and the calculated result was observed to be in a range of 0.07°C to 1.98°C.

3.2. Validation of floating solar PV

After the successful validation of the free-standing NOCT PV, the water surface was added to the bottom of the model. The height of the computational domain was then extended to 4000 mm to perform the study on the varying height. The experimental analysis of FPV by Nisar et al. [8] gives us the following observation as in the Table 3. When the same boundary condition is applied, the average temperature of the solar PV cell from the simulation is found to be 43.79°C. This value falls between the temperature range of 41°C to 44°C which is the recorded front and back temperature of the FPV panel by Nisar et al. [8]. This resembles the accuracy of the 2D FPV model in the current study to compare it with the real case physical conception.

Following the prime validation with Nisar et al. [8], again the simulation result was compared with the results of Lindholm et al. [18]. The author performed a 3D CFD simulation for an array of FPV in the study [18]. The first panel in the row was taken into account and similar boundary condition which is 25°C wind temperature, 20°C water temperature and the wind velocity range of 1 m/s to 5 m/s was applied. The resulting solar PV cell temperature in the present study was plotted against the simulation results of Lindholm et al. [18] as in the Figure 4 and illustrated in the Table 4. It can be observed that the trends of both lines in the graph are parallel and linear. Though the results are identical, the range of error in the temperature value between the present study and Lindholm et al. [18] is 5.50°C to 6.59°C. This indicates an average of 5.88°C less FPV temperature in this present analysis.

Lindholm et al. [18] stated that the addition of floating structure increased the temperature of the FPV cell by 2.9°C. Therefore, the difference in the 2D and 3D models, the exclusion of the floating structure, the difference in

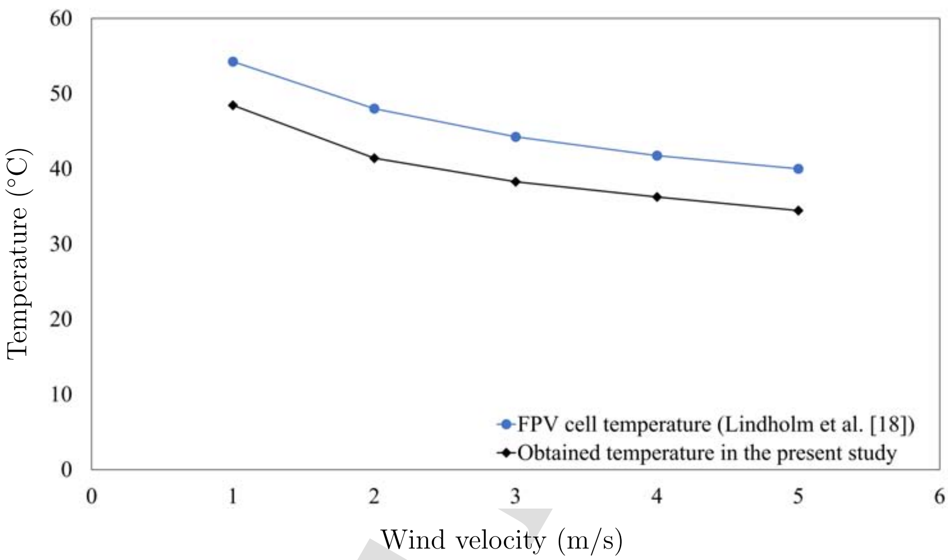


Figure 4: FPV validation with Lindholm el al. [18] where X axis is wind velocity and Y axis is solar PV cell temperature for different wind velocity from 1 m/s to 5 m/s under constant solar irradiance of 800 W/m^2, 25°C wind temperature and 20°C water temperature.

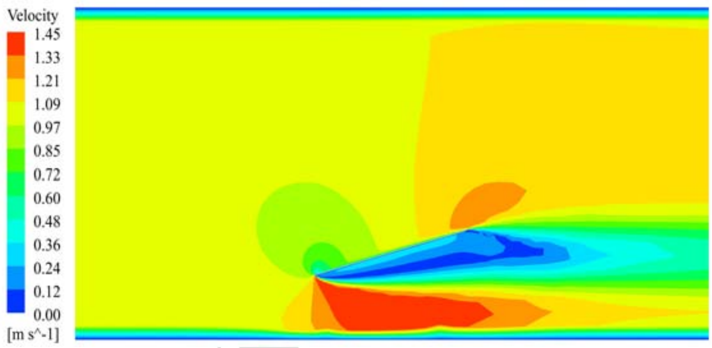
Table 4: FPV cell temperature (°C) validation with Lindholm et al. [18].

FPV cell temperature (Lindholm et al. [18])	**Obtained temperature in the present study**	**Error**
54.25	48.44	5.81
48.00	41.41	6.59
44.25	38.28	5.97
41.75	36.25	5.50
40.00	34.45	5.55

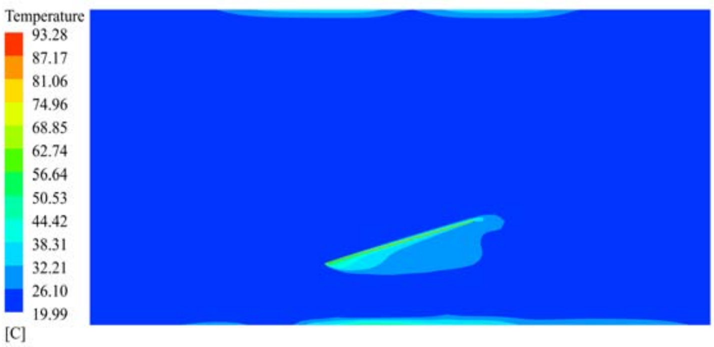
the mesh elements and the temperature of the PV cell at NOCT conditions are possible factors for the variation in accuracy.

3.3. Effect of temperature

To examine the effect of temperature, the temperature of both wind and water was varied from 20°C to 40°C. To investigate the design parameter, the tilt angle and height of the FPV were adjusted. Further, the wind velocity is modified to study its impact. The effect of these parameters on the temperature drop of solar PV cell is analysed and discussed. Figure 5 shows the contour of the wind velocity distribution and temperature that affect NOCT

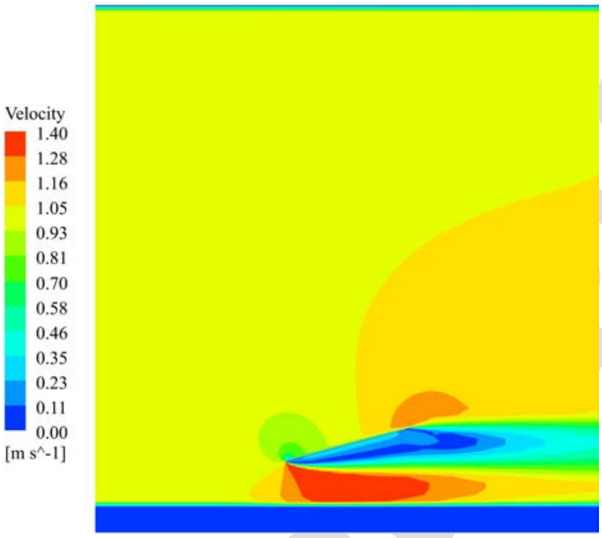


(a)

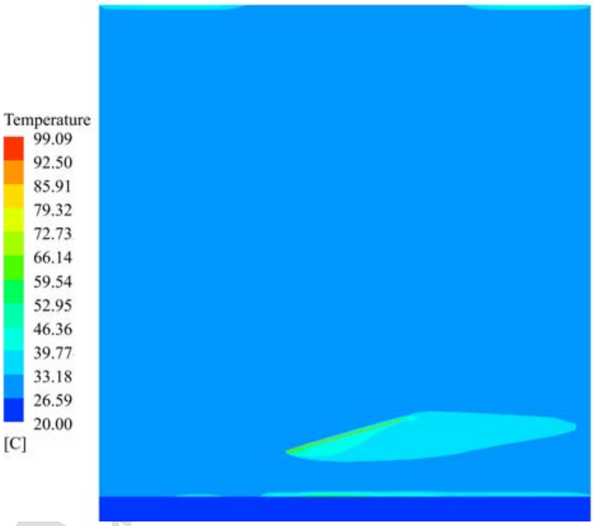


(b)

Figure 5: Velocity and temperature distribution in NOCT PV (a) Velocity contour (b) Temperature contour.



(a)



(b)

Figure 6: Velocity and temperature distribution in FPV (a) Velocity contour (b) Temperature contour.

PV. Similarly, Figure 6 displays the observation of the same in FPV. It is observed that the velocity at the edges of the PV module is slightly higher for the NOCT PV compared to the FPV under the same conditions.

At solar radiation of 800 W/m^2, the wind velocity of 1 m/s and tilt angle of 15°, the temperature of water and wind was varied. The varied temperature of wind and water along with the observation of cell temperature of FPV and NOCT PV are plotted in the Figure 7. It is observed that if the temperature of the water is 5°C higher than the wind, then the solar PV cell temperature of FPV is 2.28°C higher than the NOCT PV (simulation number 1 in Figure 7). When both the water and wind temperature are maintained equally at 20°C, again the cell temperature of FPV is 0.58°C higher than the NOCT PV as in simulation number 6 of Figure 7. At a temperature difference of 2°C higher for air, the temperature of the solar cell of FPV is 0.09°C lower than NOCT PV. Refer to simulation number 11 of Figure 7, with a temperature difference of 5°C, it is found that the FPV cell is able to show a cooling of around 1°C. Therefore, the minimum temperature difference required between water and wind to experience the

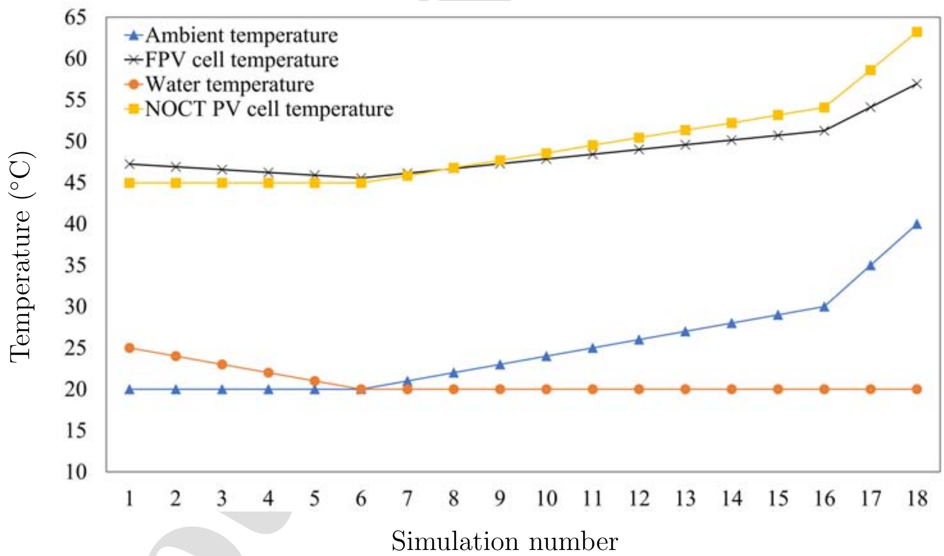


Figure 7: Effect of surrounding temperature on FPV and NOCT PV cell temperature at solar radiation of 800 W/m^2 and 1 m/s wind velocity.

enhanced power production of FPV is 5°C. It means that the temperature of the wind should be minimum 5°C higher than the water base. This result can be validated with Emre et al. [23], where the author did not observe any difference in performance between FPV and NOCT PV at low ambient temperature. The author also added that the power gain of FPV can only be experienced at high ambient temperature. It is also found that when the temperature of the water is 8°C lower than the wind, the temperature drop of FPV cell is 2°C. Therefore, for each 3°C decrease in the temperature of water, the temperature of solar PV cell of FPV reduces by 1°C. The higher the temperature difference between the wind and water, the higher the cooling effect for the PV cell in the FPV system.

3.4. Effect of wind

The flow of wind has a huge impact on cooling effect on the solar panel of FPV [24, 25]. For this analysis, the velocity of wind was varied from 1 m/s to 5 m/s for both FPV and NOCT PV, and the graph is plotted as in Figure 8. It is observed that the increase in the velocity of wind increases the cooling of

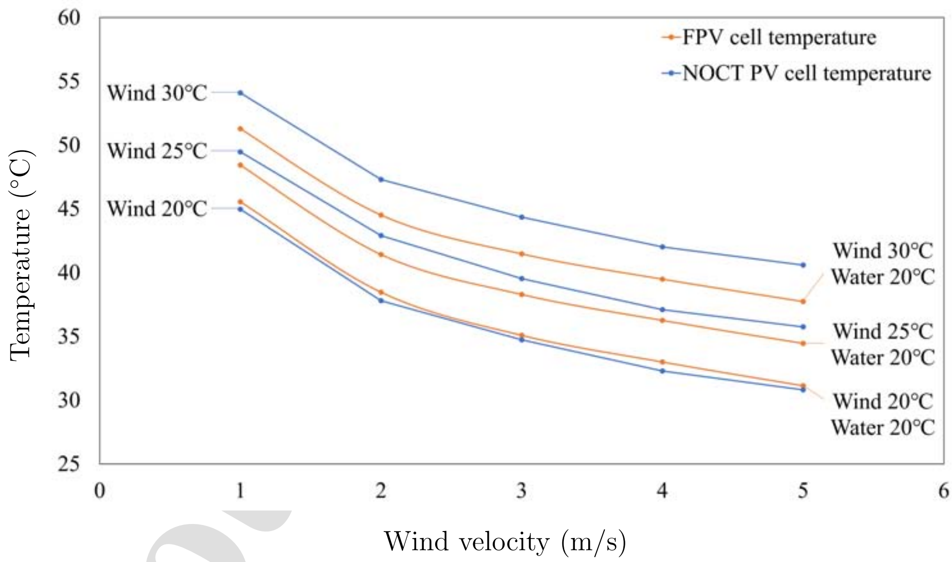


Figure 8: Effect of wind on FPV and NOCT PV cell temperature at constant solar irradiance of 800 W/m^2.

the solar cell in both FPV and NOCT PV. As defined in section 3.3, when the temperature of wind and water are same, the PV cell of NOCT PV is cooler than FPV. At the same condition, on increasing the velocity of wind, though the cooling effect of FPV is not as NOCT PV, the cell temperature reduces due to the velocity of wind. The plot lines for the PV cell temperature of FPV and NOCT PV in the Figure 8 are parallel. It shows a constant downward trend in cell temperature difference between FPV and NOCT PV with relative to the varying wind velocity. The constant cell temperature difference is approximately 1.2°C when the temperature of the wind is 5°C higher than the water. Similarly, it is 2.8°C when the temperature of the wind is 10°C higher than the temperature of the water.

3.5. Effect of height and tilt angle

To observe the impact of height and tilt angle, six different heights were varied at a range of 250 mm to 3000 mm. The heights were measured from the center of the panel to the top of water base. Similarly, the tilt angle was varied from 0° to 75° with six different angles in between. The impact of this combination of parameters on the temperature of the FPV cell was plotted as in Figure 9. For this analysis, the weather parameters were maintained adhering to the NOCT condition, where the wind velocity is 1 m/s and the solar irradiance is 800 W/m^2. To observe effective difference in the FPV cell temperature, the ambient temperature was kept at 30°C and the water is maintained at 20°C. Nisar et al. [8] stated that the lower height and the flat position (0°) in a FPV provide maximum cooling for the solar panel. Similar result was also observed in the current study where the angle 0° and 15° was observed to provide higher cooling to the FPV. At flat position the panel is kept closer to the water surface and the average temperature drop is observed to be 2.9° compared to NOCT PV. When the panel is kept at 1500 mm, the temperature drop in the PV cell increases to 4.3°C. Kjeldstad et al. [24] reported a similar result for the analysis of FPV in Kilinochi, Srilanka. The author stated that when the solar panel of FPV system is kept closer to water surface, the cooling effect provided by the FPV is affected by poor air ventilation. Therefore, for a tilt of 0°, the height of 1500 mm is found to be the best design for FPV, as in Figure 9a. When the angle of tilt is increased to 15°, 250 mm height provides maximum cooling as in Figure 9b. For the angle 30°, at a height of 250 mm, the lower end of the solar panel is much closer to the water surface. Hence, the tilt angle 30° at 250 mm for FPV shows 7°C higher cell temperature than NOCT PV as in the Figure

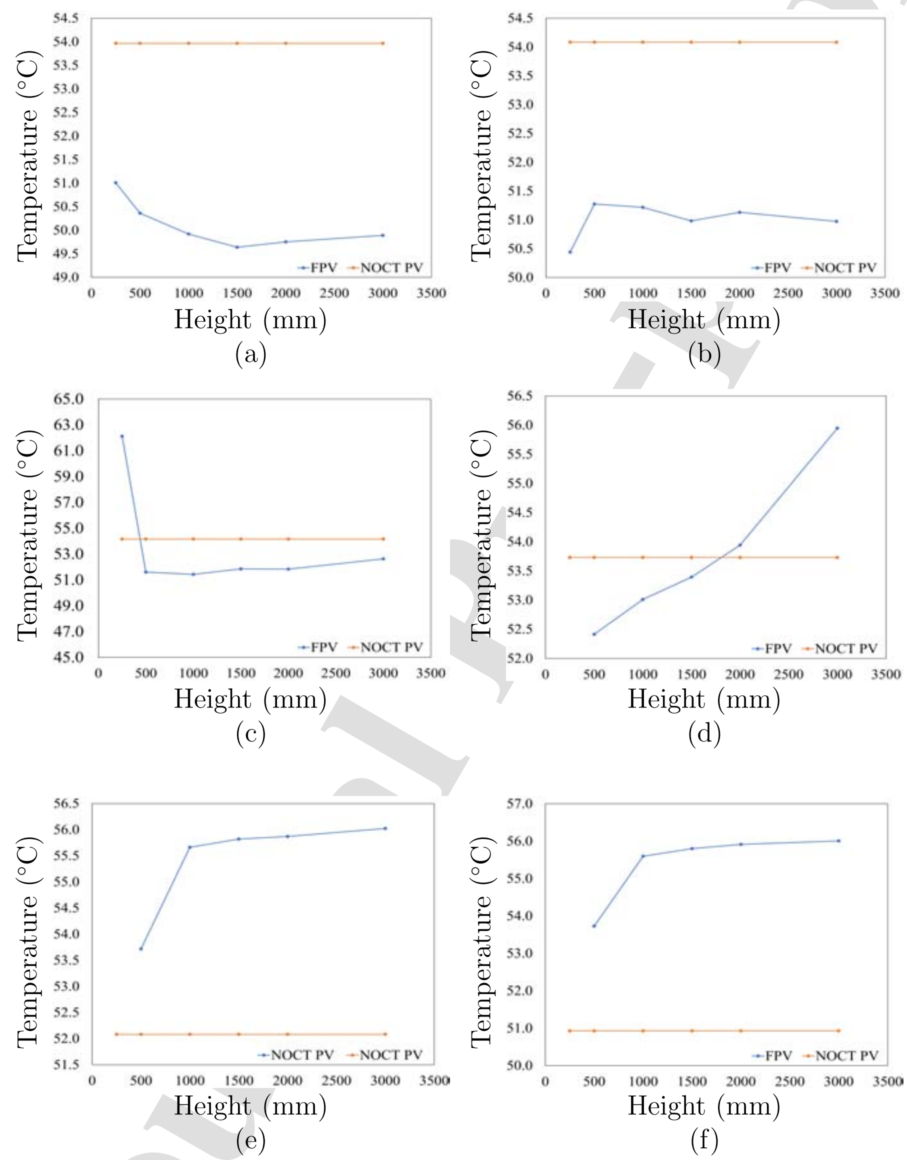


Figure 9: FPV & NOCT PV cell temperature with reference to tilt angle and height. (a) 0°, (b) 15°, (c) 30°, (d) 45°, (e) 60°, (f) 75° at a constant wind velocity of 1 m/s and 800 W/m^2 solar irradiance.

9c. Furthermore, as the increase in tilt angle immersed the lower end of the panel, the 250 mm height was avoided.

It should be noted that after an increase in the angle of 45° at an elevation of almost 2000 mm, the FPV loses its performance and the temperature drop in NOCT PV is better than that of the FPV (Figure 9d). As in Figures 9e and 9f, the solar PV cell temperature at the angles 60° and 75° is lower for NOCT PV than for FPV. It can be noticed from the contour of NOCT PV and FPV (Figure 5 and 6) that the velocity at the edges of the NOCT PV is slightly higher than the FPV. The increase in the tilt angle of the solar panel comparatively increases this difference in favor of NOCT PV providing higher velocity. Furthermore, from the Figure 8 it can be understood that the higher wind velocity extends the temperature drop in a solar PV cell. Hence, at higher tilt angle, the cooling effect of the solar cell in NOCT PV is better than the FPV. Peters et al. [25] also observed a similar effect, in which the author observed the performance loss of the FPV system compared to a roof-mounted solar PV system. In the analysis, the wind flow was affected by obstacles on its pathway of FPV. On the other hand, the free flow of wind enhanced the heat transfer for roof top solar PV system [25]. Thus,

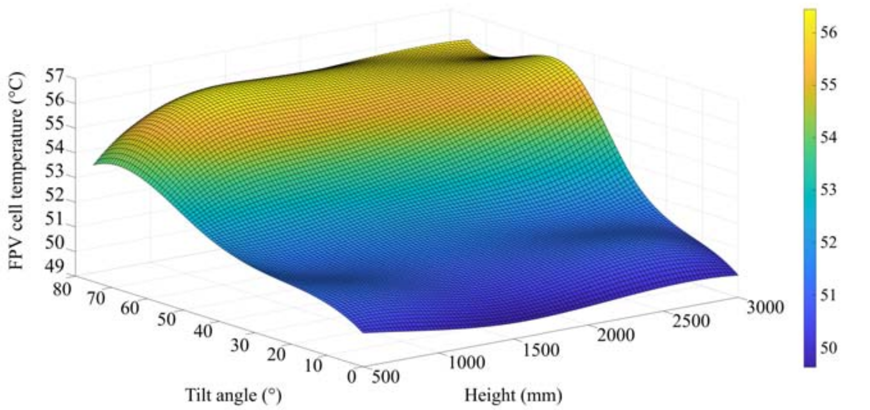


Figure 10: Impact of tilt angle and height on FPV cell temperature at 1 m/s wind velocity, 800 W/m^2 solar irradiance, 30°C wind and 20°C water temperature.

it can be concluded that the performance of FPV is better at lower height and tilt angle. In addition, Lindholm et al.[18] stated that the inclusion of floating structure increased the temperature of FPV cell by 2.9°C. Along with observations in the present study, with reference to the temperature coefficient of solar panel given by the manufacturers, the relationship between the temperature drop and power gain of a FPV can be calculated.

3.6. Design Consideration

With the PV cell temperature at the appropriate height and tilt angle obtained through multiple simulations, additional points were extracted with interpolation using MATLAB. The same was plotted as a surface graph using MATLAB for enhanced view and better understanding as in Figure 10. It can be observed that 0° tilt angle with a height of 1500 mm is the optimum design for FPV to provide maximum cooling. At this design, comparatively the solar cell of FPV is 4.33°C cooler than the NOCT PV. In general, the lower tilt angle and lower height suits the FPV to provide cooling for the PV cell. The graph in the Figure 10 illustrates the best design for FPV to be 0° to 20° tilt with a height of 1000 mm to 2000 mm. Under this condition, the temperature of the solar PV cell of FPV is 49.73°C to 51.30°C. Comparatively, this is 2.8°C to 4.25°C less than the solar PV cell temperature of the NOCT PV for the same design.

Furthermore, the effect of tilt angle and height on the temperature drop of solar PV cell in both NOCT PV and FPV are given in the Figure 11. It can be observed that the higher tilt angle and higher height, affects the performance of solar PV in FPV technology. For instance, at 3000 mm height with 75° tilt, the temperature of the solar cell is 50.93°C and 56°C for NOCT PV and FPV, respectively. This is approximately 5°C higher for FPV compared to the benchmark model used in the present analysis. Moreover, in this scenario the comparison of the FPV with the conventional solar PV systems would be appropriate. Together, the velocity of wind, air ventilation, proximity to the water surface, and the interaction of wind with the surface affect the temperature of the solar panel. Based on the observation in the present study, it can be framed that the lowest height and tilt angle less than 45° are at the top in the FPV design hierarchy to obtain the maximum temperature reduction in the PV cell. It is followed by the solar PV tilt angle 45° to 55° where the cooling effect is good at lower height and inverse at higher height. The higher height and tilt angle under NOCT condition

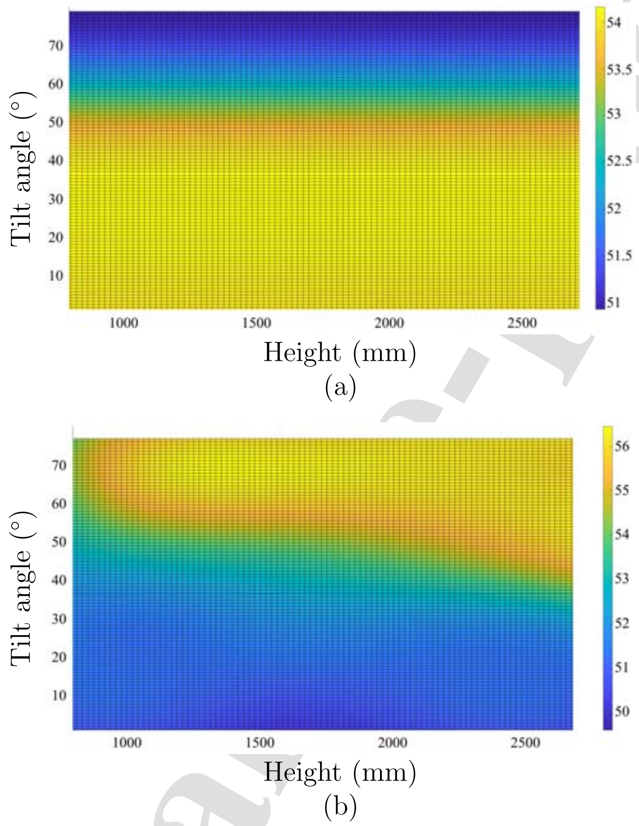


Figure 11: The temperature variation in solar PV cell due to varying tilt angle and height for (a) NOCT PV (b) FPV, at 1 m/s wind velocity, 800 W/m^2 solar irradiance, 30°C wind and 20°C water temperature.

shows 6° high temperature compared to the low height and tilt angle of FPV as in Figure 11b.

4. Conclusion

The impact of height, tilt angle, wind velocity, ambient temperature and water temperature on FPV without floating structure was analysed in this study using 2D CFD simulation. The following conclusions can be made on the basis of the observations. Water needs to be 2°C lower than the air to experience the cooling effect in a FPV. The temperature of the FPV cell decreases 1°C when the water temperature is 5°C lower than the ambient temperature. Further, for each 3°C decrease in the water temperature, the temperature of the solar photovoltaic cell decreases by 1°C. The higher wind velocity increases the transfer of heat to the surrounding and decreases the solar cell temperature in both FPV and NOCT PV. For the variation in wind velocity, the FPV cell temperature reduces constantly by 1.2°C when the temperature of the wind is 5°C warmer than water. Similarly, it is approximately 2.8°C for 10°C high ambient temperature than the water.

The study on the impact of height and tilt angle on the temperature drop of photovoltaic panel placed in water is crucial. The comparative model NOCT PV serves as the basis for comparison and analysis that resembles the cooling supplied only by wind. Whereas in an FPV the cooling is the combined contribution of wind and water. On comparison, it can be observed that the FPV temperature is higher than the NOCT PV for a tilt angle greater than 55°. The inclination of the solar panel increases the interaction of the wind with the surface of the solar panel and promotes high heat transfer. The velocity in the corner of the NOCT PV is higher than that of FPV. Therefore, the heat transfer only by wind in NOCT PV overtakes the cooling effect in an FPV for a higher height and tilt angle. FPV is highly suitable for a tilt angle less than 45° regardless of height. To be appropriate, FPV provides maximum cooling to the solar cell at a height of 1500 mm with 0° tilt angle. At this design, under NOCT condition, with a 5°C low water temperature than wind, the solar PV cell of FPV is 4.33°C cooler than that of the independent solar PV module used for the comparison in the study. This indicates the requirement of proper air ventilation and proximity of the solar panel to the water body to obtain higher cooling. Hence, the fabrication, installation and construction of FPV with low height and tilt angle is apt design to obtain maximum temperature drop in the solar cell. Consequently, it will reduce the diminution of power generation associated with the thermal loss of the PV module. Thus, the highlighted results in the current study gives general guidelines on the FPV system design.

Nomenclature

α Absorption coefficient

g Acceleration due to gravity

x	Axial coordinated
F	Body force
CFD	Computational Fluid Dynamics
ρ	Density
J_j	Diffusion flux
s'	Direction vector
ε	Dissipation rate
k_{eff}	Effective conductivity
h	Enthalpy
$Eq.$	Equation
FPV	Floating solar PV
Y_m	Fluctuating dilation in overall dissipation
GIT	Grid independence test
S_h	Heat source
e	Internal energy
k	Kinetic energy
LPV	Land solar PV
$NOCT$	Nominal Operating Cell Temperature
S	Path length
π	Phase function
PV	Photovoltaics
r	Position
I	Radiation intensity

n	Refractive index
σ_s	Scattering coefficients
ω'	Solid angle
σ	Stefan-Boltzman constant
τ	Stress tensor
SDG	Sustainable Development Goals
T	Temperature
$3D$	Three-dimensional
G_b	Turbulence kinetic energy due to buoyancy
G_k	Turbulence kinetic energy due to the mean velocity gradients
σ_ε	Turbulent Prandlt number for ε
σ_k	Turbulent Prandlt number for k
$2D$	Two-dimensional
UN	United Nations
S_k	User source term
u_i	Velocity component
V	Velocity

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Conflicts of interest

There are no conflicts to declare.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: