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ORIGINAL RESEARCH

CFD model of the heat transfer processes in an offshore photovoltaic panel

Pablo Rubial-Yáñez[1] | Luis García-Rodríguez[1,2] | María Isabel Lamas-Galdo[3] | Laura Castro-Santos[3] | Almudena Filgueira-Vizoso[3]

[1]Escola Politécnica de Enxeñaría de Ferrol, Universidade da Coruña, Ferrol, Spain

[2]Escuela Técnica Superior de Ingenieros Industriales y de Telecomunicación, Santander, Spain

[3]Universidade da Coruña, Campus Industrial de Ferrol (CIF), Centro en Tecnoloxías Navais e Industriais (CITENI), Escola Politécnica de Enxeñaría de Ferrol (EPEF), Universidade da Coruña, Ferrol, A Coruña, Spain

Correspondence
Laura Castro-Santos, Universidade da Coruña, Campus Industrial de Ferrol (CIF), Centro en Tecnoloxías Navais e Industriais (CITENI), Escola Politécnica de Enxeñaría de Ferrol (EPEF), Universidade da Coruña, Esteiro, Ferrol, A Coruña 15471, Spain.
Email: laura.castro.santos@udc.es

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Abstract
Solar energy has become increasingly important in recent years. The installed capacity has increased over the years, and today solar energy represents a significant part of the renewable energy contribution. One of the handicaps of photovoltaic panels is the cooling process. The panels are susceptible to overheating, which leads to a reduction in efficiency. One of the ways to mitigate this problem is to install the photovoltaic panels offshore, where cooling is more efficient, thus increasing power generation. Due to the lack of in-depth analysis of numerical models for studying heat transfer in offshore photovoltaic panels in the literature, this work proposes a computational fluid dynamics model to analyse the thermal performance of an offshore photovoltaic panel. The numerical model was used to characterize the heat transfer processes. The model was validated with experimental data from an onshore panel setup, where key parameters such as solar radiation, inlet air temperature, and solar cell temperature were measured. A comparison between onshore and offshore installations was made. The model showed that the average solar cell temperature in offshore conditions is 39.11°C, compared to 45.5°C for onshore panels. Over a day analysed, the average efficiency improved from, 10.7% to 11.2%. The research also highlighted the critical role of water temperature in affecting the thermal performance of PV panels. The potential impact on the marine ecosystem due to increases in water temperature was found to be negligible, supporting the sustainability of offshore PV systems. These results demonstrate the advantages of offshore photovoltaic systems over traditional onshore ones, contributing to the advancement of sustainable energy solutions.

1 | INTRODUCTION

Extreme climate change in recent years has become a major threat to human life, mainly due to the excessive use of fossil fuels and the resulting increase in carbon emissions. Therefore, it is crucial to accelerate the development of renewable energy sources and efforts to reduce carbon emissions [1]. In this regard, renewable energy resources are essential to meet the global demand and address the issues related to price fluctuations and negative environmental impacts of fossil fuels [2]. Among the different types of renewable energy, the use of solar energy for power generation is a crucial aspect of sustainable energy production [3]. Solar power is developing rapidly due to growing environmental concerns about the dangers of climate change associated with fossil fuel-based electricity generation [4]. Photovoltaic (PV) technology, despite its lower efficiency compared to other energy sources, holds great promise due to its potential for growth and development [5].

An emerging trend in solar energy is the installation of PV systems on water, with the first floating PV system installed in Japan in 2007 [6]. This innovative approach has gained traction in regions such as China, Southeast Asia, and India, offering advantages over traditional onshore installations [7]. Offshore PV installations provide a unique opportunity to harness solar energy, offering a larger installation area and the potential to tap into abundant solar resources [8]. It also contributes to green port initiatives to promote sustainable practices and reduce the environmental footprint of ports and their operations [9]. A key

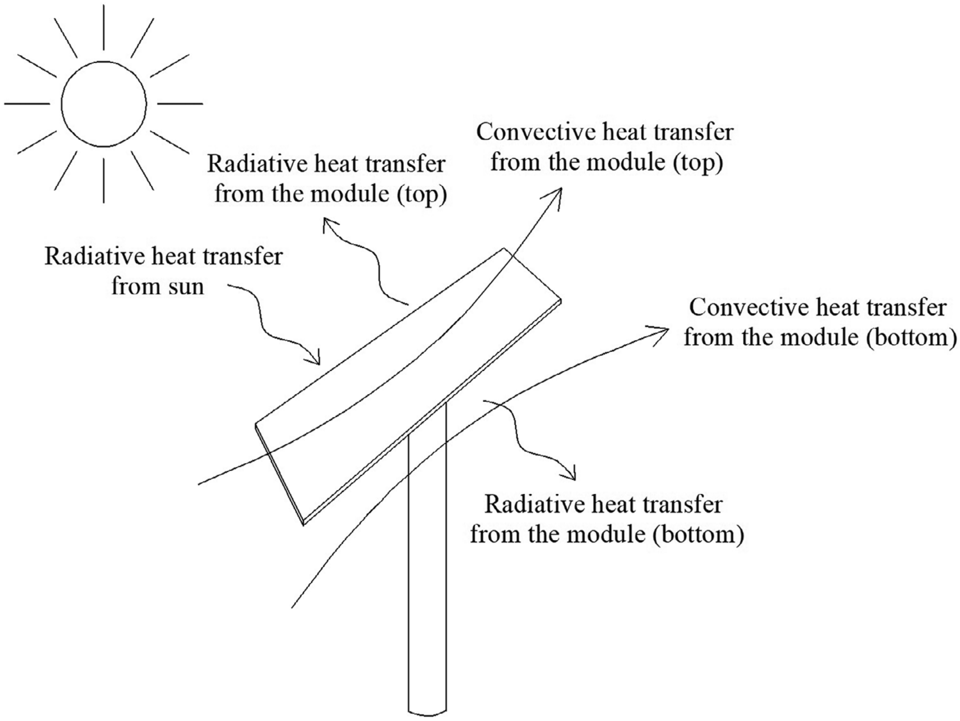

FIGURE 1 Schematic representation of the heat transfer related to an onshore PV panel.

advantage of offshore PV panels is the natural cooling effect of water, which increases panel efficiency by effectively removing heat [10]. The cooling process is essential for maintaining optimal operating temperatures and maximizing energy output, with wind speeds in the marine environment further contributing to the cooling effect [11].

Understanding and modelling the heat transfer processes within PV panels is critical to improving their performance, reliability, and lifetime. In this regard, computational fluid dynamics (CFD) has emerged as a valuable tool for analysing these processes and developing innovative cooling strategies [12]. One can refer to the work of Teo et al. [13], who designed, fabricated, experimentally studied, and developed a CFD model to analyze a hybrid photovoltaic/thermal solar panel with an innovative cooling system. Nebbali et al. [14] numerically analysed a photovoltaic solar panel cooled by a forced air system. Kumar et al. [15] conducted an experimental and numerical analysis of a solar PV panel with thermoelectric cooling. Subsequently, Saurabh et al. [16] conducted a CFD model of a hybrid PV-thermal system. Raval and Maiti, [17] carried out a CFD analysis and experimental validation to improve the overall energy efficiency of a PV solar panel through thermal energy recovery. Gujrathi et al. [18], analysed a PV solar panel with air cooling using CFD. Sustanto and Indartono [19], modelled a floating PV cooling system with loop thermosiphon. Nguyen and Do [20] estimated the efficiency of a PV cell under different wind speeds. Ozcan et al. [21] analysed the effect of cooling channels on the energy production of photovoltaic panels. Pavlovic et al. [22] analysed the thermal behaviour of monocrystalline silicon solar cells through a numerical and experimental study of the module encapsulation materials. Wodolazski et al. [23] conducted a CFD model of an air-cooled PV hybrid system coupled with a single-phase inverter. Khan et al. [24] optimized a PV panel array configuration to reduce the lift force using generic algorithms and CFD. Sierra del Rio et al. [25] developed a numerical study of the efficiency of a solar panel with heat sinks.

Despite the aforementioned literature on CFD analysis of PV modules, research specifically focused on offshore PV is still limited. Therefore, there is a need to further investigate the heat transfer processes of offshore PV systems in order to optimize their performance and efficiency. In this context, the present study presents a CFD-based approach to simulate heat transfer processes in offshore PV panels. The temperature distribution across the panel under onshore and offshore configurations was analysed and compared. Factors such as the fluid velocity and temperature were analysed. By delving into the intricacies of heat transfer in offshore PV systems, this research aims to contribute to the advancement of offshore solar power generation technologies.

2 | MATERIALS AND METHODS

2.1 | Introduction

A PV panel is subject to the heat transfer processes shown in Figure 1. Heat from the sun reaches the panel by radiation. At the same time, the panel also radiates heat transfer. Convection at the top and bottom surfaces contributes significantly to the cooling of the panel.

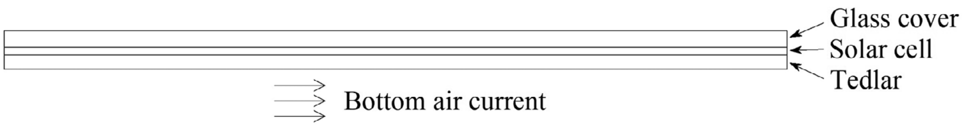

FIGURE 2 Schematic view of the photovoltaic panel considered in the present work.

When PV modules are installed offshore, strong wind and water currents above and below the panel, respectively, provide an efficient cooling system. The temperature of the solar cell is lower than in onshore installations and therefore the efficiency is higher. The CFD model proposed in the present work analyses these aspects. The model investigates the effects of natural water cooling and wind, which are critical for maintaining optimal operating temperatures. The temperature distribution changes over time under varying environmental conditions are analysed. Marine environmental factors such as water temperature, current velocity, and wind speed, which are critical to accurately simulate the cooling effects on offshore PV panels, are considered. In addition, offshore operation is compared with onshore operation. The details of the developed model are given in Section 2.2.

2.2 | CFD model and validation

The procedure followed in this work was to validate the CFD results using experimental data obtained for a terrestrial panel and, once validated, to extrapolate the model to marine installations. The experimental results of Joshi et al. [26] were used for the validation process. These authors analysed the PV panel shown in Figure 2. It consists mainly of three layers: glass cover, solar cell and tedlar. In addition, an air current was established under de panel for cooling. This is a glass-to-tedlar hybrid photovoltaic thermal (PV/T) panel. The hybrid photovoltaic-thermal (PV/T) technology combines PV for electricity generation with thermal energy collection in a single integrated unit. These hybrid panels are designed to simultaneously generate electricity from sunlight using PV cells and heat the fluid circulating underneath. This air flow under the panel facilitates cooling.

The experimental observation of this panel during a month of May at Solar Energy Park, IIT Delhi is summarized in Table 1, which provides a comprehensive data set that includes variations in solar radiation and temperature throughout the day. This table shows the solar radiation (I), temperature of the inlet air current at the bottom part (T_b), ambient air temperature at the top part (T_t), velocity of the air current at the bottom part (v_b), wind velocity at the top part (v_t), and solar cell temperature (T_c). This data set was used as a benchmark to validate the predictions of the CFD model.

To reproduce this experiment using CFD, the domain shown in Figure 3 was used. As can be seen in this figure, the panel and air underneath were included in the domain. The PV is a 1.2 × 0.45 m module. The main assumptions are listed below:

TABLE 1 Experimental data during a month of May at the Solar Energy Park, IIT Delhi, Joshi et al. [26].

Time (h)	I (W/m^2)	T_b (°C)	T_t (°C)	v_b (m/s)	v_t (m/s)	T_c (°C)
8:00	313.63	31.9	29	2.67	0.11	37.6
9:00	409.63	33.0	30	1.98	0.23	41.4
10:00	535.50	34.9	32	1.42	0.12	47.9
11:00	634.25	36.2	35	1.87	0.13	50.4
12:00	658.00	42.3	38	1.73	0.27	54.9
13:00	594.25	43.7	40	1.67	0.23	54.7
14:00	558.00	42.0	41	1.77	0.15	52.9
15:00	416.13	41.4	41	1.70	0.19	50.7
16:00	253.75	40.8	40	1.83	0.13	47.2
17:00	108.50	39.0	39	1.77	0.08	42.3

- 2D simulations were performed. The differences between 2D and 3D simulations were reported by Zondag et al., [27], who concluded that a 2D simulation is accurate enough to simulate a PV panel.
- Negligible evaporation effect. Evaporation is an endothermic process that absorbs heat from the environment. This could increase the cooling effect, especially near at noon. Besides, if some water access to the surface of the photovoltaic panel, it would draw heat away from the panel, thereby enhancing its cooling. However, this effect was neglected.
- Transient treatment. A transient simulation was performed using the data shown in Table 1. The simulation was run from 8:00 to 17:00. Each hour corresponds to a transient simulation using the values of solar radiation, temperature of the inlet air current at the bottom part, ambient air temperature at the top part, velocity of the air current at the bottom part, and wind velocity given in Table 1. Each transient simulation lasts 1 h and the boundary conditions change from hour to hour, according to Table 1. Thus, the results at the end of an hour are inputs for the subsequent hour.
- The air above the panel was not included in the domain and was simulated as a convection boundary condition.
- The air flow below the panel was treated as laminar.

The computational mesh is shown in Figure 4. It consists of 81,614 tetrahedral elements. As can be seen in this figure, the mesh was refined around the PV module in order to accurately capture the characteristics in that region. A mesh sensitivity analysis was performed and is summarized in Table 2. This table shows the solar cell temperature obtained experimentally and numerically using four different meshes with 55,112 (mesh 1),

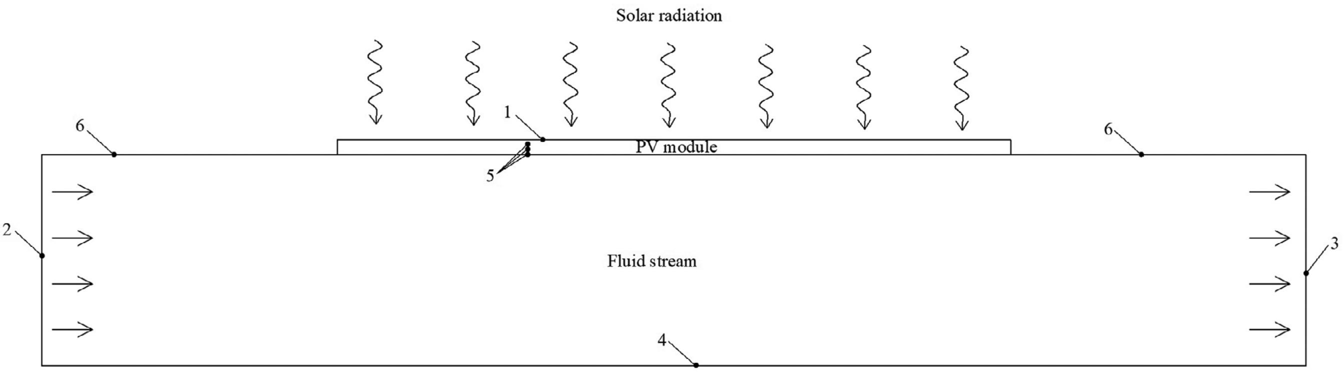

FIGURE 3 Domain corresponding to the offshore case.

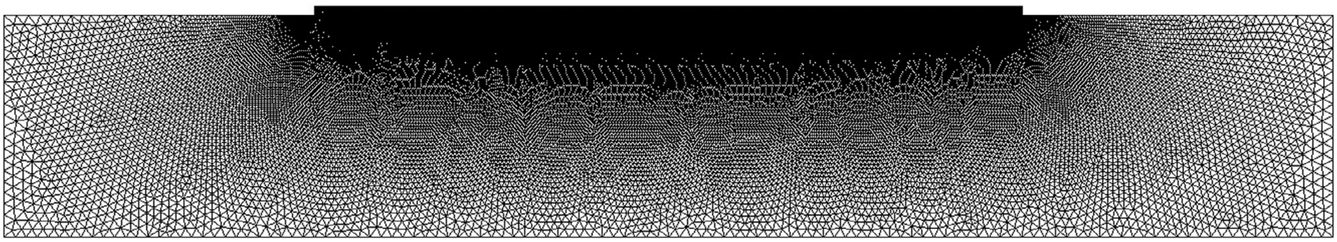

FIGURE 4 Computational mesh.

TABLE 2 Mesh sensitivity analysis.

Time (h)	T_c (°C) (experimental)	T_c (°C) (mesh 1)	T_c (°C) (mesh 2)	T_c (°C) (mesh 3)	T_c (°C) (mesh 4)
8:00	37.6	36.67	36.78	36.85	36.85
9:00	41.4	41.16	41.28	41.36	41.36
10:00	47.9	48.42	48.29	48.19	48.19
11:00	50.4	53.23	53.08	52.97	52.94
12:00	54.9	58.62	58.46	58.34	58.33
13:00	54.7	58.59	58.43	58.31	58.29
14:00	52.9	57.29	57.12	57.01	56.99
15:00	50.7	52.69	52.53	52.43	52.42
16:00	47.2	46.00	46.14	46.23	46.23
17:00	42.3	39.94	40.06	40.14	40.14
	Average error (%)	**4.4**	**4.1**	**3.9**	**3.9**

61,465 (mesh 2), 81,614 (mesh 3) and 125,342 (mesh 4) elements. The error with respect to the experimental data was calculated through Equation (1), and the average error corresponding to each mesh is shown in the table. Since meshes 3 and 4 provided the same error, mesh 3 was used for the computations.

$$\text{Error} = 100\frac{\left|T_{\text{c numerical}} - T_{\text{c experimental}}\right|}{T_{\text{c experimental}}} \tag{1}$$

The simulations were performed using the ANSYS Fluent software. The conservation equations of mass, momentum and energy were solved in the fluid medium, while only the energy conservation equation was modelled in the three solid materials that constitute the PV module (glass, solar cell, and tedlar).

The dependence of the efficiency with the temperature of the solar cell was computed through the following expression [28]:

$$\eta = \eta_{\text{ref}}[1 - \beta(T_c - T_{\text{ref}})] \tag{2}$$

where η_{ref} is the reference efficiency at the reference temperature T_{ref}, and β is a coefficient that represents the amount of efficiency loss per each degree temperature increase of the solar cell. These values were assumed to be 0.12, 25°C,

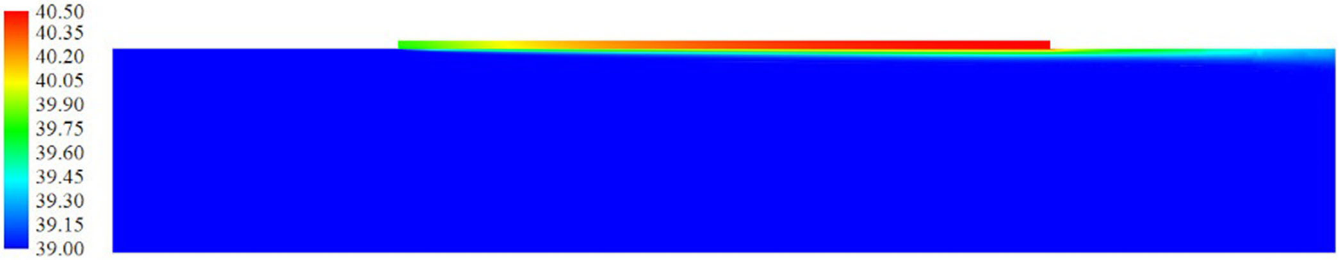

FIGURE 5 Temperature field (°C) at the end of the simulation.

and 0.0045 K^{-1}, respectively [26, 27]. Once the efficiency is calculated, the power produced by the PV module is given by:

$$P = I/\eta \tag{3}$$

This power was modelled as a heat sink in the energy equation applied to model the solar cell.

Regarding numerical parameters, the SIMPLE algorithm was used for the pressure coupling. The governing equations were discretized through a second order upwind scheme. The convergence criteria was established as 10^{-3} residual for the mass and momentum equation, and 10^{-6} for the energy conservation equation. The governing equations were solved using the finite volume method, which discretizes the domain into a mesh of control volumes. A maximum of 20 iterations per time step was established. The temporal treatment was solved through an implicit method. The period of 9 h shown in Table 1 was modelled, from 8:00 to 17:00.

The boundary conditions, numbered in Figure 3, are listed below:

- Boundary condition 1. Solar radiation (absorption and emission) and convection with air (wind). A heat transfer was applied to this surface, given by Equation (4). This equation includes the heat received from absorbed solar radiation minus the heat lost due to emitted solar radiation and convection with air (wind).

$$Q = \alpha_g I - \varepsilon_g \sigma \left(T_s^4 - T_{sky}^4\right) - h(T_s - T_t) \tag{4}$$

where α_s is the absorptivity of the surface, ε_s the emissivity of the surface, T_s the temperature of the surface, T_{sky} the sky temperature, σ the Stefan–Boltzmann constant, and h the heat transfer coefficient. The heat transfer coefficient for the convection process was computed through Equation (5) (Slimani et al., 2016; [26, 29]). It is worth mentioning that this expression is valid for moderate wind speeds. For extremely high wind speeds the linear relationship may not hold, and other effects may need to be considered.

$$h = 5.7 + 3.8 v_t \tag{5}$$

The temperature of the sky was computed by (Slimani et al., 2016):

$$T_{sky} = 0.0552 T_t^{1.5} \tag{6}$$

- Boundary conditions 2 and 3. Current velocity. The current velocity was modelled as velocity inlet (boundary condition 2) and pressure outlet (boundary condition 3).
- Boundary condition 4. Free-slip. A 0 shear stress was applied to the bottom part of the domain in order to avoid border effects.
- Boundary condition 5. Interfaces. As mentioned above, the PV module was modelled as a solid composed by three materials: glass cover, solar cell, and tedlar. The contact surfaces between these materials were modelled as interfaces. Similarly, the contact between the bottom solid (tedlar) and the fluid was also modelled as an interface boundary condition.
- Boundary condition 6. Solar radiation in the fluid flow and convection to the air, given by:

$$Q = \alpha_f I - \varepsilon_f \sigma \left(T_s^4 - T_{sky}^4\right) - h(T_s - T_t) \tag{7}$$

where α_f is the absorptivity of the fluid surface and ε_f its emissivity.

Regarding the results obtained, the temperature field at the end of the simulation, i.e. 17:00, is shown in Figure 5. The maximum temperature in the solar cell reaches 40.47°C, while the average temperature of the solar cell is 40.14°C. The results of the average solar cell temperature along the whole simulation are shown in Figure 6. The experimental results were also included in this figure, which shows a satisfactory agreement between experimental and numerical results. As mentioned previously, the error between experimental and numerical results is 3.9%. Another interesting conclusion that can be drawn from Figure 6 is that, for each simulated hour, a stable state is reached quickly. Specific conditions for each hour have been simulated as indicated in Table 1, and it has been observed that before the hour is over, the panel has already reached a stable temperature.

3 | RESULTS AND DISCUSSIONS

After validating the CFD model with experimental results in the onshore conditions described in the previous section, the next step was to simulate the same PV panel in an offshore environment. For this purpose, the air under the PV module was

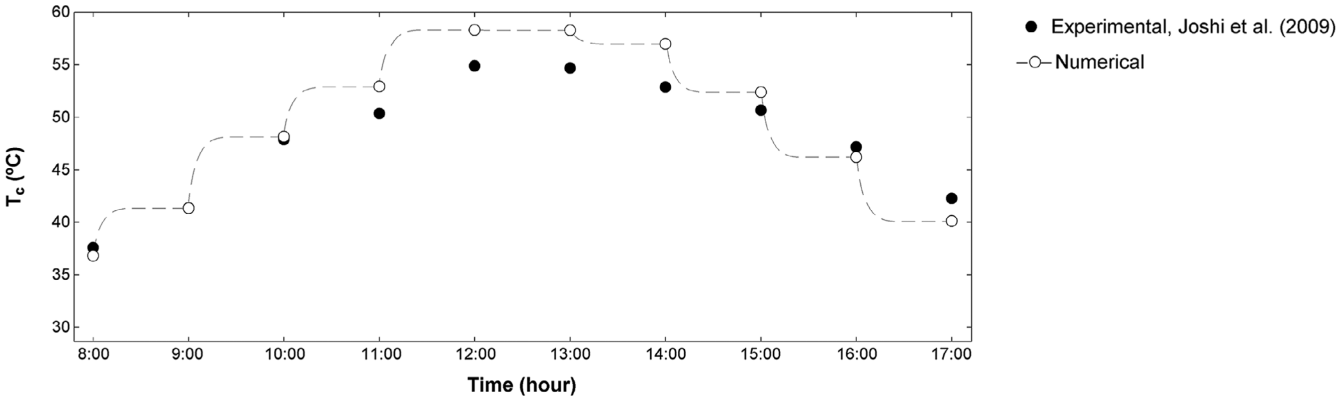

FIGURE 6 Average temperature of the solar cell. Experimental and numerical results.

FIGURE 7 Temperature field (°C) at the end of the simulation. Offshore installation.

replaced by water. In the case of water, the flow was simulated as turbulent using the k–ε model. This allows an accurate representation of the turbulent water flow around the PV panel, a critical factor in determining the convective heat transfer rates. This is particularly important in offshore environments, where turbulent flow patterns dominate due to the interaction between wind, waves, and currents. To provide a comparison under the same conditions, the solar radiation, fluid temperatures, and fluid velocities shown in Table 1 were used. The panel used for the offshore case was exactly the same as the onshore case.

The temperature field at the end of the simulation for the offshore environment is shown in Figure 7. In these results, the average temperature of the solar cell is 39.11°C, which is a value too close to the water temperature, 39°C (Table 1), illustrating the cooling capacity of water over the air that was illustrated in Figure 5. The CFD model results show that this average temperature of the solar cell in offshore conditions, 39.11°C, is significantly lower than the 45.5°C observed in onshore installations.

The significant reduction in solar cell temperature in the offshore environment can be attributed to several physical factors. Water has higher thermal conductivity and specific heat capacity than air. Water's ability to absorb and dissipate heat more effectively results in improved cooling of the PV panels. The specific heat of water (approximately 4.18 kJ/kg·K) is about 4 times greater than that of air, which explains the observed temperature differences. This cooling effect is crucial for maintaining optimal operating conditions, as higher temperatures can lead to increased resistive losses in the solar cells, thereby reducing overall efficiency. In contrast, the higher temperatures observed in onshore PV installations are due to the lower heat capacity and conductivity of air, which limits the ability of the panel to dissipate heat. Heat transfer between the PV panel and the water occurs primarily by convection, where the temperature gradient between the panel and the surrounding medium drives the heat dissipation process. In offshore conditions water facilitates a more efficient cooling mechanism. In addition, by taking turbulence into account, the simulation accurately represents the turbulence-enhanced cooling.

The simulation results show that only a very small zone of the water surrounding the offshore PV panel is slightly affected by the panel's heat dissipation. The temperature variation in the water near the PV installation is minimal, which is a positive outcome for the local ecosystem. Changes in water temperature can significantly impact marine life, particularly species sensitive to temperature fluctuations. The negligible impact observed in the present study suggests that offshore PV installations may be a sustainable option for energy generation without causing harmful effects to nearby aquatic environments. The limited thermal impact observed in the offshore environment is due to the high heat capacity of water, which can absorb large amounts of heat with minimal temperature rise. Water's ability to diffuse heat over a large volume makes it an efficient cooling medium, as opposed to air in onshore conditions, where the heat capacity is much lower. The small zone of temperature increase near the PV panel underscores the efficiency of water in dissipating heat.

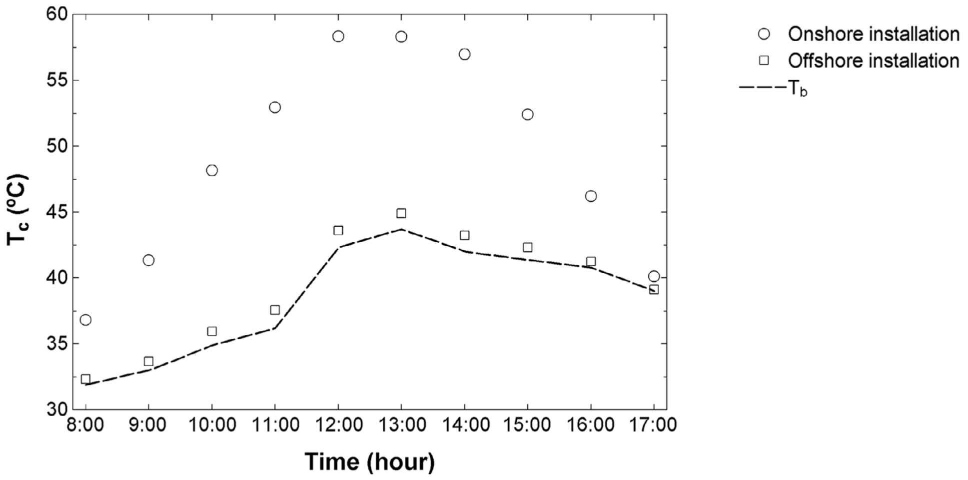

FIGURE 8 Average temperature of the solar cell numerically obtained. Onshore and offshore installation.

Even though the PV panel radiates heat into the surrounding water, the temperature remains largely stable due to the continuous movement of the water and its large thermal inertia. Besides, the turbulence of the water flow promotes mixing of water around the PV panel. This mixing plays a crucial role in distributing the heat away from the PV panel and into the surrounding environment. The turbulent water flow, combined with its high specific heat capacity, reduces the possibility of localized hot spots near the panel, minimizing the ecological impact.

It is important to note that the CFD model only considers a single photovoltaic panel. In real offshore installations, multiple panels are deployed in arrays, and their cumulative thermal effect on the surrounding water could be more significant. Larger installations could affect a broader area of the marine environment, potentially raising water temperatures to a greater extent than indicated by this single-panel study. Furthermore, temperature is not the only factor that needs to be considered when assessing the environmental impact of offshore PV systems. The panels block sunlight from reaching the marine ecosystem directly beneath them, potentially affecting photosynthetic organisms and other species that rely on sunlight. This shading effect could affect the growth of photosynthetic organisms in the water below the panels, potentially disrupting the local food chain and marine biodiversity. While the CFD model focuses on the thermal effects of the PV panel, it does not account for the shading caused by the panel, which could have these ecological consequences.

The average temperature of the solar cell over the entire simulation is shown in Figure 8. For comparison purposes, this figure also includes the corresponding temperatures for an onshore installation (i.e. the date previously shown in Figure 6), and the water temperature through a dotted line (T_b values shown in Table 1). As can be seen, Figure 8 highlights the much greater cooling capacity of water compared to air. As mentioned previously, the water flow around the PV panel significantly increases the convective heat transfer coefficient compared to onshore air cooling. The turbulent flow of water enhances mixing and increases the convective heat transfer coefficient, resulting in a more effective cooling mechanism. It is worth mentioning that this CFD model developed in the present work assumes no-wave water flow conditions and does not account for the complex, dynamic interactions between waves and water currents in real offshore environments. In reality, these interactions could influence heat transfer by potentially leading to more variable cooling effects. In addition, the CFD model does not include the evaporation of water from the panel surface, which can play a role in heat dissipation, particularly in warmer climates. Neglecting this effect might result in a slight underestimation of the cooling potential in certain offshore environments where evaporation could enhance the overall heat transfer process.

The PV panel efficiencies for onshore and offshore installations are compared in Figure 9. The average efficiencies obtained in Figure 9 are 0.107 (10.7%) for onshore and 0.112 (11.2%) for offshore. The results of this study contribute to the literature on offshore PV systems. Previous studies reported an increase in energy output of 12.5% for floating PV systems [30]. Other authors reported that the efficiency can increase up to around 30% [31]. The improvement in efficiency observed in the offshore environment is primarily due to the superior cooling effect provided by water compared to air. The results demonstrate that, while the overall increase in efficiency may seem modest (from 10.7% to 11.2%), even this slight improvement can lead to significant gains in energy output over the lifespan of an offshore PV installation. The water's cooling capability helps to maintain lower average temperatures on the solar cells, which mitigates efficiency losses commonly associated with elevated cell temperatures. This highlights the advantage of deploying PV panels in marine environments, especially in regions where water temperatures remain relatively stable and favourable throughout the year.

It is interesting to analyse the effect of the water temperature, T_b. For this purpose, the values shown in Table 1 were replaced by 10, 15, and 20°C. The results are shown in Figure 10, in particular the average cell temperature and the efficiency are

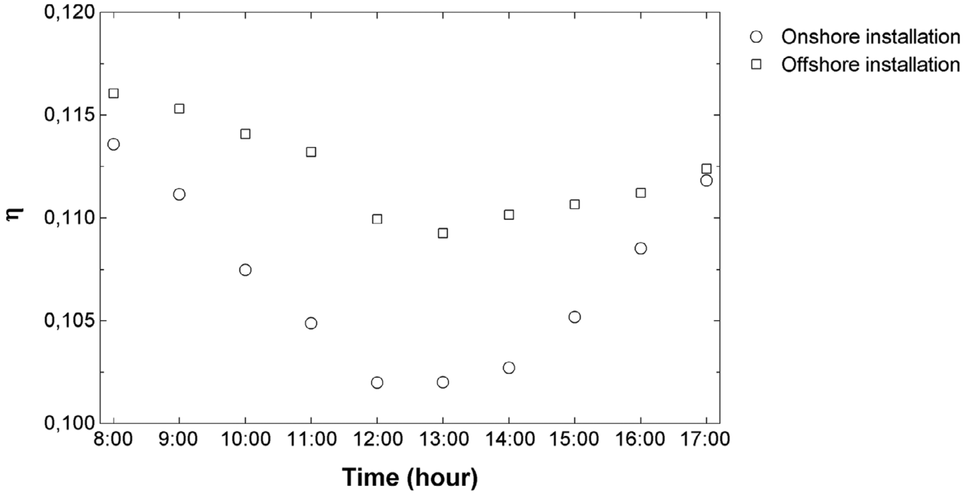

FIGURE 9 Efficiency. Onshore and offshore installation.

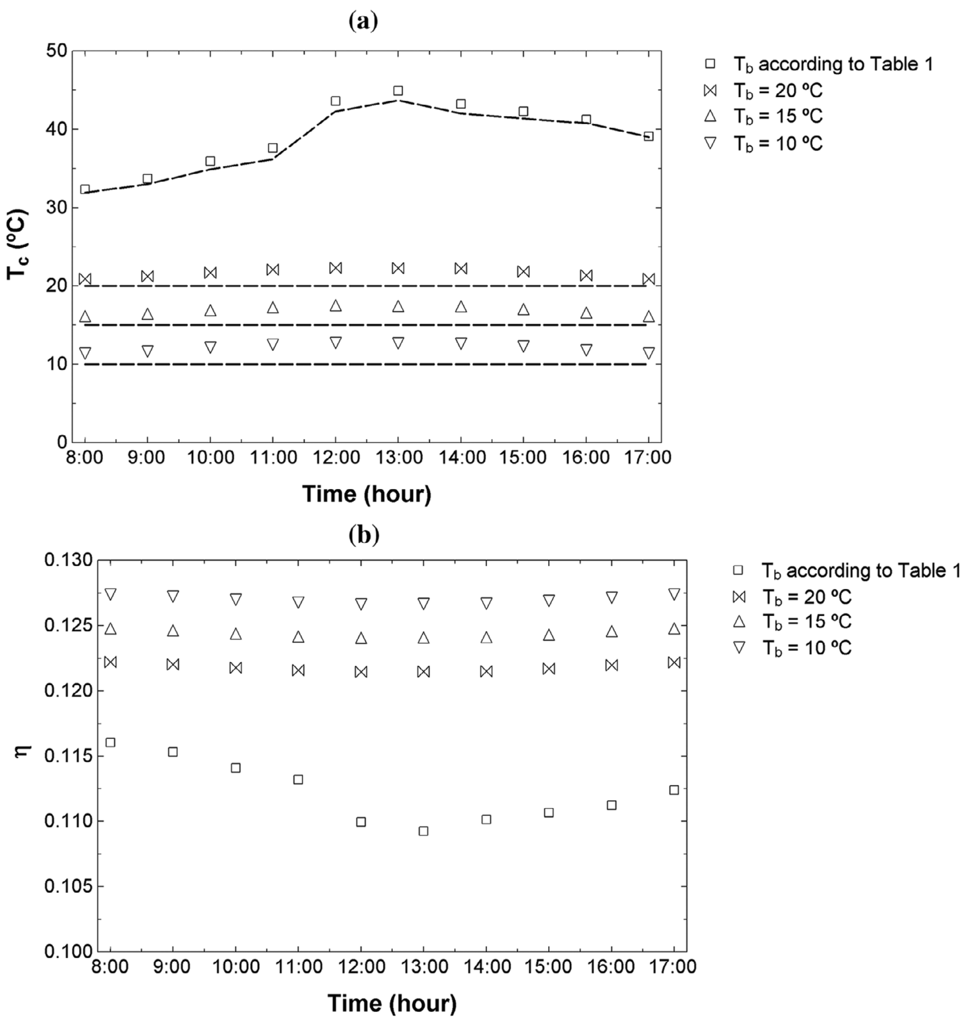

FIGURE 10 Influence of the water temperature. Offshore installation. (a) Average temperature of the solar cell; (b) efficiency.

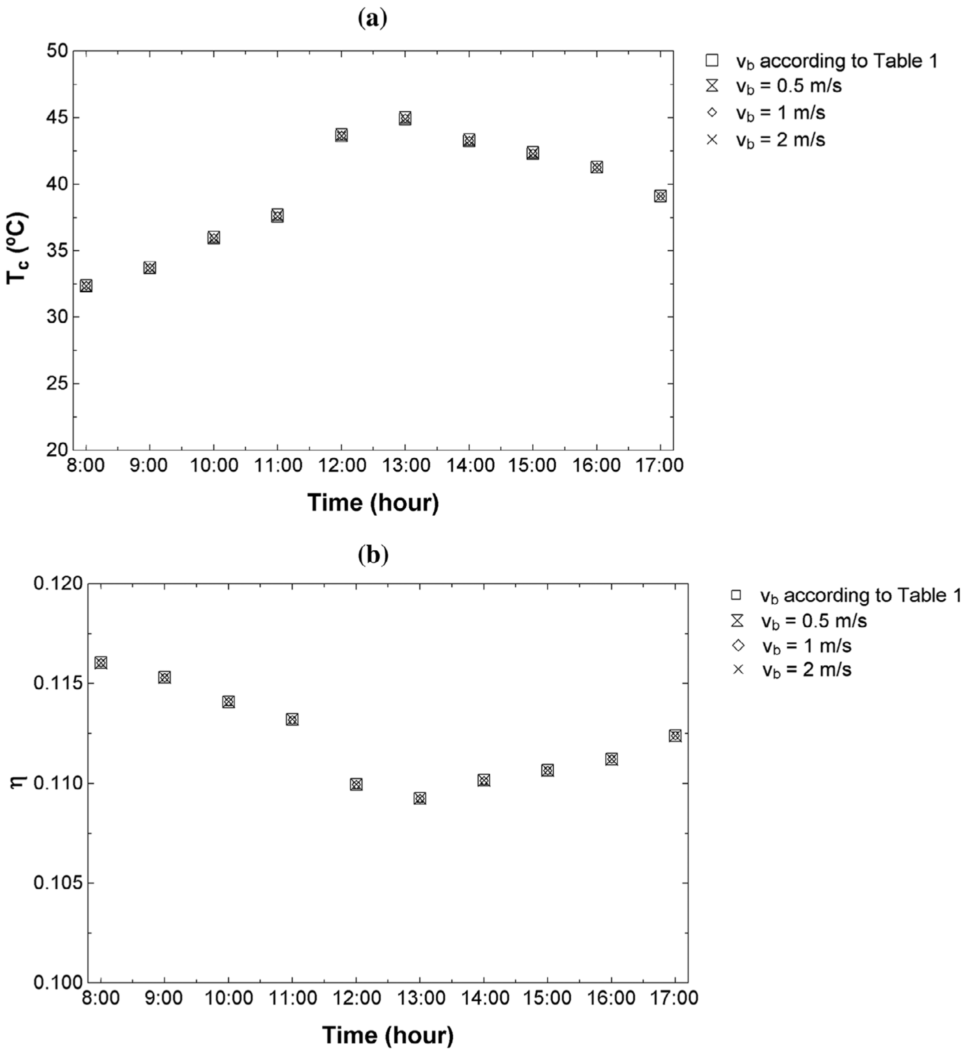

FIGURE 11 Influence of the water velocity. Offshore installation. (a) Average solar cell temperature; (b) efficiency.

shown in Figures 10a and 10b, respectively. For illustrative purposes, these T_b temperatures are also shown as dotted lines in Figure 10a. These figures show that the water temperature has an important influence on the cell temperature and thus on the efficiency. In particular, the average efficiencies obtained in Figure 10b are 0.112 (11.2%), 0.122 (12.2%), 0.124 (12.4%), and 0.127 (12.7%) for T_b according to Table 1, 20, 15, and 10°C, respectively. This finding underscores the importance of maintaining optimal water temperatures to maximize energy production.

Another interesting aspect to analyse is the effect of the water velocity, v_b. The values corresponding to Table 1 were compared with current velocities of 0.5, 1, and 2 m/s. The results of the average cell temperature and efficiency are shown in Figures 11a,b. As can be seen, the water velocity has a negligible effect on the results, providing practically the same solar cell temperatures and efficiencies for all of these current velocities analysed. As mentioned above, the effect of water velocity on the temperature and efficiency can be attributed to the dominant role of convective heat transfer mechanisms in the cooling process. While increased water flow can enhance convective heat transfer, thereby facilitating heat removal from the PV panels, the current velocities analysed (0.5, 1, and 2 m/s) may not be sufficient to overcome the threshold needed for noticeable changes in heat transfer rates. At low to moderate flow rates, the convective heat transfer coefficient does not substantially increase, as the turbulent flow regime, which significantly enhances heat transfer, may not fully develop. To further elucidate the impact of water velocity, it would be beneficial to explore higher flow rates, where the convective effects are expected to become more pronounced, leading to lower solar cell temperatures and higher efficiencies.

4 | CONCLUSIONS

The efficiency of PV panels is well documented to be temperature dependent, leading to a growing interest in optimizing cooling methods to enhance their performance. One emerging approach is the installation of PV modules in aquatic environments, where the cooling potential of water reduces the panel temperatures and, consequently, increases efficiency. In this study, a comprehensive CFD model was developed to characterize the thermal behaviour of offshore PV installations, addressing the existing gap in detailed heat transfer analysis for such systems.

The developed CFD model showed that offshore PV installations exhibit higher efficiencies than their onshore counterparts, especially when exposed to low water temperatures. Particularly, the solar cell temperature in offshore conditions was 39.11°C, compared to 45.5°C for onshore panels. Over a day analysed, the average efficiency improved from, 10.7% to 11.2% for the conditions studied in the present work. This improvement is largely attributed to the enhanced cooling mechanisms provided by the water environment. In addition, in practical applications offshore PV panels benefit from great cooling mechanics provided by strong wind and water currents, which result in lower operating temperatures for the PV modules compared to onshore installations. Briefly, the main key findings found in the present work are:

- The CFD model successfully captures the heat transfer between the PV panel and the surrounding water, illustrating the dissipation of heat away from the panel.
- The simulation showed that water as a cooling medium has a clear advantage over air, resulting in lower panel temperatures and higher overall efficiency. This finding supports the potential of offshore PV installations to improve solar energy generation, particularly in colder water environments.
- These findings underscore the significance of temperature management in offshore PV installations and their potential to outperform traditional onshore systems in terms of efficiency. It was found that the efficiency increased from 11.2% to 12.7% when the water temperature was reduced from 20 to 10°C. Optimizing offshore PV installations for cooler waters can yield further efficiency gains. In conditions where the water temperature approached ambient air temperatures, the cooling effect was diminished, suggesting that offshore installations are most advantageous in cooler water environments or regions with strong water currents.
- It was found that potential ecosystem impacts due to changes in water temperature from the presence of PV panels were negligible, suggesting that offshore installations could be deployed with minimal environmental disruption.

This finding underscores the potential of offshore installations to contribute significantly to renewable energy generation and contributes to a deeper understanding of the thermal behaviour of offshore PV panels. This methodology can be further refined and adapted for various different configurations and environmental conditions, paving the way for innovative cooling strategies. The results of this research can inform policy makers and stakeholders in the renewable energy sector about the potential benefits of investing in offshore solar technologies, contributing to the diversification of energy sources and enhancing energy security. While these results advance the understanding of heat transfer in offshore PV systems, there are several avenues for future research that could further enhance this methodology and its practical applications:

- A detailed analysis of floatability and structural stability of offshore PV systems.
- Expanding the scope to analyse multiple PV modules in a larger array, capturing the collective effects on heat transfer and cooling. Although this study modelled only a single PV panel, the approach provides a solid foundation for future research on larger-scale offshore PV arrays
- Investigating the environmental impact in stagnant or near-stagnant water bodies such as lakes, where cooling dynamics differ significantly from marine environments.
- Exploring alternative module configurations, such as inclined panels or installations on floating platforms, to optimize cooling and energy capture.
- Incorporating the effects of waves and surface dynamics, which may influence the heat exchange between the PV panels and surrounding water.
- Assessing the durability and performance of materials specific to marine environments, where factors like corrosion, saltwater exposure, and biofouling could affect long-term performance.

AUTHOR CONTRIBUTIONS

Pablo Rubial-Yáñez: Writing—review & editing. **Luis García-Rodríguez**: Writing—review & editing. **María Isabel Lamas-Galdo**: Writing—review & editing. **Laura Castro-Santos**: Writing—review & editing. **Almudena Filgueira-Vizoso**: Writing—review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

Laura Castro-Santos https://orcid.org/0000-0001-9284-1170

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