

Original Research

NUMERICAL ASSESSMENT OF THE IMPACT OF FLOATING PHOTOVOLTAIC SYSTEMS ON LAKE THERMAL REGIME

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Abstract

This study examines the impact of floating photovoltaic (FPV) systems on lake thermal conditions using numerical modelling. A comparative analysis between a reference scenario without FPV coverage and a scenario with 50% surface coverage was performed using both one-dimensional (1D) and three-dimensional (3D) modelling approaches. The 1D model was applied to simulate vertical temperature profiles based on the assumption of dominant vertical heat transport and rapid horizontal mixing. It included key heat transfer processes such as shortwave and longwave radiation, latent and sensible heat fluxes, precipitation, and convective and conductive exchanges between the atmosphere and water column. In FPV scenarios, an additional greenhouse effect beneath photovoltaic modules was considered. The 3D modelling framework complemented the analysis by providing a spatially resolved representation of lake thermo-hydrodynamics. Computational domains were generated from bathymetric data and discretized using ICEM CFD, resulting in meshes of approximately 5 million elements per domain. Results indicate that FPV coverage modifies the lake's thermal balance by reducing solar radiation input and altering surface heat exchange processes. The strongest effects were observed in intermediate depths (5–20 m), where temperature reductions reached approximately 2 °C, particularly during peak summer conditions and late afternoon hours. In deeper layers (below 30 m), FPV influence was minimal. Overall, FPV systems significantly affect thermal stratification and vertical temperature distribution, primarily through reduced surface heating.

Keywords: floating photovoltaic, lake thermal regime, thermal stratification, numerical modelling, heat transfer.

INTRODUCTION

Lakes represent a fundamental component of the hydrosphere, acting as reservoirs and transport pathways for energy and matter between atmospheric, terrestrial, and aquatic systems. Due to their high thermal inertia and relatively long water residence times compared to other inland water bodies such as rivers and lagoons, lakes play an important role in regulating regional hydrological and climatic processes. In addition to their ecological significance, lakes provide essential ecosystem services, including freshwater supply, biodiversity support, recreation, and energy production. However, increasing anthropogenic

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pressures and climate-related changes continuously alter the physical and chemical characteristics of lake ecosystems, among which thermal conditions are particularly sensitive indicators of environmental change [1].

The thermal regime of a lake is governed by the balance between heat gains and losses, commonly expressed as the net heat flux exchanged between the lake and its surrounding environment. These processes are strongly influenced by meteorological conditions, solar radiation, wind-induced mixing, and hydrological inputs, resulting in temporal variability ranging from diurnal to seasonal and long-term climatic scales. Most heat exchange occurs at the air-water interface through shortwave and longwave radiation, sensible and latent heat fluxes, and evaporative cooling. Changes in these processes directly affect lake temperature profiles, thermal stratification, mixing dynamics, dissolved oxygen distribution, and overall ecosystem functioning [1].

In recent years, floating photovoltaic (FPV) systems have emerged as an increasingly attractive renewable energy solution due to their ability to generate electricity without occupying valuable terrestrial land resources. FPV installations are particularly suitable for artificial reservoirs and mining lakes, where large water surfaces can be utilized for solar energy production while potentially reducing evaporation losses. Nevertheless, the placement of FPV systems on lake surfaces modifies the radiative and turbulent heat exchange processes between water and atmosphere. By partially shading the water surface and altering local airflow conditions, FPV systems may influence water temperature, thermal stratification, and mixing processes, thereby affecting the ecological and physical dynamics of lakes.

To assess such impacts, various numerical modeling approaches have been developed for simulating lake thermal conditions. One-dimensional (1D) and three-dimensional (3D) hydrodynamic models are widely used to reproduce thermal stratification, vertical temperature profiles, and lake-atmosphere interactions. Wang *et al.* [2] applied a 1D model to simulate thermal stratification in Lake Qiandaohu using time-dependent light attenuation coefficients and turbulent diffusivity parameters. Similarly, Šarović *et al.* [3] developed a 1D model for warm monomictic lakes and demonstrated its applicability for both short-term and long-term thermal simulations. Gaillard *et al.* [4] evaluated a multi-column lake model for Lake Geneva as a computationally efficient alternative to fully 3D approaches, while Gu *et al.* [5] and Tasnim *et al.* [6] compared the performance of 1D and 3D models in simulating thermal and oxygen dynamics.

Alongside advances in lake thermal modeling, recent studies have increasingly focused on understanding the thermal impacts of FPV systems. Exley *et al.* [7], using the MyLake model, showed that FPV installations generally reduce surface water temperatures, shorten stratification periods, and increase mixing depth, with the magnitude of impacts depending on the extent of surface coverage and system configuration. Liu *et al.* [8] reported that FPV systems cool surface waters during daytime while retaining heat during nighttime, thereby reducing diurnal temperature variability and altering local microclimatic conditions. Field measurements by Ilgen *et al.* [9] confirmed that FPV systems can cool upper water layers by up to 2.8 °C during daytime conditions. Furthermore, Yang *et al.* [10] demonstrated that FPV installations reduce incoming shortwave radiation while enhancing longwave heat retention beneath photovoltaic modules, leading to modifications in the lake heat balance.

In this context, the present study investigates the potential influence of floating photovoltaic installations on the thermal regime of an artificial lake system. The primary objective is to quantitatively evaluate how different FPV coverage scenarios affect water temperature distributions, vertical thermal profiles, and seasonal thermal stratification. By applying established thermal modeling approaches and considering site-specific hydrological and meteorological conditions, the study aims to contribute to the broader understanding of FPV-lake interactions and to support the environmentally sustainable implementation of floating solar technologies.

1D MODEL

One-dimensional (1D) lake models are widely used for simulating thermal processes and vertical temperature dynamics in lakes. These models can be applied at the deepest part of a lake while accounting for the hypsographic curve, which describes the variation of lake surface area with depth, or they may rely on simplified geometric assumptions when detailed bathymetric data are unavailable. In such cases, the lake geometry is often approximated by an equivalent cylinder with a constant surface area equal to the lake surface area and an average depth. Alternatively, a simplified conical representation may be used when only the lake surface area and maximum depth are known.

Depending on the availability of observational data, 1D models can be calibrated either as whole-lake average models or as models representing individual measurement locations. This approach is particularly suitable for small and deep lakes, where vertical thermal variability dominates over lateral variability. The underlying assumption of 1D models is that horizontal mixing processes rapidly homogenize the water body, resulting in negligible horizontal density gradients and allowing the thermal structure to be described primarily along the vertical axis.

In this study, a 1D thermal model was applied to investigate the vertical temperature dynamics under scenarios without and with floating photovoltaic (FPV) coverage. The simulations incorporated the main heat transfer mechanisms governing lake thermal conditions, including shortwave and longwave radiation, latent and sensible heat fluxes, precipitation effects, and convective and conductive heat exchange between air and water layers. For scenarios involving FPV coverage, the additional greenhouse effect beneath the photovoltaic modules was also taken into account. The resulting vertical temperature distributions for the scenarios without and with FPV coverage are presented in Figures 1 and 2, respectively.

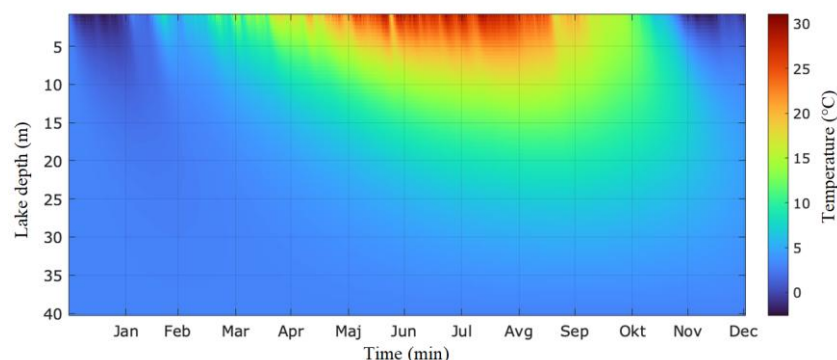


Figure 1 The vertical temperature distributions for the scenarios without FPV

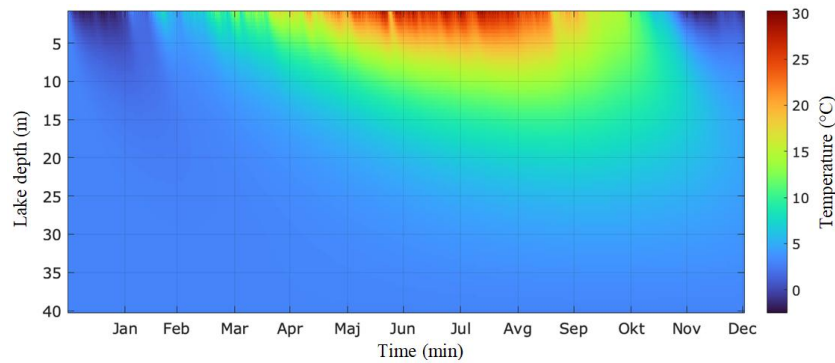


Figure 2 The vertical temperature distributions for the scenarios with FPV

3D MODEL

Three-dimensional (3D) models are used to simulate the complete thermo-hydrodynamic behavior of lakes, providing a realistic and detailed representation of the processes occurring within the water body. These models are particularly suitable for large water bodies or for simulations of specific processes where a high level of accuracy is required. In addition to temperature distribution, 3D models enable the simulation of flow fields and circulation patterns, allowing for a comprehensive understanding of lake dynamics.

The application of 3D models requires substantial computational resources as well as the availability of spatially distributed data for the specification of boundary conditions and model validation. Despite these requirements, 3D models provide valuable insight into complex physical processes in lakes and represent an important tool for both scientific research and water body management. For the present study, lake bathymetry was provided in LAS format and used to generate the computational geometry of the lake domain. Using the SolidWorks software package, two computational domains were created: the first representing the current lake conditions without floating photovoltaic (FPV) coverage, and the second representing a scenario with 50% surface coverage by FPV installations, as illustrated in Figure 3.

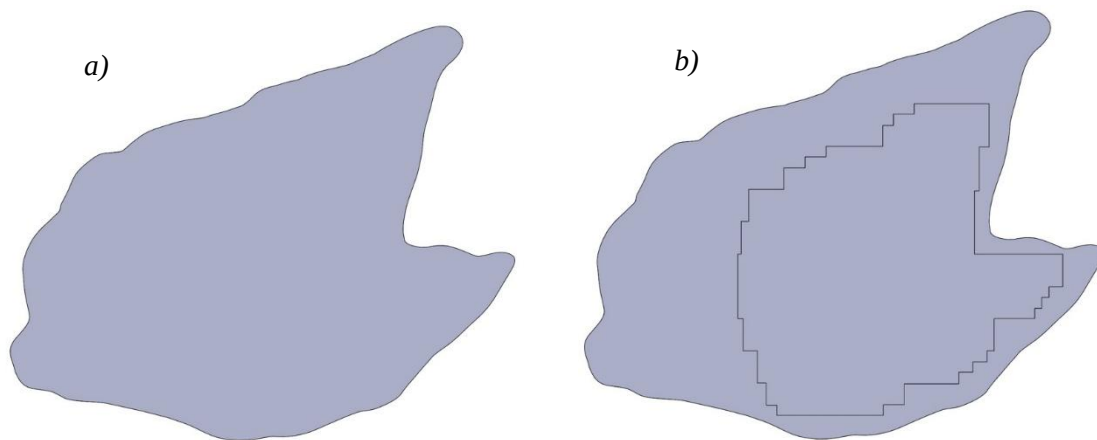


Figure 3 a) Representation of the current lake conditions without FPV coverage; b) a scenario with 50% surface coverage by FPV installations

Computational meshes for both domains were generated using the ICEM CFD software package. Due to the geometric complexity of the lake bathymetry, the domains were discretized using tetrahedral elements. In the horizontal directions (x and y), the computational domain was meshed with an element size of 5 m, as shown in Figure 4.

In the vertical direction (z-direction, corresponding to depth), a prism-layer mesh was applied near the lake surface to improve the resolution of thermal stratification processes. For the upper 20 m of the water column, a vertical element height of 0.5 m was prescribed, while below 20 m depth the element height was gradually increased to 5 m. The final computational mesh consisted of approximately 5 million elements.

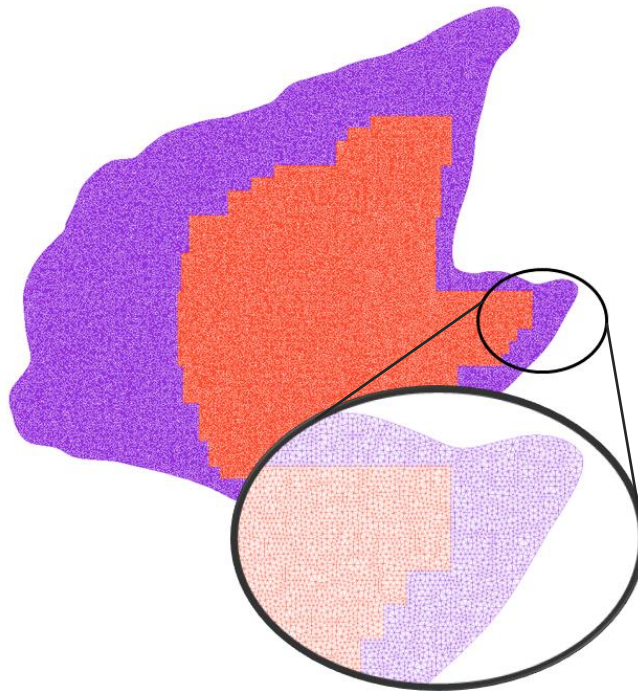


Figure 4 Computational domain mesh

The results of the 3D model analysis of vertical water temperature conditions under scenarios without and with floating photovoltaic (FPV) coverage are presented. The temperature calculations were based on governing equations which incorporate the main heat transfer mechanisms, including shortwave and longwave radiation, latent and sensible heat fluxes, precipitation effects, as well as convective and conductive heat exchange between air and water layers.

For both scenarios, transient simulations were performed using the Ansys CFX software package, which enables spatially resolved analysis of lake thermal conditions. The simulations were conducted for the warmest day of the year using a temporal resolution of 5 minutes. No-slip wall boundary conditions were prescribed at all solid domain surfaces, while a heat flux boundary condition was applied at the lake surface based on the equations used in the 1D model.

Table 1 demonstrates that FPV coverage influences lake water temperature differences (ΔT), with the magnitude of the effect depending on both time of day and water depth. At

06:00, the influence of FPV coverage is the smallest due to the low solar radiation intensity during the early morning hours. The smallest temperature difference was observed at a depth of 0.5 m ($-0.44\text{ }^{\circ}\text{C}$), while the largest difference occurred between depths of 5 m and 10 m ($-1.97\text{ }^{\circ}\text{C}$). At 12:00, when solar radiation intensity reaches its maximum, the temperature differences increase. The smallest temperature difference remained at 0.5 m depth ($-0.52\text{ }^{\circ}\text{C}$), whereas the largest difference was again observed between 5 m and 10 m depth ($-1.97\text{ }^{\circ}\text{C}$).

Table 1 Average water temperature differences between scenarios with and without FPV coverage at different lake depths at 06:00, 12:00, and 18:00

Depth/Time	6:00	12:00	18:00
0.5 m	- 0.44 $^{\circ}\text{C}$	- 0.52 $^{\circ}\text{C}$	- 0.97 $^{\circ}\text{C}$
0.5 m – 2 m	- 1.01 $^{\circ}\text{C}$	- 1.18 $^{\circ}\text{C}$	- 1.38 $^{\circ}\text{C}$
2 m – 5 m	- 1.73 $^{\circ}\text{C}$	- 1.73 $^{\circ}\text{C}$	- 1.73 $^{\circ}\text{C}$
5 m – 10 m	- 1.97 $^{\circ}\text{C}$	- 1.97 $^{\circ}\text{C}$	- 1.97 $^{\circ}\text{C}$
10 m – 20 m	-1.69 $^{\circ}\text{C}$	-1.69 $^{\circ}\text{C}$	-1.69 $^{\circ}\text{C}$
20 m – 30 m	-0.85 $^{\circ}\text{C}$	-0.85 $^{\circ}\text{C}$	-0.85 $^{\circ}\text{C}$
30 m – 40 m	- 0.22 $^{\circ}\text{C}$	- 0.22 $^{\circ}\text{C}$	- 0.22 $^{\circ}\text{C}$

The greatest temperature differences occurred at 18:00, when the cumulative daytime heating effect in the scenario without FPV coverage reached its maximum. In the reference scenario without FPV, the lake surface was exposed to direct solar radiation throughout the day, resulting in higher water temperatures compared to the FPV-covered scenario, where the photovoltaic modules reduced incoming solar radiation. Consequently, the largest temperature differences between the two scenarios were observed during the evening hours, when the accumulated thermal effect was most pronounced. The smallest temperature difference at this time occurred between depths of 30 m and 40 m ($-0.22\text{ }^{\circ}\text{C}$), while the largest difference remained between 5 m and 10 m depth ($-1.97\text{ }^{\circ}\text{C}$).

Overall, the most significant temperature reductions were observed within the intermediate depth range between 5 m and 20 m, where temperature differences ranged from approximately $-1.69\text{ }^{\circ}\text{C}$ to $-1.97\text{ }^{\circ}\text{C}$. These results confirm that FPV coverage substantially reduces water temperatures within these layers, whereas its influence becomes considerably weaker in deeper parts of the lake.

CONCLUSION

This study investigated the influence of floating photovoltaic (FPV) coverage on the thermal conditions of a lake system, with particular emphasis on seasonal temperature variability and the effects of partial surface coverage. Two scenarios were analyzed: a reference case without FPV coverage and a scenario with 50% surface coverage, enabling a comparative assessment of the impact of FPV installations on lake warming and cooling processes.

The analysis of the warmest day of the year, 20 June, demonstrated that the most pronounced temperature differences between the two scenarios occurred within the water layers between 5 m and 20 m depth, where reductions in water temperature ranged from approximately $-1.69\text{ }^{\circ}\text{C}$ to $-1.97\text{ }^{\circ}\text{C}$. These results indicate that FPV coverage has the

strongest influence within the intermediate water layers, primarily due to the reduction of incoming solar radiation and the consequent limitation of daytime water heating beneath the photovoltaic modules. In deeper layers below 30 m depth, the impact of FPV coverage was considerably smaller, with temperature differences remaining below $-0.22\text{ }^{\circ}\text{C}$, suggesting that reduced warming of the upper water layers has only a limited influence on deeper thermal conditions.

The largest temperature differences were observed during the late afternoon hours, when the cumulative daytime heating effect in the reference scenario without FPV coverage was most pronounced. The stronger solar energy absorption in the uncovered scenario resulted in significantly warmer water temperatures compared to the FPV-covered case. Consequently, the influence of FPV installations on the thermal regime was most evident within the upper and intermediate layers of the water column, while remaining negligible in deeper regions of the lake.

The obtained results confirm that FPV systems modify the thermal balance of lakes primarily through the reduction of incoming solar radiation and the suppression of surface water warming. The simulations indicate that FPV coverage can reduce water temperatures by approximately $2\text{ }^{\circ}\text{C}$ within intermediate depth layers, which may have important implications for lake thermal stratification, mixing processes, and aquatic ecosystems.

Overall, the study provides a comprehensive assessment of the impact of floating photovoltaic installations on lake thermal conditions and contributes valuable information for future environmental evaluations and sustainable spatial planning of FPV systems.

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