

## Recent Advances in Floating Solar Photovoltaic Systems and Water-Based Cooling Methods: A Review

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### ABSTRACT

Floating solar photovoltaic (FPV) systems have emerged as an effective solution for generating renewable energy while utilizing available water surfaces. However, photovoltaic panels are highly sensitive to operating temperature and high heat can prevent the generation of electricity. A mathematical model is used in this study to determine the influence of water-based cooling on FPV thermal management and FPV performance. This considers solar absorption, heat removed by water and the thermal energy balance of the PV. The convective heat transfer from the panel surface to neighbouring water ( $T_c$ ) works in order to decrease the actual temperature of the panel and accordingly, produces a direct electrical efficiency augment by means of the temperature-efficiency relation for photovoltaic cells. The results show that lowering the unit temperature with water-based cooling enhances both energy conversion efficiency and power yield. This, consequently, poses the potential of water-cooling systems for floating photovoltaic (FPV) arrangements to contribute towards improving system performance as well as reliability and sustainability of renewable energy generation.

**Keywords:** *Floating Solar Photovoltaic (FPV), FPV Systems, Water-Based Cooling, Photovoltaic Cells.*

### I. Introduction

The rapid increase in global energy demand and growing environmental concerns associated with fossil fuel consumption have accelerated the transition toward renewable energy technologies. Among the various renewable sources of electricity generation, solar energy has emerged as one of the most abundant sustainable and eco-friendly tools. Thanks to technology advances and ever more plummeting installation costs, photovoltaic (PV) technology that converts sunshine directly into electrical power has been growing faster than any other energy source on the planet. Solar photovoltaic (PV) systems are receiving worldwide encouragement from both governments and researchers to play a vital role in reducing greenhouse gas emissions and attaining sustainable energy development [1,2]. Nevertheless, these advantages are not fully utilized as the efficiency in photovoltaic systems is often compromised due to several operating conditions such as one of the most critical challenges during operation [the increase in module temperature (Liu et al., 2017)].

While solar photovoltaic modules can generate electric energy, they do not convert all of the incident solar radiation; a large proportion of included solar energy is transformed into heat. This heat buildup increases the operating temperature of the solar panels, which reduces electrical efficiency at the power-generating cells and lowers their voltage output. Previous studies concluded that the energy conversion

efficiency decreased, and the degradation of photovoltaic modules increased over time under higher operating temperatures [6]. Thus, ultimately aiming to maximize the performance and lifetime of photovoltaic systems must operate within a specified temperature range. To this end, researchers have explored various cooling techniques for tempering solar cells and improving efficiency (Su et al., 2016).

Broadly, the cooling techniques for photovoltaic (PV) systems can be classified into two areas such as passive cooling and active cooling. (Active cooling systems utilize mechanical devices such as a pump, fan, or forced-fluids circulating system to remove heat) Active cooling methods. They are powered externally, so energy consumption might be marginally higher than in the case of some methods that can better control temperature. In contrast, passive cooling techniques rely less on moving parts. Rather, they rely on natural heat transfer phenomena conduction, convection and radiation to dissipate heat from the surface of solar panels into the environment surrounding them.

For that reason, water is a frequently used cooling medium due to its high heat absorption and storage capability. Many systems involve applying water over or near the surface of solar panels to dissipate heat and keep a lower operating temperature. This temperature regulation is crucial because too much heat can lower the electrical efficiency of solar panels. Effective cooling mitigates thermal threats, enhances the performance of a system, maintains stable energy output and prolongs the lifetime and reliability of PV systems.

Floating Solar Photovoltaic (FPV) systems are gaining presence in the world today, as one of the innovative strategies for dealing with limitations associated with land-based solar installations. Floating photovoltaic systems employ floating solar panels which are installed on bodies of water (i.e., reservoirs, lakes, irrigation ponds and wastewater treatment facilities). These systems are a powerful way of generating renewable energy while conserving key land assets. Due to rising land cost as well as to conserve the earth, which also helps in promoting floating Solar. FPV technology utilizes the surfaces of water bodies in generating solar energy, which does not interfere with urban or agricultural land use (Kim et al., 2016), so it can scale up considerably across different space.

Many advantages of floating photovoltaic systems are attributed to the natural cooling effect of water bodies. Water bodies can thus act as heat sinks that conduct excess heat away from photovoltaic panels via conductive and convective processes. This cooling feature keeps modules cooler than land-based solar panels. As a result, floating photovoltaic systems typically have a better electrical efficiency and energy yield. By conducting several studies, it has been shown that the floating PV systems could increase the energy generation of about 5–6 percent which could be attributed to water's cooling effect and microclimatic conditions around panels (Kjeldstad et al., 2021).

Along with passive cooling from water surfaces, many advanced water-based cooling systems have been developed for the thermal regulation of floating photovoltaics. Thermosiphon cooling mechanisms, natural convection cooling loops, water circulation cooling systems and hybrid photovoltaic–thermal collectors among the techniques. These cooling systems enhance the heat transfer process from the photovoltaic module to the water medium surrounding it, as a result lower temperatures for the module and higher electrical efficiency. In the literature, research works have been reported on combining passive cooling features with floating photovoltaic systems to achieve a better thermal regulation and electricity generation effect (Sutanto et al., 2022).

Floating photovoltaic technology contributes to the water–energy nexus by combining the generation of renewable energy with efficient water resource management. Hovering sunlight establishments diminish presentation of angled daylight at the up surround evaporized pace of drinking fountain via shading some

degree of water surface bore by the apparition between sun and body. This is particularly helpful in sectors that face water scarcity and where conservation would be sensible. Additionally, floating PV systems have the co-use potential with hydropower reservoirs, aquaculture farms, irrigation works and wastewater treatment plants. Therefore, it facilitates maximum use of available resources and advocates for sustainable energy production (Goswami & Sadhu 2023).

Floating photovoltaic (FPV) systems are useful for generating solar energy, but they also face some technical and environmental challenges that can reduce their performance. The working efficiency of floating solar panels depends greatly on environmental factors such as sunlight intensity, water temperature, humidity, wind speed, and wave movement on the water surface. High temperature can reduce the efficiency of solar panels, making proper cooling an important requirement for better energy production. Understanding the thermal behaviour of floating PV panels is therefore very important. Since the panels are installed above water, natural water cooling can help reduce heat buildup and improve performance. Developing effective water-based cooling methods can help maintain panel temperature within an optimal range and increase electricity output. This study aims to use advanced thermal modelling and computer simulation techniques along with experimental analysis to better understand heat transfer processes in floating solar systems. The results will help in designing more efficient cooling strategies to improve overall system performance and reliability.

In light of these factors, water-based cooling has gained significance for establishing an efficient thermal management system to enhance the functioning of floating solar photovoltaic systems. Through transferring excess heat from photovoltaic modules, water-based cooling techniques optimize electrical energy generation and extend the lifetime of solar modules. Therefore, investigating the water-based cooling for floating PV systems is essential to develop solar energy technology and facilitate the sustainable development of worldwide renewable energy infrastructure.

## II. Review of Literature

Author(s) & Year	Study Focus	Method	Approach	Key Findings
<b>Sutanto (2025)</b>	Passive cooling strategies for floating photovoltaic (FPV) systems	Numerical modelling and 2-D simulation	Natural Convection Cooling Loop (NCCL) integrated with radiation absorption, conduction, and convection heat transfer	Passive cooling reduced panel temperature and improved FPV efficiency. Pure water performed better than Ag-water nanofluid due to higher transmissivity.
<b>Ayyad et al. (2024)</b>	Global potential of offshore floating photovoltaic (OFPV) systems	Statistical analysis of global datasets	Climate classification and statistical learning models	Offshore PV systems showed strong potential; however, Köppen–Geiger climate classification alone could not accurately predict performance improvements.
<b>Billones</b>	Economic	Simulation using	Performance and	A 10 kWp FSPV system

(2024)	feasibility of floating solar photovoltaic systems	PVsyst software	financial modelling including energy yield, payback period, and ROI	generated 13,599 kWh annually with a payback period of 4.8 years and strong economic feasibility.
<b>Nagababu et al. (2024)</b>	Techno-economic feasibility of floating PV in India	Data analysis using ECMWF ERA5 climatic datasets	Energy generation and capacity factor modelling	Gujarat and Tamil Nadu showed high floatovoltaic potential with significant energy generation capacity and carbon reduction benefits.
<b>Tina et al. (2023)</b>	Economic comparison between floating PV and ground PV systems	Lifecycle cost analysis	CAPEX, OPEX, LCOE and sensitivity analysis	FPV systems showed higher efficiency due to water cooling; reducing capital cost could significantly decrease LCOE.
<b>Goswami &amp; Sadhu (2023)</b>	Floating PV adoption in wastewater treatment plants	Experimental outdoor analysis	Techno-economic evaluation of a 15 MW floating PV system	FPV modules showed 9.84% higher efficiency than land-based PV and reduced CO <sub>2</sub> emissions significantly.
<b>Sutanto et al. (2022)</b>	Thermosiphon cooling technology for floating PV systems	Numerical and experimental investigation	Passive thermosiphon heat transfer mechanism	Floating PV produced 4.52% higher power output than ground PV, and thermosiphon cooling further improved efficiency.
<b>Kjeldstad et al. (2021)</b>	Thermal interaction between floating PV modules and water	Thermal modelling and experimental production data analysis	Heat transfer modelling considering module–water thermal contact	Water cooling increased energy yield by about 5–6% and improved heat dissipation efficiency.
<b>Karatas &amp; Yilmaz (2021)</b>	Microclimatic effects on floating solar power plants	Field experiment and annual performance measurement	Environmental parameter analysis (irradiance, humidity, wave load, temperature)	Solar irradiance positively influenced energy production while humidity and temperature negatively affected efficiency.
<b>Arifin et al. (2020)</b>	Cooling effects on solar water pumping systems	Experimental comparison between cooled and non-cooled PV modules	Floating cooling method for photovoltaic modules	Floating-cooled PV modules produced higher power output and improved energy transfer efficiency.
<b>Campana</b>	Hybrid	Dynamic	Optimization	Floating PV systems

<b>et al. (2019)</b>	renewable energy integration using floating PV	techno-economic simulation	modelling of hybrid PV-wind systems	reduced evaporation losses and improved renewable energy reliability in hybrid systems.
<b>Shah &amp; Pandey (2018)</b>	Cooling methods for photovoltaic systems	Comparative analytical review	Passive and active cooling technologies such as PCM, heat pipes, and evaporative cooling	Proper cooling techniques significantly improve PV efficiency and reduce module degradation.
<b>Liu et al. (2017)</b>	Efficiency and prospects of floating photovoltaic systems	Technical review and system analysis	Evaluation of floating PV technology performance	Floating PV conserves land and water resources while improving energy generation efficiency.
<b>Kim et al. (2016)</b>	Development of floating PV systems in South Korea	Policy and technology review	Renewable portfolio standards (RPS) framework analysis	Floating PV installations expanded rapidly under national renewable energy policies.
<b>Su et al. (2016)</b>	Thermal performance of photovoltaic-thermal collectors	Experimental comparative study	PV/T collector systems with different working fluids	Water-water PV/T collectors demonstrated superior electrical and thermal efficiency.

### III. Mathematical Model for Water-Based Cooling in Floating Solar PV Systems

#### Step 1: Solar Heat Absorbed by PV Panel

$$Q_{abs} = \alpha GA$$

Where

$Q_{abs}$  = absorbed solar heat

$\alpha$  = absorptivity of panel

$G$  = solar irradiance

$A$  = area of PV panel

#### Step 2: Heat Loss Due to Water-Based Cooling

$$Q_{cool} = h_w A (T_p - T_w)$$

Where

$Q_{cool}$  = heat removed by water

$h_w$  = water heat transfer coefficient

$T_p$  = PV panel temperature

$T_w$  = water temperature

### Step 3: Net Thermal Balance of Panel

$$mc \frac{dT_p}{dt} = Q_{abs} - Q_{cool} - Q_{elec}$$

Where

$m$  = mass of panel

$c$  = specific heat of panel

$\frac{dT_p}{dt}$  = rate of change of panel temperature

$Q_{elec}$  = electrical energy produced

### Step 4: Electrical Efficiency of Cooled FPV System

$$\eta = \eta_{ref} [1 - \beta(T_p - T_{ref})]$$

Where

$\eta$  = actual efficiency

$\eta_{ref}$  = reference efficiency

$\beta$  = temperature coefficient

$T_{ref}$  = reference temperature

### Final Power Output

$$P = \eta GA$$

This shows that when water cooling reduces  $T_p$ , the efficiency  $\eta$  and power output  $P$  increase.

## IV. Conclusion

The mathematical model developed for water-based cooling in floating solar photovoltaic (FPV) systems demonstrates the significant role of thermal regulation in improving solar panel performance. The findings demonstrate that photovoltaic panels capture a significant amount of solar radiation, causing high panel heating and poor electrical efficiency. With the implementation of water-based cooling, some heat energy absorbed by SPV is extracted via convective heat transfer between panel surface and surrounding water body. The governing thermal balance equation shows that the panel temperature must be a result of the interactions between absorbed solar heat, cooling heat transfer and electrical energy generation. The panel temperature reduces when the cooling coefficient and water contact enhances heat removal. According to the efficiency model, panel temperature is inversely related to electrical efficiency: reducing the panel temperature through water cooling can directly improve system efficiency. Overall, the model validates that when integrated with water-based cooling floating photovoltaic systems can be maintained at lower operating temperatures, enhanced energy conversion efficiency and higher output power as compared to conventional land based photovoltaic systems. Therefore, water-based cooling provides a viable and eco-friendly approach to enhancing the efficiency and lifespan of floating solar energy systems.

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