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A Study on Water-Based Cooling and Thermal Efficiency in Floating Solar Photovoltaic Systems

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ABSTRACT

Floating solar photovoltaic (FPV) systems have emerged as an innovative solution to address the limitations of conventional land-based solar installations while improving energy efficiency. An important problem of photovoltaic systems is the increase in panel temperature, which reduces electrical efficiency and power output. Water-based cooling assists the thermal management and operation of floating solar PV systems: a study Experimental and analytical methods are used to determine temperature differences, power generation, and efficiency in FPV systems using water-cooling models. Use of water to circulate across the rear surface of photovoltaic modules can help dissipate excess heat and keep operating temperatures lower. The cooled and non-cooled systems are compared through mathematical analysis and performance assessment. The results show that the water cooling leads to drop of panel temperature considerably, electrical efficiency enhancement and output energy increment. In addition, floating photovoltaic systems enjoy advantages like limited land consumption and reduction of water evaporation. We hope our findings based on the water-cooled floating solar photovoltaic system will encourage further studies towards the use of water-based cooling technology as a framework for enhancing the performance and sustainability of floating solar photovoltaic systems.

Keywords: *Floating Solar Photovoltaic, Water-Based Cooling, Thermal Management, Energy Efficiency, Renewable Energy.*

I. Introduction

The increasing global demand for sustainable and renewable energy sources has accelerated the development and deployment of solar photovoltaic (PV) technologies. Solar Energy is considered as one of the most enabling and cleanest energy resource that can provide an answer to the problems associated with climate change and energy security. However, traditional ground-mounted photovoltaic units have some constraints such as high operating temperatures, land availability and environmental effects. In photovoltaic, efficiency is highly dependent on high temperature conditions, small fraction of incoming solar radiation gets converted in the form of electrical energy while vast majority converts as thermal energy inside PV modules (Su et al., 2016). The increased operating temperature of solar cells due to excess heat accumulation, reduces their electrical performance. As a result, adequate thermal management techniques must be implemented to ensure photovoltaic performance and extend the lifetime of the systems.

Floating Solar Photovoltaic (FPV) systems offer a potential solution to address some of the limitations accompanying conventional land-based photovoltaic installations. FPV systems are deployed on water bodies, such as lakes, reservoirs, irrigation ponds and hydropower dams floating solar panels on anchoring structures float on water surface. This innovative technology offers an additional advantage of minimizing land footprint by using water environment around the sustainable designer as natural cooling. According to Sukarso and Kim (2020), water bodies typically have much lower temperatures than land-based surfaces, this leads to lower operating temperature of floating solar panels. Their research also revealed that floating photovoltaic systems may operate about 0.61% more efficiently than ground-mounted systems owing to the cooling effect of water.

One of the most significant benefits of floating photovoltaic systems is temperature reduction. It is well known that the electrical efficiency of photovoltaic panels can drop dramatically when operating in environments with high solar irradiance; indeed, under such conditions, panel temperatures may reach ~60°C (Majumder et al., 2023). Numerous cooling methods have been extensively studied to solve this issue, including passive cooling, active cooling, and hybrid thermal management methods. As an extremely effective technique for removing heat from photovoltaic modules, water-based cooling has been reported the most. Majumder et al. (2023) also noted that floating photovoltaic installations utilize natural water-based cooling mechanisms can enhance the efficiency of the system by almost 30% and at the same time reduce evaporation from reservoirs.

Recent analyses have also highlighted the importance of advanced cooling strategies in floating photovoltaic systems. Sutanto et al. This research developed a three-dimensional multi-physics thermal model which integrates both natural convection cooling loop and radiation filtering mechanism in the floating photovoltaic panels (2025). They found that by combining passive cooling with radiation filtering, they were able to reduce photovoltaic module temperatures by 15°C or more, increasing electrical efficiency by approximately 3%. The thermal convective cooling effect of the foraging unit indicated that the water-based thermal management made a substantial contribution to FPV systems, which accounted for nearly 64.48% thermal convective cooling effect from the study with respect to the total design of this passive unit under ideal layout.

I J A M S R
International Journal of
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Similarly, Pandian et al. (2024) Performance optimization of floating bifacial solar photovoltaic panels in tropical freshwater settings using response surface methodology and central composite design. According to their experimental results, freshwater cooling decreased panel temperatures by 1.43–2.72°C and increased bifacial photovoltaic efficiency up to 4.86%. The fresh water-cooling mechanism yielded a bifacial gain of about 3.19% higher than that of conventional cooling surfaces under solar irradiation of 950 W/m². The results clearly show that employing water-based cooling improves the operational performance and lifetime of floating solar photovoltaics.

Floating PV systems also provide significant environmental benefits and water resource management. Carvalho et al. research (2025) considered floating photovoltaic plants as one type in the frame of water–energy nexus and suggested that FPV systems produce clean electricity but also lower evaporation from reservoirs. WIDEs review showed that FPV installations can offer considerable water savings while additionally improving the efficiency of energy generation. Abdelal (2021) also showed that the installation of floating solar panels on agricultural irrigation ponds resulted in approximately 60% less evaporation losses with no negative impact on water quality while at the same time generating low-carbon electricity.

Massive deployment of floating photovoltaics has also proven its effectiveness to some extent, overcoming global challenges related to energy and water. Du et al. (2024) assessed the advantages of floating photovoltaic systems in 909 reservoirs in China, finding that coverage with FPV installations on around 30% of reservoir surfaces could yield approximately 1429.19 TWh harvested energy per year and save up to about 5.76 billion cubic meters of water concurrently. These results emphasize the large potential impact for FPV systems on sustainable energy transitions and water resource management.

Despite the benefits of floating photovoltaic (FPV) systems, several studies have been conducted highlighting possible adverse environmental effects on aquatic ecosystems. Ilgen et al. (2023) explored how FPV installations affect lake surface irradiance, wind flow, and thermal stratification respectively. FPV coverage was reported to lower surface solar irradiance by an estimated 73% and wind speed by about 23%, with slight impacts on lake thermal dynamics. Similarly, Yang et al. (2022) examined the impacts of floating solar panels on the hydrodynamics and water quality in a tropical reservoir, and noted the overall environmental effects were moderate and localized despite decreased light penetration and surface mixing occurring underneath panels.

Additionally, hybrid photovoltaic systems with integrated water-based cooling technologies have also been investigated to increase energy efficiency. For example, Mousavi et al. (2018) conducted research on a photovoltaic–thermal system combined with phase change materials and porous metal foam. The study showed that the water-cooled PV/T system had a maximum thermal efficiency of 83%, resulting in better temperature distribution over the surface of photovoltaic module. These findings highlight the importance of water-based cooling in keeping photovoltaic operating conditions at optimal levels.

In a wider energy systems context, hydropower plants can complement floating photovoltaic technology and vice versa, in addition to industry studies for further increase of renewable energy. Liu et al. 2019) proposed an integrated floating photovoltaic and pumped-storage power system capable of generating about 9112.74 MWh on a typical sunny day, which alleviates energy

IJAMSR
International Journal of
Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

imbalance, conserves land resources along with water resources. Similarly, Cazzaniga et al. Floating PV systems have been able to be integrated into the reservoir space, maximizing energy production by avoiding land-use conflicts and taking advantage of compensatory solar resources for hydropower plants (Qin et al.2019). Qin et al. (2019) [43] reported that if 10% of the total hydropower station surface area could be covered with FVP system in China, hydroelectric energy also would increase approximately 65%, indicating a potential mutual benefit between these renewable assets.

To sum up, cooling via water is a key component in the enhancement of thermal management and performance of floating solar photovoltaic systems. Due to the natural cooling alternatives of water bodies, lowered photovoltaic modules temperatures increase electrical efficiency and system durability. FPV systems also provide more environmental benefits: they require less land, reduce water evaporation and boost renewable energy generation. Whether for arrangement stability, optimal energy generation, less wasteful use of land surface or minimal ecological impact, the long-proposed concept thus rapidly moves on from just one type of implementation in water-covered spaces to a circular system as sustainable generator based not only on clean renewable resource, but also optimal positioning method with cutting-edge cooling technology. Research on system optimization, environmental issues, and planning for large scale deployment will continue so that floating solar photovoltaic systems can be rolled out in practice throughout the world.

II. Key Findings from Study

S. No.	Author & Year	Research Focus / Objective	Methodology / Approach	Key Findings
1	Sutanto et al. (2025)	Developed a thermal model for floating photovoltaic systems integrating passive cooling and radiation filtering.	Three-dimensional multi-physics thermal modelling with optimization of cooling channel height and tube spacing.	Integration of radiation filtering with passive cooling reduced panel temperature by up to 15°C, improved electrical efficiency by about 3%, and contributed 64.48% thermal convective cooling.
2	Carvalho et al. (2025)	Reviewed floating photovoltaic systems within the water–energy nexus.	Comprehensive literature review comparing FPV and ground-mounted PV performance.	Identified gaps in FPV evaporation studies and highlighted discrepancies between measured and simulated energy outputs. Hydropower reservoirs were the most common FPV sites.
3	Pandian et al. (2024)	Optimized floating bifacial solar photovoltaic panels in freshwater environments.	Response Surface Methodology (RSM) and Central Composite Design (CCD) experimental optimization.	Freshwater cooling reduced panel temperature by 1.43–2.72°C and improved bifacial efficiency by 4.34–4.86%.

4	Du et al. (2024)	Evaluated FPV potential for water conservation and carbon neutrality in China.	Reservoir database analysis and water footprint recovery modelling across 909 reservoirs.	FPV covering 30% reservoir surface could generate 1429.19 TWh electricity annually and save 5.76 billion m^3 of water.
5	Majumder et al. (2023)	Examined PV cooling technologies and their impact on FPV systems.	Review of active, passive, and hybrid cooling methods for PV panels.	Water-based cooling can improve FPV system performance by nearly 30% and reduce water evaporation by up to 60%.
6	Ilgen et al. (2023)	Studied ecological and thermal impacts of FPV systems on lake ecosystems.	Field measurements and simulation using the General Lake Model.	FPV reduced lake irradiance by 73% and wind speed by 23%, with minor thermal impacts on lake stratification.
7	López et al. (2022)	Assessed FPV deployment potential across freshwater bodies in Spain.	Geospatial analysis of water resources and solar irradiation.	FPV could supply 31% of Spain's electricity demand using 10% water surface coverage.
8	Yang et al. (2022)	Investigated hydrodynamic and water quality impacts of FPV systems.	3D hydrodynamic–ecological modelling combined with field measurements.	FPV installations increased water column stability and caused a minor temperature increase of 0.3°C beneath panels.
9	Abdelal (2021)	Examined FPV influence on water quality and evaporation in irrigation ponds.	Pilot-scale experimental system comparing covered and uncovered ponds.	Floating solar panels reduced evaporation by about 60% without negatively affecting water quality.
10	Sukarso & Kim (2020)	Evaluated cooling effects and economic feasibility of FPV systems.	Remote sensing analysis and economic performance modelling.	FPV panels operated 8°C cooler than ground systems and achieved 0.61% higher efficiency.
11	Liu et al. (2019)	Proposed integrated FPV and pumped storage power systems.	Dual-objective optimization using genetic algorithms.	System generated 9112.74 MWh electricity daily and saved 20.16 km^2 land and 19.06 million m^3 water annually.

12	Cazzaniga et al. (2019)	Investigated FPV integration with hydroelectric power plants.	Global assessment of FPV potential across major hydroelectric reservoirs.	Covering 10% reservoir area could increase hydroelectric energy production by about 65%.
13	Mousavi et al. (2018)	Studied thermal performance of water-cooled PV/T systems with phase change materials.	Numerical simulation using PCM-filled porous metal foam.	Achieved 83% thermal efficiency and 16.7% exergy efficiency with improved temperature uniformity.
14	Gaikwad & Deshpande (2017)	Discussed the importance of renewable energy due to global energy crisis.	Conceptual analysis of solar energy potential and floating PV technology.	Identified floating PV as a promising solution to reduce dependence on fossil fuels and control water evaporation.
15	Su et al. (2016)	Investigated performance of hybrid PV/T collectors with different cooling fluids.	Experimental comparison of air-water and water-water cooling systems.	Water-water PV/T collectors achieved the highest electrical and thermal efficiency among tested configurations.

III. Proposed Methodology

The present study adopts a quantitative experimental and analytical research design to investigate the effect of water-based cooling on the thermal management and electrical efficiency of floating solar photovoltaic (FPV) systems. Use of photovoltaic technology in water, or floating PV (FPV), has received considerable interest over time thanks to its potential for dual land use and the natural cooling effect from water that leads to a reduction in photovoltaic module temperature resulting in elevated efficiency (Sukarso & Kim 2020). This study investigates the cooling effects of water on photovoltaic panels and subsequently analyzes how it affects power generation and energy efficiency. Our two-salt ionic liquid is therefore a fit for floating PV systems, which should be installed on a fresh water reservoir or artificial water body (e.g. pond / lake) where the modules can safely float. The water surface serves as the support of the floating solar system and, at the same time, provides a natural cooling condition to afford dissipating heat from photovoltaic (PV) modules. These designs should have the stable water surface area, high solar irradiation exposure and easy monitoring to decide optimum for installation option as well as less shading from surrounding structures. Environmental parameters including solar radiation, flat plate temperature and wind speed are monitored throughout the study period to assess system performance.

The experimental system involves two scenarios (1) the floating photovoltaic system with water-based cooling and (2) a control system consisting of a conventional photovoltaic without cooling. A unique system for floating photovoltaic (FPV) application is proposed to overcome these heating challenges, which uses water circulation over the back surface of the panels to remove excess

IJAMSR
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excessive heat from solar radiation. Photovoltaic modules, floating platform structure, water circulation pump, cooling pipes and temperature sensors introduced into experiment in addition to solar irradiance sensor (pyranometer), devices for measuring voltage and current while measuring flow rate (digital flow meter) of distilled water as well as responsible indicators of temperature during experiments. Various studies have shown that water-based cooling can be an effective solution for improved PV module heat reduction and electrical performance (e.g., Majumder et al., 2023). There are various factors considered in the study. Independent variables are characterized by water flow, solar irradiance intensity, ambient temperature, water temperature and panel tilt angle. In turn the dependent variables are photovoltaic module temperature continual electrical power output, electrical efficiency and thermal efficiency. Conditions like panel type, orientation, and measurement duration were controlled to ensure valid comparisons of cooled vs. non-cooled systems. Data are acquired under the peaks of solar radiation using tools such as sensors and monitoring devices that measure parameters including but not limited to solar irradiance, ambient temperature, water or panel surface temperatures, voltage, current, electrical power output and water flow rate. Thermal performance analysis of cooled floating photovoltaic modules and also study on temperature difference provides better thermal management for improvement in system efficiency. In the pursuit of sustainable energy development with advanced scientific techniques, this comparative analysis exposes the benefits which can be gained from coupling floating solar photovoltaic systems with other passive renewable energy generation applications namely: water-based cooling techniques.

IV. Mathematical Approach

The mathematical approach of the present study is based on the thermal and electrical performance analysis of a floating solar photovoltaic system with water-based cooling. This is done to quantify the relation of panel temperature, water cooling and photovoltaic efficiency. Since the performance of photovoltaic modules significantly depends on operating temperature, mathematical modelling is used to calculate heat absorbed by the panel and heat removed from it through circulating water as well as it has been shown that this process can improve power output and efficiency.

Let the incident solar radiation on the photovoltaic panel be represented by G in W/m² and the effective area of the panel be A in m². The total solar energy received by the panel is expressed as:

$$Q_{in} = G \times A$$

where Q_{in} represents the total solar energy input to the panel.

The electrical power generated by the photovoltaic module is calculated by the basic electrical relation:

$$P = V \times I$$

where P is the output power in watts, V is the output voltage, and I is the output current. The electrical efficiency of the photovoltaic panel is then determined by the ratio of electrical power output to the total solar energy incident on the panel:

$$\eta_e = \frac{P}{G \times A}$$

International Journal of
Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

where η_e denotes the electrical efficiency of the photovoltaic system. Since panel temperature has a negative effect on photovoltaic efficiency, the temperature-dependent efficiency may be expressed as:

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

where η_T is the efficiency at panel temperature T_p, η_{ref} is the reference efficiency at standard test condition temperature T_{ref}, and β is the temperature coefficient of the photovoltaic module. This equation indicates that as the panel temperature increases, efficiency decreases proportionally.

The thermal energy removed by the water-cooling system is calculated using the heat transfer relation:

$$Q_{cool} = \dot{m}C_p(T_{out} - T_{in})$$

where Q_{cool} is the heat removed by cooling water, $\dot{m}$ is the mass flow rate of water in kg/s, C_p is the specific heat capacity of water, T_{in} is inlet water temperature, and T_{out} is outlet water temperature. The thermal efficiency of the cooling system is expressed as:

$$\eta_t = \frac{\dot{m}C_p(T_{out} - T_{in})}{G \times A}$$

where η_t represents the fraction of incident solar energy removed as useful thermal energy by the cooling water. To evaluate the cooling effect on module temperature, the temperature reduction due to water cooling is calculated as:

$$\Delta T = T_{uncool} - T_{cool}$$

where ΔT is the temperature drop, T_{uncool} is the temperature of the conventional non-cooled panel, and T_{cool} is the temperature of the water-cooled floating photovoltaic panel.

The improvement in electrical efficiency due to cooling can be estimated by:

$$\Delta\eta = \eta_{cool} - \eta_{uncool}$$

where η_{cool} is the efficiency of the cooled FPV system and η_{uncool} is the efficiency of the non-cooled system. Similarly, the percentage improvement in power output is given by

$$\%\, Improvement = \frac{P_{cool} - P_{uncool}}{P_{uncool}} \times 100$$

where P_{cool} is the power output of the water-cooled panel and P_{uncool} is the power output of the conventional panel.

For overall thermal balance, the energy absorbed by the photovoltaic module may be represented as:

$$Q_{in} = P + Q_{cool} + Q_{loss}$$

IJAMSR

International Journal of Advanced Multidisciplinary Scientific Research (IJAMSR) ISSN:2581-4281

where Q_{loss} denotes the remaining thermal losses to the surrounding environment through convection, conduction, and radiation.

Thus, the mathematical framework of the study provides a systematic basis for evaluating how water-based cooling reduces panel temperature, enhances heat removal, and improves the electrical performance of floating solar photovoltaic systems.

V. Conclusion

Water-based cooling plays a significant role in improving the thermal management and operational efficiency of floating solar photovoltaic (FPV) systems. FPV installations use the natural cooling nature of water bodies to reduce photovoltaic module temperature which in turn increases electrical power output and system performance. Installing of water-cooling mechanisms can remove solar radiation from thermal energy and reduce thermal loss for long-term work. Floating solar plants work on water, helping to limit the amount of land and also to decrease water evaporation. In conclusion, the competition between solar and water-cooling systems improves the entire FPV considering aspects such as harvesting efficiency in a comprehensive way that favours performance overall while meeting sustainable development goals intended to optimize renewable energy competitiveness.

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