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Harnessing Sunlight on Water: A Comprehensive Analysis of Floating Photovoltaic Systems and their Implications Compared to Terrestrial

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ABSTRACT

Floating photovoltaic solar systems offer numerous advantages, including reduced land usage, diminished water evaporation, and lowered thermal losses compared to terrestrial installations. If widely adopted, this system has the potential to generate a staggering 10,600 TWh of electricity. The widespread implementation of this technology could curtail water evaporation by approximately 30%. Floating solar power plants operate at temperatures about 20°C cooler than their terrestrial counterparts, enabling floating panels to yield up to 33.3% more energy. Furthermore, floating photovoltaic systems exhibit an 18.18% greater efficacy in curbing greenhouse gas emissions compared to their land-based counterparts. The heightened adoption of this system is driven by diverse factors, including escalating energy demand, ecological concerns, land-use constraints, and water scarcity, all contributing to sustainability. Despite the manifold benefits of these systems, there exist drawbacks associated with this technology, such as heightened panel corrosion, challenges in cleaning, and potential adverse environmental impacts that need to be addressed. This study meticulously examines the merits and challenges of floating photovoltaic systems in comparison to land-based installations through the content analysis method, meticulously categorizing pertinent research within the existing literature. Tailored approaches to cooling and cleaning, suited to the distinct installation conditions and environments of these systems, are concisely outlined. Through a comprehensive literature review and a meticulous comparison of cooling methods, it has been ascertained that the application of such strategies for floating solar plants yields an efficiency increase of 5-7% in the short term. Consequently, this study furnishes an initial guide for researchers and designers engaged in the development of both floating and land-based solar photovoltaic systems.

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1. INTRODUCTION

A country's sustainable development is contingent upon energy availability (A. Gholami, Eslami, Aryan, et al., 2019; Rezvani et al., 2023). For many years, fossil fuels held sway as the predominant energy source. However, the global appetite for energy continues to surge due to rapid population growth, escalating living standards, and expanding consumer activities (Aryanfar et al., 2021). Amid this pronounced growth, two pressing concerns have come to the fore: the depletion of fossil fuel reserves and the dire consequences of global warming resulting from the rapid release of greenhouse gases (Aryanfar et al., 2020; Minoofar et al., 2023). In response, there has been a burgeoning exploration of various forms of renewable energy as potential solutions to these challenges (Eslami et al., 2019). Consequently, the literature has introduced various hybrid and multi-generation energy systems, such as hydro/wind (Kefif et al., 2022), PV/wind (Makkiabadi et al., 2020), bio/wind/PV (A. Gholami, Tajik, et al., 2019), and PV/solar thermal systems (Ameri et al., 2023).

Among these, solar energy stands as one of the most prominent forms of renewable energy (A. Gholami, Alemrajabi, et al., 2017). The earth's surface receives solar radiation contingent upon factors like surface covering and weather conditions (A. Gholami, Saboonchi, et al., 2017). While the utilization of solar energy dates back to antiquity (Y. Gholami et al., 2018), recent times have witnessed photovoltaic systems emerging as a sustainable remedy to the current energy predicament (Guedri et al., 2022). A pivotal advantage of solar energy production lies in the broad applicability of solar photovoltaic systems across nearly every geographic region, owing to their dependence on sunlight as the primary energy source, abundantly available throughout daylight hours worldwide (Creutzig et al., 2017). These systems can be scaled from catering to the modest energy demands of individual households to meeting the substantial requirements of larger institutions (Eldin et al., 2016). Additionally, solar photovoltaics can substantially reduce the energy consumption and environmental impact of buildings (Ghaleb et al., 2023). Furthermore, the current state of affairs sees photovoltaic panels and battery combinations prominently fulfilling onboard

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power generation needs in space exploration ("Photovoltaic Power on Mars," 2003).

This broad array of photovoltaic applications has driven a surge in global photovoltaic panel capacity, rising from 41.5 GW in 2010 to 773 GW in 2020. This capacity is projected to expand by a minimum of 200% by 2025 (Song & Choi, 2016). This rapid expansion underscores the immense potential for renewable energy to ascend to a dominant energy source in the near future (Akrami, Khazaee, et al., 2018). A noteworthy advantage of photovoltaic systems lies in their environmental compatibility, low carbon dioxide emissions, and reasonable maintenance costs (Akrami, Gholami, et al., 2018). The continuous improvement in quality and cost positions photovoltaic systems with a promising long-term outlook (Eslami et al., 2022). Nonetheless, these systems face challenges akin to other energy production methods (A. Gholami et al., 2020; Rezvani et al., 2022). For instance, solar panels necessitate considerable land use, approximately 8 square meters per kW. While the possibility exists to replace panels with more efficient counterparts and reduce this footprint (Fereshtehpour et al., 2021), the absorption of solar energy can elevate panel temperatures in warm climates to 40-50°C, negatively impacting efficiency (Trapani & Millar, 2014). Another challenge involves the accumulation of dust on panel surfaces, diminishing solar radiation absorption and subsequently, panel efficiency (Aldawoud et al., 2022; A. Gholami, Eslami, Tajik, et al., 2019). Therefore, effective cleaning practices are imperative to uphold solar panel efficiency (Kazem et al., 2023). The accumulation of dust and dirt on the glass covers of photovoltaic panels leads to efficiency loss by reducing the light transmission coefficient (Gómez-Amo et al., 2019; Padilha Campos Lopes et al., 2020). The dust particles create a barrier that inhibits the passage of light, thereby reducing the amount of light reaching the photovoltaic cells.

Floating solar panels have emerged as a prospective solution to mitigate the challenges associated with ground-based photovoltaic solar systems. Instead of being installed on land, floating photovoltaic panels are situated on water surfaces, conserving precious land resources. In essence, this approach enables energy production to be established near populated areas without consuming valuable land that could otherwise be allocated for housing or agriculture. This technology also curtails water evaporation, a critical factor for nations grappling with water scarcity, particularly in regions like the Middle East and North Africa, including Iran (Figure 1) (Azami et al., 2017). According to the International Energy Agency's report, Iran ranked eighth among the top ten CO_2 emitters in 2020. Furthermore, in 2021, global energy-related carbon dioxide emissions surged by 6% to reach 36.3 billion tons, marking a historical high, spurred by the robust resurgence of the global economy following the Covid-19 crisis (Ascencio-Vásquez et al., 2019). Iran boasts substantial potential for harnessing solar energy, with approximately 300 sunny days annually covering two-thirds of its land area (equivalent to around 2800 sunny hours each year), and an average solar radiation of approximately 4.25-5.5 kWh/m^2 per day (Daneshyar, 1978; Fadai, 2007). Despite the substantial solar energy potential in Iran (A. Gholami et al., 2020), progress had been relatively sluggish until recent years. However, the pace of growth has accelerated, promising a brighter future (Pasandideh et al., 2022).

Figure 1. The amount of water available in the Mena area per person (Azami et al., 2017).

Analysis of existing literature underscores the growing attention garnered by floating photovoltaic systems, particularly due to their potential to simultaneously address energy and water challenges. These systems offer an appealing fusion of energy and water-related benefits, positioning them as a compelling choice for those seeking holistic solutions to global environmental issues. Nevertheless, the adoption of floating photovoltaic systems presents novel challenges owing to structural divergences and the distinctive installation environments compared to land-based systems. Furthermore, novel technologies such as floating panels require substantial funding for practical research, contributing to the relative scarcity of practical research in this domain. Notwithstanding, there have been notable practical applications. For instance, the experimental analysis of a 20 kWp prototype over a surface reservoir (covering approximately 350 m^2 or around 7% of the reservoir's surface area) yielded positive results, leading to the subsequent coverage of the entire reservoir (4490 m^2) for further analysis. This expanded platform generates 425,000 kWh/year of renewable energy while conserving 5,000 m^3 of water annually (equivalent to 25% of the reservoir's storage capacity) (Redón Santafé et al., 2014).

To the best of the authors' knowledge, there is a dearth of comprehensive studies that comprehensively compare terrestrial and floating photovoltaic systems across various dimensions. Hence, the present study's objectives and innovations include:

- Comparing terrestrial and floating photovoltaic systems from an energy output standpoint.
- Comparing terrestrial and floating photovoltaic systems based on operational temperatures and conditions.
- Comparing terrestrial and floating photovoltaic systems from an environmental impact perspective.
- Identifying research gaps and deficiencies pertaining to these systems.
- Enhancing understanding of infrastructure and structural development potential.

To achieve these goals, this study employs the content analysis method, reviewing some of the most pertinent and recent research conducted in this field. Based on this analysis and in alignment with the paper's objectives, the subsequent sections will delve into the initial energy production of floating systems, juxtaposed against land-based counterparts (Section 2. Energy Production and Output Power). Subsequently, operational conditions for both ground-based and floating photovoltaic systems, with a focus on cell temperature, will be explored (Section 3. Operational Temperature and Output Energy). This section reviews the principal methods and correlation models used to calculate panel temperature, along with a survey of various cooling techniques. Following that

(Section 4. Environmental Effects Evaluation), the positive and negative environmental ramifications of implementing these systems will be scrutinized. Finally, the study concludes by offering a comprehensive summary, identifying research gaps, and presenting future research recommendations (Section 5. Conclusions and Suggestions).

2. ENERGY PRODUCTION AND OUTPUT POWER

The amount of energy produced by floating photovoltaic panels can be calculated using Equation (1):

$$W = I \times A \times \eta \tag{1}$$

where I is the average hourly radiation, A is the area covered by floating panels, and η is the efficiency of panels (Durković & Đurišić, 2017). As per (Equation 1), the impact of water level fluctuations can influence the optimal angle of floating solar panels on the water surface within floating photovoltaic systems. Nevertheless, typical water level changes tend not to exert a significant influence on the ultimate energy output of the panels. The application of an anchoring system serves to mitigate performance fluctuations in floating panels. One of the most promising locales for deploying floating photovoltaic solar panels is situated behind dams. This strategic placement capitalizes on existing power transmission infrastructure, thereby curtailing associated expenses. Furthermore, it contributes to the reduction of water evaporation behind dams (Abid et al., 2019). Numerous studies have delved into such prospects. For instance, Farshtepour et al. utilized a simulation program to model five floating photovoltaic power plants intended for installation on Iran's five most pivotal dams (Kazemi, Darudzen, Karkheh, Aras, and Dosti). Their analysis encompassed the performance evaluation of these plants concerning energy production. Employing various percentages of reservoir coverage (2%, 10%, 20%, 50%, 80%), they scrutinized the efficacy of floating photovoltaic power plants (Figure 2). This investigation revealed that the aforementioned dams yield electricity production ranging from 194 to 257 kWh/m2 annually. Considering Iran's per capita annual electricity consumption of 2727 kWh per person, the coverage of one square kilometer of each dam with floating solar panels could cater to the electricity needs of approximately 90 thousand individuals (Fereshtehpour et al., 2021). Extrapolating this, if floating solar panels adorned reservoirs globally, an astounding 10,600 TWh of electricity could be generated annually. It's imperative to recognize that certain constraints may impede full coverage of water surfaces.

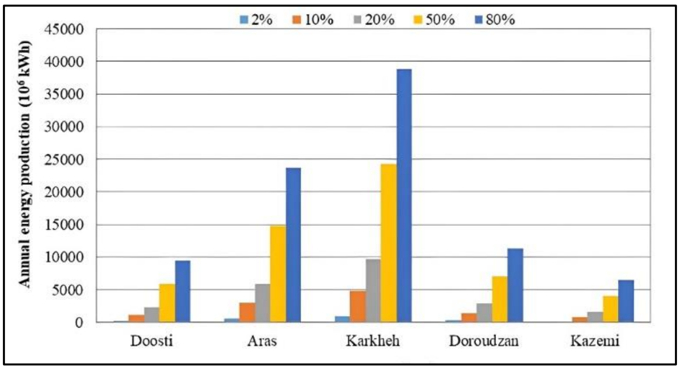

Figure 2. Annual energy production of 5 dams in Iran with reservoir coverage percentages of 2%, 10%, 20%, 50%, and 80% (A. Gholami et al., 2020).

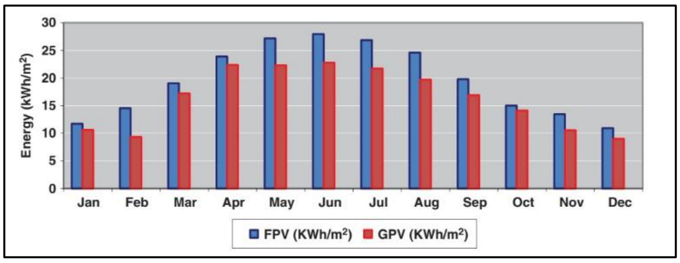

Figure 3. Energy production comparison of ground and floating panels (Semeskandeh et al., 2022).

In another study conducted in Yazd, the ANN technique was applied to investigate the effects of floating photovoltaic systems in sewage ponds. The results showed that these systems could produce 264 kWh/m^2 of electricity per year (Khalifeh Soltani et al., 2022). Besides dams and ponds, other regions have also been investigated for the development of floating photovoltaic systems. For instance, the performance of floating photovoltaic panels on the Caspian Sea was compared to terrestrial photovoltaic panels in the northern region of Iran by using the RETScreen® software (Semeskandeh et al., 2022). According to their estimation (Figure 3), floating photovoltaic panels at a fixed level produced approximately 33.3% more energy than terrestrial solar panels or 228 kWh/m^2.

While sewage ponds and open bodies of water like seas have been explored as potential sites for the implementation of floating photovoltaic systems, the most alluring and extensively studied location within the literature has been dam impoundments. This preference primarily stems from the presence of pre-existing primary electrical infrastructure in such locales, which in turn mitigates the initial costs associated with system setup. To illustrate, a theoretical investigation was conducted for the 15 Khordad Dam in Iran, aiming to compare the levels of radiation and energy output achievable through floating photovoltaic systems (Table 1) (Azami et al., 2017).

Table 1. The amount of radiation and energy produced in the 15 Khordad Dam area.

Months	Radiation (kWh/m^2)	Energy Produced (kWh)
January	137	172493
February	122	150572
March	175	212521
April	183	215014
May	187	214972
June	195	217934
July	204	225343
August	195	217531
September	183	207311
October	168	198977
November	142	174012
Sum	2022	2831196

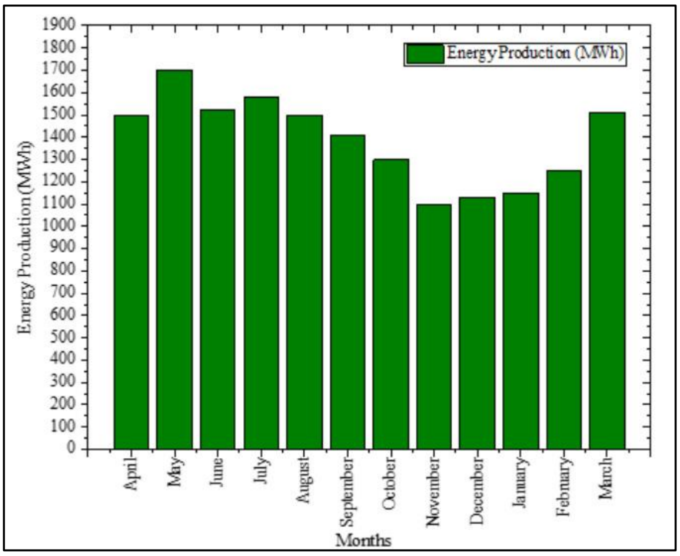

Figure 4. The amount of monthly energy production in Karun Dam 4 (Esmaeili Shayan & Hojati, 2021).

In a similar vein, another endeavor focused on assessing the performance of floating photovoltaic panels atop the "Karun the 4th" dam, utilizing PVsyst software (Esmaeili Shayan & Hojati, 2021). Notably, Karun the 4th is Iran's largest arch dam. According to this study, the energy yield from the floating photovoltaic system, encompassing over one square kilometer of the Karun the 4th dam's surface, ranges between 194 to 257 GWh (Figure 4). Consequently, the floating photovoltaic panels installed on the Karun the 4th dam have the capacity to supply electricity to an average of approximately 2260 households.

Excluding Iran, significant research has been conducted in various parts of the world concerning the development and performance of floating photovoltaic solar panels. Among these investigations, one study delved into the amalgamation of floating photovoltaic and hydroelectric power plants on a small dam in Pakistan (Rauf et al., 2019). The Ghazi Barotha dam in Pakistan was scrutinized as a potential site in this research for implementing a 200MW floating solar system. The findings revealed that the peak of solar radiation coincides with the zenith of electricity consumption in Pakistan. Consequently, the floating power plant could contribute to meeting a portion of the daytime demand, alleviating the necessity to rely solely on the hydroelectric power plant.

A study conducted in Spain also shed light on the matter (Micheli, 2021). By covering merely one percent of the reservoir surface of hydroelectric dams, Spain's overall electricity generation capacity could be bolstered by about 2GW. In such a scenario, the floating photovoltaic power plant could cater to approximately 1.7% of the nation's electrical requirements. If Spain's government were to allocate a similar proportion of hydroelectric capacity to the floating photovoltaic installation, the outcome could cover around 12% of the country's electricity demand. This article cites the average energy production of Spain as 194 kWh/m^2.

Furthermore, panels can be submerged underwater and placed beneath the water's surface. To assess the potential of submersible floating photovoltaic panels in India, the Rajghat Dam, with its expansive expanse, was chosen as a case study. With a dam height of 39 meters and a reservoir depth of 33 meters, simulations were conducted using PVsyst software by covering 25% of the panels with water. The evaluation considered an area of 22 m^2 per panel, exploring scenarios covering 10% and 25% of the dam's total area (24.21 km^2 and 60.25 km^2, respectively). The annual electricity generation projected for the floating photovoltaic power plant in this analysis was approximately 175 kWh/m^2 (Agrawal et al., 2022). In a separate study by the Indian Institute of Technology in Dhanbad (23.8144°N, 86.4412°E), the performance of floating and terrestrial photovoltaic systems was examined. Over the course of 17 months, from September 2018 to January 2020, these systems were both simulated and experimentally assessed on a small scale.

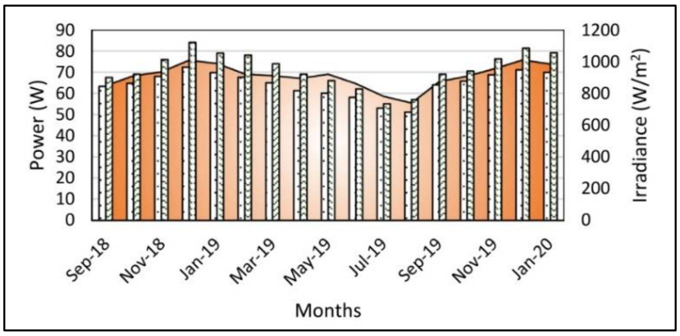

Figure 5. Comparing the output of ground and floating panels (Goswami & Sadhu, 2021).

As shown in (Figure 5), floating photovoltaic solar panels have a higher output potential than terrestrial photovoltaic solar panels. Results of this study indicate that floating panels produce higher average daily and monthly output power than land-based ones. In December 2018, the maximum output power difference between a floating panel and a land-based panel was 11.6W, while in July 2019, the minimum output power difference was only 2.8W [(Pasandideh et al., 2022]. Floating panels have a 16% higher maximum output than land-based panels (Goswami & Sadhu, 2021).

By summarizing the conducted studies and examining the simulation results presented in these works, it is evident that according to the cooling effect of panels in floating systems, the production capacity and electrical output efficiency of these systems are on average from 10% to 30% higher than terrestrial systems (Goswami & Sadhu, 2021). Therefore, one of the main factors explaining the difference in performance between floating and terrestrial photovoltaic solar systems is the difference in operating temperature between them. In the following section, we will examine the operational temperature of photovoltaic solar panels in these two systems.

Section Highlights:

- The average amount of energy produced by floating photovoltaic systems in Iran was reported to be approximately 150 to 300 kWh/m^2.
- Floating solar panels can produce on average from 10% to 30% higher energy than terrestrial systems

3. OPERATIONAL TEMPERATURE AND OUTPUT ENERGY

Solar photovoltaic panels convert solar irradiance directly into electricity. However, a portion of the incoming sunlight cannot be utilized by the panels and as a result, heat is generated and the temperature increases (Santiago et al., 2018). In previous studies, many models have been presented for estimating the temperature of land-based and floating panels. A few of these equations are presented below. Feyman obtained

Equation (2) by solving the energy balance equation for a ground panel (Faiman, 2008). T_m and T_a are panel temperature and ambient temperature; ws is wind speed; and U_0 and U_1 are heat loss coefficients. Later, a newer model to obtain cell temperature was proposed by Duffie and Beckman in 2006 (Duffie & Beckman, 2013).

$$T_m = T_a + \frac{POA}{U_0 + U_1.ws} \tag{2}$$

In Equation (3), POA_{NOCT} is the radiation in normal environmental conditions (800 W/m^2) and T_{NOCT} is the normal temperature of the panel cell. Actually, the cell temperature is in POA_{NOCT} and is usually provided by panel manufacturers.

$$T_c = T_a + \frac{POA}{POA_{NOCT}}.(T_{NOCT} - T_a).\frac{9.5}{5.7+3.8\,ws} \tag{3}$$

Alternatively, some authors have used Sandia model coefficients to describe the thermal behavior of floating panels. According to King et al. (Kratochvil et al., 2004), Equation (4) distinguishes between the cell and panel temperatures. a and b are experimentally determined coefficients and ΔT expresses the temperature difference between the cell and the back surface of the panel in the amount of radiation (1000 W/m^2).

$$T_c = T_m + \frac{POA}{1000}.\Delta T = POA.e^{a+b.ws} + T_a + \frac{POA}{1000}.\Delta T \tag{4}$$

Using the contributions of radiation, conduction, and thermal inertia to predict panel temperatures, Veldhuizen et al. proposed a model in 2015. In Equations (5), (6), k is an experimental value coefficient, γ is a factor related to the effect of relative humidity (RH) on temperature, and r is the average temperature difference between the ambient temperature and the panel due to cooling becoming during the night. The time of the thermal inertia effect is calculated by calculating the exponential moving average over several minutes.

$$T_m = T_r + (T_r - T_a).ws^a.h \tag{5}$$

$$T_r = T_a + \big(k + \gamma.(1 - RH)\big).POA - r \tag{6}$$

In recently published studies, based on a theoretical and experimental analysis, Gholami et al. (Khalifeh Soltani et al., 2022; Esmaeili Shayan & Hojati, 2021; Rauf et al., 2019) examined the effects of different environmental conditions on cell temperature (T_C). They considered the impacts of ambient temperature (T_a), radiation (G_a), wind speed (WS), dust accumulation (ρ_d), and humidity (H) to propose different semi-empirical correlation forms including Equation (7):

$$T_C = 3.408 + 0.991 \times T_a + 0.026 \times G_a - 1.117 \times WS - 0.028 \times H - 0.060 \times \rho_d \tag{7}$$

Besides, the literature has introduced several other correlation models to depict the electrical, thermal, and optical behavior of photovoltaic systems under diverse environmental conditions. A recent comprehensive study undertook the task of comparing these correlation models and forms (A. Gholami, Ameri, Zandi, & Gavagsaz Ghoachani, 2022). Additionally, a more recent and in-depth review was conducted to scrutinize various correlation models for the electrical characterization of photovoltaic systems, particularly focusing on diode-based equivalent electrical circuit models (A. Gholami, Ameri, Zandi, Ghoachani, et al., 2022). Furthermore, multiple investigations have put forth algorithms to predict the performance of PV systems (Al-Shabi et al., 2021; Sadeghi et al., 2023). However, the intricate nuances of such modeling fall beyond the purview of the current study.

Numerous studies have underscored that solar panels experience a decline in efficiency with rising temperatures (Ascencio-Vásquez et al., 2019). In light of the cooling influence of water, floating installations operate at temperatures up to 20°C lower than their land-based counterparts. This variance in operating temperature enhances energy efficiency and curbs panel degradation stemming from reduced temperatures (Mamatha & Kulkarni, 2022). To mitigate these losses and augment heat transfer between the ground and the floating panels in photovoltaic systems, various cooling solutions have been proposed. Temperature loss constitutes a noteworthy setback in photovoltaic systems. Floating photovoltaic systems deploy an array of cooling mechanisms, categorized based on whether the panel's rear surface interfaces with air or water.

3.1. Air cooling

Water commonly maintains direct contact with floating panels. Occasionally, horizontal panels are elevated above the water's surface, cooled by the surrounding air. In a study by Yadav et al. (Yadav et al., 2016), at an artificial pond in Madhya Pradesh, India, a floating panel with a 23° slope was positioned atop high-density polyethylene blocks. Their investigation delved into the performance of the floating panel. Benefiting from water's cooling effects, the floating panels exhibited lower temperatures than their ground-based counterparts following a one-day test. On average, a temperature decrease of nearly 2°C was observed compared to land-based panels, accompanied by a 0.79% efficiency increase.

While most studies on air-cooled floating photovoltaic systems focus on horizontally placed panels atop water, there are instances of horizontal panels not in direct water contact. In another study (Majumder et al., 2021), floating panels were enclosed in wood, suspended 7.5 cm above water, and a terrestrial panel was positioned at a greater elevation from the ground. A noteworthy temperature decrease of up to 1.4°C was recorded for the floating panels, underscoring the influence of water. Moreover, Goswami et al. conducted a 30-day comparison of operating temperatures between floating and ground panels in a pond in West Bengal (Goswami et al., 2019). On the hottest day, a temperature differential of up to 12°C was noted between the two, translating to a 10.2% power output advantage for the floating panels. The authors attributed these findings to the heat island effect. While terrestrial panels trap heat between the soil and the panels, the presence of water cools the surrounding air for the floating panels.

3.2. Direct water cooling

A distinct cooling approach is applied to floating panels. Although thermal photovoltaic systems also employ a working fluid to indirectly dissipate heat from solar panels, these systems fall outside the scope of this section, which focuses on direct water cooling. The heat transfer coefficient of water surpasses that of air, enabling water to lose heat more rapidly. Consequently, if horizontal floating panels maintain direct contact with water, they experience faster cooling. Periodic immersion of panels ensures a portion remains underwater, intensifying the cooling effect (Figure 6). Panels can be inclined (partially submerged) or fully horizontally immersed. This section encompasses both configurations due to their substantial water-cooling benefits.

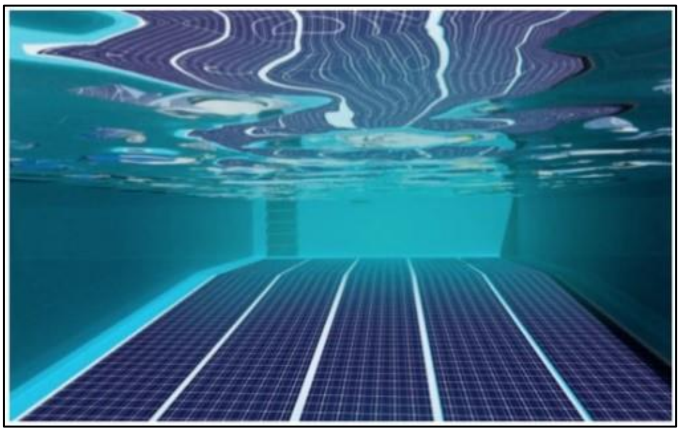

Figure 6. A view of panels submerged in water.

Complete submersion in water maximizes the cooling potential of photovoltaic panels. In this scenario, both the front and back surfaces of the panels directly interact with water. While water immersion enhances heat exchange, it simultaneously diminishes the light reaching the cells. Early research on water-immersed panels dates back to the late 1970s when, in a study (Stachiw, 1980), cells' performance across various locations was investigated. A 5% reduction in peak energy was reported in the researcher's findings. A subsequent study by Rosaklat and colleagues established that submerged solar panels, at depths less than 10 cm, outperformed terrestrial panels (Rosa-Clot et al., 2010). This conclusion aligns with the spectral variation of solar radiation at different depths in clear water. Assuming temperatures of 25°C for submerged panels and 65°C for air-cooled panels, the performance enhancement due to improved thermal conditions still surpasses the losses from light absorption by water.

However, it's important to note that this temperature disparity might not persist in different weather conditions. Ziyar et al. employed COMSOL software to model a two-sided panel, where only the lower frame directly touched water (Cazzaniga et al., 2018). Their findings confirmed significantly cooler temperatures for the water-contacting part of the panel. Yet, due to glass's low thermal conductivity, the cooling effect didn't extend across the entire panel, yielding an overall energy gain of 0.17 compared to predictions of complete air cooling. The authors cautioned against partial submersion as a viable solution for floating photovoltaic systems due to limited thermal enhancement and increased risk of panel damage. This underscores the need for further research to determine the most effective cooling approach for photovoltaic panels—total immersion, partial immersion, or floating on the water surface.

3.3. Comparison between water cooling and air cooling

Azmi et al. (Azmi et al., 2013) and Majid et al. (Majid et al., 2014) scrutinized panel performance both on land and in a floating environment. In the initial study, the authors employed a solar simulator indoors, subjecting the panels to three radiation intensities. All tests exhibited a temperature disparity between land-based and floating systems of 5°C or 6°C after a one-hour radiation exposure. On distinct days, a field sample akin to a pond was evaluated in two configurations concurrently (from 11 am to 1 pm) in an open space. With ambient and water temperatures of 30°C and 25°C, respectively, the findings unveiled a temperature reduction of nearly 15°C for floating panels compared to their land-installed counterparts.

In Thailand, a techno-economic analysis aimed to compare floating and terrestrial photovoltaic panels revealed that water cooling engendered an 11% efficiency increment and mitigated carbon dioxide emissions more effectively than surface-installed photovoltaics (Campana et al., 2019).

A separate study indicated that water-cooled panels outperformed horizontally air-cooled panels installed 32 mm above the water surface, exhibiting a 5-7% efficiency gain over a six-month period (Kjeldstad et al., 2021). This principle was further demonstrated by Mayville et al. who employed flexible thin-layer panels (Mayville et al., 2020). Deployed in North America for nearly three months across three floating foams in a waterway connected to Lake Superior, this test system reported lower temperatures for similar setups in aquatic conditions than for those out of water. Their findings indicated a temperature reduction ranging from 10°C to 20°C contingent on weather conditions. Another variant of the foam-backed design was examined by Mayville et al. at Michigan Technological University, USA (Hayibo, 2021). They approximated a 3.5% energy production increase compared to air-cooled floating panels.

Section Highlights:

- Floating installations operate at operating temperatures up to 20°C lower than land-based systems, improving energy efficiency, and curbing panel degradation.
- Water-cooled panels have a 5-7% increase in efficiency over air-cooled horizontal panels installed above the water surface.

4. ENVIRONMENTAL EFFECTS EVALUATION

Apart from influencing the output of photovoltaic panels, floating photovoltaic systems exert both positive and negative environmental effects. The study of environmental impacts related to floating photovoltaic systems remains limited due to their recent development. Notwithstanding, the ecological benefits of PV systems generally outweigh the drawbacks. However, investigations have indicated that the deployment of floating solar panels can potentially disrupt aquatic ecosystems and their biodiversity (K, 2019).

The obstruction of direct sunlight to aquatic species, for instance, can lead to modifications in the ecological cycle, impacting various aspects of the ecosystem (Song & Choi, 2016). The primary ecological impact on aquatic flora and fauna arises from the shading caused by floating photovoltaic systems, which can interfere with photosynthesis, decrease phytoplankton production on the water surface, alter the composition of flora and fauna, and influence animal behavior (Pimentel Da Silva & Branco, 2018).

Additionally, due to the inclusion of lightning protection systems in the transformer station of these systems to safeguard the power grid's integrity, regular inspections become necessary, particularly after heavy rainfall or flooding. Extreme weather conditions might result in potential damage to electrical equipment, potentially leading to environmental harm. Floating photovoltaic systems are susceptible to damage from humidity, environments with high mineral content, dust accumulation, and shading (George & Patel, 2019). It's worth noting, however, that in many instances, floating photovoltaic systems exhibit significantly more positive environmental impacts compared to their terrestrial counterparts. These beneficial effects will be elaborated upon below.

Moreover, FPV structures have their own environmental implications for the surrounding area, impacting soil, air, water, flora, and fauna. The construction-related disturbances can adversely affect soil and geo-hydrological resources. The connection of the floating structure to the substation involves processes like anchoring, cabling, and trenching, which may lead to undesirable consequences for the lake bed. This could include alterations in water quality and heightened turbidity due to sediment mobilization during anchoring. Consequently, the aquatic communities at the lake bottom might experience effects. Furthermore, FPV systems tend to generate more waste compared to traditional solar PV systems due to the use of plastic for buoyant structure wrapping. Hence, when devising waste management strategies for FPV systems, proper consideration must be given to the disposal of floating structures, which contributes to the overall environmental impact (Essak & Ghosh, 2022).

4.1. Evaporation of water

Surface water evaporation is a intricate phenomenon influenced by an array of factors encompassing water surface area, temperature, vapor pressure disparity, wind impact, atmospheric pressure, and water quality. Floating photovoltaic power plants hold the potential to curtail evaporation by covering not only the area beneath them but also the entirety of the lake or dam surface. This reduction in water evaporation can be attributed to two primary reasons. Firstly, the covered area diminishes the interaction between water and air, thereby directly contributing to evaporation reduction. Furthermore, the establishment of the power plant modifies the heat balance of the dam, leading to cooler water temperatures, which in turn curbs evaporation (Durković & Đurišić, 2017).

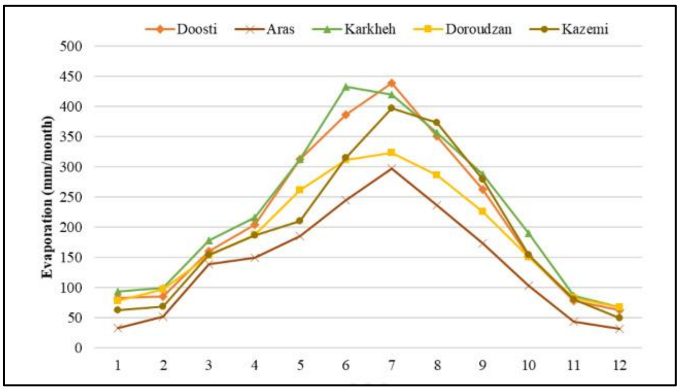

Figure 7. Evaporation rates of five Iranian dams.

Accurately estimating evaporation is of paramount importance, particularly in regions characterized by low water levels. It's worth noting that several parameters come into play when estimating water evaporation, including the presence of unsaturated air above the surface, wind velocity, solar radiation exposure on the water surface, atmospheric pressure, and the chemical properties of the water. Various methods are employed for measuring evaporation, encompassing the water budget approach, mass transfer techniques, pan evaporation measurements, the Penman-Monteith model, and the energy balance method. Among the assortment of mathematical methods, the Penman method stands out as one of the most extensively employed. Figure 7 portrays the outcomes of a study conducted on five dams in Iran, which employed floating photovoltaic solar panels and utilized the simplified Penman evaporation model (Fereshtehpour et al., 2021).

Using 10% coverage of all 5 dams, the amount of water saved by reducing evaporation is 70 million cubic meters (MCM) per year. A study near Yazd estimated the average evaporation rate to be 2.2849 m/year after t accounting for a shadow level of 2.2 km on the reservoir water. The evaporation of 3.24 MCM of water per year can be prevented by covering 90% of the surface. As a result of the reduction in evaporation caused by the installation of floating photovoltaic panels, around 1.45 MCM/km^2 of water can be saved (Khalifeh Soltani et al., 2022). A study conducted in Iran examined the amount of water evaporating from the 15 Khordad Dam in the city of Delijan, Central Province (Azami et al., 2017). In addition to the challenges associated with water scarcity, the results of this study have shown that the very high surface evaporation of water, which is primarily due to the high sunlight in this region, also results in water quality degradation. Therefore, the installation of floating photovoltaic systems can contribute significantly to preventing the evaporation of surface water in reservoirs in arid and semi-arid areas such as Delijan, as well as generating electricity. The simulation results indicated that by covering only 31565 m2 (2%) of the reservoir surface, 0.016 MCM of water is prevented from evaporating each year (Azami et al., 2017).

Figure 8 provides a visual representation of water evaporation and water conservation across different months of the year, drawing from the outcomes of this study. The research findings have been overwhelmingly positive, underscoring the substantial potential for the advancement of these systems. The study estimates an impressive rate of 0.53 million cubic meters per square kilometer (MCM/km^2) for evaporation prevention and water conservation.

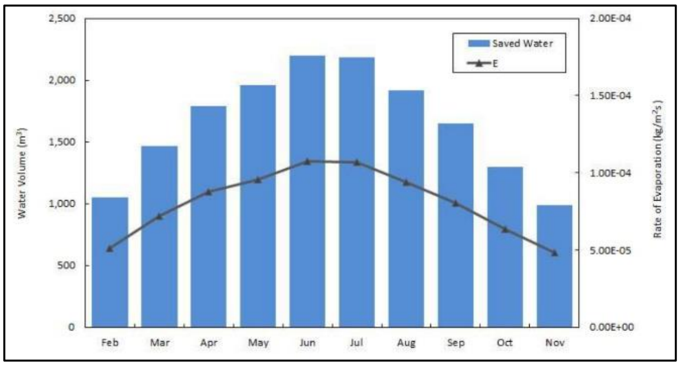

Figure 8. The amount of water saved and the monthly evaporation of the 15 Khordad dam.

In various regions around the world grappling with water and energy challenges, floating photovoltaic systems have emerged as an innovative and laudable solution. In Singapore reservoirs, Melvin and Xiang examined the impact of solar panels on curtailing water evaporation (Melvin, 2015). Their findings indicate that installing floating solar panels above water dams can lead to an almost 30% reduction in evaporation rates. This approach not only helps conserve water and minimize water evaporation but also enhances hydroelectric power generation during peak radiation hours, thereby addressing blue water challenges. Additionally, research in this domain reveals that covering 25% of the Rajghat dam can curtail evaporation by 0.95 MCM/km^2, ultimately resulting in an increased hydroelectric power output of 482.86 MWh (Agrawal et al., 2022).

4.2. Carbon dioxide

The greenhouse gas emission index stands as a pivotal parameter for assessing the environmental impact of distinct energy production systems, expressed in terms of carbon dioxide equivalence. In Iran, the average carbon dioxide emission per kilowatt-hour of electricity produced using fossil fuels was 767.5 g/kWh in 2013. One of the prominent advantages of floating photovoltaic systems compared to terrestrial systems lies in their capacity to mitigate greenhouse gas emissions. Focusing on Fershtepour's study of five dams in Iran (Fereshtehpour et al., 2021), the annual reduction in carbon dioxide emissions is outlined in (Table 2).

Table 2. The amount of carbon dioxide ($ktCO_2$) emission prevented for the five dams in Iran.

Coverage Percentage	Doosti	Aras	Karkheh	Kazemi
2	173.126	434.437	714.233	118.613
10	865.629	2173.545	3571.164	593.064
20	1731.258	4347.089	7142.328	1186.128
50	4328.146	10867.723	17855.821	2965.320
80	6925.033	17388.356	28569.313	4744.512

The outcomes of the research suggest that with just 2% coverage of the reservoir surface, floating systems could diminish greenhouse gas emissions by a minimum of 118 $ktCO_2$ per year. A theoretical evaluation of the deployment of a floating photovoltaic power plant at the 15 Khordad Dam in Delijan estimates a reduction in greenhouse gas emissions equivalent to 1819.6 tCO_2 over 20 years (Azami et al., 2017). This study also delved into the carbon dioxide emissions arising from the manufacturing process of these panels, as presented in (Table 3).

Table 3. Embedded carbon in monocrystalline installations.

Process	Mono-crystalline PV ($kgCO_2/m^2$)
Manufacturing process	51.1
PV panels	20.1
Inverter	2.3
Balance of system	2.3
Capital inputs	18.4
Structural support	19.9
Transportation	0.53
Total	114.63

The inherently greater efficiency of floating photovoltaic solar systems positions them as environmentally friendlier overall. Table 4 furnishes a comparative overview of environmental analyses concerning floating panels on Caspian Lake (Semeskandeh et al., 2022). The data illustrates that a 5 kW floating photovoltaic system can avert approximately 5.2 tCO_2 emissions (equivalent to 104 tons over 20 years). This reduction translates to saving 2243.4 liters of gasoline annually (44868 liters over 20 years).

In contrast, installing an equivalent amount of terrestrial photovoltaic solar systems would prevent around 4.4 tCO_2 in annual greenhouse gas emissions. Consequently, floating photovoltaic panels exhibit an approximate 18.18% greater capacity to curtail greenhouse gas emissions in comparison to terrestrial systems.

Table 4. Comparison of carbon dioxide produced by floating and ground panels (Semeskandeh et al., 2022).

Panel Type	Annual Reduction of Greenhouse Gas Emissions	Equivalent To Liters of Gasoline Not Consumed Per Year
FPV	5.2 tCO_2	2243.4
GPV	4.4 tCO_2	1879.9

4.3. Solutions for dust accumulation

Dust accumulation negatively affects photovoltaic panels' performance and their efficiency is reduced (Huang et al., 2019). According to some studies, dust accumulation reduces the electricity generation of panels by 15% per day (Deb & Brahmbhatt, 2018). Considering the installation environment of panels in floating and terrestrial systems, the dust challenge is much greater in terrestrial systems (Rahbar et al., 2022). However, the challenge of settling salt and other minerals on floating panels is more challenging. Solar panel cleaning has been the subject of numerous research studies (AlMallahi et al., 2022; A. Gholami et al., 2021). Cleaning techniques of floating photovoltaic systems, however, have not been comprehensively studied since they are a relatively new concept and are located in a different environment. Because these systems are installed near water, less dust is attracted to them. Nonetheless, multiple water-based and waterless cleaning techniques can be employed to remove accumulated dust from the surfaces and lessen its adverse effects (Figure 9) (Cai et al., 2019; A. Gholami, Eslami, Tajik, et al., 2019).

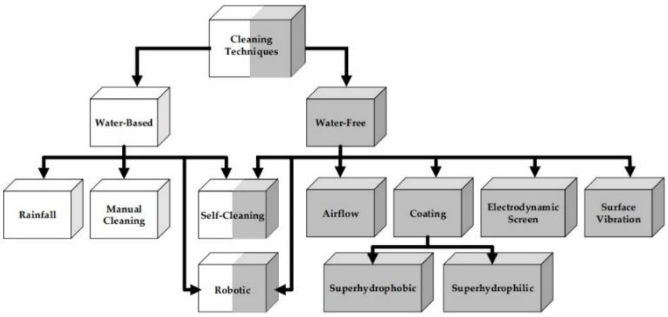

Figure 9. Panel cleaning techniques (Cai et al., 2019).

Only a few of the techniques listed in Figure 9 apply to these systems. The examples include rainfall, robots, manual cleaning with brushes, creating diverse covers, and airflow and wind (Zahedi et al., 2021). For land-based photovoltaic panels, Maryam Nooman et al. conducted that robot water-based cleaning techniques improved the performance of the photovoltaic system and reduced dust accumulation on the photovoltaic panel's surface (AlMallahi et al., 2022).

Section Highlights:

- Floating photovoltaic systems can reduce evaporation rates by almost 30%.
- Floating systems can reduce greenhouse gas emissions by about 18% more than terrestrial systems.
- Dust accumulation for floating photovoltaic systems still needs much more attention.

5. CONCLUSIONS AND SUGGESTIONS

The environmental and energy-related advantages of floating photovoltaic systems have garnered significant attention. Multiple studies have been conducted to investigate these systems' performance from specific perspectives. Given the increasing interest in both floating and terrestrial photovoltaic systems, the present study undertakes a comprehensive content analysis and assessment of these systems through a literature review. The initial phase encompassed a detailed overview of floating systems, succeeded by an evaluation of their technical and environmental benefits. Based on research findings, floating systems outperform ground-based counterparts in energy production due to their proximity to water and enhanced cooling capabilities. Also, their manufacturing process results in lower carbon dioxide emissions. These systems contribute to reduced water evaporation, increased hydroelectric power generation, and water conservation, particularly when deployed partially on water surfaces behind dams in regions with low water levels. Moreover, the article delves into cooling and cleaning methodologies for floating panels. This review study serves as an initial endeavor to underscore the significance of installing floating photovoltaic systems atop Iran's reservoirs, driven by key governing factors. An examination of the literature unveiled the following insights:

- Floating panels yield approximately 33.3% more energy than terrestrial solar panels. If deployed across global reservoirs, they hold the potential to generate an annual electricity output of 10,600 TWh.
- Floating panels operate at temperatures around 20°C lower than land-based systems.
- Research indicates that water-cooled panels outperform air-cooled counterparts placed 32 mm above the water surface, boasting a 5-7% efficiency increase in the short term.
- These systems can curtail water evaporation rates by nearly 30%, concurrently serving as a catalyst for enhanced hydroelectric power production.
- Evidence suggests that floating photovoltaic systems can reduce greenhouse gas emissions by approximately 18.18% compared to land-based systems.

Consequently, the implementation of floating photovoltaic systems presents an appealing investment prospect for sustainable energy generation, aligning with cost reduction and environmental benefits. However, despite the manifold advantages of floating systems, pertinent concerns have surfaced in the literature. Vulnerability to humidity, high mineral content environments, and dust renders FPV systems more susceptible to damage. Long-term environmental implications necessitate in-depth exploration in future investigations. Moreover, a comprehensive assessment of potential electrical integration, including the synergy with hydroelectric power plants, warrants attention. Analyzing floating structure aerodynamics to minimize water evaporation while averting other environmental ramifications is also imperative. Given the reduced airborne dust over water reservoirs compared to land, its influence on cleaning frequency and associated methodologies should be a focal point of forthcoming research, subject to experimental evaluation.

6. ACKNOWLEDGEMENT

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