The Temperature of Floating Photovoltaics: Case Studies, Models and Recent Findings

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Abstract

In floating photovoltaics (FPV), modules are installed on water to alleviate the land requirement of this energy source. In addition, FPV installations are expected to work at lower operating temperatures compared to land based photovoltaic (LPV) systems, thanks to the cooling effect of water. If confirmed, these lower temperatures would (i) increase the energy yield and (ii) reduce degradation and performance losses, boosting the cost-competitiveness of FPV. However, some recent works have reported cases of FPV systems working at higher temperatures than co-located LPV systems. The present review gathers the literature on the thermal behavior of FPV, outlining the models and discussing the experimental results currently available. It is found that FPVs of different configurations can experience different thermal behaviors, not always necessarily better than LPV. In particular, air- and water-cooled FPV systems should be always distinguished, in light of their diverse cooling mechanisms. Initial comparative analyses make it possible to identify designs and conditions that can favor the heat transfer in FPV compared to LPV. The role of additional factors on the FPV temperature, such as the PV material or the more frequent biofouling, is also discussed. Last, estimations of the economic impact of the thermal behavior on the FPV costs and competiveness are presented.

Highlights

- The literature available on floating photovoltaic (FPV) temperatures is reviewed.
- Water-cooled FPV are expected to achieve lower temperatures than air-cooled FPV.
- The thermal behavior of FPV varies depending on the design and the local conditions.
- Wind is the main cooling agent for FPV systems installed above water surface.
- More experimental and comparative studies on the topic are recommended.

Keywords

Floating Photovoltaic; Operating Temperature; Cooling; Thermal Models; Solar Energy; Literature Review.

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Nomenclature

Symbols

a	Empirical determined coefficient
b	Empirical determined coefficient [s/m]
G_T	Irradiance [W/m^2]
h	Convective heat transfer coefficient [W/m^{2}K]
NOCT	Normal Operating Cell temperature [°C]
POA	Plane of array irradiance [W/m^2]
r	Temperature difference between ambient and module [°C]
Ta	Ambient temperature [°C]
Tm	Module temperature [°C]
Tr	Module's temperature due to radiation [°C]
Tw	Water temperature [°C]
U	Heat loss coefficient [W/m^{2}K]
Uc	Constant heat transfer component [W/m^{2}K]
Uv	Convective heat transfer component [W/m^{2}K]
ws	Wind speed [m/s]
α	Empirical wind factor
γ	Relative humidity factor
ΔT	Cell vs. Module temperature difference [°C]
φ	Wind direction [°]
α_{PV}	Absorption coefficient of solar irradiation
η	Module efficiency

Abbreviations

FPV	Floating Photovoltaics
LPV	Land-based Photovoltaics
PV	Photovoltaics
RH	Relative Humidity [%]

1. Introduction

The deployment of affordable and clean energy is among the objectives of the United Nations Sustainable Development Goals for 2030 (Department of Economic and Social Affairs (DESA), 2016). Photovoltaics (PV) is one of the renewable technologies experiencing the most important growth, thanks to its low cost, versatility and easy-installation (SolarPower Europe, 2020). In between 2010 and 2020, the global PV capacity has gone from 41.5 GW to 773 GW and, by 2025, it is expected to further increase by at least 200% (SolarPower Europe, 2020).

However, PV and renewable energies in general have a higher land requirement than conventional sources (Capellán-Pérez et al., 2017). This means that a major deployment of PV installations could subtract land to agriculture and/or pose risks to biodiversity, if PV is built on land available for low prices but of high ecological value (Serrano et al., 2020). Therefore, the PV community has been looking at alternative solutions, such as floating photovoltaics (FPV), to prevent the achievement of global energy goals at the expenses of biodiversity and/or food production.

In FPV, the PV modules are installed on water surfaces instead of land. This avoids the land-use competition and generally grants lower rent fees. As shown in Fig. 1, FPV has reached in just about a decade a global capacity of 2.6 GW (Haugwitz, 2020), which is expected to double by the end of 2022 (Deloitte, 2022). In addition, recent forecasts anticipate a FPV capacity of 13 GW by 2025 (Deloitte, 2022), able to provide up to the 2% of the global electricity production by 2030 (Cazzaniga and Rosa-Clot, 2021).

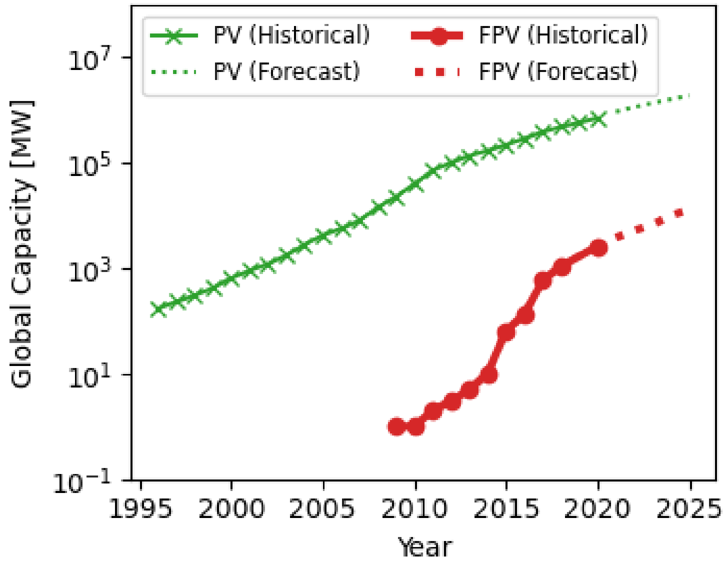

Fig. 1. Evolution and forecast of cumulative PV and floating PV (FPV) capacities worldwide. Adapted from (Micheli, 2021)*, with the addition of LPV forecasts from* (SolarPower Europe, 2021) *and FPV forecasts from* (Deloitte, 2022)*.*

The deployment of FPV is being favored by different factors. In addition to the lack of land requirement, FPV can limit the water evaporation and lower the cost of renewable energy, especially when coupled with hydropower (World Bank Group et al., 2018). However, this hybridization is still at an early stage of development. Additional potential benefits of FPV are the lower reported operating temperatures compared to land-based PV (LPV), typically attributed to the cooling effect of water. Since the PV efficiency rises inversely to the temperature, lower operating temperatures prospect higher energy yields and longer durability for FPV. However, some authors (Lindholm et al., 2021; Peters and Nobre, 2022) have recently raised doubts on the improved thermal behavior of FPV, reporting that the better heat transfer is not necessarily a feature of all FPV designs, especially for air-cooled configurations.

Understanding the correct thermal behavior of FPV systems is essential to support the development and the deployment of this technology. FPV systems, indeed, are typically mounted at low-tilt angles compared to LPV to limit the wind load on the floating structure (Silvério et al., 2018). While these are close to the optimal tilt angles in the regions surrounding the equator, at higher and lower latitudes the low angles can generate greater reflection and angular losses, reducing the FPV yield. Lower operating temperatures can, at least partially, counterbalance the low-tilt-related losses. A techno-economic analysis (Campana et al., 2019) showed that FPV with a boost in efficiency of 11% due to cooling could achieve sensibly higher reliability and lower levelized costs of electricity compared to LPV in Thailand. A more recent study conducted in the same country (Cromratie Clemons et al., 2021) demonstrated that, a 10% higher efficiency due to the better cooling could halve the cost of FPV electricity compared to LPV, achieving similar payback periods. Similarly, a study published in 2020 (Padilha Campos Lopes et al., 2020) found that a cooling-driven 5% raise in energy output could make FPV cost-competitive with LPV in Brazil. In addition, a different work (Micheli, 2021) showed that, if the expected lower operating temperatures were confirmed, FPV could already compete with LPV in Spain in terms of lifetime cost of electricity and profits.

In light of the ongoing discussion and of the significant consequences on the energy and economic performance of FPV, the present work aims at collecting and systematically assessing the knowledge on the thermal behavior of FPV. Most of the available reviews, listed in 2.2, have presented comprehensive assessments of FPV, covering multiple aspects of this technology. However, while the expected thermal benefit of FPV is often mentioned, a critical discussion on this subject is missing. The present review addresses this lack, sharing case studies, available models and the most recent findings on the operating temperatures of FPV. This way, the correlations between FPV designs and thermal behaviors are discussed and future potential research lines are identified.

The paper is structured as follow. Section 2 provides an overview on the thermal losses of PV and on the FPV technology, focus of this work. In particular, Section 2.1 describes the effect that temperature has on the efficiency of PV modules and presents some of the most common thermal models. Section 2.2 illustrates the characteristics of FPV and explains the novelty of this work in light of the already existing reviews. Section 3 reports and discusses the findings shared in the literature on the thermal performance of FPV, classified according to the cooling medium: air or water.

2. Background

2.1. The effect of temperature

PV modules directly convert solar radiation in electricity. However, most of the incoming sunlight cannot be used by the modules and is therefore converted into heat, which raises the temperature of the PV cell. The efficiency of the PV modules lowers while the temperature rises and therefore it is important to keep it at minimum. In addition, the cell temperature is one of the main degradation precursors for PV modules (Ascencio-Vásquez et al., 2019). High absolute module temperatures, indeed, in combination with other specific conditions, can cause hydrolysis- and photo-degradation, whereas high temperature variations can lead thermo-mechanical stresses.

PV modules are made of various semi conductive materials and these do not have all the same response to temperature. Their behaviors are typically expressed by the temperature coefficients, which describe the rate at which the various electrical outputs of the modules vary with the respect to temperature (King et al., 2000). These are negative if the parameter’s value decreases as the temperature rises, as for the open-circuit voltage and the maximum power. They are positive otherwise, as for the short-circuit current. As shown in Fig. 2, different materials have different temperature coefficients. Typical values for power range between -0.45 %/°C for crystalline-Silicon technologies and -0.20 %/°C for amorphous-Silicon (Theristis et al., 2018).

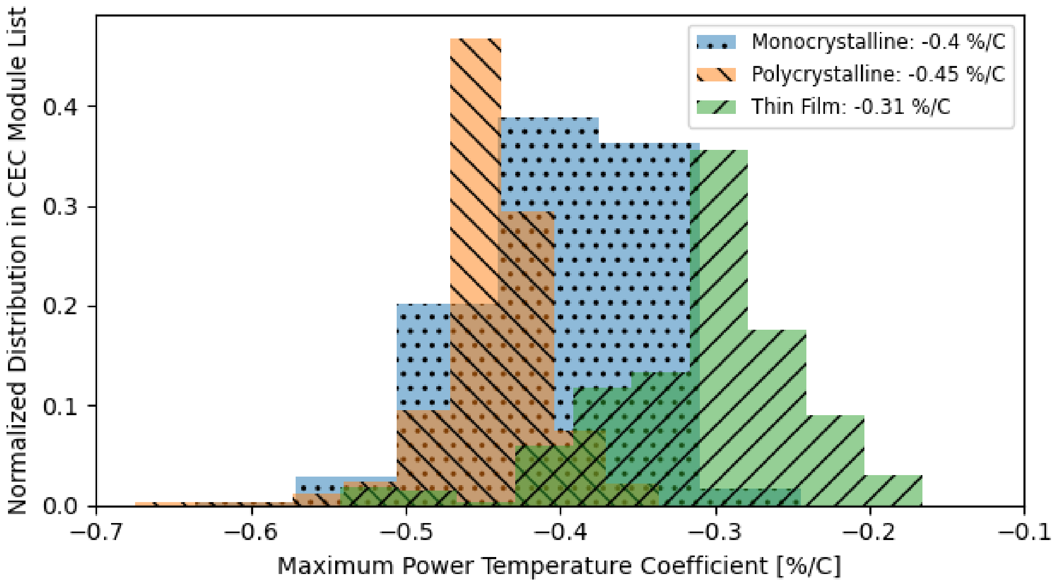

Fig. 2. Distribution of maximum power temperature coefficients for power for the modules reported in the list of the California Energy Commission (California Energy Commission, 2021)*. The legend shows the median value found for each PV material. The distribution is normalized so that the sum of the bars for each material is 1.*

The temperature can affect the performance and cause damages to PV also when it is not uniform across the modules. Weak solder joints, micro-cracks and partial shadings can cause localized heating phenomena known as hot spots. In these cases, a cell, or part of it, experiences temperatures significantly higher the rest of the PV module (García et al., 2014), favoring degradation.

Various cooling solutions have been proposed to limit these threats and to enhance the heat transfer from the front glass and/or the back surface of the module (Maleki et al., 2020). These solutions can be classified as active and passive. Active cooling requires external energy to operate, whereas passive cooling works thanks to the exploitation of natural laws and is the most common solution in PV. Water has been often employed as coolant, even in passive configurations, because of its high specific heat capacity and low-cost (Kandeal et al., 2020). In this light, the proximity to water has often been pointed out as an intrinsic advantage of FPV, as it has been expected to favor the passive cooling mechanisms.

Several models have been proposed to estimate the temperature of PV cells and modules from the local conditions and the system configuration (Santiago et al., 2018). Providing a comprehensive review of them is not the scope of this work. However, it is worth mentioning those that have found application in FPV.

Most of the data available so far on the temperature of FPV modules have been produced adopting the PVsyst model (PVsyst SA, n.d.). PVsyst is a software package for PV modelling and employs an equation based on that proposed by Faiman (Faiman, 2008). By solving the energy balance of a PV module, Faiman obtained the followed equation:

$$T_m = T_a + \frac{POA}{U_0 + U_1 \cdot ws} \tag{1}$$

where T_m and T_a are the PV module and ambient temperatures, *ws* is the wind speed, and U_0 and U_1 are heat loss coefficients. This model was adapted by PVsyst (PVsyst SA, n.d.) to calculate the temperature of a PV cell (Tc) as follows:

$$T_c = T_a + \frac{POA \cdot \alpha_{\mathrm{PV}} \cdot (1 - \eta)}{U_c + U_v \cdot ws} \tag{2}$$

where α_{PV} is the absorption coefficient of solar irradiation, typically set to 0.9, and η is the module efficiency, whose default value is 0.1. U_c is known as constant heat transfer component, while U_v is the convective heat transfer component and allows accounting for the effect of the wind. Faiman experimentally found, for seven different modules, average values of 24.9 W m^{-2} K^{-1} and 7.55 W m^{-3} s K^{-1} for U_0 and U_1, respectively. However, in many cases, a single constant heat loss coefficient is considered, U, defined as $U = U_c + U_v \cdot ws$. The higher the U-value, the lower the PV operating temperature. PVsyst recommends U-values of 29 W m^{-2} K^{-1} for well-ventilated systems and of 15 W m^{-2} K^{-1} in case of insulated modules.

An earlier model was proposed by Duffie and Beckman (Duffie and Beckman, 2006):

$$T_c = T_a + \frac{POA}{POA_{NOCT}} \cdot (\mathrm{T_{NOCT}} - T_a) \cdot \frac{9.5}{5.7 + 3.8\, s/m \cdot ws} \tag{3}$$

where POA_{NOCT} is the irradiance at nominal terrestrial environmental conditions (800 W/m^2) and T_{NOCT} is the Normal Operating Cell Temperature. This is the temperature of the cells at POA_{NOCT} and is typically provided by the modules' manufacturers.

Alternatively, some authors have made use of the Sandia model's coefficients to describe the FPV thermal behavior. This model, presented by King et al. (King et al., 2004), differentiates between the cell and module temperatures:

$$T_c = T_m + \frac{POA}{1000\, Wm^{-2}} \cdot \Delta T = POA \cdot \mathrm{e}^{a + b \cdot ws} + T_a + \frac{POA}{1000\, Wm^{-2}} \cdot \Delta T \tag{4}$$

where a and b are empirically-determined coefficients and ΔT expresses the temperature difference between the cell and the module back surface at an irradiance level of 1000 W m^{-2}. Both a and b have negative values, which decrease for modules and configurations that favor the heat exchange. In the original work (King et al., 2004), a ranged between -2.8 and -3.6, b between -0.04 s/m and -1.1 s/m, and ΔT between 0°C for insulated modules and 3°C for modules in open rack configurations.

Veldhuis et al. (Veldhuis et al., 2015) proposed a model that takes into account the contributions of radiation, convention and thermal inertia. This model built up on a previous one proposed by Ross (Ross, 1976), which was based only on ambient temperature and irradiance. In the approach of Veldhuis et al. (Veldhuis et al., 2015), the temperature of the module is first calculated as:

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

where h is the convective heat transfer coefficient, and α is an empirical wind factor. The contribution of the radiation is calculated as:

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

where k is an empirical value known as Ross coefficient, γ is a factor related to the impact of the relative humidity (RH) on the temperature, and r is the average temperature difference between the ambient and PV module temperature due to radiative cooling during nighttime. The effect of the thermal inertia is than accounted by calculating an exponential moving average over a few-minute period.

In 2020, Tina et al. (Tina et al., 2020) proposed a three-layer thermal model for both monofacial and bifacial LPV modules. This methodology allows calculating the temperatures of the cell, of the front glass and of the back surface. It takes into account the contribution of radiation, convection, and conduction, and considers the effect of the albedo radiation on the back surface. The authors found root-mean square errors ≤ 1.15°C when the results of the model were compared with the temperatures of PV modules in Catania, in the South of Italy.

2.2. Floating Photovoltaics

FPV has already been the subject of a number of reviews. Trapani and Santafé (Trapani and Redón Santafé, 2015) portrayed the status of the technology in 2014, listing onshore FPV plants installed in the 2007-2013 period and describing also novel FPV designs able to withstand harsher sea conditions. They reported that the owners of a 500 kW plant in Bubano, Italy, claimed a 20-25% increase in electricity output due to the cooling effect of water. A first comprehensive review was presented in 2016 by Sahu et al. (Sahu et al., 2016). In this work, the authors discussed advantages and disadvantages of this technology compared to other PV applications. Among the FPV pros, they listed an increased efficiency caused by the lower ambient temperature due to cooling effect of water. In addition, they analyzed the economics of FPV and reviewed commercial available designs. A mention to the cooling effect of water was also present in the review published by Ranjabaran et al. (Ranjbaran et al., 2019). This work analyzed the literature available at the time on FPV, discussing also its reliability and durability and its contribution to the CO_2 emissions cut. In addition, the authors presented a detailed overlook of electrical interconnections and converters issues in PV. The review of Pringle et al. (Pringle et al., 2017) analyzed the potential interaction between FPV and aquaculture (i.e. farming of aquatic organisms for food production). This work listed natural cooling as the primary technical advantage of FPV. In 2018, Cazzaniga et al. (Cazzaniga et al., 2018) reviewed floating and submerged PV designs and solutions, including active cooling systems. A comprehensive handbook published in 2019 (World Bank Group et al., 2019) stated that temperatures of FPV, unless thermally insulated or poorly ventilated, should be conservatively assumed at least as low as those of LPV.

In 2020, Rosa-Clot and Tina (Rosa-Clot and Tina, 2020a) published a book on FPV, with one chapter focused on water-based cooling mechanisms (Rosa-Clot and Tina, 2020b). In the same year, Naganthini et al. (Nagananthini et al., 2020) authored a chapter on thin film-based FPV. Three additional reviews have been published just in 2021. Gorjian et al. (Gorjian et al., 2021) dedicated one section of their comprehensive review to the PV modules cooling techniques and listed a few studies specifically focused on the FPV operating temperature. The authors also reported a number of issues experienced in different phases of the lifetime of FPV systems and discussed the environmental and economic impact of FPV. A review specifically focused on cleaning strategies for FPV was published by Zahedi et al. (Zahedi et al., 2021). Last, Kumar et al. (Kumar et al., 2021) reviewed active cooling techniques and discussed the feasibility and environmental effects of FPV. Their paper included also a section on the FPV temperature, with a preliminary report on the effects of the FPV design on the temperature.

As it can be seen, lower operating temperatures have been often presented as one of the advantages of FPV compared to LPV. However, given the variety of designs available and some recent findings (Lindholm et al., 2021; Peters and Nobre, 2022), a discussion on this subject is needed. For this reason, the present work collects previous studies that have specifically investigated the thermal behavior of FPV and/or reported information on its operating temperature. Since most of the PV capacity makes use of passive cooling, the present review only focuses on this configuration and on the natural advantages that the presence of water has been expected to provide to FPV systems.

3. Literature Review

From a thermal perspective, the FPV systems can be classified into two groups, with a division based on whether the back surface of the module is in contact with air or water. Each group is discussed individually in one of two following subsections (3.1 for air) and (3.2 for water). Tilted FPV modules are generally cooled by air, even if some partially submerged designs have been presented (and are discussed in 3.2). Horizontal FPV modules are typically in direct contact with water. In some cases, however, horizontal modules have been suspended above the water surface, and are therefore air-cooled.

3.1. Air-cooled FPV

Many case studies have been presented in the literature on the thermal and electrical performance of FPV. However, most of the studies are site- and/or design-specific and are difficult to generalize.

Choi (Choi, 2014) investigated the performance of various FPV systems in Korea. First, the author found that a 100 kW and a 500 kW FPV systems on the Hapcheon dam produced yields in between 10% and 13.5% higher than a LPV system installed 60 km away. In addition, the author compared the performance of a FPV system and a LPV system, co-located and installed with an 11 degree-tilt also in Korea. The FPV showed a consistently better capacity factor during the investigated period (January to July 2012). The author justified the result with the lower operating temperatures registered by the FPV, due to the reflection and the cooling effect of the water. FPV was estimated to work at an efficiency 11% higher than LPV. In support to the conclusion, the author plotted the temperature of the two systems for eight days. It can be seen that, in some of the days, FPV experiences temperatures up to 5 to 10 degrees lower for FPV. However, interestingly, the LPV module consistently achieves lower temperatures during the night.

One of the FPV systems of the previous study was subject also to a subsequent analysis by Suh et al. (Suh et al., 2020). The authors found that the NREL's System Advisor Model (SAM) (Blair et al., 2018) underestimated the FPV yield by 15%. The difference was attributed to the lack of a specific thermal model for FPV, as the deviation between observations and estimations was found to increase in the months with higher temperatures and irradiances. The authors were able to reduce the error to 9% when the modelled yield was increased by 10%, as in (Choi, 2014). However, the authors highlighted that the difference between observations and estimations varied with the seasons. Therefore, they advised avoiding using a fixed multiplication factor for FPV throughout the year. The authors recommended, instead, where possible, adjusting the FPV cooling factor to the local specific water, air and temperature conditions.

The findings of Choi's investigation (Choi, 2014) were later used also in other FPV modelling efforts. Song and Choi increased by 11% the yield predicted by SAM (Blair et al., 2018) to estimate the output of a FPV system installed on a Korean mine pit lake (Song and Choi, 2016). A 10% factor was employed by (Cromratie Clemons et al., 2021) as well for the calculation of the energy outputs of FPV potentially deployed in different reservoirs in Thailand.

Yadav et al. (Yadav et al., 2017) studied the performance of a 23-degree tilted FPV module mounted on high-density polyethylene blocks on an artificial pond in Madhya Pradesh, India. A single-day experiment resulted in lower temperatures for FPV, attributed to the cooling effect of the water, which led to a 0.79% increase in efficiency.

Recently, El Hammoumi et al. (El Hammoumi et al., 2021) conducted an 5-day experimental investigation on FPV mounted on a water PVC pool at different inclination. In this case, the back of the modules was mostly free of obstructions. The authors found, during the daylight time, mean FPV temperatures in between 2 and 3°C lower than that of LPV modules installed at 30° tilt. Even in this case, the result was explained by the lower water temperature compared to air: the temperature difference increased during the day, reaching the maximum (12 to 15°C) during the afternoon.

While most of the literature on air-cooled FPV makes use of tilted FPV, some examples of horizontal modules not in contact with water are present. In Majumder et al. (Majumder et al., 2021), the FPV module was placed inside a wooden basin, 7.5 cm above the water, whereas the LPV module was mounted at a greater distance from the ground. The authors recorded lower temperatures for FPV, up to a maximum of 1.4°C. The authors attributed the temperature drop to the natural air convention occurring under the FPV module and to the presence of cooler ambient-temperature above water. The importance of the water in FPV cooling was proved through an additional experiment: the same FPV configuration was used to conduct a test without water in the basin. In this case, the FPV module (suspended in the basin without water) returned higher temperatures compared to the LPV, due to the lack of free airflow in an enclosed environment such as the empty wooden basin.

Goswami et al. (Goswami et al., 2019) compared the operating temperatures of FPV and LPV modules in a pond in West Bengal over 30 days. They measured a FPV temperature consistently lower than LPV, with differences up to 12 degrees on the hottest day, resulting in a daily power output 10.2% higher for FPV compared to LPV. The authors explained the results referring to the "Heat Islanding" effect. In LPV, the heat remains trapped between the soil and LPV modules, whereas the air surrounding the FPV module is cooled by the water. From one the figures, it appears that the module were installed below ground level, inside a pool; this could have affected the air flow and its potential cooling effect, according to the phenomenon described by (Majumder et al., 2021). A subsequent study, presented by some of the authors (Goswami and Sadhu, 2021), showed consistently higher temperatures for LPV over a longer 16 month period. The difference in monthly average temperature between FPV and LPV went from a minimum of 6 degree in winter to a maximum of 22 degrees, resulting in an efficiency gain for FPV of $1\%_{abs}$.

Some authors have been trying to model the thermal performance of FPV, sharing parameters and equations that could be used to estimate the FPV operating temperatures in different locations and conditions. Kamuyu et al. (Kamuyu et al., 2018) analyzed the performance of a 33 degree tilted FPV site in Korea and presented two empirical equations to predict the module's temperature:

$$T_{m1} = 2.0458 + 0.9458 \cdot \mathrm{T_a} + 0.0215 \cdot \mathrm{G_T} - 1.2376 \cdot \mathrm{ws} \tag{7}$$

$$T_{m2} = 1.8081 + 0.9282 \cdot \mathrm{T_a} + 1.021 \cdot \mathrm{G_T} - 1.2210 \cdot \mathrm{ws} + 0.0246 \cdot \mathrm{T_w} \tag{8}$$

where T_a and T_w are the ambient air and water temperatures, G_T is the irradiance, and ws is the wind speed. The equations were able to model the module's temperature over a year with average errors of 2.1% and 4.4% respectively. This means that the addition of fourth variable, T_w, increased the modelling error in this case. Despite that, equation (8) was used by a successive study (Sukarso and Kim, 2020) to estimate the temperature of FPV modules potentially installed in a reservoir in Indonesia. The authors of this work compared the FPV temperature with that of LPV systems, calculated using the equation by Duffie and Beckman

(Duffie and Beckman, 2006). They estimated a FPV efficiency up to 0.6% higher than LPV, due also to an average 8 °C difference in temperature between water and ground surface temperature.

In a recent study, Tina et al. (Tina et al., 2021a) have analyzed the thermal behavior of monofacial and bifacial FPV systems, using hourly average data collected in Catania (Italy) over two clear-sky and two cloudy days in 2019. They employed both the PVsyst and the Sandia models, in equations (2) and (4) respectively, finding Uc = 31.9 W/m^2K, Uv = 1.5, a = −3.743 and b = −0.0746 s/m for the monofacial system and Uc = 35.2 W/m^2K, Uv = 1.5, a = −3.876 and b = −0.0738 s/m for the bifacial one. The models returned R^2 higher than 0.95 and errors in between 0.4% and 1.1% in the estimation of the modules' temperatures. In both cases, these parameters confirm a slightly better thermal exchange for FPV compared to LPV. In addition, they suggest a better heat transfer for bifacial modules. This is in line with that reported for land-based modules by Lamers et al. (Lamers et al., 2018), which found slightly higher U-values for bifacial panels compared to monofacial panels.

The same authors made use of the Catania's system data to develop a thermal model for FPV (Tina et al., 2021b), based on that proposed in (Tina et al., 2020). In addition to convection, they took into account also the cooling effect of radiation and evaporation, finding errors < 1 degree in temperature estimation. The model was employed to study the effect of wind on FPV cooling. It was found that the difference between LPV and FPV temperatures dropped from 6°C to 1.5°C and from 10°C to 4°C for monofacial and bifacial modules, respectively, at wind speeds decreasing from 10 to 0.5 m/s, under a constant 1000 W/m^2 irradiance.

Kjeldstad et al. (Kjeldstad et al., 2021) analyzed the performance of a pilot FPV system located on an inner branch of a fjord in Norway. In this case, the modules were placed on a hydro-elastic floating membrane, so that they could be cooled by water. For experimental purposes, they modified one of the setups, creating a 32-mm air gap between the modules and the water, so that these could act as air-cooled references. They found that the air-cooled configuration underperformed compared to the water-cooled one. However, despite the smaller thickness of the air gap compared with most air-cooled designs, the air-cooled string achieved a U-value of 46 W/m^2K, higher than that typically employed for well-ventilated PV system (PVsyst SA, n.d.).

In addition to sharing installation-specific measurements, some studies have tried to identify the correlations between the FPV design and its thermal behavior. Making use of data from a large FPV testbed in Singapore, Liu et al. (Liu et al., 2018) presented a comprehensive field analysis, which included, in addition to a thermal analysis, also information on FPV degradation, bifaciality and operational challenges. They compared the performance of 9 FPV systems and of a well-ventilated LPV system installed 1.5 m above the roof of the inverter room. They found that all the FPV systems worked at lower temperatures compared to the LPV, thanks also to the consistently higher wind speeds registered offshore compared to onshore. However, they also highlighted that the temperature difference changed depending on the weather and irradiance conditions and that temperature inhomogeneity could occur on the FPV platform. The authors were able to classify the FPV systems depending on their structure and their thermal behavior (Fig. 3):

- "Free standing": modules mounted high above the water and experiencing excellent cooling due to good air ventilation.

- “Small footprint”: modules mounted close to the surface with a small degree of water surface coverage.
- “Large footprint”: modules mounted close to the water with a larger surface coverage.
- “Insulated”: large footprint installations, with modules mounted in an east-west facing configuration. These have the worst cooling, lower than that of the reference LPV, because of the reduced ventilation.

In 2021, Dörenkämper et al. (Dörenkämper et al., 2021) presented an additional investigation taking into account FPV and LPV systems installed in the Netherlands and in Singapore. On top of the footprint-classification, they identified the exposure of the FPV modules’ back surface as key factor in the thermal behavior. Indeed, they found that “open structure” FPV modules, i.e. with the back surface directly exposed without obstructions to the water surface, could achieve U-values as high as 57 W/m^2K (Fig. 3), twice the typical value attributed to well-ventilated LPV system. Conversely, “close structure” FPV modules showed lower U-values, in between 36 and 41 W/m^2K. These were still higher than the U-values found for two deep-inland LPV systems, but in line with the 39 W/m^2K recorded for a near shore LPV system. Last, the authors analytically confirmed the significant impact of the higher wind speeds above water compared to land on the installations of both countries.

The importance of the wind cooling in FPV thermal management had already been highlighted by Peters and Nobre (Peters and Nobre, 2020) in 2020 and was then confirmed by the same authors in a more recent analysis (Peters and Nobre, 2022). The authors monitored two systems in an artificial shallow water body in Cambodia and found higher operating temperatures for the FPV compared to the LPV system mounted on the roof of the inverter room. The result is in line with that later reported by (Dörenkämper et al., 2021), which, as aforementioned, found a slightly higher U-value for a near-shore, open rack and free standing LPV compared to two large-footprint and close structure FPVs. Using the Veldhuis model (Veldhuis et al., 2015), Peters and Nobre (Peters and Nobre, 2022) were able to attribute the result to the reduced wind speed experienced by the little-below-ground FPV compared to the 3m-above-the-ground LPV. In addition to the surface friction, which reduces the wind speed close the ground, they explained that the presence of grass, bushes and one-story structures surrounding the water basin in this case further affected the wind hitting the FPV. These obstructions, however, did not affect the wind on the rooftop LPV installation. Moreover, the authors acknowledged the potential impact of the difference sizes of the two installations, as the rows of 5 degree-tilted modules of the larger FPV system could have acted as wind shades. In conclusion, Peters and Nobre (Peters and Nobre, 2020, 2022) warned that one should not always expect lower operating temperature in FPV systems, especially in conditions of low wind speeds and low module height, and that the system designs should favor wind cooling over water-related cooling for FPV not in direct-contact with water.

Similar conclusions were presented by Lindholm et al. (Lindholm et al., 2021), which modelled the performance of water- and air-cooled FPV. Their analysis confirmed the strict dependence of air-cooled FPV cell temperatures on the wind speed, showing a difference in U-value between a wind speed of 1 m/s and 7 m/s even higher than 30 W/m^2K. However, the authors in this case also highlighted that, while the wind speed decreases, the contribution of the thermal radiation between water and the elevated air-cooled module increases. At wind speeds of 1 m/s, neglecting the thermal radiation contribution was found to produce an overestimation of the cell temperature as high as 10°C.

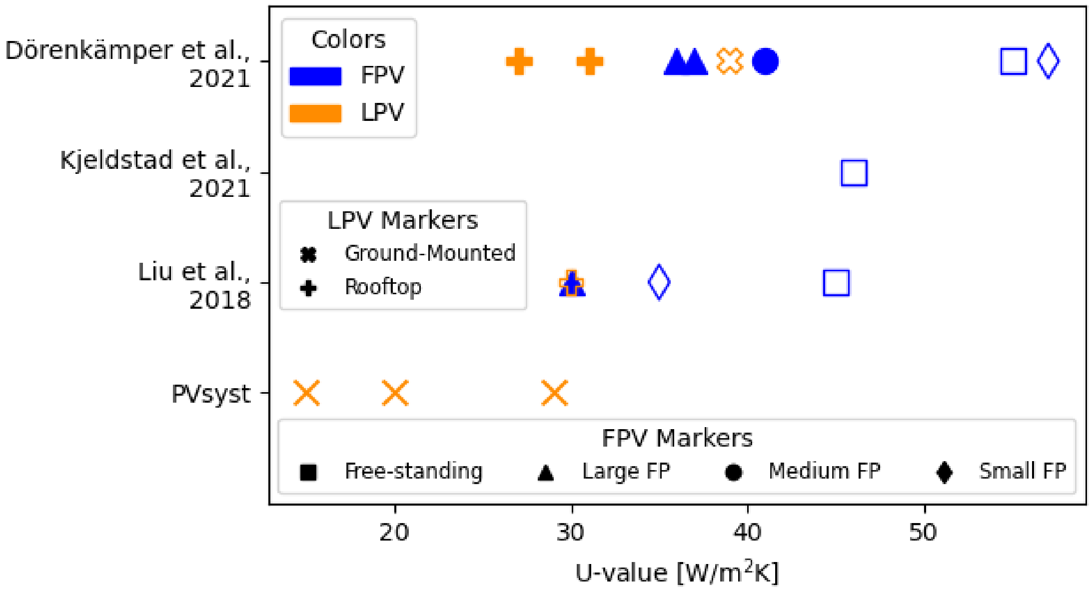

Fig. 3. Median U-values reported in the air-cooled FPV-related literature (Dörenkämper et al., 2021; Kjeldstad et al., 2021; Liu et al., 2018). *Blue-colored markers refer to FPV; orange-colored markers refer to LPV. Filled markers indicate close structures in FPV and near-shore systems in LPV. Transparent markers indicate open structures in FPV and inland (i.e. far from water) systems in LPV. PVSyst values are not differentiated between ground-mounted and rooftop systems* (PVsyst SA, n.d.).

It should be mentioned that, while most of the literature focused on the onshore FPV, Golroodbari and van Sark (Golroodbari and van Sark, 2020) developed a mathematical model to evaluate the performance of open sea FPV. Their analysis estimated higher performance ratio for a FPV system in the North Sea compared to a LPV system installed in the Netherlands, mainly result of the lower and more constant temperatures of the open sea.

Last, it is worth mentioning that, in some cases, previous studies have been wrongly cited as references for the better FPV cooling. This is the case of Yoon et al. (Yoon et al., 2018), who found improved performance when comparing a tracked FPV system and a fixed LPV and did not explicitly mention a water temperature effect. Other works have estimated better thermal performance for FPV, assuming in input however arbitrary lower temperatures for air above water compared to air on land. Assuming an air temperature 5 degree lower on water bodies compared to land, due to the expected cooling effect of water, authors of (Liu et al., 2017) estimated a 3.5 degree difference between the temperature of FPV and LPV, and an efficiency raise up to 2%. The same assumption was later employed by Mittal et al. (Mittal et al., 2018), who compared the modelled performance of a LPV and FPV plants in Jodhpur, India. Referencing the work of (Liu et al., 2017), the authors assumed a 5°C temperature difference between ground and water surface, finding a 2.48% increment in annual energy generation due to a 14.56% drop in module temperature.

3.2. Water-cooled FPV

Optimal tilt angles minimize the angular and reflection losses, so that a larger amount of radiation can reach the semi-conductive material. In the areas most close to the Equator, the optimal tilt angles are typically small (Majid et al., 2014), while at northern or southern latitudes their value is significantly higher. Despite that, a horizontal FPV configuration can be still selected to reduce the land occupancy and the intra-row shading among the modules. In addition, horizontal FPV modules can be place in direct contact with water and therefore can benefit of its higher heat transfer coefficient compared to air. For these reasons, horizontal and water-cooled FPV modules have been also investigated in the literature and are commercially available nowadays. Furthermore, in some cases, modules have been submerged in water in order to increase even more the cooling effect of water. In these cases, modules can be tilted (and only partially submerged) or horizontal (and fully submerged). These configurations have also been included and reviewed in the present section because both of them benefit of the major cooling contribution of water.

The performance of water-cooled FPV modules have been typically compared with that of either air-cooled FPV or LPV modules. In their work, Kjeldstad et al. (Kjeldstad et al., 2021) showed that water-cooled modules overperformed horizontal modules mounted at 32-mm from the water surface, achieving yield 5 to 7% higher over a 6 month period. The authors found U-values as high as 81 W/m^2K for the water-cooled FPV, significantly higher than any value reported for air-cooled modules (Fig. 3). Interestingly, they showed that the modeling error was lowered if water temperature was employed in place of air temperature in equation (2). Similar conclusions were reported in a different work by some of the authors (Lindholm et al., 2021), which showed U-values consistently higher for water-cooled FPV modules compared to the air-cooled ones. Their model demonstrated that while the cell temperature in water-cooled modules is almost independent of the wind speed, this still affects the U-values. Indeed, U-values as high as 86.5W/m^2K were reported in high wind conditions. However, the main cooling factor in this configuration is the water temperature: the cell temperature is shown, indeed, to increase at the same rate as the water temperature.

In 2014, Trapani and Millar (Trapani and Millar, 2014) proposed a thin film flexible floating PV and deployed a 570 W prototype in a small rainfall water storage pond by the Ramsey Lake, in Canada. Additional modules were stacked into the ground. Despite a soiling-driven drop in performance after a 45-day exposure, the authors recorded lower temperatures and a 5% higher yield for the FPV compared to the ground-mounted system.

Flexible thin-film modules were adopted also by Mayville et al. (Mayville et al., 2020). In this case, the modules were mounted on top of three floating foams and the test system was deployed for almost three months on a waterway connected to Lake Superior in North America. The authors reported lower temperatures for the same setup in floating conditions compared to out-of-the-water conditions. The temperature reduction ranged in between 10°C and 20°C and varied depending on the weather and on the foam.

A similar foam-backed design was investigated in the thesis of Hayibo (Hayibo, 2021), conducted, as the previous study (Mayville et al., 2020), at the Michigan Technological University (USA). In this case, the equation proposed by Kamuyu et al. (Kamuyu et al., 2018) was adapted to the water-cooled floating device:

$$T_m = -13.2554 + 1.2645 \cdot \mathrm{T_a} + 0.0128 \cdot \mathrm{G_T} - 0.0875 \cdot \mathrm{T_w} \quad (9)$$

In this case, the wind speed was not considered, due to the dominant cooling effect of water on the back surface. This new equation described the temperature profile of the water-cooled FPV better than the original model. Using this equation, the authors estimated a 3.5% higher energy production compared to an air-cooled FPV module.

Azmi et al. (Azmi et al., 2013) and Majid et al. (Majid et al., 2014) compared the performance of the same module in LPV and FPV configurations. In the first work (Azmi et al., 2013), the authors conducted the study indoor, using a solar simulator, under three radiation intensities.

After one hour of exposure, in all the tests, a difference in between 5°C and 6°C was found between the LPV and FPV. In the second work (Majid et al., 2014), the two configurations were outdoor tested in the same time window (11AM to 1PM) on two different days on a so-called pond simulator. Also in this case, the results showed temperatures approximately 15°C lower for FPV compared to LPV for ambient and water temperatures of 30°C and 25°C respectively.

Ho et al. (Ho et al., 2016, 2015) investigated the possibility of using phase change materials to lower even more the temperature of the FPV. They found that water-saturated microencapsulated phase change material (MEPCM) layers attached to the back of the modules could raise the efficiency of the modules by up to $2\%_{rel}$.

To maximize the cooling effect of water, one could submerge the photovoltaic modules. This way, both the back and the front surfaces of the modules are in direct contact with water. However, apart from the improved thermal exchange, water immersion reduces the amount of incoming light reaching the PV cell. Indeed, water is a light absorber, especially at red-infrared wavelengths (Rosa-Clot et al., 2010). The first investigations on water-submerged modules date back to the late 70s, when Stawich (Stachiw, 1980, 1979) investigated the performance of PV cells in various locations. The author empirically found a 5% loss in power output if modules were submerged at the visual contrast limit depth compared to the above-water conditions due to the water absorption. In addition, Stawich highlighted the importance of the water visibility on the performance of the modules.

More recently, taking into account the variation in solar spectrum at different clear water depths, Rosa-Clot et al. (Rosa-Clot et al., 2010) estimated that submerged panels can achieve higher efficiency than land-based modules at depths lower than 10 cm. At these depths, assuming submerged and air-cooled module temperatures of 25°C and of 65°C, the thermal gains are still greater than the losses due to the water light absorption. The authors showed that single- and poly-crystalline silicon modules could benefit the most of low-water depth immersion, because of the higher temperature coefficients. However, submerged amorphous silicon modules could achieve higher efficiencies than LPV at higher depths than the crystalline modules (up to 20 cm). This is due to the shortest wavelengths at which their spectral response peaks, which are less impacted by the water absorption. This conclusion was also supported in a following study (Rosa Clot et al., 2017), where the performance of CdTe and CIS was also simulated. The results of the model developed in the original work (Rosa-Clot et al., 2010) were validated by a four-month test, conducted in Pisa (Italy), in which single-crystalline modules were immerged at 4 cm and 40 cm. The results showed that a horizontal crystalline silicon module submerged at 4 cm depth in water increased its efficiency by $11\%_{rel}$ compared to in-land operation. Conversely, increasing the depth up to 40 cm lowered the efficiency by $23\%_{rel}$. The experiment was extended in a subsequent publication by Lanzafame et al. (Lanzafame et al., 2010), where the authors showed that the efficiency gain for submerged modules mainly occurred at irradiances higher than 600 W/m^2. Also a later investigation by Tina et al. (Tina et al., 2012), with additional experimental data, confirmed the findings of (Rosa-Clot et al., 2010). An example of a potential application of submerged modules was proposed in (Rosa Clot et al., 2017), where the performance of PV modules mounted on the swimming pool floors was investigated.

Additional studies have looked into the correlation between water depth and FPV performance improvement. An empirical correlation between relative efficiency and water depth was reported by (Abdulgafar et al., 2007). When a polycrystalline module was immersed in colder than air water tank, the authors registered higher FPV performance for water depth until 6 cm at least. These results are in line with the conclusions of a different experimental study (Mehrotra et al., 2014). A 4 cm water depth immersion was also recommended by an experimental study conducted in India by Sheeba et al. (Sheeba et al., 2015), who investigated the PV performance in water depths up to 20 cm under various water flow rates.

Building on the findings of (Rosa-Clot et al., 2010), Elminshawy et al. (Elminshawy et al., 2021) tested the thermal and electrical behavior of a partially submerged module. In this case, the lower 10 cm-high portion of a tilted module was immersed in water. The experiment was conducted in an outdoor pool over a few days, using an air fan to reproduce the effect of wind blowing from various directions at different speeds. The authors showed an increase power production with the wind speed and found the lowest operating temperatures for wind blowing from the North (φ=0°) and the lowest from the South (φ=180°). They also proposed the following empirical equation:

$$\ln(T_m) = 3.63 - 0.0068 \cdot \varphi - 0.0549 \cdot \mathrm{ws} - 0.0109 \cdot \varphi \cdot \mathrm{ws} - 0.0598 \cdot \varphi^2 - 0.007 \cdot \mathrm{ws}^2 \tag{10}$$

However, the equation does not include water temperature and irradiance. The first one is expected to affect the cooling effect of water, whereas the second is known to have a role in PV module temperature as it expresses the amount of incoming energy in a PV module.

Using the COMSOL multiphysics software package, Ziar et al. (Ziar et al., 2021) modelled a bifacial module with only the lower frame only in direct contact with water. While confirming the considerably lower temperature for the portion in contact with water, the authors found that the cooling effect did not extend to rest of the module because of the low thermal conductivity of the EVA and the glass. Overall, the model predicted an increase in energy of 0.17% compared to a fully air-cooled case. In light of this limited gain and of the higher risks of degradation, the authors did not consider partial submersion as a durable bifacial FPV solution.

3.3. Discussion

A clear distinction, at least in terms of thermal behavior, emerges from the literature between the FPV cooled by air and by water. This might look obvious to some, but the two types of floating technologies have been often been reported as one.

Previous authors seems to agree on the fact that water-cooled FPV modules experience lower operating temperatures compared to LPV and to air-cooled LPV. This motivated by the higher heat transfer coefficient of water that will facilitate the thermal transmission. The better cooling can be also expected at water temperatures higher than air temperatures. This can be demonstrated by comparing the findings of Kjeldstad et al. (Kjeldstad et al., 2021) and Dörenkämper et al. (Dörenkämper et al., 2021). These studies made use of the same model, PVsyst, to describe the behavior of water- and air-cooled FPV systems respectively. According to (2), the temperature of a water-cooled FPV cell will be lower than that of an air-cooled one if the following condition is met:

$$T_w + \frac{POA \cdot \alpha \cdot (1 - \eta)}{U_w} < T_a + \frac{POA \cdot \alpha_{\mathrm{PV}} \cdot (1 - \eta)}{U_a} \tag{11}$$

where U_w and U_a are the U-values for water- and air-cooled modules respectively. Fig. 4 shows how much higher the water temperature can be respect to air depending on the air-cooled U-value (U_a) and on the irradiance. The results show that, thanks to the higher U-value, water is allowed to achieve higher temperatures than air to achieve the same cell temperature. Also, it can be seen that this allowance rises with the irradiance.

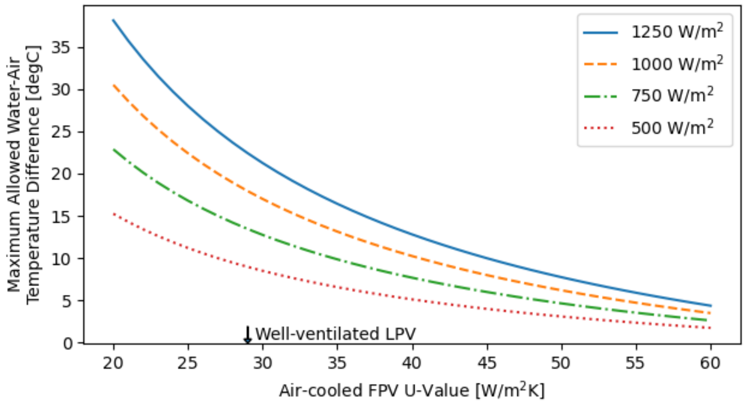

Fig. 4. Maximum allowed difference in water to air temperature difference depending on air-cooled U-value to have lower operating temperatures for water-cooled FPV compared to air-cooled FPV. The water-cooled U-value is fixed to 81 W/m²K, as in (Kjeldstad et al., 2021)*. α and η are set to 0.9 and 0.1 respectively, as recommended by PVsyst* (PVsyst SA, n.d.)

Air-cooled FPV systems require more complex evaluations than the simple lower-than-LPV temperature assumption. The most recent literature seems to converge on the dominance of wind-cooling (through convection) over water-cooling (through radiation) (Dörenkämper et al., 2021; Liu et al., 2018; Peters and Nobre, 2022; Tina et al., 2021b). The design of the FPV system is likely to play a key role in the thermal behavior, as small footprints and open designs (i.e. FPV modules with back surface are widely exposed to the water) have been found to facilitate the air circulation and therefore the heat exchange (Dörenkämper et al., 2021; Liu et al., 2018). While secondary, the contribution of the radiative exchange between modules and water could still be of value, at least in low-wind conditions (Lindholm et al., 2021), even if additional investigations are needed. However, apart from the system's design, one should not neglect also the impact of the site on the FPV thermal exchange. The presence of buildings or vegetation or a basin located few meter below ground can lower the wind speeds and affect the FPV temperature (Peters and Nobre, 2022).

The works of Rosa-Clot et al. (Rosa-Clot et al., 2010; Rosa Clot et al., 2017) highlighted an additional factor that plays a role in the thermal behavior of FPV, in addition to the system's configuration and local weather conditions. This is the temperature coefficient, which is strictly correlated to the PV material (Fig. 2). When modelling the performance of submerged modules, Rosa-Clot et al. (Rosa-Clot et al., 2010; Rosa Clot et al., 2017) showed the best efficiency improvements for crystalline silicon and CIGS modules because of the lower coefficients (i.e. highest in absolute values) compared to CdTe and amorphous silicon. However, the results reversed as the water depth increased because of the water attenuation effect on higher wavelengths that affect more the low-energy bandgap materials (m-Si, p-Si, CIGS). The temperature coefficient is an important parameter also for non-submerged modules: the lower its value (i.e. the higher its absolute value), the higher the temperature dependence. A recent analysis (Micheli, 2021) quantified the economic value of the temperature coefficients for air-cooled modules. Decreasing the temperature coefficient by $-0.001C^{-1}$ was found to reduce the average yield in Spain by 15 kWh/kW/year for LPV and by only 2 kWh/kW/year for FPV.

As mentioned in 2.1, the presence of hot spots is an additional temperature-related issue that can affect the PV performance and reliability. The non-homogeneous accumulation of soling is a known potential source of hot spots (García et al., 2011). Soiling consists of the deposition of dust, dirt and contaminants on the surface of PV modules and affects PV system worldwide (Ilse et al., 2019). Soiling can have different sources and patterns. For example, while FPV modules are expected to be less affected by dust contamination than LPV, they are probably more exposed to biofouling and bird droppings (World Bank Group et al., 2018). This type of soiling is typically distributed as "blotches" and can occur in multiple places across the PV modules' surface, leading possibly to the formation of hot spots (Kazmerski et al., 2017). For these reasons, as highlighted by Ziar et al. (Ziar et al., 2021), one can expect for FPV modules a higher risk of greater spatial temperature variance compared to LPV systems. This can potentially lead to more frequent soiling-induced hot spots and permanent damages. However, no specific studies are yet available on this topic.

In addition to the effects of the environment on the FPV performance, one should take into account the impact that FPV installations themselves can have on the environment. FPV can be expected to impact wind speeds and water temperatures. PV modules indeed necessarily generate shades, reducing the amount of visible sunlight reaching the water. This reduced incoming radiation can be expected to lead to cooler water surfaces. However, Armstrong et al. (Armstrong et al., 2020) pointed out that, at the same time, the presence of modules could also reduce the outgoing heat fluxes, resulting in warmer surface water in some occasions. In addition, one should take into account that FPV modules could act as wind barriers. Therefore, while the lower radiation would lead to lower temperatures, the reduced winds can cause limited wind mixing, increasing water stratification and therefore the water surface temperature. The two factors were recently studied also by Exley et al. (Exley et al., 2021). The authors estimated that the presence of FPV is likely to reduce the surface water temperature, but also highlighted the possibility of warmer water temperatures when wind speed is reduced significantly more than solar radiation. The magnitude of the induced changed would vary with the FPV surface coverage: minor temperature changes should be expected for small coverages (<10%), whereas these would become more significant for larger coverages (>50%). Yang et al. (Yang et al., 2021) conducted a valuable investigation on the energy budget of floating photovoltaic systems, concluding that longwave radiation dominate their thermal balance. Indeed, the authors found that, while the presence of modules reduces the shortwave radiation reaching the water, the incoming longwave radiation increases because of the high temperature of the FPV modules during the day. In addition, the night radiation cooling is affected. Overall, they found higher air and water temperatures under the modules compared to open water.

It has been mentioned that the thermal behavior can be key for the cost-competiveness of FPV. In this light, some studies have also estimated the potential economic revenues and/or losses due to different thermal behaviors between FPV and LPV. One of the most common metrics to evaluate the economics of PV is the Levelized Cost of Electricity (LCOE), which expresses the cost of each kWh of electricity generated by a system over its entire lifecycle. Hafeez et al. (Hafeez et al., 2022) analyzed the feasibility a FPV system potentially installed in Islamabad, Pakistan, and found that the LCOE of FPV would decrease by 0.09 USD cents/kWh (corresponding to ˜2%) per each 5 degree drop in module's temperature. A different work modelled the economics of FPV across Spain (Micheli, 2021), and estimated that, on average, 4 to 5 €/kW could be invested to increase the U-value by 1 W/m^{2}K (in the 29-68 W/m^{2}K range, R^2=0.95).

Overall, the review suggests that, because of the many variables, the operating temperatures of FPV, at least for air-cooled modules, should not be considered necessarily lower than in LPV. Indeed, even if most of the evidences report better cooling for FPV, as resumed in Table 1, cases of higher temperatures in air-cooled FPV than in co-located LPV have been also presented. These have been attributed to low wind speed conditions (Peters and Nobre, 2022) or specific module's designs (Dörenkämper et al., 2021). In particular, the works in (Dörenkämper et al., 2021; Liu et al., 2018) demonstrate the importance of design and geometries on the FPV heat transfer. However, while these studies represent first valuable contributions towards the understanding on the FPV thermal behavior, the number of data point available so far make it possible to get to only preliminary conclusions: open structures and small footprints are the factors that favors the most the heat exchange in air-cooled FPV. However, by looking at the results in Table 1, one can expect additional conditions, such the tracking configuration, the tilt and azimuth angles or even the bifaciality of the modules, to also potentially affect the heat transfer of FPV systems. For these reasons, sharing more case studies and models on the FPV thermal behavior is essential to better understand its cooling mechanisms and the factors that can favor and/or obstacle the dissipation of heat.

Table 1. Summary of the mean values of parameters for FPV thermal modelling extracted from field studies. The parameter marked with an asterisk (*) was calculated using water temperature instead of air temperature.

Cooling mechanism	Configuration	Location	Uc	Uv	U	A	B	R^2	Reference
Air-cooled	Tracked, small footprint and open structure	Inland lake in the Netherland, near the sea	24.4	6.5	57			0.57 (for Uc and Uv)	(Dörenkämper et al., 2021)
Air-cooled	17◦-tilted, East-West oriented, large footprint and closed structure	Inland lake in the Netherland, near the sea	25.2	3.7	37			0.28 (for Uc and Uv)	(Dörenkämper et al., 2021)
Air-cooled	7◦-tilted east, Large footprint and close structure, SG	Tengeh Reservoir, in Singapore, near the sea	34.8	0.8	36			0.59 (for Uc and Uv)	(Dörenkämper et al., 2021)
Air-cooled	12◦-tilted east, medium footprint and close structure, SG	Tengeh Reservoir, in Singapore, near the sea	18.9	8.9	41			0.58 (for Uc and Uv)	(Dörenkämper et al., 2021)
Air-cooled	10◦-tilted east, free standing and open structure, SG	Tengeh Reservoir, in Singapore, near the sea	35.3	8.9	55			0.52 (for Uc and Uv)	(Dörenkämper et al., 2021)
Air-cooled	20◦-tilted open structure with monofacial modules	Pond in Catania, Italy	31.95	1.5		-3.743	−0.0746	0.97-0.98.	(Tina et al., 2021a)
Air-cooled	20◦-tilted open structure with bifacial modules	Pond in Catania, Italy	35.22	1.5		-3.876	-0.0738	0.96-0.97.	(Tina et al., 2021a)
Air-cooled	Horizontal bifacial module, 3.2-cm of a floating membrane	Fjord's Inner branch on Norwegian west coast			46				(Kjeldstad et al., 2021)
Water-cooled	Horizontal bifacial module on a floating membrane	Fjord's Inner branch on Norwegian west coast			71*				(Kjeldstad et al., 2021)

Future works should take into account some of the recommendations and of the lessons learnt from previous studies. As also advised in (Peters and Nobre, 2022), experts should make available also data on ambient and water temperature, irradiance, and wind conditions, in addition to thermal coefficients (e.g. U-values) and recorded module temperatures. This additional information is essential to better understand the cooling mechanisms of FPV in different conditions. It will also make it possible to correlate with more accuracy the FPV temperature and its causes. For this same reason, where possible, experimental comparisons of FPV and LPV performance should be conducted on the same days, to assure the same experimental conditions, rather than on different days. If not possible, the weather irradiance and weather data for both periods should be shared. Additionally, particular care should be put in building the LPV setup to provide a better comparison; in some of the previous cases, the reference LPV module was mounted in configurations that could have negatively affected its thermal behavior, such as inside an empty water pond or distanced just a few centimeters from the surface. Last, given the weather conditions dependence of the heat transfer, extended experimental campaigns are recommended, in order to avoid conclusions based only on short time periods.

4. Conclusions

Floating photovoltaics is one of the arising solutions able to alleviate the land-use competition for photovoltaics. In addition to limited land requirement, FPV is often attributed lower operating temperatures than LPV and it is therefore expected to work at higher efficiencies. If confirmed, the improved thermal behavior could contribute making this technology cost-competitive and successful. In this light, the present work assesses the current knowledge on the thermal behavior of FPV systems, reviewing in-depth the literature available on the topic.

So far, the publications on FPV have been often site- or design-specific, making it difficult identifying universal conclusions. However, the present review points out that, in order to describe better their thermal behavior, FPV systems should classified as either water- or air-cooled. According to the available literature, the first ones can be expected to achieve lower temperatures than LPV, because of the better heat transfer of water. In addition, the data suggests that these lower temperatures could be experienced even for water temperatures higher than air. Also air-cooled systems can achieve better thermal performance than LPV, but examples of higher-than-LPV temperatures have been reported in the literature. Some initial comparative experimental studies have been presented, showing that some designs favor the heat exchange (open structure and/or small footprints), whereas FPV with close structures and larger footprints can experience temperature higher than LPV. The results are explained by the role of the wind speed in air-cooling; the highest heat transfers are found for designs that favor the airflow. However, for the same reason, some local conditions can obstacle the heat transfer of FPV, such as low wind speeds, the system installed below ground level and/or the presence of vegetation and buildings around the basins.

Some studies have also shared parameters and models to make it possible to estimate the FPV temperature anywhere. However, given the young age of the technology and the variety of designs already available on the market, additional experimental and comparative studies are recommended. For the full understanding of the thermal mechanisms of FPV, it will be essential, indeed, to share not only thermal parameters and temperatures recorded by field systems, but also the local conditions of temperature, irradiance and winds. Some final recommendations have been made based on the previous literature to strengthen the findings of future experimental investigations.

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