Influence des conditions aux limites thermiques sur la production de systèmes photovoltaïques flottants.

Influence of the thermal environmental conditions on the performance of floating photovoltaic panels.

Davide ROMAGNOLI [1,2], Martin THEBAULT [1], Christophe MENEZO [1], Marco FOSSA[2]

[1]LOCIE, Université Savoie Mont Blanc, CNRS, UMR5271, Le Bourget du Lac, France
[2] DIME - Department of Mechanical, Energy, Management and Transportation Engineering, University of Genova, Italy

Résumé - Les panneaux solaires représentent l'une des principales technologies dans le domaine des énergies renouvelables ; parmi eux, les panneaux photovoltaïques flottants (FPV) suscitent un intérêt croissant sur le marché. Cette étude a pour but d'explorer le comportement des panneaux photovoltaïques flottants par rapport aux panneaux photovoltaïques au sol, ainsi que leurs gains en termes de rendement énergétique. Pour ce faire, un système FPV a été simulé et l'impact des conditions thermiques environnementales a été étudié. L'analyse a été réalisée à l'aide d'un code Python et de sa bibliothèque Pvlib pour les panneaux solaires et a été développée pour quatre sites différents : France, Italie, Singapour et Pays-Bas.

Abstract - Solar panels represent one of the main technologies within the renewable energy category; among them, Floating Photovoltaics panels (FPV) are attracting increasing interest on the market. This study aims to explore the behaviour of FPV compared to Ground mounted PV and its Energy Yield gains; this was done by varying parameters that best represent different operating conditions influenced by the presence of water. The analysis was conducted using a Python code and its Pvlib library for solar panels and was developed for four different locations: France, Italy, Singapore, Netherlands.

Nomenclature

GPV	Ground PhotoVoltaics	G_{POA}	Global Horizontal Irradiance, W.m^{-2}
FPV	Floating PhotoVoltaics	U_0	Empirical heat transfer coef., W.K^{-1}m^{-2}
EY	Energy Yield	U_1	Empirical heat transfer coef., Ws. K^{-1}m^{-3}
TMY	Typical Meteorological Year	T_{cell}	Temperature photovoltaic cell, K
CO_2	Carbon Dioxide	T_{amb}	Ambient temperature, K
HDPE	high-density polyethylene	v_{air}	Local wind speed, m.s^{-1}
		$T_{50/50}$	Temperature with half influence, K
		$T_{80/20}$	Temperature with percentage influence, K
		T_{lake}	Temperature of the water, K

1. Introduction

This research focuses on Floating Solar Photovoltaic (FPV) systems, a rapidly growing renewable energy technology. The demand for energy is projected to increase globally, and renewable energy sources, including solar power, are critical to meet this demand while reducing CO_2 emissions. Solar energy is currently the fastest-growing renewable source, with photovoltaic (PV) technology accounting for 3.6% of global electricity [1]. FPV systems, which

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involve placing solar panels on floating structures over water bodies, are becoming increasingly popular due to their ability to keep panels cool, enhancing efficiency but mostly to compete with GPV for saving lands for other purposes; this cooling effect also benefits the water beneath, reducing evaporation. Existing literature suggests that installing PV modules on water surfaces reduces their operating temperatures compared to conventional ground-based systems. This temperature reduction directly translates into improved electrical performance and prolonged module lifespan, as elevated temperatures negatively impact both efficiency and material degradation rates [2]. Accurate modelling of thermal effects in FPV installations is therefore crucial for reliably predicting their performance benefits. Current models primarily incorporate meteorological parameters such as irradiance, ambient temperature, wind speed, and water temperature to simulate module thermal behaviour as well as empirical relationship for the convective heat transfer coefficients ([3], [4], [5]). However, most of these models remain site-specific and heavily dependent on local characteristics (e.g., albedo, heat transfer coefficients) or their underlying assumptions. In the present work, we conduct a parametric analysis centred around existing sites to assess potential energy production gains and quantify their sensitivity to the assumptions made.

2. Floating PV general overview

FPV panels are installed on floating structures placed on water surfaces like lakes, ponds, or irrigation canals. Their increasing use is driven by the scarcity of land in certain areas and the potential benefits provided by water, such as natural cooling, which improves panel performance. The key difference between FPV and Ground-mounted PV (GPV) systems is the supporting structure, typically made of High-Density PolyEthylene (HDPE) floats, which provide stability and other materials for buoyancy include hydro-elastic membranes and polystyrene foam [6]; also, the mooring system is crucial for maintaining the stability of the floating structure, allowing it to oscillate in response to wave movements where electrical cables are insulated with water-resistant materials to ensure safety. The design must consider several factors, such as location, which should be free from shadows, close to the power grid, and with favourable weather conditions (high irradiance, minimal fog, and moderate wind). Water characteristics, such as temperature and salinity, also play an important role. Maintenance should be easily accessible, and the presence of water simplifies cleaning. The most important advantages and disadvantages gathered by [7] of FPV are listed here in Table 1.

Advantages	Disadvantages
Cooling effects	Material degradation
Performance increase	Wind negative effect
Water saving	Ice problems
Biodiversity positive impact	Biodiversity negative impact
Lower land use	Ageing

Table 1 *: Advantages and disadvantages of Floating PV according to [8]*

3. Methodology

3.1. Case Study

Within this work, the aim is to investigate the performance in terms of energy production of floating solar panels and how this is affected by environmental parameters such as Albedo, lake temperature, heat transfer coefficients and location. Python software was used to do this numerical analysis, based on actual weather data and parametric values obtained from the literature. In particular, the library code called "pvlib", developed by Sandia Laboratories was used for the data processing. One of the objectives of this work is to create a code that could evaluate the energy production performance of photovoltaic solar panels with boundary conditions that are representative of those of a floating PV system.

3.2. Input data, models and hypothesis

The ***meteorological data*** were obtained, for each location, from the PVGIS database [8].

For all listed parameters, reference was made to the location-specific TMY (typical meteorological year). The derived geographical parameters describing the chosen locations are listed in Table 2.

	Latitude	Longitude	Altitude	Optimized tilt for Energy Production [°] [8]
Netherlands	53.127	6.695	0	39
Singapore	1.377	103.662	0	2
Italy (South)	37.326	14.955	25	29
France	45.805	5.888	231	36

Table 2*: Relevant data for chosen locations*

In this work***, the albedo*** was defined as follows: for the reference case for FPVs the albedo is set to the value of 0.1, while for the case of GPVs the value of 0.2 was used. On the other hand, the range of this parameter, for FPV, considered in the sensitivity analysis is from 0.05 to 0.28 [9].

The cell temperature, i.e., the temperature at which the panel is operating has a great influence on the efficiency of the system. For its determination, there are several models in literature. Within these correlations, the parameters that are always considered are ambient temperature and global horizontal irradiance and some of them also consider wind speed influence. Different models were analysed: Faiman [9], Tamizh Mani [10], King [11], Skoplaki [12], Duffie & Beckham [13] and Sandia [14]. and a comparison of them is presented, in Figure 1. In this figure, the cell temperature evolution during a day in August in the Italian location is showed. Among these models, Faiman's was selected due to its reliability and wider use in the literature.

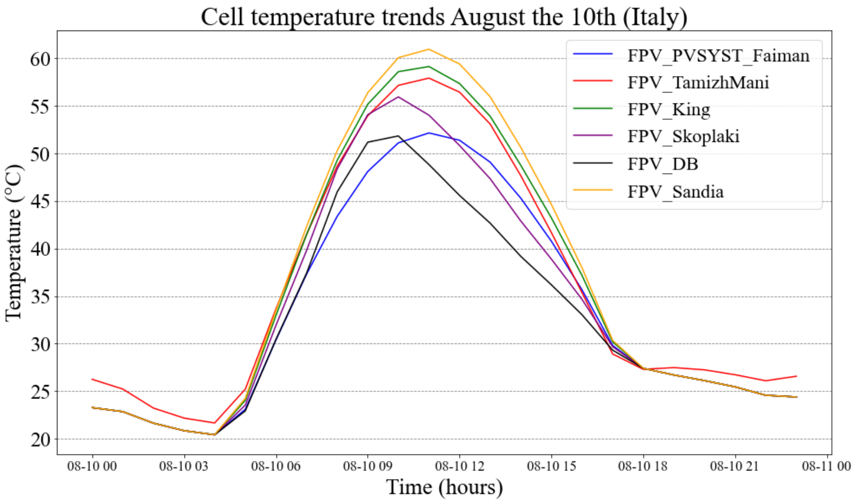

Figure 1*: Cell temperature as modelled by the different temperature models*

This model is based on a heat balance and can be formulated as

$$T_{cell} = T_{amb} + \frac{G_{POA}}{U_0 + U_1 * v_{air}}, \tag{1}$$

where T_{cell} [K] is the temperature of the photovoltaic cell that we want to estimate, T_{amb} [K] is the ambient temperature in the surroundings of the panel, G_{POA} [$\frac{W}{m^2}$] is the global horizontal irradiance of the place where the panel are installed, U_0 [$\frac{W}{K*m^2}$] and U_1 [$\frac{W*s}{K*m^3}$] are the empirical heat transfer component and v_{air} [m/s] is the local wind speed.

The two parameters that play a key role within the formula are ***the heat transfer coefficients*** $\boldsymbol{U_0}$ ***and*** $\boldsymbol{U_1}$. These values are empirical and depend on many parameters such as PV design, its integration, the local conditions. In its work, Faiman's coefficients for GPV determined values of 25 [$\frac{W}{K*m^2}$] for U_0 and 6.8 [$\frac{W*s}{K*m^3}$] for U_1. Nevertheless, almost each PV designs has its own set of U values, especially in particular configurations such as FPV. Figure 2 shows some of the values available in the literature for FPV and GPV in different places. [NL=Netherlands, SGP = Singapore, IT = Italy, Sandia standard, PVSyst standard]

The ***ambient air temperature*** in the immediate proximity of the body of water, where the solar panels are installed, is the last parameter investigated. Within this study, different assumptions will be used to understand how the EY values are affected by it. The temperatures models used to create this sensitivity analysis are listed below:

- <u>Ambient temperature</u> (Tamb): The basic ambient temperature used is the hourly temperature provided by the PVGIS database [8] for a TMY and is the temperature measured at a height of 2 metres at a given location.
- <u>Lake water temperature</u> (Tlake): The site https://seatemperature.info/ was used for themonthly main water temperature of the various locations chosen as the object of study.
- <u>Half Temperature</u> ($T_{50/50}$): In order to have a more extensive sensitivity analysis, we have taken as a possible case, not perfectly true to reality, in which the ambient temperature is an average value between the value of the temperature chosen and the water's one.
- <u>Percentage Temperature</u> ($T_{80/20}$): For this last modelling, a proportionality has been chosen; in fact, this temperature has been considered as 80% of the ambient temperature and 20% of the water temperature.

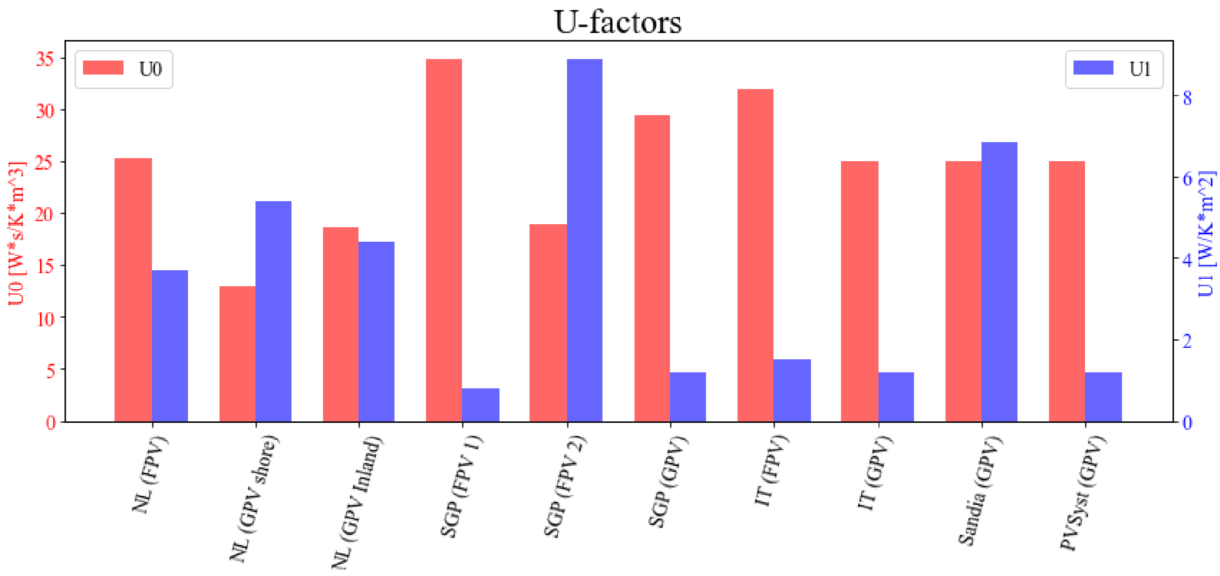

Figure 2 : *Heat transfer coefficient (U0 and U1) of the Faiman's model available in the literature for different locations and configurations* [5], [15]

4. Parametric Analysis

In this section, a parametric analysis is carried out on the three parameters that affect the energy production of a panel and are of particular relevance in the application of FPVs; this is necessary in order to better understand which of these parameters is most influential in determining energy production. Throughout the analysis, heat transfer coefficients referring to Sandia standards for GPVs. No empirical heat transfer coefficients have been found for France in the literature, and therefore those of the Netherlands [5] were used instead.

4.1. Parametric Analysis on U-values

The first analysis developed here relates the variation that the heat transfer coefficients U_0 and U_1 have on the energy yield of a panel.

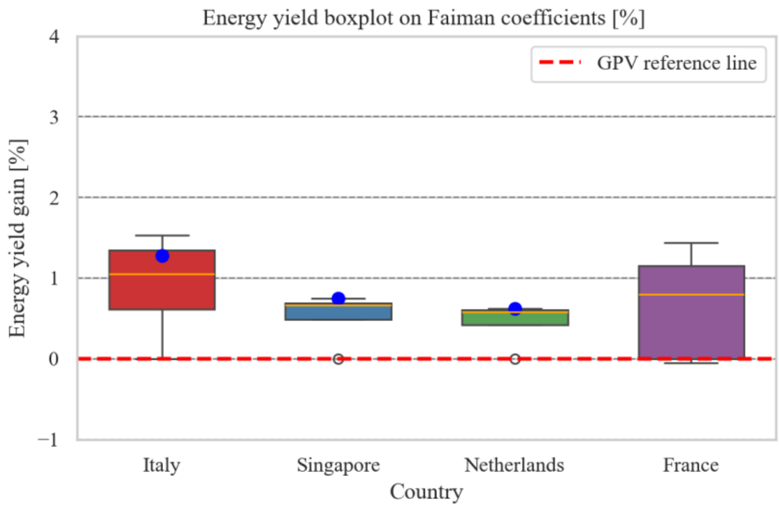

Figure 3 : Relative gains, for each location, in energy production due to parametric analysis of U-Values compared to reference GPV

Here in Figure 3 are collected the increases, or decreases, obtained from the various cases analyzed for the sensitivity on the two heat transfer coefficients in Faiman's formula. The blue dots are representative of the reference case with regard to FPVs in that specific location; on the other hand, the dashed line in red represents, also for the graphs in the following paragraphs, the reference line of GPVs also in the specific location analyzed. It can be seen that the heat transfer coefficients calculated at the location corresponding to the study location are the case with the largest increase for Singapore and the Netherlands, while for Italy it is slightly below the maximum obtainable.

4.2. **Temperature Parametric analysis**

Figure 4 shows the sensitivity analysis conducted on the temperature models, here the Faiman coefficients and the albedo were not varied but the temperature models were. Italy is also the one with the largest increase among the locations analyzed; this is because the effect on the modelling of ambient temperature is more impactful at lower latitudes, such as Italy, than at higher latitudes, such as the Netherlands.

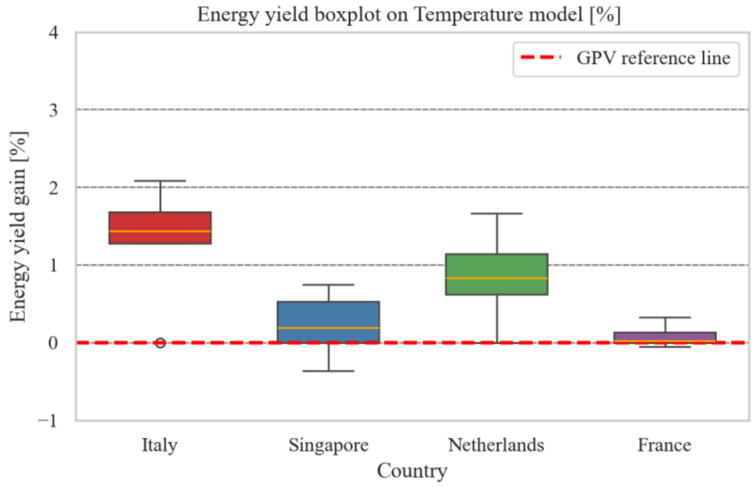

Figure 4 : Relative gains, for each location, in energy production due to parametric analysis on ambient temperature models compared to reference GPV

4.3. **Albedo Parametric analysis**

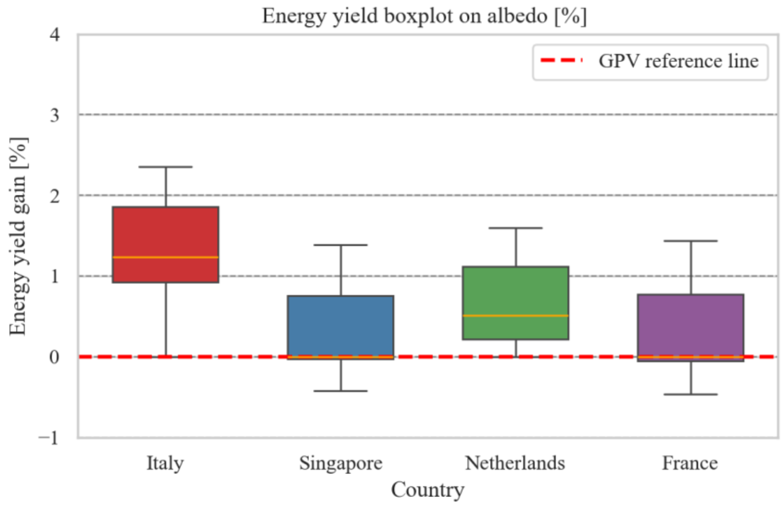

Figure 5: Relative gains, for each location, in energy production due to parametric analysis on albedo values compared to reference GPV

The third parameter on which the sensitivity analysis was performed, keeping the other parameters constant, is albedo. This parameter depends on environmental conditions and the reflectivity of the surroundings of the panels and it has an important impact on energy production. As can be seen in Figure 5, albedo can result in percentage increases of over 2%, especially for the Italian case; in general, with albedo greater than or equal to the reference used, *i.e.* 0.1, all cases are advantageous when compared to the reference GPV.

4.4. **Cumulative parametric analysis**

Boxplots in Figure 6 represent the increases, in absolute and percentage values of EYs that were obtained with the sensitivities presented in the three subsections 4.1, 4.2, and 4.3.

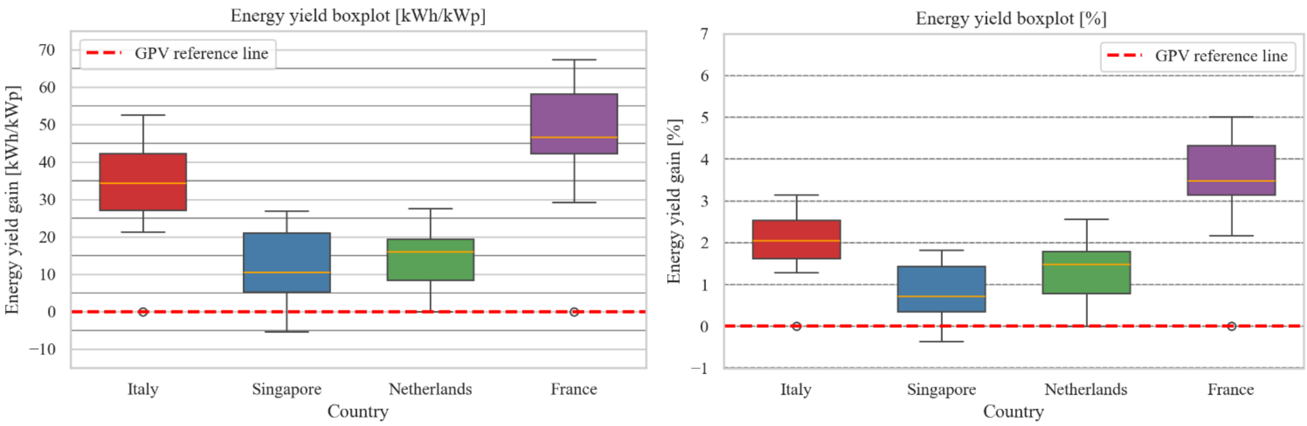

Fig. 6: Relative and absolute increases in energy production due to the full parametric analysis compared to the reference GPV, per location

Here we analyse each state in more detail:

- Italy: The percentage change that is obtained for Italy is a maximum gain, compared to the GPV case, of over 3% and at the absolute value of about 53 kWh/kWp. As can be seen, in general, even in the most conservative case there is a relative gain of 1.2% over the terrestrial solution; based on this discussion, the application proves to be beneficial in terms of annual energy production, regardless of the situation.
- Singapore: The maximum percentage here does not exceed 2%, as can be seen sometimes FPV case are unfavourable compared to GPV, this is mainly due to the negative influence of water temperature, which in tropical areas can exceed ambient temperature. In energy terms, the maximum that can be gained by applying FPVs is about 26 kWh/kWp.
- Netherlands: Here the absolute gain is about the same as in Singapore but the relative gain is higher, about 2.7%; this is because in absolute terms the Dutch EY is lower than in Singapore. Also, here all FPV cases are favourable compared to the terrestrial one.
- France: In this case, both percentage and absolute gains are the most profitable, with the maximum gain touching 5% compared to the GPV solution. However, for this location alone, the results are affected by a large initial approximation regarding the heat transfer coefficients; for this reason, they may be more affected by error due to the lack of actual measured data for these environmental conditions.

5. Discussion and conclusion

To conclude, it can be stated that in the study presented, all the cases referred to FPVs present situations that are better than the reference GPVs; in fact, each case analyzed brings positive relative increases for all locations. It is emphasized that the maximum increases reach values between 2% and 5% depending on the case analyzed. With regard to the influence of each parameter, it is reported that albedo is the parameter that has the greatest impact on energy production, but for lower latitudes, the ambient temperature model also has a significant impact. The heat transfer coefficient on the other hand has a great impact if the correct one, measured for the chosen location, is not used. The present work remains numerical (despite based on some experimental correlations) and should be further confirmed by on-site measurements.

Acknowledgements

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