Heliyon 8 (2022) e10088

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Energy performance analysis of tracking floating photovoltaic systems☆

Giuseppe Marco Tina *, Fausto Bontempo Scavo

DIEEI, University of Catania, Viale Andrea Doria 6, Catania, 95125, Italy

ARTICLE INFO

Keywords:
Floating photovoltaic
Renewable energy
Solar energy
One axis tracking
Two axis tracking
Bifacial modules

ABSTRACT

Floating photovoltaic systems (FPV) are an innovative technology, in which photovoltaic modules are installed on water surfaces with the aim of reducing land occupation and at the same time increasing its efficiency and creating synergies with aquaculture and hydroelectric plants. The purpose of this study is to evaluate the energy performance on an annual basis of a fixed G/FPV (ground/floating photovoltaic) system, with vertical, horizontal or two-axis tracking, with mono or bifacial modules. The simulated data for FPV (floating PV) systems are compared with those of a GPV (ground PV) system through performance indexes. The analysis of the energy output is carried out depending on the geometric variables of the plant. The energy production of PV systems is highly dependent on the local climate. Therefore, the study was developed for two locations characterised by different components of diffuse solar radiation, one at high latitudes and the other at mid-latitudes. The two locations are: Anapo Dam in Sicily (Italy) and Aar Dam in the Lahn-Dill district (Germany).

As for the gain due to the bifaciality of the systems with bifacial modules, it can be stated that for the analyzed configurations, a gain greater than 3% can be obtained for Anapo Dam in Sicily and greater than 4% for Aar in Germany.

As for the gain due to the natural cooling of the modules, it can be stated that for the analyzed configurations, a gain of more than 5% can be obtained for Anapo Dam in Italy and greater than 4% for Aar in Germany.

If the overall gain due to bifaciality tracking and cooling is considered, the following gains are obtained for the two locations Anapo and Aar respectively: 16.9% and 14.4% for Horizontal E-W system; 27.6% and 23.3% for Horizontal N–S system; 31.3% 27.8% for One Axis Vertical system; 47.4% and 42.5% for Dual axis system.

1. Introduction

Solar energy is considered one of the most promising energy alternatives since it is sustainable and is present in every part of the world [1]. The most common application for the use of solar energy are photovoltaic systems (PV) [2]. The rapid increase in the demand for electricity and the rapid depletion of fossil fuels have led to a notable increase in the number of photovoltaic systems, even on a large scale. However, most large-scale photovoltaic system installations have potentially significant land consumption because their installation requires large areas of land [3]. This limitation can be overcome by implementing FPV systems installed on water surfaces such as lakes, irrigation tanks or in the basins of hydroelectric plants [4].

Some scientists often raise some doubts about the advantages of FPV systems, such as:

- Greater mechanical stresses due to waves. The presence of a tracking system in a floating PV installation can exacerbate the mechanical wear caused by the movement of the platform, whereas the problem of mechanical stress caused by waves is much less severe in onshore applications compared to offshore applications. In particular, the constant movement of the platform can be a challenge for the mechanical joints and connections. This is especially true for platforms where there is frequent relative movement between modules. An example of this is the interruption of equipotential bonding wires/tapes. Equipment earthing is important for the electrical safety of personnel and equipotential bonding is used to earth modules and frame structures. During operation we have observed several cases where the wires have broken, even in cases where there was sufficient slack. Therefore, it might be necessary to implement improved cable management on floating platforms;

☆ This article is a part of the "Design, Operation and Reliability of Large PV Systems" Special issue.

* Corresponding author.
E-mail address: giuseppe.tina@unict.it (G.M. Tina).

https://doi.org/10.1016/j.heliyon.2022.e10088
Received 11 January 2022; Received in revised form 1 April 2022; Accepted 21 July 2022

- Higher humidity compared to ground systems, near the plant. However, the literature is lacking regarding the study of this topic in the case of photovoltaic systems installed on water. Regarding this point, in [5] the problem of degradation due to humidity is addressed and discusses the damage to the photovoltaic module and the inverter caused by combination of edge delamination, water penetration, and high string voltage.

Regarding the aging phenomena, the floating PV modules installed in floating systems, compare to the ones installed on the ground, are certainly exposed to a negative factor that is the higher relative humidity, but also two positive factors such as to lower daily maximum cell temperature and daily temperature fluctuations [6]. Moisture ingress into PV modules is certainly a phenomenon that needs to be carefully investigated. In this context, ambient/operating temperature, humidity and the influence of UV radiation are the most important environmental and climatic factors.

The design of the PV modules and the properties of the polymer materials also determine how quickly a material will equilibrate with the ambient humidity during operation. Typically, moisture can enter the module from the outside due to manufacturing defects or during transport. PV module degradation and power loss can be accelerated by the presence of moisture (inside or outside the PV module) together with high temperatures and UV radiation, which in turn can lead to delamination and discolouration of the encapsulations. Potential induced degradation (PID), corrosion of the metal contacts, optical losses, degradation of the PV cells, adhesion losses and other related material degradation [7]. The combined failure of PV panels and PV inverters is caused by delamination of the edges with water ingress and high string voltage. The electrical discharge channel occurs between the string of solar modules and the grounded frames of the PV modules. The result of the discharge channel caused by edge delamination is the shutdown of the inverter and some months later the complete destruction of the inverter due to the damage of the protective relay [5]. Specifically for FPV systems, measures to prevent or limit the degradation mechanisms of PV modules due to moisture penetration into the modules are a critical issue in the development and selection of materials for PV modules that can withstand the specific operating conditions in the aquatic environment. In this context, targeted research into encapsulation materials with optimal moisture barrier properties and edge seals for PV applications is promising for achieving higher performance over the lifetime of PV modules and thus lower cost per peak watt (Wp) of electricity from PV devices. The presence of moisture can have another negative effect on reducing incident radiation. When moisture is present, three cases can occur when light hits water droplets: it can be refracted, reflected or diffracted. These effects reduce the reception value of the direct component of solar radiation. The humidity changes the irradiance non-linearly and the irradiance itself causes small variations of Voc in a non-linear way and large variations of Isc in a linear way, so that power and efficiency decrease [8]. A better understanding of the effects of humidity on irradiance and irradiance on voltage and current is shown in [9] using a case study in the tropical climate of Nigeria. The non-uniform distribution and the wide range of water vapour particle sizes in the atmosphere are the reasons for the non-linear deviations of irradiance from relative humidity. Larger scattering angles occur with smaller water vapour particles. More diffraction is also the result of more water vapour particles in the atmosphere. It is obvious that when relative humidity is much higher in tropical countries like Malaysia, the irradiance decreases disappointingly. Wind speed has an inverse effect on relative humidity, which in turn affects the irradiance received [9]. However, the presence of a large water surface (e.g. large lakes and rivers) can strongly influence the humidity of a geographical area, while the presence of a limited surface can presumably lead to localised fogs such as advection fog. Advection fog is caused by moist air moving over a colder surface and the resulting cooling of the air near the surface below its dew point temperature. Advection fog occurs both over water (e.g. steam fog) and over land but, it disappears during the day, so its impact on FPV production could be limited.

Despite the doubts raised, floating photovoltaic systems have attracted hight attention both from a research point of view and from a market perspective thanks to the benefits widely discussed in the literature linked to their installation, namely: land saving [10]; the effect of cooling the modules due to the favourable microclimate near the installation [11]; the improvement of water quality due to the reduction of photosynthesis and algae growth [12]; the increase of 4–7% (depending on the season and geographical location) of the energy generated compared to ground-based photovoltaic installations [11]. FPV systems are also advantageous from an economic point of view if the construction costs of the ground system also include land costs [13].

FPV systems are gaining traction across the world. As reported by IRENA in [14], globally, during 2020, around 2.6 GW of total capacity of floating solar PV projects were either under construction or fully functional around the world.

Given that photovoltaic cell technology is reaching its maximum theoretical efficiency, in recent years, systems installed on water have been proposed to increase energy yield, which enjoy the aforementioned benefits, but new installation configurations have also been explored. In the literature some fixed or tracking type solutions have been proposed which will be listed below.

Cazzaniga in [15] proposed floating rafts called "gable slender", which in addition to having a simpler anchoring and buoyancy system, allows the installation of a greater number of modules with the same surface, compared to the classic inclined system and south facing. Additional positive aspects of this configuration are: "walkability", that is the possibility of creating corridors for access to the plant on foot, useful for maintenance; the recirculation of air caused by the tunnel created under the modules which allows natural cooling and cost competitiveness (20 c $ per Watt) compared to the classic floating solutions proposed in the past.

To increase the energy collected, in recent years, high efficiency [16] and bifacial modules have been installed that capture the solar irradiance also on the rear [17].

To increase the reflected radiation, the surface below the module is treated with light colored materials with high reflection coefficients. In the case of floating systems, the average reflection coefficient of water is on average lower than that of the ground but by using light-colored materials for the floats and highly reflective surfaces at the rear of the modules, a twofold advantage, to increase the energy yield of the system and reduce the evaporation phenomenon since the water surface where the system is located is entirely covered.

As regards the tracking FPVs, after a careful bibliographic analysis, it was found that there is no study that discusses the issue of the performance of these plants, therefore, the present research work wants to fill this gap in the research, proposing a performance evaluation of several practically feasible tracking systems. That is, systems with a horizontal axis with E-W and N–S orientation with mono and bifacial modules; Tracking systems with a vertical axis with monofacial PV and dual axis tracker with monofacial PV.

The performances of the considered types of tracking systems are compared and referred the analogue but installed to the ground. The floating structures and the moorings have to be sized considering the wind forces, that are also related with the tilt of the modules. In this the horizontal and two axis systems are considered with different ranges of tracking angles.

In order to make such comparisons, two aspects in particular must be taken into account:

- Temperature of the PV cells: The ambient temperature near the floating modules may be slightly lower than the temperature measured on the mainland due to evaporation and the local microclimate. Suitable heat exchange coefficients must therefore be chosen in the thermal models used to evaluate the temperature of the PV

cells. For ground systems, the temperature estimation models from [18] are used, while for FPV systems the models from [11] are used.
- Albedo: The albedo of a water body is very low (0.1, which is much lower than the normal value of 0.2 for ground). For large monofacial plants, the albedo provides a very limited contribution to energy production, as the radiation reflected from the ground is seen by the first row of modules and the inclination of the PV modules is usually low. In bifacial systems, on the other hand, the back of the modules also catches the reflected solar radiation, so their contribution can be greater.

1.1. Overview of tracking FPV

The purpose of using ground-based or floating tracking systems, is to increase the energy collected by photovoltaic systems. A recent article explains that single-axis and dual-axis tracking PV systems with appropriate control systems can increase electrical energy by 22–56% compared to fixed PV systems. The wide range in energy yield depends mainly on the local climate, but also on the PV technology [19].

The technology of ground-based tracking systems is now quite mature and reliable as it has been researched and perfected for several years. The application of such solutions to floating systems needs to be carefully considered, taking into account not only the lack of a fixed anchor but also the disturbances caused by buoyancy, i.e. the presence of waves and wind. To overcome these problems, important adaptations or completely alternative technical solutions to those for ground-based systems must be found, both in terms of structure and tracking algorithms.

The solutions useable for FPVs are different so it is worth make a list, as follows:

- Trackers inside a confinement facility whose floating platform is surrounded by an anchored structure (circle or polygon) and an appropriate electric motor makes the platform rotate with respect to the fixed structure;
- Tracking with a partial confining structure that are called external rope
- Tracking without a confining structure: using submerged reference structures or by bow thrusts;
- Tracking to a horizontal axis using the "gable" structure.

A system, based on a carousel mechanism, where a fixed part is anchored to the ground with ballast, in which a mobile platform rotates on which the photovoltaic panels are installed, is proposed in [10].

Sunfloat proposed in [21] a cable system with partial boundary, whose azimuthal movement is ensured by the winches placed around the structure.

In [10], a tracker without the limiting structure was proposed, which can also be installed in deep basins and is connected to the ground by three chains forming an equilateral triangle. This system makes it possible to reduce construction costs and is more functional than other solutions proposed in the past. The movement is ensured by the bow thrusters, which generate the torque that causes the azimuth movement.

A HAT (Horizontal Axis Tracker) system that can offer significant advantages, especially for low latitudes is proposed [10]. The problem that immediately arises in HAT is shadowing, which can easily be solved in a ground-mounted system by increasing the area occupied.

K-water (Korea Water Resources Corporation) in Korea has installed the world's first 100 kW tracking floating photovoltaic system inside a confinement facility [22]. In it there are four 24.8 kW systems, one of which is passive tracking, one automatic and two fixed systems.

The SCINTEC company has developed and built two TFPV systems in Italy, in 2010 at Cantina Petra and in 2011 at Lake Colignola. The feature of the latter system is the use of mirrors to reflect solar radiation onto the photovoltaic panels [23].

In the academic field, several studies have been conducted on TFPV, but many topics are completely unexplored and a considerable effort is required to fill these gaps. Below is an overview of the works developed to date.

In [23] an algorithm for tracking on FPV systems is proposed, which compensates the azimuth angle error due to the continuous movement of the floating structure for wind and waves, using a GPS receiver and a geomagnetic sensor.

In [20], sensor-based controls are suggested that take two different approaches: one uses shading patterns to find the solar position and optimal orientation, and the other is based on images captured by a wide-angle camera pointing the sky and orient the system, in the direction in which there is more light. With these systems, an accuracy of 0.5° is guaranteed in the event of cloudy skies.

Choi [23], proposes the finite element study of the mechanical structure of a 100 kW plant in which it evaluates the impact of the wind and uses different materials for the simulations including, steel, aluminium, polyethylene (PE) and reinforced polymeric plastic with fibers (FRP). For floats that are subject to corrosion, glass fiber reinforced plastic (GFRP) and polyethylene (PE) have been proposed; In the study he also includes the control algorithm of the confined tracker in which there are a passive and an active system.

In [24] a dual axis tracking system with management software in an Arduino environment is proposed. For handling, stepper motors are used.

However, the systems listed above absorb energy for the movement of the tracking mechanisms through actuators. Furthermore, being placed in environments with high humidity, in the long term they could deteriorate more quickly than the components installed on the ground, this would cause a greater frequency of maintenance and therefore higher costs.

The TFPV system proposed in [25], is of the passive type, that is, it uses wave energy to automatically adjust the position of the system, without the aid of mechanical drive components such as motors, which as previously anticipated could cause increase maintenance costs during the useful life cycle of the plant. Although floating-tracking PV systems have higher specific investment costs, the higher electricity production compared to fixed floating PV system make them competitive from a levelized cost of electricity point of view [26].

To get a clear picture of the current research in the field of floating photovoltaics with tracking, a summary table is proposed. In Table 1 the articles are classified by category and summarized the results achieved in each work.

2. Methodology

In this paragraph, the methodology that leads to the results obtained regarding the different cases examined will be illustrated. Enel global thermal generation.

2.1. Sites and photovoltaic systems data

The performance study of a floating system was developed for two basins: one high latitude (Aar Dam, DE) and one mid-latitude (Anapo, IT). Weather data was taken from the Meteonorm database, with a 1-h step for the whole year. To calculate the incident solar radiation on the plane of the photovoltaic modules, starting from the horizontal radiation data, the Perez transposition model is used, which is more sophisticated and precise than others [35]. In the simulations, the albedo is assumed to be constant and equal to 10%, since in most cases FPV systems are installed in locations where the occurrence of waves is limited. It is obvious that the phenomenon of scattering of reflected radiation occurs when the water surface ripples noticeably. Therefore, the assumption of a constant albedo is no longer possible [11]. These two locations were chosen to evaluate the behaviour of the bifacial modules at different

Table 1. Summary of the main works in TFPV.

Ref	Year	Title	Remarks and Key Findings	Category
[26]	2018	Optimization and assessment of floating and floating-tracking PV systems integrated in on- and off-grid hybrid energy systems	Floating tracked PV systems have higher specific investment costs, but the higher electricity production compared to fixed installed floating PV systems makes them competitive from a levelized cost of electricity perspective, especially with a reliability of more than 45%.	Optimization, integration of FPV in grid
[20]	2018	Floating photovoltaic plants: Performance analysis and design solutions	It suggests and classifies different types of structures for floating tracking systems. In particular, it describes structures with or without confinement. It also proposes solar alignment systems for floats, which cannot have the same characteristics as ground systems as there are external disturbances such as waves and wind.	Review
[27]	2017	RAST: RoundAbout Solar Tracking	It proposes the installation of floating systems in correspondence of the roundabouts of the roads and describes the advantages of the RASTs such as the use of zero-cost areas, the increase in energy due to the tracker and the cooling system.	Innovative solution of installation
[28]	2020	Electrical Behavior and Optimization of Panels and Reflector of a Photovoltaic Floating Plant	It proposes the so-called FTCC (Floating Tracking Cooling Concentrating) which are photovoltaic panels positioned on a floating platform with tracker, reflectors and cooling system made with nebulizers. The average annual yield per kWp installed can increase by 60–70% compared to a fixed system, depending on the climatic conditions.	Evaluation of performances
[29]	2015	Sun-Spotter floating solar-tracking spotlight	It proposes the so-called Sun-spotters which represents the dual-axis solar tracking integrated within a floating kinetic structure, driven by an innovative motion method.	Innovative solution of installation
[25]	2019	Design and Optimization of a Wave Driven Solar Tracker for Floating Photovoltaic Plants	It proposes a passive FPV tracking system, without the use of energy-consuming actuators	Modeling, design and experimental analisys
[30]	2014	A study on major design elements of tracking-type floating photovoltaic systems	The basic concept of a floating PV system with a power of 100 kW, which is tracked, as well as the application plan for the tracking algorithm and the rotation mechanism of the structure, which is an important design element, were explained.	Design and tracking alghoritm
[23]	2014	A study on Development of Rotary Structure for Tracking- Type Floating Photovoltaic System	FRP materials were selected for the structure of a floating photovoltaic system in the form of a circular rotational model to develop a floating photovoltaic system in the form of a rail. A finite element analysis and a wind load analysis in a wind tunnel were carried out to analyse the safety of the structure. In addition, the durability of the structure was analysed with tensile and compression tests as well as dynamic tests.	Design, modeling and experimental analisys
[31]	2019	Development of Tracking Algorithm for Floating Photovoltaic System	An algorithm is developed to effectively control the azimuth angle for tracking photovoltaic systems under floating conditions. To verify the developed algorithm, the prototype of the floating photovoltaic system is fabricated and the developed algorithm is applied to the system. The algorithm shows good feasibility of tracking on the prototype.	Design and tracking alghoritm
[32]	2020	Tracking Systems. Floating PV Plants	General overview of floating systems, description of the different tracking systems, performance evaluation of a system with a horizontal axis (15%–32%), proposal of the gable solution with horizontal axis tracking.	Overview
[33]	2014	Installation and Safety Evaluation of Tracking-type Floating PV Generation Structure	An advanced floating PV generation system made of PFRP and SMC is designed. The design includes solar elevation tracking by tilting the photovoltaic arrays and solar azimuth tracking by rotating structures. Finite element analysis (FEA) results are also presented to confirm the stability of the whole structure under the external loads.	Design and modeling structure
[34]	2019	Design and development of dual axis sun tracking system for floating PV plant	A two- axis tracking system is used and the mechanism is explained. Torque calculations are made for selecting the correct stepper motor and hybrid linear actuator. Different materials for the platform are compared. A prototype made of wood is designed and developed.	Design and construction
[22]	2016	Application of Floating Photovoltaic Energy Generation Systems in South Korea	A discussion is offered on recent research on floating PV systems and the installation of floating PV power plants in Korea from 2009 to 2014.	Review

latitudes, where the percentage of diffuse horizontal irradiance (DHI) is different with respect to the global horizontal irradiance (GHI) and the effects of natural cooling of FPV are different due to different climatic conditions.

The PV floating/area systems analysed consist of two PV arrays, one of monofacial modules and the other of bifacial modules. The system simulations were developed using the PVsyst software tools, while the data processing was performed in the MATLAB environment.

Each array, whose nominal power is 16.32 kW for the monofacial and bifacial systems, has 48 modules divided into 4 strings connected to a multi-string inverter equipped with separate MPP trackers. The modules are Jinkosolar Si-mono JKM340M-60H–V (monofacial) and JKM340M-

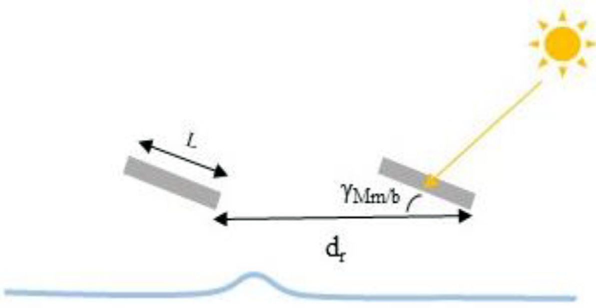

Figure 1. Geometric variables of the floating PV system.

60H-BDVP (bifacial). The number of inverters is 2 and the model is SMA SunnyBoy 9.0 kW 9000TLUS-12.

The model of the PV system is bi-dimensional, the effect of shading was considered linear, i.e. without evaluating the electrical effect. For the bifacial model, mismatch losses on the back of the module of 2.5% and losses due to shading of the structures of 2.5% were considered [36]. In addition, a transparent portion of 10% was taken into account.

2.1.1. Configurations analysed

This work analyzes the performance of floating and ground PV, with tracker or fixed systems. Specifically, the following configurations will be analyzed:

- FXPVm (Fixed PV Monofacial)
- FXPVb (Fixed PV Bifacial)
- HATPVm (Horizontal Axes Tracker PV Monofacial)
- HATPVb (Horizontal Axes Tracker PV Bifacial)
- VATPVm (Vertical Axes Tracker PV Monofacial)
- 2AXTPVm (Dual Axis Tracker PV Monofacial)

The simulations are carried out by varying three geometric parameters of the photovoltaic systems, namely tilt angle ($\gamma_{Mm/b}$ (°)), distance between the rows d_r normalised respect to length of modules L and azimuth angle Φ (the value of 0 correspond to axes parallel to N–S and 90 parallel to E-W). The representation of the variables is reported on Figure 1.

Table 2 shows the lower and upper limits of the variables.

Table 2. Geometrical variables of the PV systems.

Variable	Min. value	Max. value
2AXTPV		
$\gamma_{Mm/b}$ (°)	0–50	
d_r/L	2.1	3.0
Φ(°)	±120	
HATPV		
$\gamma_{Mm/b}$ (°)	-30/-50	30/50
d_r/L	2.1	3.0
Φ(°)	0	90
VATPV		
$\gamma_{Mm/b}$ (°)	20	30
d_r/L	2.1	3.0
Φ (°)	-120	120
FXPV		
$\gamma_{Mm/b}$ (°)	20	30
d_r/L	2.1	3.0
Φ(°)	0	0

Figure 2 shows photos and renderings of various systems analysed in this article. This is (a) fixed, (b) E-W, N–S, (c) vertical axis, (d) double axis.

2.1.2. Thermal losses

Faiman [18] model of equation Eq. (1) is used to estimate the temperature of the modules. In this work, the quantity U_0 and U_1 for the FPV are chosen respectively as follow [11]:

- 35.22 W/m^2 K and 1.5 W/m^3 s K for bifacial
- 31.92 W/m^2 K and 1.5 W/m^3 s K for monofacial

The coefficients U_0 and U_1 for the floating systems were obtained using an optimisation algorithm (fmincon from MATLAB) that made it possible to minimise the RMSE between the temperature measurements carried out at Enel Green Power's experimental facility (Enel Innovation Lab of Catania (IT)) and the numerical results of the Faiman model [11]. To obtain physically correct data, constraints are set within which U_0 and U_1 had to vary.

For GPV systems, the coefficients U_0 and U_1 are chosen as suggested in PVsyst software [37].

$$T_{pv} = T_{amb} + \frac{\alpha_{pv}\, G_{fr}(1 - \eta_{STC})}{U_0 + U_1 w_v} \tag{1}$$

U_0 describes the effect of the radiation, while the U_1 describes the effect of the wind, on the temperature of the module.

2.2. Performances comparison indices

In this paper, the yearly energy yield Y', in kWh, is evaluated (it is the sum of hourly average power values under the hypothesis that the system works at maximum power point, MPP), then it is normalized with respect to peak power, in kW obtaining Y that are the equivalent operating hour. Eqs. (2) and (3) show the normalize yearly energy yields, where the subscripts m and b indicate the monofacial and the bifacial system, respectively:

$$Y_m = \sum_{t=0}^{n} \frac{P_{mpp,m}(t)\Delta t}{P_{p,m}} = \frac{Y'_m}{P_{p,m}} \tag{2}$$

$$Y_b = \sum_{t=0}^{n} \frac{P_{mpp,b}(t)\Delta t}{P_{p,b}} = \frac{Y'_b}{P_{p,b}} \tag{3}$$

It is worth noting that Y'_b is normalized with respect to the front-side module power $P_{p,b}$.

The bifacial gain, BG (in %), is defined in Equ. 4 as:

$$BG = 100\frac{Y_b - Y_m}{Y_m} \tag{4}$$

The BG is used to evaluate the energy gain of a bifacial system compared to a monofacial system with the same configuration and same typology of system (calculated only for FPV).

The comparison of the performance between the GPV and FPV systems is important for evaluating the actual increase in energy produced due to natural cooling. To evaluate this effect, the floating gain (FG) is calculated in %, according to Eq. (5), as:

$$FG = 100\frac{Y_{fl} - Y_{gr}}{Y_{gr}} \tag{5}$$

The index FG is used to compare the yield of a floating system compared to a ground system with the same configuration. The reference is the ground system, where the heat exchange coefficients of the thermal models correspond to those normally used for free-standing systems with air circulation, and compared to the floating systems, whose heat

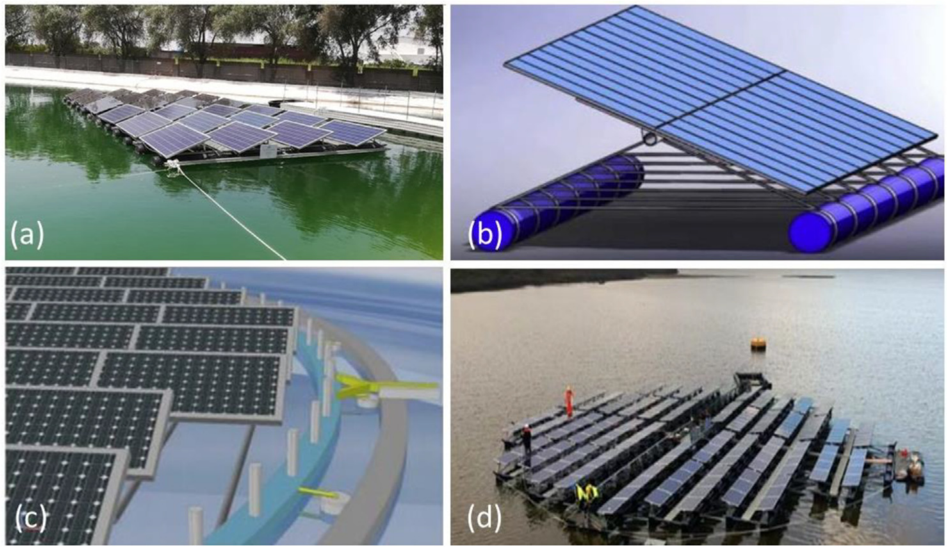

Figure 2. Representation of different systems analysed, (a) fixed, (b) E-W, N–S, (c) vertical axis, (d) double axis [10, 11].

exchange coefficients of the thermal models correspond to those obtained for the experimental floating system installed in Enel Green Power's "Enel Innovation Lab" in Catania (IT) [11].

To compare the tracking systems (TPV) with the fixed systems (FXPV) is used the TG which is calculated by Equ. 6, as:

$$TG = 100\frac{Y_{TFm/b} - Y_{FXFm/b}}{Y_{FXFm/b}} \tag{6}$$

TG is calculated comparing the same module technology (monofacial tracking with monofacial fixed or bifacial tracking with bifacial fixed).

From the combination of the performance indices listed above, the following indices can be obtained:

TBG which is the energy gain of the bifacial tracking system compared to the fixed system, calculated only for the floating system is reported in Eq. (7).

$$TBG = 100\frac{Y_{TFb} - Y_{FXFm}}{Y_{FXFm}} \tag{7}$$

TFG which is the energy gain of the floating tracking system compared to the fixed ground system monofacial or bifacial is described in Eq. (8).

$$TFG = 100\frac{Y_{TFm/b} - Y_{FXGm/b}}{Y_{FXGm/b}} \tag{8}$$

TBFG, which is the energy gain of the floating bifacial tracking system compared to the fixed ground monofacial system, is reported in Eq. (9).

$$TBFG = 100\frac{Y_{TFb} - Y_{FXGm}}{Y_{FXGm}} \tag{9}$$

All the indices are in percentage (%).

3. Results

In this paragraph will be showed the results in terms of performances for the locality previously mentioned that have a different meteorological characteristics and are Anapo (IT) with coordinates 37.11° N, 15.13° E and Aar (DE) with coordinates 50.69° N, 8.45° E.

For simplicity, in the follow tables, the locality Anapo will be reported with the number 1 while Aar with the number 2.

3.1. Fixed systems

Table 3 shows the Y (equivalent operating hours) values of fixed ground and floating systems analysed, BG (bifacial gain) and FG (floating gain) only for floating system. BG values are obtained by comparing the same bifacial with monofacial configurations (for example 30° bifacial FXPV vs 30° monofacial FXPV). Y values of FXFPV will be used as a reference for comparing the energy yield of mono and bifacial tracking systems.

In all fixed system configurations, the locality Aar has a greater gain due to the bifaciality than the locality Anapo as the quantity of diffuse radiation in the Aar is greater. In fact, according to [38] the radiation reflected from the ground captured by the module, depends on the albedo, the global and diffuse radiation and the view factor. So for the same global radiation, view factor and albedo, the greater the diffuse radiation the greater the energy gain due to bifaciality. Another important effect that is highlighted by the simulations in the case of bifacial systems is that the BG also increases as the distance between the rows of modules increases. In addition to the mutual shading between the rows in the front of the modules, there is the effect of the projection of their shadow on the ground and therefore the blocking of the reflected radiation, thus making them more sensitive to the geometric configuration parameters of the field.

The energy gain (FG) obtained by FPV systems is due to the cooling of the modules. In fact, they work at lower temperatures with the same other climatic conditions, and near of the modules, there is a favorable microclimate that allows an exchange of energy between the modules and the environment, better than in ground systems.

The difference in FG between the systems installed in the same locations and with different geometrical configuration, is linked only to solar radiation, however, the difference in FG with the same geometric configuration between different locations is due to the solar radiation, ambient temperature and then of the quantity of evaporated water.

Regarding the FG of the fixed system, the higher value is obtained for the Anapo locality with the configuration: $\gamma_{Mm/b} = 30°$, dr/L = 3.0.

3.2. Horizontal single-axis tracking system E-W

Table 4 shows the Y (equivalent operating hours), of each type of system analysed and BG, FG for floating systems. BG values are obtained

Table 3. $Y_{m/b}$ for fixed F/GPV systems.

			Locality											
			1			2			1			2		
			d_r/L											
			2.1						3.0					
System	$\gamma_{Mm/b}$ [°]	Module	Y [h]	BG [%]	FG [%]	Y [h]	BG [%]	FG [%]	Y [h]	BG [%]	FG [%]	Y [h]	BG [%]	FG [%]
FXGPV	20	M	1722.7	-	-	957.8	-	-	1726.3	-	-	964.0	-	-
		B	1757.0	-	-	981.1	-	-	1764.5	-	-	990.2	-	-
	30	M	1737.4	-	-	956.5	-	-	1748.2	-	-	973.0	-	-
		B	1779.4	-	-	987.9	-	-	1796.9	-	-	1009.0	-	-
FXFPV	20	M	1803.0	-	4.7	989.6	-	3.3	1806.9	-	4.7	996.0	-	3.3
		B	1844.2	2.3	5.0	1016.1	2.7	3.6	1852.1	2.5	5.0	1025.5	3.0	3.6
	30	M	1819.6	-	4.7	989.6	-	3.5	1831.0	-	4.7	1006.7	-	3.5
		B	1868.8	2.7	5.0	1024.4	3.5	3.7	1887.4	3.1	5.0	1046.3	3.9	3.7

by comparing the same bifacial with monofacial configurations (for example ±50 bifacial system vs ±50 monofacial). FG values allow to evaluate the increase in performance due to the natural cooling of the modules of the FPV compared to the GPV, in various configurations for mono and bifacial modules.

Comparing the BG of the fixed system with the tracking one, it can be seen that in the latter, higher values are obtained in all the cases analyzed. This is to be attributed to the fact that during the day, excluding sunrise and sunset, the shadow cast by the modules is limited to the one below them, without affecting the nearby water surface.

The maximum values of BG = 3.1% is obtained in the case of configuration ±50° TPV for $d_r/L = 3.0$ in Anapo Dam and 4.6% in Aar Dam.

Also in this case, as in the case of a fixed system, there is a higher BG for Aar where the diffusion factor is higher.

The FG values range from 4.8% to 5.2% for Anapo and 3.4 to 3.8 for Aar. The same considerations made for the fixed system can be made for this system. The differences in FG between this system and the fixed are really small and are attributable to the difference in solar radiation captured by the two systems.

With the same inclination (γ) and technology (m, b), then moving horizontally in the Table 4, between $d_r/L = 2.1$ and 3, the energy difference ranges from a minimum of 1 to a maximum of 2% for Anapo and from a minimum of 2 to a maximum of 3% for Aar. This consideration could be useful in the evaluation phase of the LCOE since as reported in [32] being that the cost of the raft is proportional to the surface covered, it is necessary to understand if the increase in energy due to the increase in the covered surface is able to make more the system with greater interdistance is competitive and therefore compensates for the cost increase.

Table 5 shows TG values for mono and bifacial FPV systems. Specifically, tracking systems are compared with fixed in different geometric configurations. The TG is calculated in function to the distance between rows.

With the effect of tracking, can be obtain an increase in energy up to 9.0% in the Anapo locality and 7.6% in Aar for the configurations analysed.

Table 6 shows TBFG values of TFPV which take into account the effect of energy gain due to tracking, natural cooling and the bifaciality of modules. So, the comparison is between floating bifacial tracker and fixed monofacial ground.

It can therefore be concluded that a bifacial E-W floating horizontal axis tracking system can increase the yield compared to a fixed ground system by 16.9% for Anapo Dam and 14.4 for Aar Dam.

3.3. Horizontal single-axis tracking FPV system N–S

Table 7 shows the Y values (equivalent operating hours) of each type of system analysed and BG, FG for floating systems. BG values are obtained by comparing the same bifacial with monofacial configurations (for example ±50 bifacial TPV system vs ±50 monofacial TPV). FG allow to evaluate the increase in performance due to the natural cooling of the modules of the TFPV compared to the TGPV, in various configurations for mono and bifacial modules.

In this case the BG is lower than both E-W and fixed systems. In the latter, in fact, at sunrise and sunset no shadows will be cast on the back and this leads them to be more advantageous in terms of BG than N–S systems. Despite this, the N–S systems are more advantageous in terms of energy collected, compared to the fixed and E-W trackers.

Table 4. $Y_{m/b}$ for Horizontal single-axis tracking E-W F/GPV systems.

System	$\gamma_{Mm/b}$ [°]	Technology	Locality											
			1			2			1			2		
			d_r/L											
			2.1						3.0					
			Y [h]	BG [%]	FG [%]	Y [h]	BG [%]	FG [%]	Y [h]	BG [%]	FG [%]	Y [h]	BG [%]	FG [%]
TGPV	±30	M	1811.3	-	-	994.2	-	-	1821.2	-	-	1010.8	-	-
		B	1851.3	-	-	1024.3	-	-	1866.6	-	-	1044.9	-	-
	±50	M	1839.2	-	-	988.6	-	-	1866.0	-	-	1018.6	-	-
		B	1885.2	-	-	1028.1	-	-	1918.5	-	-	1063.1	-	-
TFPV	±30	M	1897.5	-	4.8	1028.1	-	3.4	1908.0	-	4.8	1045.4	-	3.4
		B	1945.3	2.5	5.1	1061.7	3.3	3.7	1961.3	2.8	5.1	1083.1	3.6	3.7
	±50	M	1928.9	-	4.9	1023.3	-	3.5	1957.2	-	4.9	1054.7	-	3.5
		B	1982.8	2.8	5.2	1066.5	4.2	3.7	2018.0	3.1	5.2	1103.1	4.6	3.8

Table 5. $TG_{m/b}$ for Horizontal single-axis tracking system E-W.

System comparison		Technology	Locality			
			1	**2**	**1**	**2**
			d_r/L			
TFPV	**FXFPV**		**2.1**		**3.0**	
$\gamma_{Mm/b}$ [°]			**TG [%]**			
±30	20	M	5.2	3.9	5.6	5.0
		B	5.5	4.5	5.9	5.6
	30	M	4.3	3.9	4.2	3.8
		B	4.1	3.6	3.9	3.5
±50	20	M	7.0	3.4	8.3	5.9
		B	7.5	5.0	9.0	7.6
	30	M	6.0	3.4	6.9	4.8
		B	6.1	4.1	6.9	5.4

The highest TG value is obtained for the ±50 TFPV vs 20° FXFPV combination.

Table 6. TBFG for Horizontal single-axis tracking FPV system E-W.

System comparison		Locality			
		1	2	1	2
		d_r/L			
$TFPV_b$	**$FXGPV_m$**	**2.1**		**3.0**	
$\gamma_{Mm/b}$ [°]		**TBFG [%]**			
±30	20	12.9	10.9	13.6	12.4
	30	12.0	11.0	12.2	11.3
±50	20	15.1	11.4	16.9	14.4
	30	14.1	11.5	15.4	13.4

The maximum and minimum values that can be obtained from comparison of TFPVb and FXGPVm are, TBFG = 16.9% and 14.4%.

The maximum values are obtained in the case of configuration ±50° TPV for $d_r/L = 3.0$: BG = 2.9% for Anapo and 4.2 for Aar. The higher BG of Aar compared to Anapo is due to the greater amount of diffuse radiation in Aar.

The FG values range from 4.8% to 5.3% in Anapo and from 3.3% to 3.7 in Aar. The values obtained are very similar to those of the previously analyzed cases as the cooling behavior of the modules is very similar. There is a slight difference linked to the solar radiation captured which in the case of N–S systems is greater.

With the same inclination (γ) and technology (m, b), then moving horizontally in Table 7, between $d_r/L = 2.1$ and 3, the energy difference ranges from a minimum of 2 to a maximum of 4% for Anapo and from a minimum of 3 to a maximum of 6% for Aar. In this case, compared to the Horizontal E-W, the energy collected has a higher sensitivity respect to the distance between the rows.

This consideration could be useful in the evaluation phase of the LCOE since as reported in [32] being that the cost of the raft is proportional to the surface covered, it is necessary to understand if the increase in energy due to the increase in the covered surface is able to make more the system with greater interdistance is competitive and therefore compensates for the cost increase.

Table 8 shows TG values for mono and bifacial FPV systems. Specifically, tracking systems are compared with fixed in different geometric configurations.

Compared to the E-W, the N–S one with the same geometric configurations is much more performing. This can be seen by comparing the two tables of TG for the E-W and N–S system.

Table 9 shows TBFG values of TFPV which take into account the effect of energy gain due to tracking, natural cooling and the bifaciality. So the comparison is between floating bifacial tracker and fixed monofacial ground.

It can therefore be concluded that a bifacial N–S floating horizontal axis tracking system can increase the yield compared to a fixed ground system by 27.6% in intermediate latitude and 23.3 in higher latitude.

3.4. Vertical single-axis tracking system

For this type of TFPV, simulations are carried out only for the monofacial system as the software tool does not allow to simulate bifacial modules with a vertical tracker.

Table 10 shows the equivalent operating hours Y, for the configuration with vertical tracker on ground and on water, with monofacial modules and FG of floating systems.

FG values range from 5.0% to 5.3%. for Anapo and 3.6 to 3.9 to Aar. The values obtained are very similar to those of the previously analyzed cases as the cooling behavior of the modules is very similar.

With the same inclination (γ), then moving horizontally in the Table 10, between $d_r/L = 2.1$ and 3, the energy difference ranges from a minimum of 1 to a maximum of 2% for Anapo and from a minimum of 2 to a maximum of 3% for Aar.

Also in this case, as in the case of the Horizontal E-W system, the sensitivity of the energy respect to the interdistance is rather limited.

Table 11 shows TG for Vertical single-axis tracking system.

Table 7. $Y_{m/b}$ for Horizontal single-axis tracking N–S F/GPV systems.

System	$\gamma_{Mm/b}$ [°]	Technology	Locality											
			1			**2**			**1**			**2**		
			d_r/L											
			2.1						**3.0**					
			Y [h]	**BG [%]**	**FG [%]**	**Y [h]**	**BG [%]**	**FG [%]**	**Y [h]**	**BG [%]**	**FG [%]**	**Y [h]**	**BG [%]**	**FG [%]**
TGPV	±30	M	1925.5	-	-	1047.2	-	-	1969.5	-	-	1077.9	-	-
		B	1963.7	-	-	1075.2	-	-	2014.0	-	-	1110.3	-	-
	±50	M	1960.0	-	-	1047.2	-	-	2040.4	-	-	1100.8	-	-
		B	2005.1	-	-	1085.2	-	-	2092.8	-	-	1144.2	-	-
TFPV	±30	M	2018.3	-	4.8	1083.1	-	3.3	2064.2	-	4.8	1115.0	-	3.3
		B	2064.6	2.3	5.1	1114.8	2.9	3.6	2117.2	2.6	5.1	1151.2	3.3	3.6
	±50	M	2056.9	-	4.9	1084.4	-	3.5	2141.9	-	5.0	1140.8	-	3.5
		B	2110.5	2.6	5.3	1126.5	3.9	3.7	2203.5	2.9	5.3	1188.5	4.2	3.7

As far as the N–S systems are concerned, the BG speech cannot be analogous to that of the E-W systems as their shadow will be projected under them during the whole day, thus affecting the rear part of the double-sided module [39].

Table 8. $TG_{m/b}$ for Horizontal single-axis tracking system N–S.

System comparison		Technology	Locality			
			1	**2**	**1**	**2**
			dr/L			
TFPV	**FXFPV**		**2.1**		**3**	
$\gamma_{Mm/b}$ [°]			**TG [%]**			
±30	20	M	11.9	9.4	14.2	11.9
		B	12.0	9.7	14.3	12.3
	30	M	10.9	9.4	12.7	10.8
		B	10.5	8.8	12.2	10.0
±50	20	M	14.1	9.6	18.5	14.5
		B	14.4	10.9	19.0	15.9
	30	M	13.0	9.6	17.0	13.3
		B	12.9	10.0	16.7	13.6

The highest TG value is obtained for the ±50 vs 20° combination and is equal to 19.0% for Anapo and 15.9 for Aar Dam.

Table 9. TBFG for Horizontal single-axis tracking FPV system N–S.

System comparison		Locality			
		1	2	1	2
		d_r/L			
$TFPV_b$	**$FXGPV_m$**	**2.1**		**3.0**	
$\gamma_{Mm/b}$ [°]		**TBFG [%]**			
±30	20	19.8	16.4	22.6	19.4
	30	18.8	16.6	21.1	18.3
±50	20	22.5	17.6	27.6	23.3
	30	21.5	17.8	26.0	22.2

The maximum values that can be obtained from comparison of TFPVb and FXGPVm are, TBFG = 27.6% for Anapo and 23.3 for Aar.

Table 12 shows the TFG values which take into account the effect of the energy gain due to the tracking and natural cooling of the floating system compared to the monofacial ground system.

From what can be seen from the energy yield data, the vertical axis system is more efficient than horizontal axis system.

It is not the objective of this work but, although this system is more advantageous respect to horizontal tracker, from an energy point of view, the economic aspect must be evaluated. The previous ones are made with rafts with a gable structure, this one with a vertical axis can be of a different type: carousel, with or without a confinement structure. The cost therefore depends on the type of tracker used.

It would also be advisable to analyze the optimal configuration that minimizes LCOE, taking into account that as in the case of the horizontal system E-W, this system is not very sensitive to the interdistance.

Table 11. TG for Vertical single-axis tracking system.

System comparison		Locality			
TFPV	**FXFPV**	**1**	**2**	**1**	**2**
		d_r/L			
		2.1		**3.0**	
γ_{Mm} [°]		**TG [%]**			
20	20	16.2	15.2	17.4	16.5
	30	15.1	15.2	15.8	15.3
30	20	23.2	21.1	25.5	23.7
	30	22.0	21.1	23.8	22.4

The maximum TG values are obtained for the TFPV configuration with 30° tilt and $d_r/L = 3.0$ compared with a fixed system with 20° tilt and is 25.5% for Anapo and 23.7 for Aar.

Table 12. TFG for Vertical single-axis tracking monofacial FPV system.

System comparison		Locality			
		1	2	1	2
		d_r/L			
TFPV	**FXGPV**	**2.1**		**3.0**	
γ_{Mm} [°]		**TFG [%]**			
20	20	21.6	19.0	22.8	20.4
	30	20.5	19.2	21.3	19.3
30	20	28.9	25.1	31.3	27.8
	30	27.8	25.3	29.7	26.7

The maximum values of TFG obtainable for the configuration analysed are, 31.3% and 27.8 in Anapo and Aar respectively.
The TFG values for the vertical tracker are higher than horizontal N–S and E-W.

To reduce the probable excessive costs linked to the structure, it would certainly be worth considering the realization of such systems with bifacial modules and reflective surfaces in the back, using light-colored floating spheres that increase the albedo compared to that of water. Since these systems can be made with confined structures, technically it would not be necessary to install additional components that allow the spheres to be contained.

3.5. Dual axis tracking system

For this type of TFPV, simulations are carried out only for the monofacial system as the software does not allow to simulate bifacial modules with a 2 axes tracker.

Table 13 shows the equivalent operating hours Y, for the configuration with 2 axes tracker in Anapo and Aar Dam.

Table 10. $Y_{m/b}$ for Vertical single-axis tracking and fixed F/GPV system.

System	Φ [°]	$\gamma_{Mm/b}$ [°]	Locality							
			1		2		1		2	
			d_r/L							
			2.1				3.0			
			Y [h]	FG [%]	Y [h]	FG [%]	Y [h]	FG [%]	Y [h]	FG [%]
TGPV	±120	20	1993.9	-	1100.6	-	2019.2	-	1120.3	-
		30	2108.8	-	1153.7	-	2152.5	-	1186.0	-
TFPV	±120	20	2094.2	5.0	1140.1	3.6	2120.7	5.0	1160.6	3.6
		30	2220.6	5.3	1198.5	3.9	2266.9	5.3	1232.3	3.9

Table 13. $Y_{m/b}$ for Dual-axis tracking F/GPV system.

System	Φ [°]	$\gamma_{Mm/b}$ [°]	Locality							
			1		2		1		2	
			d_r/L							
			2.1				3.0			
			Y [h]	FG [%]	Y [h]	FG [%]	Y [h]	FG [%]	Y [h]	FG [%]
TGPV	±120	0–50	2380.5	-	1291.0	-	2407.2	-	1316.1	-
TFPV	±120	0–50	2515.1	5.7	1346.9	4.3	2544.7	5.7	1373.7	4.4

Table 14. TG for Dual axis tracking system.

System comparison		Locality			
		1	2	1	2
		d_r/L			
TFPV	**FXFPV**	**2.1**		**3**	
	γ_{Mm} [°]	TG [%]			
Φ = ±120	20	39.5	36.1	40.8	37.9
γ_{Mm} = 0-50	30	38.2	36.1	39.0	36.5

Table 15. TFG for Dual axis tracking system.

System comparison		Locality			
		1	2	1	2
		d_r/L			
TFPV	**FXFPV**	**2.1**		**3**	
	γ_{Mm} [°]	TFG [%]			
Φ = ±120	20	46.0	40.6	47.4	[1]42.5
γ_{Mm} = 0-50	30	44.8	40.8	45.6	41.2

For the analyzed configurations the FG values are 5.7% in Anapo and 4.3–4.4 in Aar. The values obtained are very similar to those of the previously analyzed cases. The same considerations made previously can be reported in this case.

With the same inclination (γ), then moving horizontally in Table 13, between $d_r/L = 2.1$ and 3, the energy difference is 1% for Anapo and 2% for Aar. In this case, the energy collected has a lower sensitivity respect to the distance between the rows.

Considering that the dual-axis tracking system is rather complex and certainly requires greater maintenance [32] as the moving mechanisms and components are greater than in the cases previously analyzed, it is necessary to evaluate the economic convenience of increasing the interdistance.

Table 14 shows the gain of the tracking effect.

With the effect of dual tracking alone, without considering the effect of cooling, the energy collected could increase up to almost 41% in Anapo and 38% in Aar.

Table 15 shows the gain due to cooling and tracking, then comparing fixed system on ground with the tracking system on water.

Thanks to the dual effect of cooling and tracking, up to 47.4% for Anapo and 42.5% for Aar more energy than fixed systems can be collected.

It is not the aim of this work, but although this system is absolutely more advantageous in terms of energy balance compared to the previously analysed systems, the economic aspect must also be evaluated.

4. Conclusions and future works

This study aims to present a preliminary bibliographic research concerning the floating tracking photovoltaic systems studied so far in the literature and, to fill the existing gap concerning the evaluation of the energy performance of tracking FPV systems.

The energy performance of a fixed G/FPV (ground/floating photovoltaic) system with vertical, horizontal or biaxial tracking, with monofacial or bifacial modules, was evaluated on an annual basis, taking into account passive cooling due to the evaporation effect of the PV modules in the FPV system.

It can be said that, for the analyzed configurations, it is possible to obtain a gain due to the bifaciality greater than 3% for the Anapo dam in Italy and greater than 4% for the Aar dam in Germany.

The gain due to the natural cooling of the modules, which can be obtained for the analyzed configurations, is near to 6% for Anapo Dam in Italy and near to 4.5% for Aar in Germany.

The gain due to the tracking, natural cooling and bifaciality for the two localities Anapo and Aar is respectively: 16.9% and 14.4% for the horizontal E-W system; 27.6% and 23.3% for the horizontal N–S system; 31.3% 27.8% for the One Axis Vertical system; 47.4% and 42.5% for the dual axis system.

The energy evaluation, to acquire even more meaning, must necessarily be accompanied by the economic one which would allow to evaluate feasibility of these systems. This study, in fact, is preliminary to works that will be carried out in the future, which will make it possible to fill the economic aspect and have an overall view of the subject.

It will therefore be necessary to carry out a comparative economic analysis between the various plant solutions previously listed based on the cost of capital (CAPEX), the operating and maintenance cost (OPEX) and the levelised cost of electricity (LCOE), also considering any revenues. deriving from the economic valorisation of the annual volume of water available for other uses for the reduction of evaporation caused by the partial coverage of the water surface.

Furthermore, to make these systems even more competitive it will be necessary:

- study economic and effective solutions that increase the reflection of water and at the same time do not cancel the cooling effect by evaporation. In this regard, some research bodies are evaluating the insertion of reflective surfaces anchored to the aluminum structures or of light-colored floating hollow spheres placed on the surface of the water and in correspondence with the double-sided modules within the confined structure. These solutions seem feasible but must be tested to verify their real effectiveness.
- optimize the integration of floating photovoltaic plants (FPV) with hydroelectric plants which would allow to increase the utilization factor of the integrated hybrid system compared to the values of the individual plants and therefore their overall profitability.

FPV systems, in fact, have a potential advantage if installed on the storage basins of hydroelectric plants to exploit the residual capacity of pre-existing electrical plants by exploiting the complementarity of energy sources and the programmability of hydroelectric plants with water basins.

The optimal coupling of these two systems will have to take into account various aspects influenced by the presence of the floating system, including:

- interference from a structural point of view as the anchoring, mooring and floating systems must be designed taking into account the existing structures;
- maximize both the energy produced and that fed into the grid to which the hybrid system is connected;
- the environmental impact, as the FPV system must not cause damage to the surrounding environment and fauna;

Declarations

Author contribution statement

Giuseppe Marco Tina: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Fausto Bontempo Scavo: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Funding statement

This work was supported by the Italian Ministry of Education (MIUR) by “the Notice 12/2017, who financed the industrial Ph.D.” PON FSE-FESR RICERCA E INNOVAZIONE 2014–2020 AZIONE I.1.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] A. Sahu, N. Yadav, K. Sudhakar, Floating Photovoltaic Power Plant: A Review, Renewable and Sustainable Energy Reviews, 2016.
[2] D.S. Kumar, G.M. Yagli, M. Kashyap, D. Srinivasan, Solar irradiance resource and forecasting: a comprehensive review, IET Renew. Power Gener. (2020).
[3] A.E. Cagle, et al., The land sparing, water surface use efficiency, and water surface transformation of floating photovoltaic solar energy installations, Sustain. Times (2020).
[4] R. Cazzaniga, M. Rosa-Clot, P. Rosa-Clot, G.M. Tina, Integration of PV floating with hydroelectric power plants, Heliyon 5 (6) (2019), e01918.
[5] V. Poulek, et al., PV panel and PV inverter damages caused by combination of edge delamination, water penetration, and high string voltage in moderate climate, IEEE J. Photovoltaics (2021).
[6] A.B. Subramaniyan, R. Pan, J. Kuitche, G. TamizhMani, Quantification of environmental effects on PV module degradation: a physics-based data-driven modeling method, IEEE J. Photovoltaics 8 (5) (2018) 1289–1296.
[7] O.K. Segbefia, A.G. Imenes, T.O. Saetre, Moisture ingress in photovoltaic modules: a review, Sol. Energy 224 (2021) 889–906.
[8] S. Mekhilef, R. Saidur, M. Kamalisarvestani, Effect of dust, humidity and air velocity on efficiency of photovoltaic modules, Renew. Sustain. Energy Rev. 16 (5) (2012) 2920–2925.
[9] B.A.L. Gwandu, D.J. Creasey, Humidity: a Factor in the Appropriate Positioning of a Photovoltaic Power Station, Renew. Energy, 1995.
[10] M. Rosa-Clot, G.M. Tina, Floating PV Plants, 2020.
[11] G.M. Tina, F. Bontempo Scavo, L. Merlo, F. Bizzarri, Comparative analysis of monofacial and bifacial photovoltaic modules for floating power plants, Appl. Energy (2021).
[12] S. Gorjian, H. Sharon, H. Ebadi, K. Kant, F.B. Scavo, G.M. Tina, Recent technical advancements, economics and environmental impacts of floating photovoltaic solar energy conversion systems, J. Clean. Prod. (2021).
[13] H. Hafeez, A. Kashif Janjua, H. Nisar, S. Shakir, N. Shahzad, A. Waqas, Techno-economic perspective of a floating solar PV deployment over urban lakes: a case study of NUST lake Islamabad, Sol. Energy (2022).
[14] IRENA, Offshore Renewables, An Action Agenda for Deployment, 2021.
[15] R. Cazzaniga, Floating PV structures, in: Floating PV Plants, 2020.
[16] K. Masuko, et al., Achievement of more than 25% conversion efficiency with crystalline silicon heterojunction solar cell, IEEE J. Photovoltaics (2014).
[17] S.A. Pelaez, C. Deline, P. Greenberg, J.S. Stein, R.K. Kostuk, Correction: model and validation of single-Axis tracking with bifacial PV, IEEE J. Photovoltaics 9 (2019) 715–721.
[18] D. Faiman, Assessing the outdoor operating temperature of photovoltaic modules, Prog. Photovoltaics Res. Appl. (2008).
[19] S. Seme, B. Štumberger, M. Hadžiselimović, K. Sredenšek, Solar photovoltaic tracking systems for electricity generation: a review, Energies 13 (16) (2020) 4224.
[20] R. Cazzaniga, M. Cicu, M. Rosa-Clot, P. Rosa-Clot, G.M. Tina, C. Ventura, Floating photovoltaic plants: performance analysis and design solutions, Renew. Sustain. Energy Rev. 81 (May 2017) 1730–1741.
[21] [Online]. Available: Floating Solar https://floatingsolar.nl/. last accessed on July 2022.
[22] S.H. Kim, S.J. Yoon, W. Choi, K.B. Choi, Application of floating photovoltaic energy generation systems in South Korea, Sustain. Times 8 (12) (2016) 1–9.
[23] Y.K. Choi, Y.G. Lee, A study on development of rotary structure for tracking-type floating photovoltaic system, Int. J. Precis. Eng. Manuf. 15 (11) (2014) 2453–2460.
[24] J.M. Wang, C.L. Lu, Design and implementation of a sun tracker with a dual-axis single motor for an optical sensor-based photovoltaic system, Sensors (2013).
[25] R. Xu, C. Liu, H. Liu, Z. Sun, T.L. Lam, H. Qian, Design and optimization of a wave driven solar tracker for floating photovoltaic plants, IEEE/ASME Int. Conf. Adv. Intell. Mechatronics, AIM (2019-July) 1293–1298, 2019.
[26] P.E. Campana, L. Wästhage, W. Nookuea, Y. Tan, J. Yan, Optimization and assessment of floating and floating-tracking PV systems integrated in on- and off-grid hybrid energy systems, Sol. Energy 177 (December 2018) 782–795, 2019.
[27] M. Rosa-Clot, P. Rosa-Clot, G.M. Tina, C. Ventura, RAST: RoundAbout solar tracking, Energy Proc. 134 (2017) 598–606.
[28] G.M. Tina, M. Rosa-Clot, Electrical behavior and optimization of panels and reflector of a photovoltaic floating plant, 26th Eur. Photovolt. Sol. Energy Conf. Exhib. (2011).
[29] A.D.C. Pronk, D. Dizdar, W.A. Schuurmans, Sun-Spotter, Gravity point Displacement as Solar-Tracking Principle, 2015.
[30] Y.-K. Choi, N.-H. Lee, A.-K. Lee, K.-J. Kim, A study on major design elements of tracking-type floating photovoltaic systems, Int. J. Smart Grid Clean Energy 3 (1) (2014) 70–74.
[31] Byung-Moon So and Ik-Tae Im, “Development of tracking algorithm for floating photovoltaic system, journal of the semiconductor & display technology,” J. Semicond. Disp. Technol., vol. 18.
[32] Marco Rosa-Clot, Giuseppe Marco Tina, Tracking Systems. Floating PV Plants, Elsevier, 2020, pp. 79–87.
[33] M.-J. Jang, S.-H. Kim, Y.-G. Lee, S.-B. Woo, S.-J. Yoon, Installation and safety evaluation of tracking-type floating PV generation structure, J. Korean Soc. Adv. Compos. Struct. 5 (1) (2014) 1–8.
[34] S.K. Natarajan, A. Kumar, R. Mohamed, R. Rathna, S. Mondal, S.K. Suraparaju, Design and development of dual axis sun tracking system for floating PV plant, IOP Conf. Ser. Earth Environ. Sci. 312 (2019).
[35] https://www.pvsyst.com/help/models_meteo_transposition.htm. last accessed on July 2022.
[36] C. Zhao, J. Xiao, Y. Yu, J.-N. Jaubert, Accurate shading factor and mismatch loss analysis of bifacial HSAT systems through ray-tracing modeling, Sol. Energy Adv. (2021).
[37] PVsyst. https://www.pvsyst.com/help/thermal_loss.htm. last accessed on July 2022.
[38] I. Shoukry, J. Libal, R. Kopecek, E. Wefringhaus, J. Werner, Modelling of Bifacial Gain for Stand-Alone and In-Field Installed Bifacial PV Modules, 2016.
[39] D. Berrian, J. Libal, M. Klenk, H. Nussbaumer, R. Kopecek, Performance of bifacial PV arrays with fixed tilt and horizontal single-Axis tracking: comparison of simulated and measured data, IEEE J. Photovoltaics (2019).