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Comparative analysis of the energy performance of floating and ground-mounted photovoltaic power plants

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***Abstract*—This paper presents a comparative energy yield analysis of ground-mounted photovoltaic (GPV) and floating photovoltaic (FPV) power plants at 10 locations in the northern hemisphere. The GPV power plant operates at the optimum tilt angle. The FPV power plant operates with the standard tilt angles of 5 and 12 (°). Four electrical efficiencies are analyzed. Using a Mathematica© code, the optimum tilt angle for the GPV plant and the energy generated by each of the PV plants have been calculated. The proposed evaluation indicator is the energy gain with respect to the GPV plant. In locations with latitudes below 31 (°), FPV plants with an tilt angle of 12 (°) perform best. At latitudes above 31 (°), higher electrical efficiencies are needed for FPV plants with tilt angles of 12 (°) to obtain better results. FPV plants with tilt angles of 5 (°) need very high electrical efficiencies to be more efficient than GPV plants.**

***Index Terms*—Floating photovoltaic system, Ground-mounted photovoltaic systems, Electrical efficiency, Tilt update frequency.**

I. Introduction

Even though both floating photovoltaic (FPV) and ground-mounted photovoltaic (GPV) power plants generate clean, renewable energy with low greenhouse gas emissions as they utilize solar technology, they exhibit distinct differences:

(i) FPV power plants do not require land for deployment. FPV power plants offer the advantage that they do not need to be located on land, whereas GPV plants can occupy up to 25 years of productive land that could otherwise be used for agricultural purposes [1]. Where land is less fertile, the area occupied by a GPV plant could be used for forestry purposes, providing another source of income. On the other hand, FPV power plants allow for the liberation of land that can be repurposed for agricultural or forestry projects.

(ii) FPV power plants reduce the evaporation of the water body where they are installed. By installing FPV power plants, the evaporation of the water body on which they are situated can be decreased [2]. Given that water scarcity is a critical issue affecting global populations, reducing evaporation from open water surfaces has the potential to increase the availability of drinking water. Evaporation depends on several factors, such as water surface and temperature [1]. The photovoltaic modules of FPV power plants serve as a protective layer, limiting evaporation from the body of water. Agrawal et al. [1] conducted a study on water evaporation in an Indian reservoir, where they demonstrated this fact.

(iii) Concerns related to degradation and corrosion of FPV power plant materials. Goswami et al. [3] analysed the degradation of PV modules in both plants, and concluded that the degradation rate of the GPV system was slightly lower.

(iv) At present, the initial investment costs for FPV power plants are higher compared to GPV systems [4].

(v) Concerns related to maintenance costs. Due to the environment in which FPV plants are deployed, maintenance costs may be higher [4].

(vi) PV modules in FPV power plants may have a restricted tilt angle to prevent damage from wind loads, waves, or water currents. However, low tilt angles can lead to a reduction in power generation, which can have an undesirable impact [6].

(vii) FPV power plants have the potential to generate more electricity compared to GPV systems. The efficiency of PV modules has been analysed for both plants [3], concluding that the FPV power plants perform better.

This study focuses on items (vi) and (vii), and analyzes 10 locations of ground-mounted and floating PV plants in the

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northern hemisphere.

The specific contributions of this study are as follows: (i) An investigation into the impact of the tilt angle of PV modules on the incident solar irradiance for both ground-mounted and floating PV plants; (ii) An examination of the effect of electrical efficiency on the power output of both types of plants; and (iii) A comprehensive analysis of the energy gain of ground-mounted and floating photovoltaic power plants.

II. GOVERNING EQUATIONS

The equation used to calculate the power output of both power plants is [7]:

$$P_{PV} = (\tau \cdot \alpha) \cdot I_t \cdot \eta_e \tag{1}$$

where P_{PV} is the power output of a PV module (W/m^2), τ is the solar transmittance of glazing (dimensionless), α is the solar absorptance of PV layer (dimensionless), I_t is the total incident solar irradiance (W/m^2), and η_e is the efficiency of the PV module (dimensionless). The product of transmittance and absorption $(\tau \cdot \alpha)$ is typically assumed to be 0.9 [8], [7].

According to equation (1), the electrical power generation of PV modules depends mainly on two parameters: the incident solar irradiance and the electrical efficiency of the PV module. In the following, we will analyse how the type of PV plant influences these parameters.

A. Electrical efficiency for each type of PV plant

The equation presented by Evans [9] is commonly used in many works [10], [11] to determine the electrical efficiency of a photovoltaic module, and is given by:

$$\eta_e = \eta_{ref} \cdot [1 - \beta_{ref} \cdot (T_c - T_{ref})] \tag{2}$$

where η_{ref} is the electrical efficiency of the photovoltaic module at reference temperature (dimensionless), β_{ref} is the temperature coefficient (1/^{o}C), T_c is the PV cell temperature (^{o}C), and T_{ref} is the reference temperature (^{o}C). Among other technical parameters, the manufacturer of the PV module provides the value of η_{ref} and β_{ref}. The η_{ref} value normally refers to a temperature of 25 (^{o}C) and a solar irradiance of 1000 (W/m^2).

As can be seen from equation (2) the electrical efficiency depends on the operating temperature of the module. Power generation is reduced as the temperature of the PV module increases.

The T_c parameter can be estimated using various types of models [11]. Many models consider only ambient temperature and incident solar irradiance, while some models also incorporate wind speed as a factor. An example of such models is the one that determines T_c as a function of the Normal Operating Cell Temperature (NOCT) [12], [13]:

$$T_c = T_a + (NOCT - 20) \cdot \frac{I_t}{800} \tag{3}$$

where T_a is the ambient temperature (^{o}C) and I_t is the total incident solar irradiance (W/m^2). The NOCT value is calculated under standard conditions, which include a solar irradiance of 800 (W/m^2), an ambient temperature of 20 (^{o}C), and a wind speed of 1 (m/s) at the height of the PV module.

The electrical efficiency of PV modules installed in FPV plants may be affected by different factors compared to PV modules located in GPV plants. Several studies have investigated this topic [14]. El Hammoumi et al. [2] conducted an experimental investigation of two PV systems, an FPV system and a GPV system, with similar power. According to the test results, the average temperature of the modules in the FPV system was consistently lower than that of the modules in the GPV system, with a maximum difference of 2.74 (^{o}C). As a result, the FPV system generated up to 2.33% more energy per day than the GPV system. Oliveira-Pinto and Stokkermans [15] conducted a comparative study between FPV and GPV systems and found that the FPV system had a higher electrical efficiency in the range of 0.31% to 2.59%, depending on the floating solar technology used. Liu et al. [14] conducted an experimental study and found that the temperature of PV modules in an FPV system was generally 5 (°C) to 10 (°C) lower than the temperature of modules in a similar PV system installed on a rooftop. As a result, the electrical efficiency of the modules in the FPV system increased by 10%.

El Hammoumi et al. [2] presented an experimental investigation of two PV systems, FPV system and GPV system, of similar power. The test results showed that the average temperature of the modules of the FPV system was always lower compared to that of the modules of the GPV system, with a difference of up to 2.74 (^{o}C). As a result, the FPV system generated up to 2.33% more energy per day than the GPV system. Oliveira-Pinto and Stokkermans [15] presented a comparative study between FPV and GPV systems, obtaining a higher electrical efficiency of the FPV system in the order of 0.31% to 2.59%, depending on the floating solar technology. Liu et al. [14] showed through an experimental study that the temperature of PV modules in an FPV system was generally 5 (°C) to 10 (°C) lower than the temperature of modules in a similar PV system installed on a rooftop, which increased the electrical efficiency of the modules in the FPV system by 10%. Choi [16] analyzed the electrical efficiency of an FPV system and a GPV system, verifying that the electrical efficiency in the modules of the FPV system is 11% higher. Hence, a few research works indicate that the rise in electric effectiveness is less than 5%, whereas some studies suggest it to be in the range of 5% to 11%.

B. Incident solar irradiance for both type of PV plant

According to Duffie and Beckman [12] the solar irradiance incident on the photovoltaic modules can be determined by the equation:

$$\begin{aligned} \mathbb{I}_t(n,T,\beta,\gamma) = \\ \mathbb{I}_{bh}(n,T) \cdot \frac{\cos\theta_i}{\cos\theta_z} + \mathbb{I}_{dh}(n,T) \cdot \left(\frac{1+\cos\beta}{2}\right) + \\ + \left(\mathbb{I}_{bh}(n,T) + \mathbb{I}_{dh}(n,T)\right) \cdot \rho_g \cdot \left(\frac{1-\cos\beta}{2}\right) \end{aligned} \tag{4}$$

where $\mathbb{I}_t(n,T,\beta,\gamma)$ is the total solar irradiance (W/m^2), $\mathbb{I}_{bh}$ is the beam irradiance on a horizontal plane at the PV plant location (W/m^2), $\mathbb{I}_{dh}$ is the diffusse irradiance on a horizontal plane at the PV plant location (W/m^2), θ_i is the incident angle (^{o}), θ_z is the zenith angle of the Sun (^{o}), β is the tilt angle (^{o}), γ is the azimuth angle (^{o}), and ρ_g is the ground reflectance (dimensionless).

$\mathbb{I}_{bh}$ and $\mathbb{I}_{dh}$ are affected by the local distribution of cloud cover. To account for this fact, the procedure presented by [17] has been used to determine these irradiances the meteorological conditions of the PV plant for each day of the year. This method has demonstrated its accuracy and easy applicability to different climates [18]. These parameters affect both types of PV plant in the same way.

The parameter θ_i can be determined by the equation proposed by Duffie and Beckman [12]:

$$\cos\theta_i = \sin\delta\cdot\sin\lambda\cdot\cos\beta - \sin\delta\cdot\cos\lambda\cdot\sin\beta + \cos\delta\cdot\cos\lambda\cdot\cos\beta\cdot\cos\omega + \cos\delta\cdot\sin\lambda\cdot\sin\beta\cdot\cos\omega \quad (5)$$

where δ is the declination (^{o}), λ the latitude (^{o}), β the tilt angle (^{o}), ω the hour angle (^{o}) and assuming that γ the azimuth angle (^{o}) for these PV systems is 0 (^{o}) in the northern hemisphere and 180 (^{o}) This parameter θ_i affects both types of PV plant equally.

The parameter ρ_g varies depending on the type of PV plant analyzed. A value of 0.2 is usually adopted for GPV plants [19]. In contrast, in FPV plants this value is significantly lower. Agrawal et al. [1] considered a typical value of $\rho_g = 0.1$ for a floating PV plant. Liu et al. [14] used a testbed to evaluate the ρ_g of a water body, obtaining values ranging from 0.05 to 0.07. Oliveira-Pinto and Stokkermans [15] analyzed different GPV plant technologies, using $\rho_g = 0.05$.

The tilt angle plays a crucial role in deciding the solar radiation that falls on PV panels. For GPV plants, this factor primarily relies on the installation site's latitude, the direct irradiance received on a flat surface, and the diffused irradiance received on a flat surface [6]. Moreover, factors like the surface area available, shading, and accumulation of dirt can also impact the determination of the most favorable inclination angle [20]. For FPV plants, the tilt angle is selected based on the mounting system's stability. The tilt angle of the mounting structure should prevent any adverse impact caused by wind loads, water currents, or waves. The conventional tilt angles used for this purpose are either 5 (^{o}) [21], [22] or 12 (^{o}) [22]. Table I illustrates a few instances of FPV plants.

Table I. Tilt angles used in FPV plants.

P (MWp)	Locations	β (^{o})	γ (^{o})
14.80	Tamilnadu (India)	12	0
21.57	Chaiyi (Taiwan)	12	0
1	Wallonia (Belgium)	12	0
5	Alentejo (Portugal)	5	0
0.147	Benguerir (Morocco)	5	0

As observed, the tilt angle adopted in such installations is minimal, resulting in a short gap between the rows of PV panels. This, in turn, leads to negligible shading between the modules.

By integrating Eq. (4) from sunrise (T_R) to sunset (T_S), the total solar irradiation on the surface of the PV modules can be calculated:

$$\mathbb{H}_t\left(n,\beta\right) = \int_{T_R(n)}^{T_S(n)} \mathbb{I}_t(n,T,\beta)dT \quad (6)$$

where $\mathbb{H}_t$ is the total solar irradiation on the surface of the PV modules (Wh/m^2), n is the day of the year (day), and T is the solar time (h).

The annual energy output of a PV module was calculated as follows:

$$E_{PV} = (\tau\cdot\alpha)\cdot\mathbb{H}_t\left(n,\beta\right)\cdot\eta_e \quad (7)$$

where E_{PV} is the energy output of a PV module (Wh/m^2).

C. Energy gain

The concept of energy gain (EG) is commonly used to evaluate the influence of parameters such as tilt angle, azimuth angle, etc. on a given PV system [23]. In order to compare the energy performance of the two types of PV plants studied, the following equation is introduced to facilitate their analysis:

$$EG = \frac{E_{GPV} - E_{FPV}}{E_{GPV}} \times 100 \quad (8)$$

III. Results and discussion

This section aims to evaluate the impact of the PV plant type on the PV field's yearly energy output for each installation. To achieve this objective, a Mathematica software code has been created to estimate (i) the optimal tilt angle of the GPV plant and (ii) the energy generated by both types of plants.

The research was carried out at ten locations situated in the northern hemisphere: (1) Medellin (Colombia), (2) Bangkok (Thailand), (3) Morelia (Mexico), (4) Karachi (Pakistan), (5) Cairo (Egypt), (6) Almeria (Spain), (7) Toronto (Canada), (8) Wien (Austria), (9) Hamburg (Germany), and (10) Helsinki (Finland). The geographic features of the investigated locations are presented in Table II.

Table II. Data of locations under study.

Loc.	Latitude	Longitude	Alt. (m)
1	$06°14'38''N$	$75°34'04''W$	1469
2	$13°45'14''N$	$100°29'34''E$	9
3	$19°42'10''N$	$101°11'24''W$	1921
4	$24°52'01''N$	$67°01'51''E$	14
5	$30°29'24''N$	$31°14'38''W$	41
6	$36°50'07''N$	$02°24'08''W$	22
7	$43°39'14''N$	$79°23'13''W$	106
8	$48^o15'00''N$	$16°21'00''E$	20
9	$53^o33'00''N$	$10°00'03''E$	19
10	$60°10'10''N$	$24°56'07''E$	23

The solar radiance levels of the examined sites have been considered by utilizing the technique outlined by [17] while accounting for the real weather conditions. This method employs the monthly mean values of direct and diffuse solar irradiance received on a horizontal plane as its inputs. For these solar irradiance predictions, the PVGIS [24] database has been utilized.

A. Estimated annual irradiation

In the case of GPV power plants, the optimum tilt angle can be determined by various methods [25], [18]. In this work, the procedure that maximizes the total irradiance falling onto the PV modules is used [18]. Table III shows, for the 10 locations under study, the optimum tilt angles.

Table III. Optimum tilt angles (^{o}).

Locations	β_{opt}	Locations	β_{opt}
Medellin	4.5	Almeria	30.3
Bangkok	13.2	Toronto	30.6
Morelia	19.9	Wien	32.9
Karachi	23.6	Hamburg	36.8
Cairo	24.2	Helsinki	38.6

In the case of FPV power plants, the standard values for the tilt angle are (see Table I): 5 (^{o}) [21], [22], and 12 (^{o}) [22]. As all the locations studied are in the northern hemisphere, the optimum azimuth angle used is 0 (^{o}) [12]. In this work the values of ρ_g used will be 0.2 [19] and 0.05 [15], for GPV and FPV power plants, respectively.

Based on the equation (6), the annual solar irradiation is calculated taking into account the effects of different weather conditions. Table IV shows the annual solar irradiation for the 10 study sites.

Table IV. Annual solar irradiation (MWh/m^2).

Location	GPV plant	FPV plant	
	$\mathbb{H}(\beta_{opt})$	$\mathbb{H}(5^o)$	$\mathbb{H}(12^o)$
Medellin (Colombia)	1.8300	1.8300	1.8203
Bangkok (Thailand)	1.8854	1.8203	1.8852
Morelia (Mexico)	2.1786	2.1231	2.1624
Karachi (Pakistan)	2.2411	2.1540	2.2065
Cairo (Egypt)	2.2803	2.1815	2.2395
Almeria (Spain)	2.1126	1.9497	2.0254
Toronto (Canada)	1.4484	1.3459	1.3928
Wien (Austria)	1.3449	1.2337	1.2807
Hamburg (Germany)	1.1769	1.0466	1.0950
Helsinki (Finland)	1.0685	0.9359	0.9813

The results shown in Table IV are in line with the study presented in [6]. As the difference between the tilt angles used in both plants increases, the annual solar irradiation obtained in the FPV plant decreases.

B. Energy gain

From the equation (7), the electrical energy generated by each PV plant is calculated.

In addition to the tilt angles mentioned above, the electrical efficiency of the PV modules obtained in the operation of each PV plant involves the following scenarios:

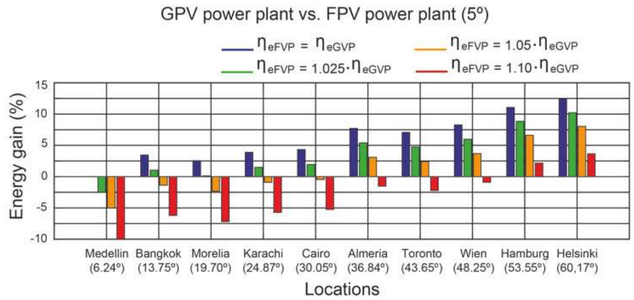

Fig. 1. Comparison energy gain of the GPV plant vs. the FPV plant (5^o).

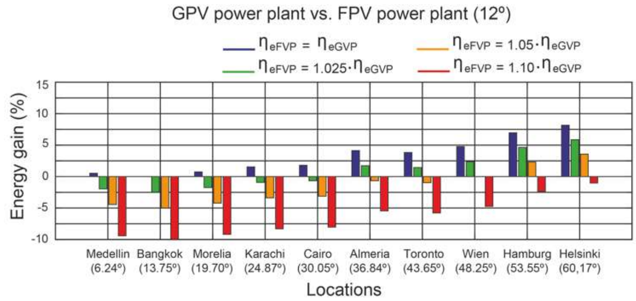

Fig. 2. Comparison energy gain of the GPV plant vs. the FPV plant (12^o).

(i) Scenario A: $\eta_{eFPV} = \eta_{eGPV}$. In this scenario, the influence of incident solar irradiance predominates.
(ii) Scenario B: $\eta_{eFPV} = 1.025 \cdot \eta_{eGPV}$ [15].
(iii) Scenario C: $\eta_{eFPV} = 1.05 \cdot \eta_{eGPV}$.
(iv) Scenario D: $\eta_{eFPV} = 1.1 \cdot \eta_{eGPV}$ [14].

Fig. 1 and Fig. 2 show the energy gain (see equation (8)) at the sites studied.

From Fig. 1 and 2 it can be seen that:

(i) In scenario A, the influence of the incident solar irradiance on the generated energy output is predominant. Therefore, the GPV plant always obtains better results.
(ii) In scenario B, as the difference between the tilt angles used in both plants increases, the GPV plant results in better performance.
(iii) In scenario C, the effect of electrical efficiency benefits the FPV plant. Thus, it minimizes the effect of the tilt angle.
(iv) In scenario D when the tilt angle of the FPV plant is 12 (^{o}), the influence of the electrical efficiency on the generated energy is predominant. Therefore, the FPV plant always performs better. In the FPV plant configuration with a tilt angle of 5 (^{o}), it also performs better, except at high latitudes.

Therefore, in locations with latitudes below 31 (°), FPV plants with a tilt angle of 12 (°) perform best. For higher latitudes, higher electrical efficiencies are necessary for FPV plants to obtain better results. FPV plants with tilt angles of 5 (^{o}) need very high electrical efficiencies to be more efficient than GPV plants.

IV. Conclusions

This paper presents a comparative energy yield analysis of ground-mounted photovoltaic and floating photovoltaic power plants at 10 locations in the northern hemisphere. The ground-mounted photovoltaic power plant operates at the optimum tilt angle. The floating photovoltaic power plant operates with the standard tilt angles of 5 and 12 (^{o}). Four electrical efficiencies are analyzed, from no influence to high influence. The combination of tilt angles and electrical efficiencies define the study scenarios. Using a Mathematica© code, the optimum tilt angle for the ground-mounted photovoltaic plant and the energy generated by each of the PV plants have been calculated. The proposed evaluation indicator is the energy gain with respect to the GPV. In summary, our analysis yields the following conclusions: (i) In locations with latitudes below 31 (^{o}), FPV with an tilt angle of 12 (^{o}) perform best; (ii) At latitudes above 31 (^{o}), higher electrical efficiencies are needed for FPV with tilt angles of 12 (^{o}) to obtain better results; (iii) FPV plants with tilt angles of 5 (^{o}) need very high electrical efficiencies to be more efficient than GPV. Therefore, FPV with 12 (^{o}) tilt angle obtain better results than the configuration with 5 (^{o}) tilt angle.

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