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A. Namoune[*1],
orcid.org/0009-0008-0022-8466,
A. Chaker[1],
orcid.org/0000-0002-5111-1478,
I. Saouane[1,2],
orcid.org/0009-0000-9599-6039

1 – Laboratory of Energetic Physics, Faculty of Exact Science, Department of Physics, University Frères Mentouri Constantine 1, Constantine, Algeria
2 – Department of Matter Sciences, Chahid Laarbi Tebessi University, Tebessa, Algeria
[*] Corresponding author e-mail: amina.namoune@student.umc.edu.dz

OPTIMIZING SOLAR PANEL TILT ANGLES ACROSS DIVERSE ALGERIAN TERRAIN

Purpose. To optimize the efficiency and performance of a solar system by maximizing the capture of solar radiation through determining the most optimal solar panel tilt angle.

Methodology. Stochastic techniques are presently utilized for estimating, optimizing, and predicting various solar energy systems. The authors have developed an algorithm that simulates the echolocation behavior of bats.

Findings. To attain this objective, we evaluated different angles of inclination for the incident energy surface that will maximize the sunlight. Next, we compared the intensity of incident solar energy from a horizontal surface and the same surface tilted at the optimum angle. As a result, we determined the optimal tilt angles for other Algerian cities not covered by this study, based on two factors: geometry and climate, using multiple linear regression analysis. The results obtained reflect average monthly and annual values for solar panel tilt angles. These results depend on the latitude and sunshine levels of the locations studied.

Originality. The present study introduces a computational algorithm that utilizes the echolocation behavior of bats to determine the most advantageous tilt angle for a photovoltaic (PV) panel.

Practical value. Optimizing solar panel angles across various terrains in Algeria is crucial for maximizing the energy efficiency of photovoltaic installations. The optimization algorithm based on the echolocation behavior of bats allows for the determination of optimal angles by taking into account regional, climatic, and seasonal variations, thereby increasing energy production. This innovative approach offers an effective solution for improving the profitability of solar systems while contributing to sustainable development.

Keywords: *optimal angle, solar panels, solar irradiation, Stochastic techniques, optimization algorithm, echolocation of bats*

Introduction. The placement of photovoltaic panels is crucial in order to maximize their capacity [1]. A possible solution is to implement a solar tracker, which is designed to follow the trajectory of the sun and adjust the inclination angle of the sensor accordingly. The use of tracking systems enables efficient capture of solar radiation; however, it can be costly and may not be suitable for all solar systems [2]. For this reason, our research will focus on determining the optimal annual tilt angle for solar panels to provide maximum solar energy output. The optimal angle depends on several factors such as altitude, longitude, and atmospheric conditions.

Numerous research studies have been conducted worldwide to determine the optimal tilt angle of solar panels. These studies used various optimization techniques such as genetic algorithm (GA), artificial neural networks (NAR), ant colony optimization (OCF), particle swarm optimization (PSO), and others [3].

Chang [4] developed a computer simulation program using the particle swarm optimization method with nonlinear time-varying evolution (PSO-NTVE) to ascertain the optimal tilt angle of photovoltaic (PV) modules in Taiwan. According to the findings, Hengchun experiences the highest annual solar radiation of 2,658.69 kWh/m^2, while the conversion efficiency of the modules varies from 13.14 % in Taitung to 13.39 %. Furthermore, it is important to note that Hengchun exhibits a higher annual efficiency compared to Kaohsiung due to the fact that the average monthly temperature of the PV module in Kaohsiung surpasses that of Hengchun during that period. According to the findings, the optimal angle for the Hengchun region on an annual basis is 15.17, while for Kaohsiung it is 15.79.

Talebizadeh and Mehrabian [5] used the genetic algorithm to determine the optimal tilt and surface azimuth angles of solar collectors and photovoltaic panels for the purpose of maximizing solar radiation. The study demonstrated that the most beneficial surface azimuth angles for daily, monthly, and annual periods are at zero degrees. Furthermore, adjusting the collector to the daily tilt angle results in a slight increase in the incident energy of the collector when compared to the monthly tilt angle.

The optimal angle of the PVT panel was calculated by Tabet, et al. [6] using the particle swarm optimization method. The study used theoretical models to compute solar radiation on both horizontal and tilted surfaces under clear sky conditions. The findings revealed that the ideal angle for optimal solar radiation varies throughout the year, with a minimum value of 0 in June and a peak of 58 in December and January.

To determine the tilt angle parameters of the solar PV panel, Saouane, et al. [7] used the ant colony optimization (ACO) technique. The Muneer model was employed to compute the solar irradiation on a horizontal inclined surface under clear sky conditions. The angle exhibited seasonal variation, with a minimum value of 0° observed in June and a maximum value of 59° observed in December and January. The findings indicate a complete correspondence between the computed and anticipated outcomes.

Datta, Bhattacharya, and Roy [8] assessed the MTA of Kolkata, India, utilising the same optimisation procedure. It was determined that the incident solar radiation on the photovoltaic panel experienced a 10 % increase in comparison to a horizontal configuration.

In a study conducted by Pon Vengatesh Ramamurthi [9], a remote solar power plant monitoring computing system was developed. This system utilized the latest digital technology of Internet of Things (IoT) to monitor various parameters of the power plant, including the solar panel tilt angle (β°). Additionally, the system was able to control the solar panel tilt angle using genetic algorithm (GA) to optimize the PV power output.

An algorithm was proposed by Emanuele Calabrò [10] to determine the optimal tilt angle of solar panels. This algorithm utilizes global horizontal solar radiation data obtained from terrestrial weather stations. A simulation was conducted utilising information sourced from the European Solar Radiation Atlas, in conjunction with several empirical models of diffuse solar radiation. The optimal tilt angle was determined through a linear regression analysis that correlated with latitude, resulting in correlation coefficients ranging from 0.944 to 0.993.

The authors in Ismail, et al. [11] employed a genetic algorithm to ascertain the optimal ground azimuth and tilt angles for every month, season, and year. The authors additionally disclosed the annual energy output of single photovoltaic tracking systems.

These investigations show that an essential consideration is the ideal tilt angle of a solar panel. The present study introduces a computational algorithm that utilizes the echolocation behavior of bats to determine the most advantageous tilt angle for a photovoltaic (PV) panel. The aforementioned computation is executed utilizing a theoretical framework to assess the overall solar radiation. In order to accomplish this objective, an assessment will be conducted to determine the optimal tilt angles of the incident energy surface that enhance this rate. We will proceed to compare the incident solar energy intensity on a horizontal surface with that of the same surface tilted at the optimal angle. Upon conclusion of this study, we will ascertain the optimal tilt angles for additional Algerian cities that were not included in this study. This will be determined based on two factors, namely geometric and climatic considerations, utilizing the multiple linear regression analysis.

The obtained results depict the mean monthly and yearly tilt angle values of a solar panel. The outcomes are contingent upon the latitude and amount of sunshine in the locations being utilized.

Theory. Solar Energy Intensity. The theoretical modeling of solar irradiation can be complicated. The outcome is contingent upon various factors such as climatic, geographical, and weather conditions [12]. The Liu and Jordan model is considered the most straightforward approach for simulating solar radiation on an inclined surface.

The total solar radiation incident on a tilted plane at an angle β from the horizontal can be expressed as a sum of three components. These include a direct ray (I_b), an isotropic diffuse ray (which arrives uniformly from the sky vault regardless of its direction), and a ground-reflected diffuse ray (I_d) [13].

The generalized Liu & Jordan relation is expressed in the following format as referenced by sources [12].

$$I_g = I_{bh}R_b + \frac{I_{dh}(1+\cos\beta)}{2} + \rho(I_{bh}+I_{dh})\frac{(1-\cos\beta)}{2}; \quad (1)$$

$$R_b = \cos\theta / \sin h,$$

where θ is the Incidence angle.

$$\cos\theta = \sin\varnothing\sin\delta - \cos\varnothing\sin\delta\sin\beta + \\ + \cos\varnothing\cos\delta\cos h\cos\beta + \sin\varnothing\sin\beta\cos\delta\cos h, \quad (2)$$

where h is the height of the sun.

$$\sin h = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega, \quad (3)$$

where δ is the declination of the sun.

$$\delta = 23.45\sin\left(\frac{360}{365}(j+284)\right), \quad (4)$$

where ω is the hourly angle.

$$\omega = 15(tsv - 12), \quad (5)$$

where tsv is true solar time in hours.

$$TSV = TL - TU + \left(\frac{\Delta t + \Delta\lambda}{60}\right) = TL - \left(TU - \frac{\lambda}{15}\right) + \frac{\Delta t}{60}, \quad (6)$$

where TU is Universal time, which is the time difference from the Greenwich meridian. In Algeria, $TU = +1$. TL – Legal time: time given by a watch. λ – Longitude of location. Δt – equation of time correction.

$$\Delta t = 9.87\cdot\sin^2\left(\frac{360}{365(J-81)}\right) - \\ -7.35\cdot\cos\left(\frac{360}{365(J-81)}\right) - 1.5\cdot\sin\left(\frac{360}{365(J-81)}\right). \quad (7)$$

Global solar irradiance on a horizontal plane is

$$I_{gh} = I_{bh} + I_{dh}. \quad (8)$$

The diffuse illuminance by clear sky obtained on a horizontal plane is

$$I_{dh} = I_c(0.2710 - 0.2939\cdot\tau_b)\cdot\sin h. \quad (9)$$

The relationship of direct illumination on a horizontal surface is

$$I_{bh} = I_c\cdot\tau_b\cdot\sin h, \quad (10)$$

where τ_b is atmospheric transmission coefficient of beam radiation.

$$\tau_b = a_0 + a_1\exp\left(K / \sin h\right), \quad (11)$$

with

$$a_0 = r_0[0.4237 - 0.00821(6 - Z)^2];$$

$$a_1 = r_1[0.5055 - 0.00595(6.5 - Z)^2];$$

$$K = r_K[0.2711 - 0.01858(2.5 - Z)^2],$$

where Z *is* Observer altitude; r_0, r_1 and r_K are Dimensional correction coefficients (Table 1).

Photovoltaic cell modeling. The establishment of photovoltaic cell models is achieved through the use of equivalent electrical circuits. The models exhibit variations in their mathematical methodologies and coefficients utilized for computing the current and voltage of the photovoltaic module.

The selection of the two-diode model was based on its close approximation to the actual behavior of the solar cell. It takes into account the mechanism of charge transfer within the cell. The inclusion of an extra diode emulates the chemical reactions resulting from electron recombination in the corresponding circuit [14].

In this model the equation below represents the output current of the photovoltaic cell

Table 1

Corrective coefficients

Kind of weather	r_0	r_1	r_K
Tropical	0.95	0.98	1.02
Summer (average altitude)	0.97	0.99	1.02
Winter (average latitude)	1.03	1.03	1.03

$$I = I_{ph} - I_{s1}\left[\exp\left(\frac{q(V+IR_s)}{AKT_j}\right)-1\right]- \\ -I_{s2}\left[\exp\left(\frac{q(V+IR_s)}{2AKT_j}\right)-1\right]-\left(\frac{V+IR_s}{R_{sh}}\right). \quad (12)$$

The open circuit voltage V_{0C} is formed as follows

$$V_{OC} = \frac{KT}{q}\ln\left(\frac{I_L}{I_0}\right). \quad (13)$$

Thefficiency of the PV module is

$$\eta_{PV} = \eta_{ref}\left[1-\beta(T_{\text{mod}}-T_{ref})+\gamma\log\left(\frac{G}{G_{ref}}\right)\right]. \quad (14)$$

The coefficients for solar irradiation and temperature, denoted as γ and T respectively, have been provided by the manufacturer.

The formula applied for calculating the power output of the photovoltaic generator is as follows

$$P_{pv} = Y_{pv}f_{pv}\left[\frac{G_T}{G_{T.STC}}\right]\left[1+\alpha_P(T_C - T_{C.STC})\right]. \quad (15)$$

Optimization. To optimize the capture of solar energy, we will calculate the ideal angle of inclination for a south-facing solar collector. We aim to optimize the functional as defined by equation (1). The bat algorithm will be used to translate a python macro program for this purpose.

The Branch and Bound Algorithm (BA) is a recent and highly effective approach for addressing a range of optimization challenges [15]. The process involves running a search in n-dimensional space using a random initial population of N bats, as implemented by BA. The updated BA results provide the nth bat/solution with new bats and velocities denoted as $X^{(t+1)}$ *and* $V^{(t+1)}$ at iteration $t+1$. The equations pertaining to this update are as follows [15]

$$\alpha_i = \alpha_{\min} + (\alpha_{\max} - \alpha_{\min})\beta; \quad (16)$$

$$V_i^{t+1} = V_i^t + (X_i^t - X^{best})\alpha_i; \quad (17)$$

$$X_i^{t+1} = X_i^t + V_i^{t+1}, \quad (18)$$

where β is a constant random number between [0, 1].

The X_{best} solution is currently the most optimal option available.

The pulse frequency emitted by the i^{th} bat during the current iteration is denoted by α_i, where $\alpha_{\min}$ and $\alpha_{\max}$ represent the minimum and maximum values of the pulse frequency, respectively. The value of α_i is initially selected within the range of $[\alpha_{\min}, \alpha_{\max}]$.

The location of each bat is updated during each iteration for the purpose of local search.

The equation explaining the movement of bat exploitation is provided as follows

$$X_i^{t+1} = X_i^t + \lambda A^t, \quad (19)$$

where $X_i^{(t+1)}$ is the new position of bat I; X_i^t is the old position of bat I; λ is a random number that takes values in the interval [–1, 1]; At is the average loudness of all bats in the population.

The intensity of local search is determined by the amplitude and frequency of echolocation pulses emitted by bats. It is noteworthy that the variables accountable for the integration of the amalgamation of local and global motion are the amplitude (A_i) and the frequency (r_i) of the pulse. During the initial stages of the search process, the level of loudness is elevated while the emission of pulses remains low. During the stage of prey detection, the intensity of the bat's vocalizations begins to diminish while the frequency of pulse emission gradually rises.

The values of A_i and R_i are updated based on the following equations [15].

$$r_i^{t+1} = r_i^0(1-\exp(-\gamma t)); \quad (20)$$

$$A_i^{t+1} = \delta A_i^t, \quad (21)$$

where δ and γ are constants.

The bat temporarily stops making sounds when it finds its prey and this occurs when A_i is zero. For any value of δ between zero and one and γ is greater than zero, then we have $A_i^t \to 0$, $r_i^t \to r_i^0$.

Applications of the Bat algorithm and its variants are shown in Fig 1.

Results and discussion. Radiation from the sun is measured in terms of the daily average solar power received by a certain location. The latter varies depending on things like height, latitude, and longitude as well as environmental factors like temperature, precipitation, sunlight, clouds, haze, and fog. Daily solar energy is determined by integrating a radiation curve against time, as the instantaneous radiation fluctuates.

These criteria and conditions for solar energy conversion are used in the design of photovoltaic systems. At the chosen locations, the tilt angle must be adjusted delicately every month. In order to maximize solar energy collection, we will employ the model developed by Liu and Jordan for simulating solar radiation on a slanted surface.

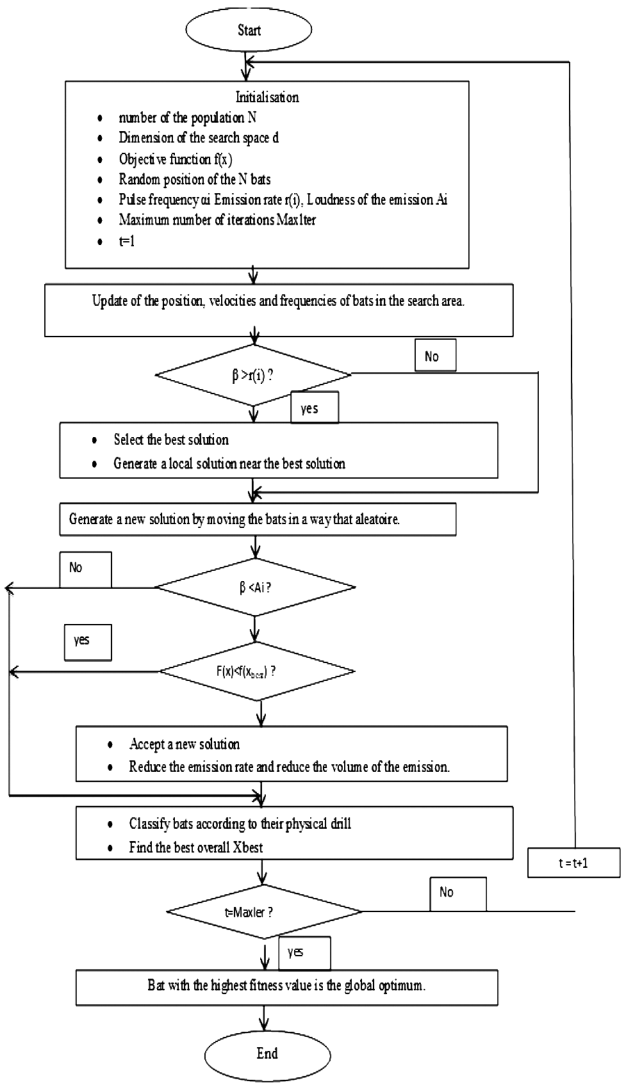

Fig. 1. Determination of the optimal angle of inclination utilizing BA

This research will be conducted across a range of climatic conditions in Algeria. Our diverse climates result from our country's geographical location, which ranges from the mild climate of the Mediterranean to the dry, hot conditions of the Sahara. Algeria is divided into four climate zones (*A*, *B*, *C* and *D*) according to the Algerian Thermal Regulation (DTR) [16]:

Zone A is the coast, including the northern extremity of mountain ranges.

Zone B is the plain behind the coast.

Zone C is the high plateaus between the Atlas Mountains and the Sahara Desert.

Zone D is the Sahara Desert.

For the purposes of this calculation, four cities were selected: Algiers, Constantine, Naâma, and Temanghasset, which are located in climatic zones *A*, *B*, *C* and *D*, respectively. You may find all of their geospatial information in Table 2.

From the first to the final day of each month, the program is executed at an inclination of zero to ninety degrees. It is known that maximal solar radiation is achieved at the optimum degree of inclination. Each of the four cities goes through the same process. Fig. 2 displays the acquired results.

Fig. 2 shows that the average monthly tilt angles for all of the cities in this research range from 0 degrees (horizontal) to 60 degrees (higher latitude), drop from January to April, and maintain horizontal throughout the period "April – July", before increasing from August to December.

Quantitative and qualitative assessments are made by contrasting the calculated angles of inclination with the actual angles of inclination gleaned from the research by John Wesley G. Jims [17]. The results obtained indicate complete confidence, indicating agreement between computed and projected values.

It may not be clear to the user of a solar application or system to adjust the tilt angle monthly to maximize radiation output. As a result, the best course of action is to determine the ideal receiver tilt, based on which the panel may be left in place throughout the year with little loss of absorbed energy relative to making monthly adjustments (Table 3).

Fig. 3 depicts a monthly solar irradiance received at a horizontal angle of 0° and at the annual optimal angle for each respective city. The power output derived from the annual tilt angle of a PV module differs significantly from that obtained by maintaining a horizontal orientation. This demonstrates the practicality of determining the optimal angle for maximizing power generation.

When comparing the intensity of solar energy incident on a panel with an ideal annual tilt angle to a panel with a tilt angle of 0°, or horizontal, the performance of the tilted solar panel is assessed. The table presented below illustrates that the efficiency of collector configurations with an annual tilt angle is comparatively higher.

Figs. 4–7 depict the global solar irradiance values on an inclined plane, which has been optimized for each month of the year. The power generated for each hour of the day is determined by calculating the average power output during that specific hour. The power output fluctuates throughout the day, with variations observed between morning and evening.

The maximum solar irradiance for Algiers and Constantine cities is approximately 800 W/m^2 throughout the year.

Table 2

Geometric data of the selected cities

	Latitude	Longitude	Altitude, m
Algiers	36°45'N	6°02'E	186
Constantine	36°21'N	6°36'E	574
Naâma	33°15'N	0°18'E	1,172
Temanghasset	22°47'N	5°31'E	1,372

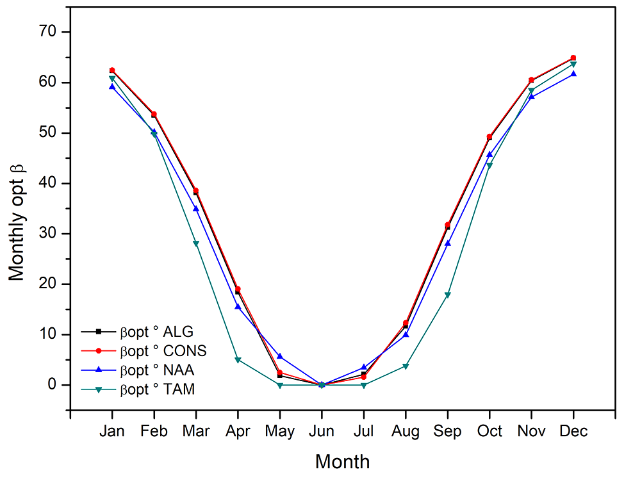

Fig. 2. Evolution of the monthly optimal angle of inclination during the different months of the year

Table 3

The optimal annual tilt angle for each city

	Optimal annual tilt angle, °
Algiers	37.9
Constantine	37
Naâma	35.1
Temanghasset	27.6

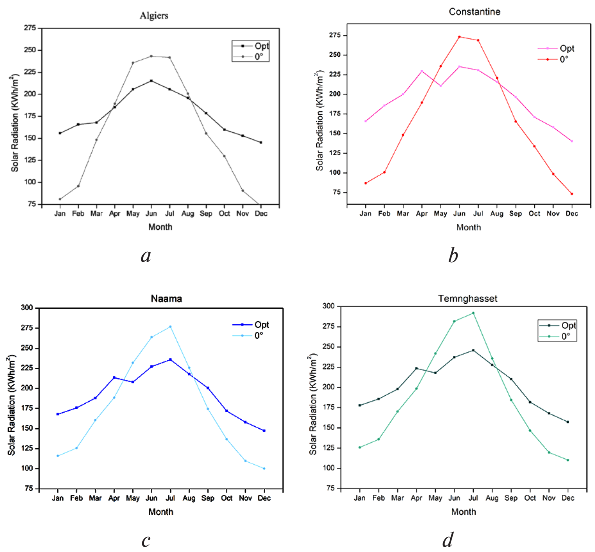

Fig. 3. Monthly solar irradiation on the horizontal and inclined planes

The solar irradiance levels in March are estimated to be around 900 W/m^2, while during December, the levels drop to approximately 800 W/m^2.

The maximum solar irradiance for the cities of Naama and Temnghasset remains consistent at approximately 1,000 W/m^2 throughout the year. The solar irradiance levels typically range from approximately 1,100 W/m^2 during March to below 900 W/m^2 in December, particularly during the winter season.

The objective of this study is to determine the optimal angles of inclination for various Algerian cities that were not included in the initial analysis. This will be achieved through the use of multiple linear regression analysis, which involves processing data to establish linear polynomial adjustment equations. The analysis will focus on the relationship between two

Table 4

Annual solar irradiation on the inclined plane in an optimal way

	Opt	0°
Algiers	1,842	1,763
Constantine	1,993	1,866
Naâma	2,430	2,272
Temanghasset	2,890	2,512

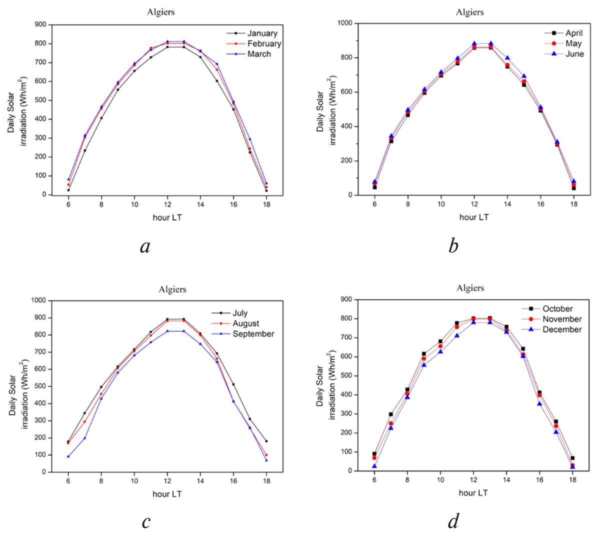

Fig. 4. Daily irradiation on the inclined plane in an optimal way, Algiers

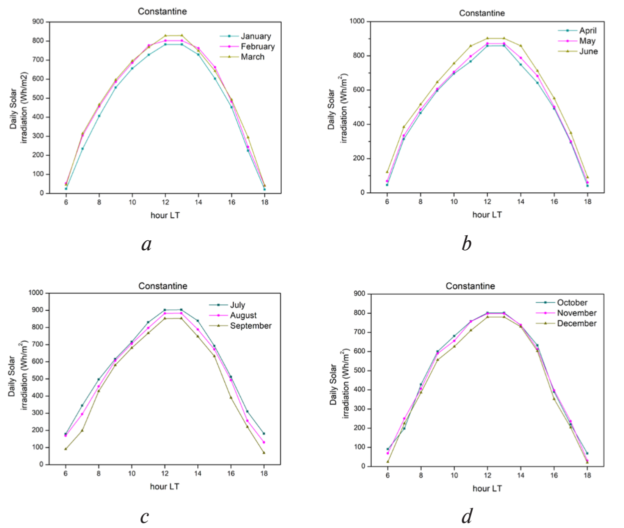

Fig. 5. Daily irradiation on the inclined plane in an optimal way, Constantine

key geometric and climatic factors, namely latitude and sunshine, and the optimal annual angle.

The resulting equation will provide a quantitative means of assessing the relationship between these variables (Fig. 8).

The annual optimal tilt for any city in Algeria can be estimated using the latitude and annual global solar irradiation with the following equation.

$$\beta = -0.00156659 \cdot Ig + 0.72962996 \cdot Lat + 14.894094.$$

Conclusion. The objective of this study was to optimize specific parameters of PV modules to enhance their electrical performance. The simulation method utilizing the bat algorithm was employed to determine the optimal tilt angle values

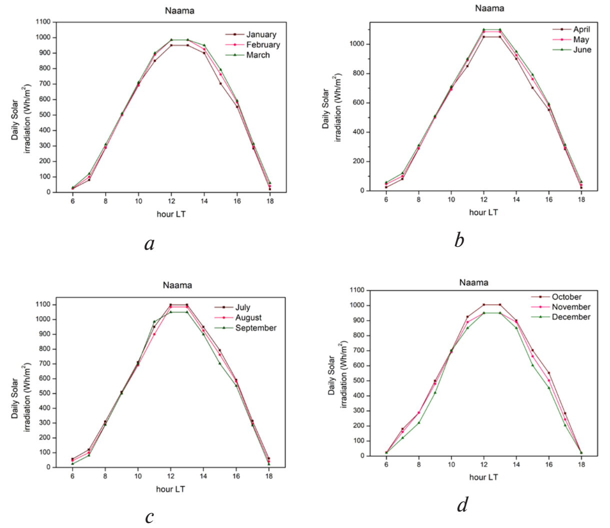

Fig. 6. Daily irradiation on the inclined plane in an optimal way, Naama

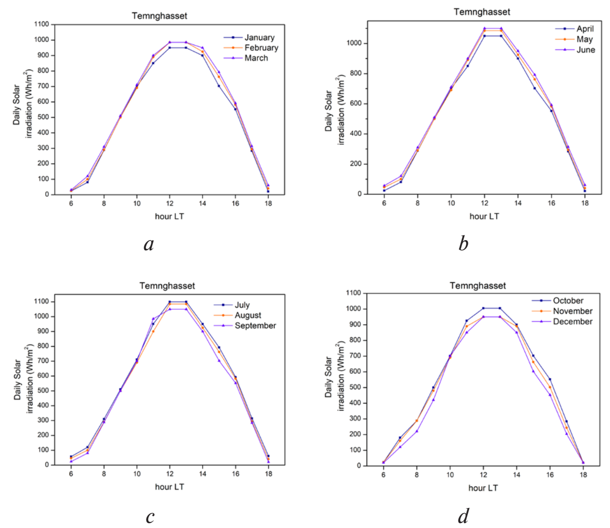

Fig. 7. Daily irradiation on the inclined plane in an optimal way, Temnghasset

for PV panels in Algeria. Jordan's model calculated solar radiation on both horizontal and inclined surfaces.

The results obtained indicate the optimal angle variation throughout the year, with a minimum value of 1° in June and a maximum value of 60° in December and January. To optimize

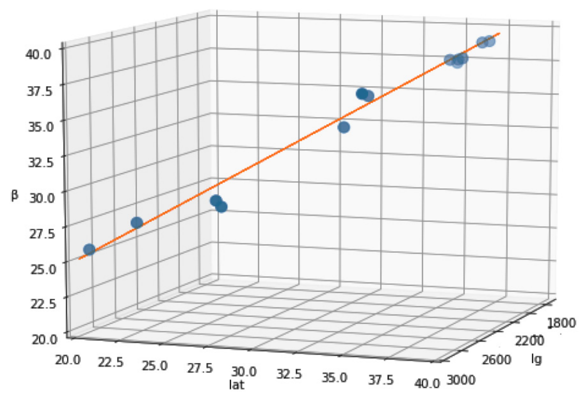

Fig. 8. Relationship between the two variables (latitude, sunshine) and the optimal annual tilt angle for Algerian cities

solar energy collection, it is advisable for collectors to adjust the tilt angle of photovoltaic panels periodically rather than maintaining a fixed angle throughout the year. The production of energy remains contingent upon receiving solar energy, which is subject to random fluctuations.

Furthermore, a correlation is derived through the analysis of the produced data to determine the most suitable yearly inclination angle for any given location within Algeria. This study aims to facilitate a precise estimation, design, and effective utilization of readily accessible solar energy, thereby contributing to the sustainable development of our nation.

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Оптимізація кутів нахилу панелей сонячних батарей на різноманітній місцевості Алжиру

А. Намуне[*1], *А. Чакер*[1], *І. Сауане*[1,2]

1 – Лабораторія енергетичної фізики, факультет точних наук, кафедра фізики, Університет Братів Ментурі в м. Константіна 1, м. Константіна, Алжир

2 – Кафедра наук про матерію, Університет імені Шахіда Лаарбі Тебессі, м. Тебесса, Алжир

[*] Автор-кореспондент e-mail: amina.namoune@student.umc.edu.dz

Мета. Оптимізувати ефективність і продуктивність системи за рахунок максимального уловлювання сонячної радіації шляхом визначення оптимального кута нахилу панелей.

Методика. У даний час стохастичні методи використовуються для оцінки, оптимізації та прогнозування різних систем уловлювання сонячної енергії. Авторами розроблено алгоритм, що імітує ехолокаційну поведінку кажанів.

Результати. Для досягнення мети ми оцінили різні кути нахилу поверхні падіння енергії, які максимізують сонячне проміння. Далі ми порівняли інтенсивність падаючої сонячної енергії з горизонтальної поверхні та тієї ж поверхні, нахиленої під оптимальним кутом. У результаті визначені оптимальні кути нахилу панелей для інших алжирських міст, не охоплених цим дослідженням, на основі двох факторів: геометрії та клімату, з використанням множинного лінійного регресійного аналізу. Отримані результати відображають середньомісячні й річні значення кутів нахилу сонячних панелей. Ці результати залежатимуть від широти та рівня сонячного світла в місцях, що обстежуються.

Наукова новизна. У цьому дослідженні представлений обчислювальний алгоритм, що використовує модель ехолокаційної поведінки кажанів задля визначення найбільш вигідного кута нахилу фотоелектричної панелі.

Практична значимість. Оптимізація кутів розташування сонячних панелей на різних рельєфах в Алжирі має вирішальне значення для максимізації енергоефективності фотоелектричних установок. Алгоритм оптимізації на основі ехолокаційної поведінки кажанів дозволяє визначати оптимальні кути з урахуванням регіональних, кліматичних і сезонних коливань, тим самим збільшуючи виробництво енергії. Цей інноваційний підхід пропонує ефективне рішення для підвищення прибутковості сонячних систем, одночасно сприяючи сталому розвитку.

Ключові слова: *оптимальний кут, сонячні панелі, сонячне випромінювання, стохастичні методи, алгоритм оптимізації, ехолокація кажанів*

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