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Solar panels' energy efficiency optimisation using mathematical methods with computerisation of calculations

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Abstract. Solar energy development in Ukraine is reaching peak values and will increase in the coming decades. For this reason, it is important to use various methods of optimising panel's operation to increase their energy efficiency. Given the fact that the angle of the sun's rays incidence has the greatest influence on the efficiency of photovoltaic cells on the working surface, it is important to find the stationary (non-rotating) system's optimal angle of inclination and forecast the generated power. The purpose of the work was to determine the dependency between the power generated by the photovoltaic element and the angle of the sun's rays incidence and to develop a universal document that would allow automatic calculation of the optimal solar panels' inclination angle relative to the horizon and the maximum daily generated power. Calculations were performed analytically using functions and digital tools of mathematical software, elements of the mathematical theory of optimisation. As a result of the study, a digital file was created that automatically calculates the optimal solar panel inclination angle and the maximum generated power depending on the change in this angle. An algorithm was developed that allows to automate calculations based on the mathematical theory of optimisation and the means of specialised mathematical software. The research work carried out will allow to increase the solar modules efficiency in the simplest way without material costs for additional equipment and time costs for mathematical calculations of the technical parameters of the system. Implementation of research results in practice will increase the profitability of solar panels

Keywords: solar energy; automation of calculations; profitability; ecology; search for the optimum; solar panel inclination angle

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Introduction

The development of alternative energy becomes a priority for Ukraine and many countries around the world. The percentage of energy sources that will be produced from alternative types will grow from 1 (as of 2015) to 13% (forecast for 2035) (Pavlov *et al.*, 2022) This is due to the constant reduction and increase in the price of reserves of natural resources (oil, coal, gas, etc.), the significant negative impact on the environment of traditional energy processes, emissions of carbon dioxide, nitrogen oxides and sulphur into the atmosphere, pollution by dust and radioactive particles. In Ukraine, as noted by Yu. Kolontaievsky *et al.* (2019), the technically achievable annual solar energy potential allows for saving about 5 billion m^3 of natural gas.

The operational principle of the solar cell is based on the photo effect phenomenon – the knocking out of free electrons from the material atoms by the sunlight photons flow. The efficiency of the solar module photovoltaic cells is affected by several main factors. In the work of A. Khotian *et al.* (2019) considered the influence of the angle of incidence of the light flux on the photovoltaic cell efficiency. Research by D. Zibalov (2022) identifies photocell quality as one of the important factors. The work of D. Ostrenko & O. Kollarov (2020) considered such aspects as the influence of temperature, contamination of the module and atmosphere (dust, smoke), uniformity and intensity of lighting, which depend on weather conditions.

The search for ways to improve the efficiency of solar modules is carried out in many directions. In the work of H.S. Majdi *et al.* (2021), the authors suggested using systems of active cooling of the solar panels surface. The efficiency of energy generation decreases by 10% or more due to the heating of the working surface. Studies have shown that active heat dissipation systems can increase the life of a photovoltaic panel from 30 to 50 years. Active air cooling increases the efficiency coefficient by 11.2%, passive – by 1.41%, and water – by 5.36%.

The analysed studies showed that the angle of sunlight falling on the working surface has the greatest influence on the photovoltaic cells efficiency, but using the special rotary devices that maintain the optimal angle of 90° is limited by their high cost. Therefore, the goal of this work was to find the optimal angle of inclination of a stationary (non-rotating) system and predict the generated power.

Materials and Methods

The highest efficiency of the solar installation is achieved when the sun's rays fall normal to the receiving surface. But constant maintenance of an optimal angle of 90° is impossible due to physical processes (rotation of the Earth around its own axis, change of seasons). A schematic representation of the change in the optimal angle of panel inclination relative to the horizon during the year is shown in Figure 1.

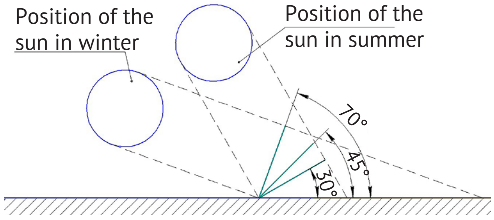

Figure 1. Schematic representation of the change in the optimal angle of inclination of the solar panel depending on the year season
Source: developed by the authors

The design of the installation (Fig. 2) was developed for calculating the optimal tilt angle of the panel during the year, which consists of two solar modules, oriented to the East and the West respectively.

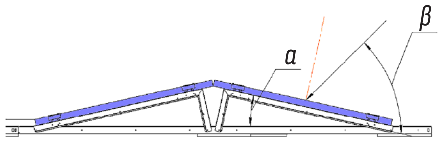

Figure 2. Design of the solar module system
Source: developed by the authors

To simplify calculations, the total generation per day of only half of the system was found. The dependence on the latitude of the area, the day of the year, the hour and length of the day, the level of insolation, the coefficient of light reflection, and the scattering of solar radiation were not taken into account. The reference power of the solar flux was taken as the average annual value on the territory of Ukraine W_i = 1,200 W/m^2. The dependence of the power of the sun's rays on the angle of incidence β is:

$$W(\beta) = W_i sin\beta. \quad (1)$$

In the projected model, the solar flux is a vector. One of the components of this vector was singled out for calculating and taking into account the power generated by the panel:

$$W_y(\alpha, \beta) = W_i sin(\alpha + \beta), \quad (2)$$

where α – the angle of inclination of the panel relative to the horizon, which must be found.

The function of the energy generation power is obtained. To obtain the objective function of daily energy generation, depending on the angle of inclination of the panel to the horizon, the integral of this function was found in the range from 0 to 90°:

$$\int_0^{90} W_y(\alpha, \beta) d\beta = W_y(\alpha). \quad (3)$$

The maximum value of the function, which corresponds to the optimal value of the angle of inclination, was found by finding the critical points of this function. MathCAD software for mathematical calculations was used to computerise the calculations.

Results and Discussion

The need for electrical energy rapidly increases due to the rapid development of technologies, energy-intensive industries, and urbanisation processes. The economic aspect plays an important role – the cost of renewable energy sources is significantly lower than the cost of fossil fuels, while the cost of such energy is higher. Focusing on alternative energy is the key to the energy independence of all countries. In Ukraine, the development of renewable energy is one of the five priorities of post-war recovery and further building up of the country's energy capacity, because the energy sector of Ukraine has suffered from huge losses. In 2024, targeted and large-scale attacks on facilities that ensure the production, transmission, and distribution of electricity continue. In the conditions of attacks on the country's energy infrastructure, the consequences of which are partial or complete planned and emergency power outages, the transition to alternative decentralised energy sources is the only means to meet the energy needs of the population.

It is necessary to choose the most effective natural energy resources available in this region for the productive development of renewable energy. The most promising is solar energy in connection with the favourable geographical location of Ukraine and the degree of availability of one or another type of alternative energy for an individual consumer. The process of converting solar energy into electrical energy is environmentally safe and is especially relevant in wartime conditions, as it is the only way to obtain electrical energy in some regions.

The length of daylight hours in Ukraine allows the efficient use of solar modules for 7-9 months a year, as reported by the State Agency for Energy Efficiency and Energy Saving of Ukraine (Energy of the sun, n.d.). The annual flow of sunlight per 1 m^2 of horizontal surface in the southern regions of Ukraine is 1,250-1,350 kW/m^2, and its duration is approximately 2,000 hours. As of 2024, there are no devices capable of working directly on pure solar energy, so science has invented methods of converting solar energy into electrical energy. The most common devices for transforming solar energy into electrical energy are solar panels. One of the advantages of such energy sources is the possibility of continued operation after the disconnection of destroyed modules due to air attacks.

Installing solar panels is a promising capital investment, particularly, in the engineering industry. In the process of work, plants and factories consume a significant amount of energy, which increases the cost of finished products and, as a result, expensive electricity reduces the profitability and competitiveness of manufacturing and repair factories. The large territory of manufacturing enterprises allows for the installation of a significant number of solar panels, and relatively small initial capital investments have an economically beneficial payback period at the scale of the enterprise. The generated clean energy can be used for production purposes or as an additional source of income. The problem lies in the relatively low efficiency of devices (18-25%), which requires finding ways to increase it. For this, it is important to conduct scientific research in the field of solar energy with practical testing of the proposed hypotheses and created structures.

The stages of calculating the optimal inclination angle by the method of differential calculation of the function of two variables implemented in the MathCAD software are given below in MathCAD terms and symbols. Let the initial value of the maximum power be W_i = 1,200. Function (3) of two variables is integrated from 0 to 90°:

$$f(\alpha) = \int_0^{90} W_y(\alpha, \beta) d\beta \rightarrow 1{,}200 \cdot cos(\alpha) - 1{,}200 \cdot cos(\alpha + 90). \quad (4)$$

The first derivative of the objective function is found:

$$f(\alpha) := \frac{d}{d\alpha} f(\alpha) \rightarrow 1{,}200 \cdot sin(\alpha + 90) - 1{,}200 \cdot sin(\alpha). \quad (5)$$

Figure 3 shows finding the critical points of the objective function.

Given
$f_1(\alpha) = 0$
$\alpha > 0$
M: = Find(α) → 0.55309

Figure 3. Finding the critical points of the objective function in the MathCAD software
Source: developed by the authors

Optimal tilt angle of the panel is:

$$deg(\alpha) := \frac{M \cdot 180}{\pi} \longrightarrow 31.69. \quad (6)$$

The second derivative of the objective function is found:

$$f_2(\alpha) := \frac{d}{d\alpha} f_1(\alpha) \rightarrow 1{,}200 \cdot cos(\alpha + 90) - 1{,}200 \cdot cos(\alpha);$$
$$f_2(M) = -2{,}042.2. \quad (7)$$

The value of the objective function at the maximum was calculated. The maximum generated power in W/m^2 is $f(M)$ = 2,042.2. Thus, the optimal angle of inclination of the solar panel in the proposed model is α = 31.69°. This value of the angle will allow to reach the maximum value of the generated power of 2,042.2 W/m^2.

A significant number of various methods of increasing the energy efficiency of solar systems have been proposed by other scientists. For example, systems for cleaning panel surfaces have been developed (Sinchuk *et al.*, 2020). Studies have shown an increase in generated power from 2,000 to 2,300 kW (15%) using a magnetic cleaning system. In the article Ye. Korniienko *et al.* (2023) the authors proposed a method of controlling the power generation system using wireless technologies. If the generated electricity covers the needs of consuming objects, then its surplus is directed to charging batteries. When they are fully charged, the energy is sent to the network at the "green" tariff. If the amount of generated energy is insufficient for the needs of the consumer, the batteries are switched on. If they are discharged, power comes from the mains, additionally charging the batteries. When there is no voltage in the network, a diesel or gasoline generator is switched on.

One of the most successful ways to increase the energy efficiency of solar panels is the use of trackers, which are mechanisms capable of automatically changing the angle of inclination of the working surface. The greatest efficiency is achieved when the sun's rays fall normal to the panel. The moving part of the tracker can change its position, track the position of the Sun, and orient the panel as needed. The tracking system designed in the work Ye. Korniienko *et al.* (2023) demonstrates an increase in the energy efficiency of solar panels by 25%. Basically, their high cost limits the wide use of trackers.

The authors I. Vashchyshak & V. Tsykh (2020) conducted comparative studies of the solar panels' energy efficiency with systems of directing mirrors, Fresnel lenses to create additional optical flow on the surface of solar panels. Measurements of electric power showed that additional mirrors can increase the initial energy by 35-60%. But at the same time, the temperature on the working surface increases significantly. In addition, the use of the mirror system requires additional areas for their placement, which is not always possible and expedient. The work M. Myroshnichenko & K. Klen (2022) considers increasing the accuracy of forecasting the amount of produced energy due to the use of mathematical predictive models.

Therefore, most of the feasible ways and methods of improving energy efficiency are expensive, which increases the cost of generated electricity. This work presents a successful and inexpensive method of installing solar systems at an optimal angle of 31.69° to the horizon, which does not require additional costs and maintenance, but provides maximum generation in a stationary state compared to other methods of stationary installation. However, the panel turned to the East will generate more in the morning and afternoon, and will generate significantly less in the evening and will actually be idle. The panel turned to the West will work vice versa.

Conclusions

The article analyses and briefly describes various approaches to increasing the energy efficiency of solar systems. All approaches have a rational point and a good proposition to increase the generated power, but also have significant disadvantages. For example, there is a high cost of manufacturing, installation and maintenance, low reliability in operation, the need for power supply, etc. It has been proven that the installation of solar systems according to the proposed scheme at an angle of 31.69° to the horizon can achieve the maximum energy generation capacity compared to installation at any other angle without motion. The advantages are small costs for a special design of the support, no need for maintenance, and energy independence of the method. The disadvantage is the fact that the two panels in the system work during the day alternately, which leads to a partial idle time of the solar panel.

In further studies, it is planned to supplement the calculations with additional variables, such as the latitude of the area, the day of the year, the hour and length of the day, the level of insolation, the coefficient of light reflection, and the scattering of solar rays. The goal is to find new solutions for increasing the energy efficiency of stationary installed solar systems.

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None.

Conflict of Interest

None.

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Оптимізація енергоефективності сонячних панелей математичними методами з комп'ютеризацією розрахунків

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Анотація. Розвиток сонячної енергетики в Україні сягає пікових значень і буде у наступні десятиліття тільки посилюватися, тому для підвищення енергоефективності роботи панелей важливо застосовувати різноманітні способи і методи оптимізації їх роботи. З огляду на те, що найбільший вплив на ефективність фотоелементів чинить кут падіння сонячного проміння на робочу поверхню, актуальним є питання знаходження оптимального кута нахилу стаціонарної (неповоротної) системи та прогнозування згенерованої потужності. Мета роботи полягала у визначенні зв'язку потужності, згенерованої фотоелектричним елементом, від кута падіння сонячних променів та розробці універсального документу, який дозволить автоматично розраховувати оптимальний кут нахилу сонячних панелей відносно горизонту та максимальну добову генеровану потужність. Виконано обчислення аналітичним методом зі застосуванням функцій та цифрових інструментів математичного програмного забезпечення. Крім того, використано елементи математичної теорії оптимізації. У результаті дослідження було створено документ, який автоматично обчислює оптимальний кут нахилу сонячної панелі та максимальну генеровану потужність у залежності від зміни цього кута. Розроблено алгоритм, який дозволяє максимально автоматизувати процес розрахунків і побудови графіків функцій за рахунок використання елементів математичної теорії оптимізації та засобів спеціалізованого математичного програмного забезпечення. Проведена дослідницька робота дозволить підвищити коефіцієнт корисної дії сонячних модулів у найбільш простий у реалізації спосіб без матеріальних затрат на додаткове обладнання і часових затрат на проведення математичних обчислень технічних параметрів системи, а впровадження результатів дослідження на практиці дозволить збільшити прибутковість сонячних панелей

Ключові слова: сонячна енергетика; автоматизація розрахунків; прибутковість; екологія; пошук оптимуму; кут нахилу панелі