ISSN 2518-7325 (Online), ISSN 2306-1677 (Print)
Land Management, Cadastre and Land Monitoring
Received: 28.04.2026; Accepted: 15.05.2026; Published: 30.06.2026;
http://dx.doi.org/10.31548/zemleustriy2026.02.06

UDC 620.92:621.317.38/.39]:[692.4:721]:[711:911.37]

CALCULATION OF THE ILLUMINANCE COEFFICIENT AND ENERGY PERFORMANCE INDICATORS OF BUILDING ROOFS IN THE DESIGN OF URBAN DEVELOPMENT

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Abstract. *The use of solar panels as a power source not only for industrial enterprises but also for private buildings began in Ukraine at the beginning of the 21st century. Their widespread implementation became noticeable approximately ten years later, when the number of households equipped with solar power plants increased rapidly due to the introduction of the so-called "green tariff." The need for autonomous energy supply for individual buildings became even more urgent as a result of the war.*

The object of this research can be considered the exposure of the slopes of gable roofs in residential area planning, while the purpose is to determine the amount of light energy reaching roof slopes of different exposures equipped with solar panels.

The article aims, based on the principles of geodetic astronomy, to determine the optimal parameters for the orientation of solar panels on building roofs in order to obtain the maximum amount of electrical energy. The calculations were carried out for the day of the summer solstice in the city of Ivano-Frankivsk. The value of the optimal roof inclination angle was taken from existing literature sources. The conducted research illustrates how the orientation of a building roof affects the potential for solar energy use. The results of calculations of the solar energy coefficient K and the amount of solar energy Ec for various orientation options of a gable roof make it possible to draw relevant conclusions. The research results showed that the optimal option for roof slope exposure for the installation of small-scale energy facilities is the East–West orientation, which makes it possible to obtain the maximum amount of solar energy throughout the entire daylight period. In this case, the eastern slope is active from sunrise until noon, while the western slope is active from noon until sunset. With a North–South roof orientation, the southern roof slope demonstrates increased activity during a relatively short period around noon, which is insufficient to achieve a high level of efficiency throughout the entire daylight period. Naturally, the illumination of the northern slope, and consequently

its efficiency in electricity generation, is the lowest. Roofs with diagonal orientations (northwest–southeast or northeast–southwest) ensure a relatively uniform supply of sunlight throughout the daylight period.
Keywords: *residential development design, autonomous energy supply, solar energy, building roof, illumination coefficient.*

Relevance of the Topic. In the design of residential areas, the placement of small buildings, especially private houses, requires consideration of certain features, among which illumination both inside the premises and on the roof can play an important role, since the roof may be used for the installation of solar panels, that is, for the building's energy supply. The use of solar panels as mini power plants by both industrial enterprises and household consumers began in Ukraine about 25 years ago. In particular, over the last decade, due to the introduction of the "green tariff," this practice has become much more widespread. Ukrainian energy facilities are characterized by a rather high level of centralization. Therefore, the decentralization of the energy sector is extremely important, including the large-scale creation of small-scale energy facilities, particularly solar power plants. At present, due to the war, autonomous energy supply for buildings and related research have become increasingly relevant. Since solar power plants are mainly used to ensure the energy independence of private households and enterprises, owners install solar panels on building roofs.

Consequently, when designing residential developments, it is desirable to orient such buildings in a certain way in order to obtain the maximum possible amount of electrical energy.

Analysis of Recent Research and Publications. It can be considered that the beginning of this century has been marked by the rapid development of solar energy. Thus, [4] examines the use of solar energy systems in buildings, emphasizing early-stage design strategies aimed at improving energy efficiency. Given the limited roof space of high buildings, façades are proposed as a promising alternative for solar energy generation. This includes consideration of the environmental and urban context, building form and orientation, façade configuration, and typology-specific characteristics for residential, office, and mixed-use buildings. Reference [14] emphasizes that, under conditions of daily simulation, building orientation significantly affects airflow patterns and ventilation efficiency, although the distribution of surface temperature remains relatively consistent across different orientations. In conclusion, there is a correlation between building orientation and thermal performance, which provides design recommendations In conclusion, there is a correlation between a building's orientation and its thermal performance, which provides design recommendations that can improve thermal comfort and promote energy efficiency in similar housing in the future. Reference [15] notes that the geometric shape and configuration of the roof are important design factors.

Chinese researchers identified a gap in the majority of research studies, which have not yet considered "roof geometry" as a determining design factor for photovoltaic energy generation [13]. In this study, the authors tested their hypothesis by examining and comparing the balance between solar energy harvesting and the consumption and saving of energy resulting from uncontrolled daylight penetration, glare, and solar heat gain associated with different roof geometries in a subtropical climate. Reference [7] presents studies on determining insolation conditions and selecting the optimal orientation of residential buildings with consideration of the latitude of the city of Poltava. The study emphasizes that today there is a transition from standard construction projects to individual design, while the process of increasing residential density in cities through new construction in historically developed areas continues. Increasing buildings density and the number of storeys inevitably worsen insolation conditions in the living spaces of existing buildings due to the additional shading of their windows, which reduces the duration of sunlight exposure. Therefore, the factors of rational territory planning, optimal building orientation according to the cardinal directions, and the proper selection of the number of storeys and building configuration become especially important. Reference [8] presents the results obtained in Australia, which receives approximately 1,000 times more solar radiation annually than the country's total energy production. Rooftop solar photovoltaic systems can therefore provide a significant share of the nation's overall energy supply. Architectural design and roof orientation have a substantial impact on the energy efficiency of rooftop solar systems. However, these aspects have received insufficient attention in academic literature.

In the study [9], for the purpose of practical justification, the aesthetic design of five typical roof design schemes (including flat, shed, gable, hip/four-sided, and butterfly roofs) was examined in order to compare the energy generated by solar systems installed on each design. It was established that the optimal roof inclination angle is approximately 35°, which is nearly equal to the geographical latitude of the studied location, and that the shed roof design provides the maximum potential for solar energy generation compared to other roof design schemes. Study [11], using the example of the former Zastavna District of Chernivtsi Region, substantiates a methodology for the efficient use of land resources for the development of solar energy based on remote sensing and GIS technologies. Reference [3] presents the results of modeling the processes of solar energy absorption by specific land plots. References [1; 5] provide calculations of the quantitative value of solar radiation energy for land plots in Ivano-Frankivsk region, carried out using two methodologies that may be applied to solving our research problem. The region under investigation is also the subject of the study [10], devoted to geoinformation modeling of insolation level. GIS technologies were also used in one of the authors' previous studies to investigate landslide processes [6].

In general, it can be considered that the problem addressed in this study has been solved mainly through experimental methods, while the issue of obtaining quantitative values on the basis of theoretical principles has not been sufficiently covered.

The purpose of the article is to substantiate the optimal exposure of the slopes of a gable roof, taking into account the solar altitude angle.

The objectives of the article are:

- based on the principles of geodetic astronomy, to calculate the illumination coefficients of a gable roof depending on the spatial orientation of the roof slope, the Sun's altitude above the horizon, and the slope azimuth;

- to calculate the amount of solar energy received by the roof surface depending on its spatial orientation;

- to determine the optimal spatial orientation of a gable roof.

The **object** of this research can be considered the orientation of building roofs in the design of residential developments, while the subject is the calculation of the amount of solar energy reaching roof slopes equipped with solar panels.

***Materials and research methods*.** The material for the study is a gable roof of a particular exposure. During the research, logical methods (comparison, generalization), as well as experimental and mathematical (computational) methods, were applied.

Experimental calculations

The amount of solar energy E_C, falling on the roof surface is determined by the formula [2]

$$E_C = E_O \cdot K$$

where E_O is the solar constant. It characterizes the intensity of solar radiation and depends on location, weather conditions, and time. The solar constant characterizes the amount of solar energy and is measured in kWh/m² over a certain period, i.e., an hour, a day, or a year. K is the coefficient of solar energy received by the roof surface depending on its exposure (azimuth) A and roof pitch angle i. Its value is used for comparative analysis.

The coefficient K is the cosine of the angle between the roof surface normal and the direction toward the Sun [2; 12]:

$$K = \cos H \cdot \sin i \cdot \cos\left(180 - A \pm \cos^{-1}\frac{\sin\varphi \cdot \sin H - \sin\delta}{\cos\varphi \cdot \cos H}\right) + \sin H \cdot \cos i \qquad (2)$$

where

H — solar altitude;

i — roof pitch angle;

A — roof exposure (azimuth);

φ — geographical latitude of the observation site;

δ — solar declination.

The calculations presented below were performed for the day of the summer solstice, June 22, when the maximum solar altitude (H) at latitude φ = 49° (Ivano-

Frankivsk) at noon equals 64, and the Sun's declination δ = 23.5°. As for the roof pitch angle *i*, literature sources indicate that the optimal roof pitch angle for the geographical latitudes of Ukraine 44–52° is approximately 40° [1; 5].

In formula (2), the minus sign "–" before the cosine is used for calculating the coefficient *K* before noon, while the plus sign "+" is used after noon.

The results of calculating the solar energy coefficient *K* for the gable roof orientation variants shown in Fig. 1 are summarized in Tables 1–4.

The average value of coefficient (K) from sunrise until noon on the eastern slope is 0.87417522, which corresponds to a solar energy value of *Ec* = 1,19 кВт·год/м^2 (рис. 1а; табл. 1). The analogous result was obtained for the western slope during the time interval from noon until sunset.

Table 1

Solar Energy Coefficient (K) for Roof Orientation (a) (Eastern and Western Slopes)

slope azimuth *A*	solar altitude, *H*										
	10°	20°	30°	40°	50°	64°	50°	40°	30°	20°	10°
	K	*K*	*K*	*K*	*K*	*K*	*K*	*K*	*K*	*K*	*K*
E 90°	0.710596	0.849841	0.93908	0.978934	0.966136	0.800463	0.207512	0.005874	0	0	0
W. 270°	0	0	0	0.005874	0.207512	0.800463	0.966136	0.978934	0.93908	0.849841	0.710596

The average value of coefficient *K* from sunrise to sunset on the northern slope is 0.410304, which corresponds to a solar energy value of *Ec* = 0.56 кВт·год/м^2 (Fig. 1b; Table 2).

The average value of coefficient *K* from sunrise to sunset on the southern slope is 0.457668, which corresponds to a solar energy value of *Ec* = 0.62 кВт·год/м^2 (see Fig. 1b; Table 2).

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Table 2

Solar Energy Coefficient K for Roof Orientation (b) (Northern and Southern Slopes)

slope azimuth, *A*	Solar altitude, *H*										
	10°	20°	30°	40°	50°	64°	50°	40°	30°	20°	10°
	K	*K*	*K*	*K*	*K*	*K*	*K*	*K*	*K*	*K*	*K*
N. 0°	0.392108	0.400889	0.409129	0.416576	0.423005	0.429929	0.423005	0.416576	0.409129	0.400889	0.392108
S. 180°	0	0.123116	0.356915	0.568231	0.750643	0.947104	0.750643	0.568231	0.356915	0.123116	0

The average value of coefficient K from sunrise until noon on the south-eastern slope and from noon until sunset on the north-western slope is 0.742409, which corresponds to a solar energy value of E_c =1 kWt/m^2 (Fig. 1c; Table 3).

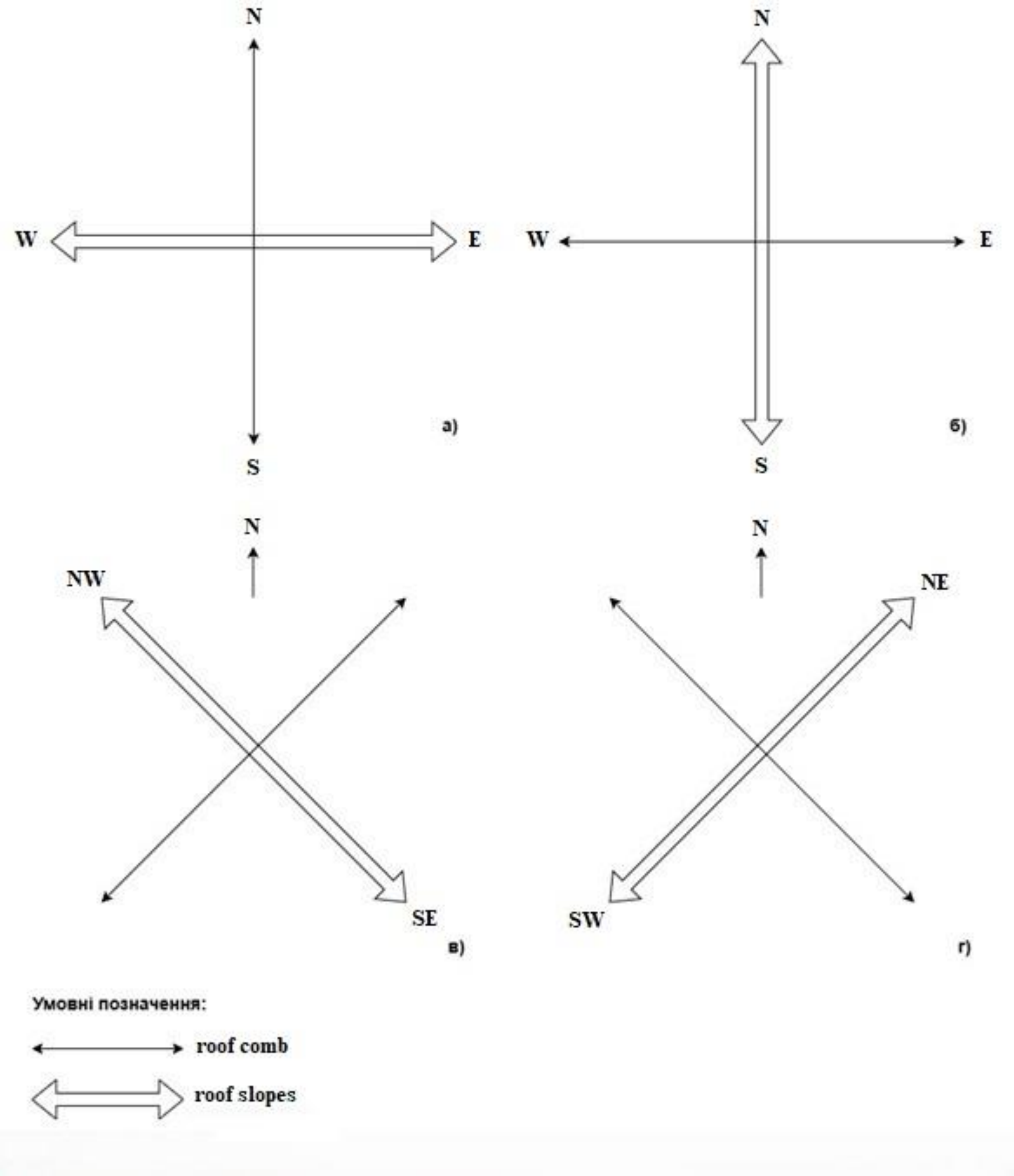

Figure 1. Variants of Gable Roof Orientation

The average value of coefficient K from sunrise until noon on the north-eastern slope and from noon until sunset on the south-western slope is 0.742409, which corresponds to a solar energy value of E_c =1 kWt/m^2 (Fig. 1d; Table 4).

Table 3

Solar Energy Coefficient K for Roof Orientation (в) (North-Western and South-Eastern Slopes)

slope azimuth, A	Solar altitude, H										
	10°	20°	30°	40°	50°	64°	50°	40°	30°	20°	10°
	K	K	K	K	K	K	K	K	K	K	K
SE 135°	0.358228	0.579459	0.757754	0.890051	0.970876	0.950524	0.434448	0.201993	0	0	0
NW 315°	0	0	0.00829	0.094757	0.202772	0.584825	0.739201	0.782815	0.794675	0.775875	0.72463

Table 4

Solar energy coefficient K for roof orientation d) (north-eastern and south-western slopes)

slope azimuth, A	Solar altitude, H										
	10°	20°	30°	40°	50°	64°	50°	40°	30°	20°	10°
	K	K	K	K	K	K	K	K	K	K	K
NE 45°	0.72463	0.775875	0.794675	0.782815	0.739201	0.584826	0.202772	0.094757	0.00829	0	0
SW 225°	0	0	0	0.201993	0.434448	0.950524	0.970876	0.890051	0.757754	0.579459	0.358228

Results and Discussion

The conducted study clearly illustrates how the orientation of a building roof affects the potential for solar energy utilization. The results of calculating the solar energy coefficient K and the amount of solar energy E_c for different orientation variants of a gable roof allow the following conclusions to be drawn.

1. The first East–West orientation variant is characterized by maximum efficiency: the eastern (90°) and western (270°) slopes receive the greatest amount of solar energy. This is explained by the fact that direct sunlight reaches them at the most favorable angle during peak periods (morning hours for the eastern slope and evening hours for the western slope). At the same time, the average value of the received solar energy E_c amounts to 1.19 kWh/m^2.

2. The second North–South orientation variant proved to be less efficient. In our case, the southern side (180°) showed a result almost two times lower than the

East–West orientation (Ec = 0.62 text{kWh/m2. This can be explained by the shorter duration of the period with maximum solar energy coefficients K on the southern slope compared to the eastern or western slopes (see Tables 1–2).

The minimum efficiency of the northern slope (0°), for which Ec = 0.56 kWh/m2, is expected, since this slope mainly receives diffused light.

The diagonal roof orientation includes the following two variants: south-east–north-west and north-east–south-west. In this case, the roof slopes are rotated by 45° relative to the main axes (azimuths 45°, 135°, 225°, and 315°).

3. In the first case, the south-eastern slope (135°) from sunrise until noon and the north-western slope (315°) from noon until sunset provide approximately the same amount of solar energy — about 1.0 kWh/m^2.

4. In the second case, the north-eastern slope (45°) from sunrise until noon and the south-western slope (225°) from noon until sunset showed a similar result – 1.02 kWh/m^2.

This indicates that such roof orientation can be recommended for stable electricity generation in autonomous systems where it is important to ensure a uniform inflow of energy throughout the daylight period, without extreme peaks or drops.

Table 5 presents a comparison of the obtained results.

Table 5

Reasearch findings

	Roof orientation	Time of the day	Average value of the K coefficient per day	Average daily solar energy Ec, kWh/m²	Total solar energy Ec per day, kWh/m²		Characteristics
1	East	sunrise – noon	0.874	1.19	9.52	19.04	Maximum efficiency
	West	noon–sunset	0.874	1.19	9.52		Maximum efficiency
2	North	sunrise – sunset	0.410	0.56	8.96	18.88	Maximum efficiency
	South	sunrise – sunset	0.458	0.62	9.92		Insufficient effectiveness
3	Southern Easr- noon	sunrise – noon	0.751	1.02	8.16	16.16	Uniformity
	Northern West	noon – sunset	0.734	1.00	8		Uniformity

4	Northern East	sunrise – noon	0.734	1.00	8	16.16	Uniformity
	Southern West	noon – sunset	0.751	1.02	8.16		Uniformity

Conclusions

According to the obtained research results, the most efficient orientation variant of a gable roof for the further installation of solar panels is the East–West orientation, since it ensures the maximum generation of solar energy throughout the daylight period. In this case, the eastern side of the roof will “operate” from sunrise until noon, while the western side will operate from noon until sunset.

As for the North–South roof orientation, the results indicate that the southern roof slope will have a rather short peak period (a few hours) around noon, when the illumination coefficient reaches its maximum value, which is insufficient for maintaining a high level of efficiency throughout the entire daylight period. The northern slope, as expected, has the lowest level of illumination and, consequently, the lowest efficiency.

Both variants of diagonal orientation ensure a uniform inflow of solar energy throughout the daylight period. The obtained results may be applied in the planning and design of residential developments. The presented results approximately coincide with those reported in [5], but they are quantitative and theoretically substantiated.

Further research on the addressed problem may be related to determining the insolation values of dome-shaped and flat roofs depending on the Sun’s altitude above the horizon and the geographical latitude of the area, as well as to testing the results of this study in real territories using GIS technologies.

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РОЗРАХУНОК КОЕФІЦІЄНТУ ОСВІТЛЕНОСТІ ТА ЕНЕРГЕТИЧНИХ ПОКАЗНИКІВ ДАХІВ БУДИНКІВ ПРИ ПРОЄКТУВАННІ ЗАБУДОВИ НАСЕЛЕНИХ ПУНКТІВ

Анотація. *Використання сонячних батарей як джерела живлення не тільки для промислових підприємств, а й для приватних будівель почалось в Україні на початку 21 століття, а широке впровадження почало спостерігатись приблизно через 10 років, коли кількість домогосподарств із встановленими сонячними електростанціями стрімко зросла у зв'язку із запровадженням так званого «зеленого тарифу». Ще більше необхідність використання автономного енергозабезпечення окремих будинків назріла в зв'язку з війною.*

Об'єктом даних досліджень можна вважати експозицію схилів двоскатних дахів будинків при плануванні територій населених пунктів, а метою – визначення кількості енергії світла, що надходить на скати дахів різної експозиції з розміщеними сонячними панелями.

У статті поставлене завдання на основі положень геодезичної астрономії знайти оптимальні параметри для орієнтування сонячних батарей на дахах будівель, щоб отримати максимальну кількість електроенергії. Обчислення здійснені для дня літнього сонцестояння в умовах м. Івано-Франківськ. Значення оптимального кута нахилу даху будинка взято з наявних літературних джерел. Виконане дослідження ілюструє, як орієнтація даху будівлі впливає на потенціал використання сонячної енергії. Результати розрахунків коефіцієнта сонячної енергії K та величини сонячної енергії Ec для різних варіантів орієнтації двоскатного даху дозволяють зробити відповідні висновки. Результати дослідження засвідчили, що оптимальним варіантом експозиції схилів даху з метою встановлення об'єктів малої енергетики є варіант Схід – Захід, який дає змогу отримувати максимальну кількість сонячної енергії впродовж усього світлового дня. В такому разі схил східної експозиції буде активним від сходу Сонця до полудня, а західної – від полудня до заходу Сонця. При орієнтації даху Північ – Південь південний схил даху відзначатиметься підвищеною активністю впродовж досить короткого часу близько полудня, що є недостатнім для отримання високого рівня ефективності впродовж усього світлового дня. Закономірно, що освітленість північного схилу, а отже – його ефективність при виробництві електроенергії,

є найнижчою. Дахи діагональної орієнтації (північний захід – південний схід або північний схід – південний захід) дають змогу впродовж світлового дня забезпечувати рівномірне надходження сонячного світла.
Ключові слова: *проєктування забудови, автономне енергозабезпечення, сонячна енергетика, дах будинку, коефіцієнт освітленості.*