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Assessment of a Solar PV System Installation on the Roof of a Building

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Abstract[1]— In recent years, there has been a growing trend to install solar panels on the roofs of buildings in Ulaanbaatar. These systems play an important role in improving the independence of electricity supply and reducing urban greenhouse gas emissions. Some roof surfaces in urban buildings are unsuitable for installing solar systems. This study assessed the suitability of solar energy resources and installing solar power systems on the roofs of buildings in urban areas. It also identifies factors affecting the roof that are suitable for installing a solar electrical system. The 15 kW system installed on the roof of the 8th building of the MUST was designed using PVsol software, and the results were developed. The solar energy level on the roof of the building is Ri = 0.78, indicating that it is a highly suitable roof for installing solar power systems.

Keywords—solar radiation, roof suitable for solar radiation and solar electrical system installation, shading.

I. Introduction

Of the renewable energy technologies, solar energy is the most widely used because it has the advantage of being simple to generate, use, and maintain. Solar power systems (PV-photovoltaics) are one of the simplest energy conversion devices designed to use solar energy efficiently. Due to the large amount of land required to build a solar power plant, it is impossible to install it in urban areas. In recent years, technologies such as PV systems and solar heat collectors have been widely used on the roofs of urban buildings. This transforms existing buildings from an energy consumer to an energy producers [1].

An effective way to find a suitable roof and evaluate its efficiency is essential for the optimal placement of the PV system [2, 3]. Solar radiation reserves depend on many factors, and several modelling techniques are used to calculate. In recent years, the ability of solar energy to combine meteorological and geographic information with artificial intelligence has been predicted [4-7]. Senkal and Kuleli [6] studied solar radiation calculations using satellite measurements. The method based on the composite and diffuse radiation vectors described by Liu Jordan's model [8] was developed by Izkierdo [9]. This method is suitable for estimating the geographical distribution of roof surface area, making it possible to evaluate the potential of PV in the country. Jochem et al. [10] first used Mobile Laser Scanning (MLS) technology to calculate the solar energy intensity of building facades, which resulted in increased interest in installing PV systems in building construction [11]. The purpose of this study is to study the source of solar radiation on the roof of a building.

To accurately calculate solar energy resources, the location of the roof of the building, the effects of cloud cover, atmospheric distribution, surface slope, orientation, shading of nearby objects, and the environment must be carefully considered. This is because the effect of these parameters instantly reduces the intensity of solar radiation on the roof of the building. Some of these factors need to be modelled or measured because physical models cannot accurately describe them.

II. Calculation and Evaluation

A. Solar radiation

Instantaneous solar radiation is the amount of radiation received by the sun at a particular time in the area. The sundial is based on the angular motion of the sun. Local time changes slightly compared to the movement of the sun.

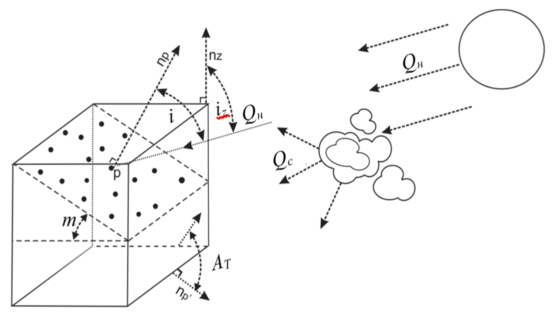

Figure 1. Map of solar radiation on a solar generator

Figure 1 shows Q_n -combined and Q_c-diffused radiation, np is the normal vector at the selected point, nz is the normal vector on the horizontal surface, m is the angle of inclination of the solar device, A_T is the azimuth, i is the angle of reflection of the sun's rays, and iz is the horizontal. shows the zenith angle of the surface.

Duffy and Beckman proposed the sundials:

$$\omega = t - 4(\lambda_M - \lambda_p) + E \qquad (1)$$

Here: λ_m is the geographic meridian of the time zone of the place, λ_p- for each point of longitude; this parameter depends on the local time. Changes in the Earth's rotation as described by E-Spencer.

$$\mathrm{E} = 229.2 \cdot (0.000075 + 0.001868 \cdot \cos(\mathrm{B}) - 0.032077 \cdot \sin(\mathrm{B}) - 0.014615 \cdot \cos(2\mathrm{B}) - 0.04089 \cdot \sin(2\mathrm{B})) \qquad (2)$$

$$\mathrm{B} = \frac{(\mathrm{n}-1)360^0}{365} \qquad (3)$$

Here: n is the number of the day

On the way to the device, the sun's rays are scattered by the atmosphere, clouds and other obstacles. The amount of direct and diffused radiation arriving at a location is measured using a pyranometer as the average time in hours and days. Direct radiation can be found by subtracting diffused radiation from the total solar radiation. The impact of reflected radiation is small and will not be considered in this study.

If the direct beam incident on a horizontal surface is known, multiply the displacement coefficient by the following formula.

$$Q_{n.sh} = Q_{sh} R_{sh} \text{ , [кW/m}^2\text{]} \qquad (4)$$

Here: R_{sh}- conversion factor;

It is the ratio of the straight beam in the inclined plane to the straight beam in the horizontal plane.

$$R_{sh} = \frac{\cos(i)}{\cos(i_z)} \qquad (5)$$

The angle of incidence of direct sunlight on a horizontal surface:

$$\cos(i_z) = \cos(\delta)\cos(\varphi)\cos(\omega) + \sin(\delta)\sin(\varphi) \qquad (6)$$

When solar-powered devices are placed on the surface of a terrene, they are placed in a certain direction and at a certain angle to maximize the sun's rays. The angle of reflection of direct solar radiation incident on the surface of a sloping solar device at a certain angle (m) in a given azimuth (A_T) is given by the following formula.

$$\cos(i) = \sin(\delta)\sin(\varphi)\cos(m) - \sin(\delta)\cos(\varphi)\sin(m) * \cos(A_T) + \cos(\delta)\cos(\varphi)\cos(m)\cos(\omega) + \cos(\delta) * \sin(\varphi)\sin(m)\cos(A_T)\cos(\omega) + \cos(\delta)\sin(\varphi) * \sin(A_T)\,sin(\omega) \qquad (7)$$

Here: δ- the angle of inclination of the sun, φ - the latitude, ω- the time angle of the sun, and m- the angle of inclination of the solar system.

The angle of incidence of direct solar radiation with the plane of the Earth's equator is called the angle of inclination of the sun (δ). It can be determined by the formula near Cooper.

$$\delta = 23.45 \cdot sin\frac{284+n}{365} \cdot 360 \qquad (8)$$

Here: The Earth's axis forms an angle of $23{,}45^0$ degrees with the plane of the Sun's orbit.

ω is the time angle depending on the time of the sun, and the 1hour step is $360^0/24 = 15^0$. This angle indicates where it is in relation to the sunset (for example, 10:00 is equal to 30^0 and 14:00 is equal to $+30^0$).

Q_d of the diffuse radiation at a given point is found by the following formula.

$$Q_d = Q_{sh} R_{sh} \text{ , [кW/m}^2\text{]} \qquad (9)$$

Where: R_{shn} is the transfer coefficient of Q_{sh};

Using the solar system's tilt angle, consider the scattering of the scattered radiation isotropic and find the transfer coefficient.

$$R_{\text{шс}} = cos^2\frac{m}{2} \qquad (10)$$

B. Shading calculations

The roof of a building can be shaded by environmental features, other structures, vegetation, chimneys and other objects. The direction of solar radiation is calculated as a vector from the position of the sun to the arithmetic center of the solar PV system.

The current position of the sun can be calculated using the Solar Positioning Algorithm (SPA) developed by the National Renewable Energy Laboratory.

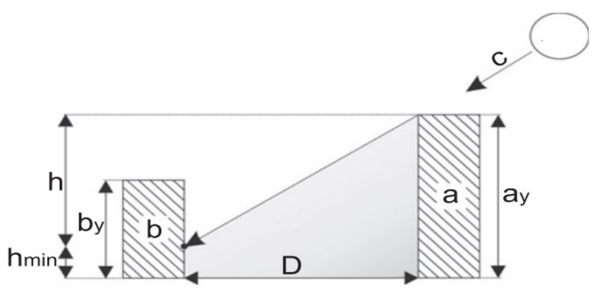

Figure 2. An image to determine whether an object is shaded by an object.

The unit change in the height of the solar radiation vector $c = [c_x\ c_y c_z]$-is determined as follows.

$$\mu = \frac{C_y}{\sqrt{C_x^2 + C_z^2}} \qquad (11)$$

Using the above formula, c represents the change in height as D passes through the horizontal space between two objects given by $a = [a_x\ a_y a_z]$ and $b = [b_x\ b_y b_z]$.

$$h = D\mu = \sqrt{(a_x - b_x)^2 + (a_z - b_z)^2}\mu \quad (12)$$

To avoid falling into the shadow of a, the minimum height of b must be h_{min} = ay-h, as shown in Figure 2. Therefore, if $b_y < h_{min}$, b is overshadowed by a.

Vegetation affects the shading of buildings to a certain extent. Plants can be classified as deciduous or coniferous. Deciduous plants shed their leaves in the fall and then grow in the spring. Conifers have leaves all year round. Veer-Lambert's law assumes that all canopies are horizontally homogeneous to approximate the vegetation cover's light absorption. Based on this law, the light absorption coefficient $\chi \epsilon$ (0,1) is used, as suggested by Jackson and Palmer.

$$\chi = 1 - e^{-K \cdot LAI} \quad (13)$$

Here: K- extinction coefficient [0, 1], LAI- Leaf area index [0, 1].

The relationship between the absorption coefficient and the shading coefficient S_p = max (S_p, χ), results in the same effect as the shadow. The extinction coefficient K depends on the zenith angle and the slope distribution of the canopy leaf.

B. Solar Energy Assessment

The instantaneous total radiation Q_n of a given point is determined by the following expression.

$$Q_n = Q_{nsh}\left(1 - S_p\right) + Q_{nsh}\text{ , [кW/m}^2\text{]} \quad (14)$$

The shading coefficient needs to be calculated. Diffuse radiation is reflected in shaded areas. Areas with the partial shade of plants receive less direct radiation. The total amount of solar radiation is the amount of solar radiation that reaches the device at a specific location and time. The amount of solar energy (J_p) incident on the surface per day is calculated by taking into account the Q_n radiation, which depends on the time between sunrise (T_{ss}) and sunset (T_{ss}).

$$J_p = \int_{Tsr}^{T_{ss}} I_p(t)dt,\text{ [кWh/m}^2\text{]} \quad (15)$$

The annual solar energy (P_p) incident on the surface is calculated by the following expression.

$$\mathrm{P}_p = \frac{1}{365}\sum_{n=1}^{365} J_{pn},\text{ [кWh/m}^2\text{]} \quad (16)$$

C. Identify and evaluate the roof of the building

It is important to identify and evaluate buildings that are not suitable for the installation of solar systems. The following criteria will be used in the evaluation. These include the location of buildings, protected areas within the city, cultural heritage buildings, the presence of chimneys or windows and shutters on the roof, and the shape and slope of the roof.

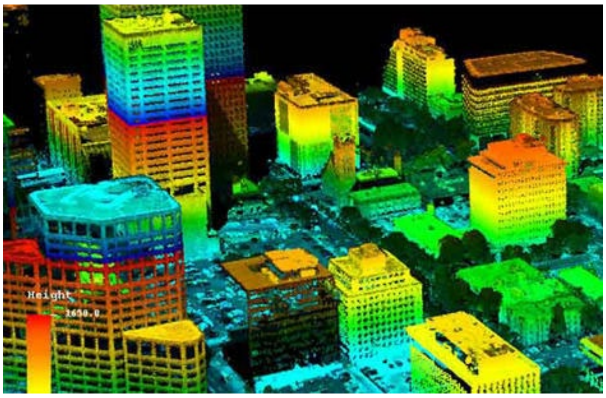

Figure 3. Identify and evaluate roofs where solar power systems can be installed.

The roof is then divided into several segments. Calculate the amount of solar energy incident on each roof segment and the annual solar energy (P_{pi}) for that segment.

$$P_{si} = \frac{\sum_{P_j \in S_i}^{|S_i|} P_{pj}}{|S_i|} \quad (17)$$

Here: Here, p_j is the point in the segment s_i, P_{pj} is the solar energy that hits the point p_j, and s_i is the selected points within the segment.

Then calculate the solar energy rating (R_i) for each point s_i of a given segment by the ratio between P_{si} and P_{si}, max segments.

$$R_i = \frac{|\overline{P_{si}}|}{(\overline{P}_{s1,}\overline{P}_{s2}, \ldots . \overline{P}_{sn})max} \quad (18)$$

The level of solar energy (R_i) depends on the annual amount of solar energy incident on the surface. The possibility of installing a solar electrical system on the roof of a building will be assessed at the following levels.

III. RESEARCH SECTION

A. Research object

UNDP, in collaboration with the Ministry of Construction and Urban Development, funded by the Global Environment Facility (GEF) and the NAMA project calculated using

The plant used a 15 kW SG15KTL (380-800 B) inverter manufactured by Sungrow, which supplies electricity directly to the central grid and operates in parallel with the grid. HTM330PA-72, manufactured by HT Solar, China, 330 W, 1957x992x40mm, total 50 pieces, multi-crystal silicon screen (Si-poly, Vmp = 37.52 V, I_{mp} = 8.8 A, efficiency 17%). Figure 9 shows a 15 kW solar power system installed on the roof of the 8th building of the Mongolian University of Science and Technology.

Figure 4. 15kW solar electric system installed on the roof of the 8th building of the Mongolian University of Science and Technology

The connection of the solar electrical system consists of a total of 4 parallel groups. Figure 4 shows the general wiring diagram for a 15 kW solar power system.

Each of the first two parallel groups consists of 12 serial screens, with a family power of 7.92 kW, a current of 17.6 A and a voltage of 450.24 V, for a total of 24 screens.

The next two parallel groups each consist of 13 serial screens, with a family power of 8.58 kW, a current of 17.6 A, a voltage of 487.56 V and a total of 26 PVs. The system was installed at an angle of 47^0, facing south, and fixed to a concrete foundation using a special stainless steel.

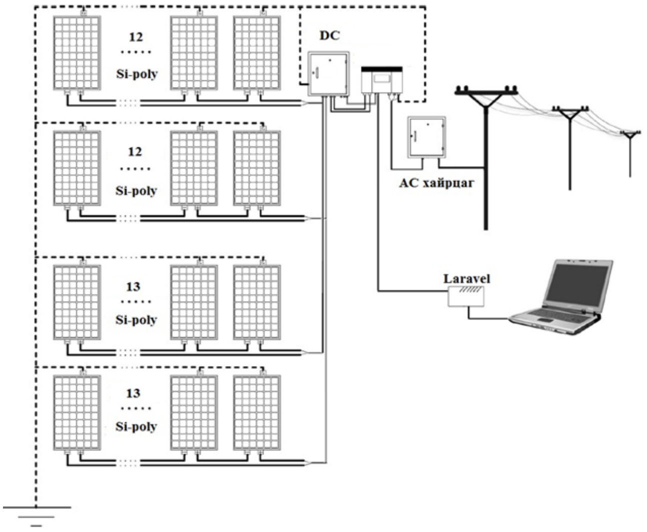

Figure 5. Schematic diagram of the operation of a solar electrical system

B. Evaluate the efficiency of a roof-mounted solar electrical system

The objects were modelled using the PVsol program, and the simulation results are shown in Table 1.

Table 1. Solar PV system performance

№	***Simulation parameters***	***Simulation results***
1	PV plant power generation	16.5 kW (DC)
2	Annual power generation	1151.9 кWh/ кW (DC)
3	Power supply to the grid (AC)	19,215 кWh / year
4	Inverter power consumption	208 kWh / year
5	Amount to prevent CO_2 emissions	8934 kg / year
6	Performance ratio	89.9%

Table 2 shows the total solar radiation incident on the horizontal surface of Ulaanbaatar, the total outdoor air temperature, the total solar radiation incident on the solar generator and the scattered radiation depending on the solar altitude.

Table 2. Calculation of solar energy resources

Month	The total radiation incident on the horizontal plane, [kWh / m²]	Diffuse radiation incident on the horizontal plane, [kWh / m²]	Outdoor tempera ture, [° C]	The height of the sun, degrees	The total radiation incident on a sloping surface, [kWh / m²]
1	50.443	16.945	-24.496	-17.645	130.74
2	75.427	23.25	-20.028	-11.059	149.46
3	124.02	41.905	-7.5927	-1.6974	178.48
4	145.04	65.261	2.4047	8.2026	156.38
5	173.3	82.704	9.9611	15.913	160.16
6	171.49	80.787	16.425	19.516	148.86
7	163.74	95.508	19.035	18.009	141.48
8	140.85	77.196	16.233	11.761	139.69
9	116.27	49.701	9.2506	2.6208	148.34
10	88.312	33.983	-0.47491	-7.3063	143.35
11	53.11	20.562	-13.1	-15.516	118.04
12	40.676	14.669	-22.26	-19.445	109.2

Direct sunlight travels through clouds and the atmosphere on its way to the horizontal surface, absorbing and reflecting some of the compounds and particles. It is also called diffuse radiation because it deviates from the influence of the environment, trees, shrubs, plants and buildings.

Figure 6 shows the relationship between the total solar radiation incident on the horizontal and inclined surfaces and the scattered radiation, and the height of the sun. Depending on the height of the sun, air quality, cloud cover, precipitation, and weather effects, it can be seen that on average, 42% of the total solar radiation reaching the horizontal surface per year is diffuse radiation.

The 8th building of the Mongolian University of Science and Technology is a 12-storey 45.8m high building.

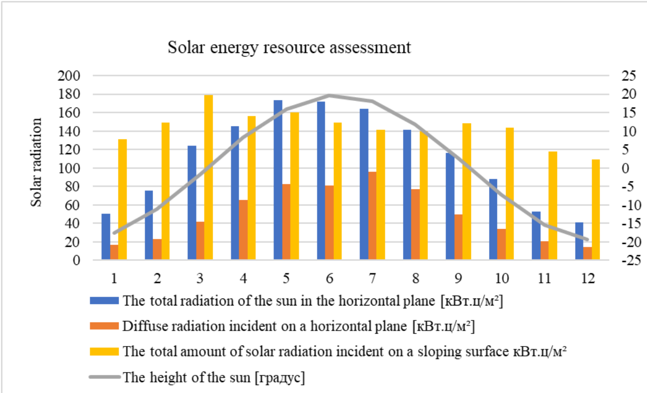

Figure 6. Estimation of solar energy resources

According to Equation (18), the solar energy level on the roof of the building is $R_i = 0.78$, which is a high value. There are no shady buildings near the building, the solar system is oriented vertically at an angle equal to the latitude of Ulaanbaatar, and there are no other shading objects on the roof, making it a suitable site for the installation of solar power systems.

IV. Conclusion

International experience shows that solar power generation systems have been widely used in urban construction in recent years. As urbanization increases, it is advisable to introduce solar power systems into buildings, but it is important to evaluate the available facilities before installing them. In urban areas, air pollution is caused by industrial and human activities, and these atmospheric compounds contribute to the formation of diffuse radiation. Shading also occurs depending on the type of tree and leaf size in the vicinity of the building. These reduce the efficiency of the solar power system and affect the amount of energy produced. Therefore, before installing a solar electrical system on the roof of a building in an urban area, it is important to study these parameters and evaluate in advance whether a possible roof is available.

In this study, a 15kW solar power system installed on the roof of the 8th building of the Mongolian University of Science and Technology (MUST) assessed the solar energy resources and determined whether the roof could be installed. The study shows that the roof of the building is suitable for installing solar systems.

In the future, urban planning should focus on levelling the height of nearby buildings following international standards, studying the impact of trees and shrubs in many ways, and increasing green building. This has the advantage of transforming existing buildings into energy producers rather than just energy consumers.

V. References

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