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A METHOD TO ESTIMATE SOLAR PANEL ORIENTATION EFFECTIVITY

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In the past years, new photovoltage (solar panel) systems have been installed rapidly, for instance, in regular households. Investment decisions have often been made without knowing all technical facts and information, which are affecting total energy production of photovoltage systems. In this work, we have made a simple model, which shows solar panels energy production with the different orientation angles of solar panel. Our results show that if panels are installed more than 30 degrees from the optimal orientation, the energy production drops drastically. This result applies to both azimuth and tilt angles. The developed model is very adaptive, and it can use any locations and all orientation angles. We confirm our calculation result by making a measurement with a small (30 W) test solar panel. The model and measurement results have a good relationship (correlation coefficient, $R^2 = 0.7$). The obtained result is satisfactory by taking into account the fact that measurements were made during the variable weather conditions and over long period of time (six months).

Keywords: *Energy production, photovoltage system, renewable energy, solar panel.*

1. INTRODUCTION

Renewable energy sources such as solar power have become very popular in the past years without reason. The usage of fossil fuels plays a major role in the climate change. Thus, it is important that renewable energy sources are put into use in a larger scale. Solar power is one alternative energy source for fossil fuels. Besides, the prices and installation costs of small-scale solar power systems have dropped drastically in the past few years. Solar panel (or photovoltage, PV) alignment is a major factor when studying carefully their energy production. Both tilt and azimuth angles have their own effect on the energy production. Regular households have been actively installing small-scale photovoltage systems when the electricity price has been increasing at the same time. The development is positive. However, investment plans in regular households are made partly without knowing true facts. The PV system vendor might give too positive information about PV system payback times and PV energy production, for instance. Especially, the azimuth alignment is critical for the total, annual energy production. For instance, if the photovoltage system is installed on the top of the roof of a small residential building, which has an east-west alignment, the energy production is far from the optimal situation.

The tilt angle is the angle of the photovoltaic modules from the horizontal plane for a fixed mounting. In some contexts, the term "elevation angle" is also used, as each latitude has an own optimal tilt angle. Some general rules have been given when choosing the optimal tilt angle. The basic rule has been that the tilt angle should be equal to the latitude angle of the site. Usually, PV panels are directed to the south, which gives the optimal energy production. Optimal energy production could be achieved when panels are tracking the Sun over the whole day. However, this is not usually very economical. Besides, such a PV system is more complicated, and they need more regular maintenance.

In this work, we have created a simple mathematical model to estimate the annual solar panel system production. Besides, we have tested our model in practice. A single 30 W solar panel has worked as a test environment, and we have compared its output with the created model output. Thus, we have managed to validate our model. The test setup is in northern Europe (Finland). The model itself is generic, and it can be used in other location as well. Some estimations about optimal tilt angles in different locations have been done earlier, e.g., [1]–[5]. For instance, the research [4] uses National Solar Radiation Database. Therefore, this model is less mathematical, and it uses real solar radiation data. Purely mathematic models have also some disadvantages. Prevailing weather conditions, including the cloud coverage, are not included in the analysis. The information about the altitude above sea level could be useful information when defining accurate PV energy production. This also has a minor effect on energy production.

We are not taking a stand how much energy a regular house could produce, for instance, it depends on the size of the installation. However, our model gives relative information about energy production with different orientation angles. Our results could be used in all kind of installations from small-scale production to the large solar power plant.

Section 2 presents formulas and the theoretical background for the solar position estimation. In addition, the photovoltage energy production estimation principle is explained. The results and observations are presented in Section 3. Finally, the conclusions are made in Section 4, including further investigation topics and improvement ideas.

2. SOLAR POSITION

The first step when starting to estimate the energy production of the photovoltage system, it is important to define the solar position in the location under investigation. The hour angle (*HA*) is the first parameter when calculating solar elevation and azimuth angles. Twelve noon in a local solar time (*LST*) is a time when the Sun is the highest in the sky. Local time (*LT*) usually varies from *LST* because of the eccentricity of the Earth's orbit, and because of human adjustments such as time zones and daylight saving. In this calculation, we did not include an effect of the eccentricity of the Earth's orbit. The total effect is small. A local solar time can be calculated as follows:

$$LST = LT + \frac{TC}{60}, \tag{1}$$

where LT is local time in hours and TC is a time correction factor. A time correction factor can be calculated as follows:

$$TC = 4 \times (lon - 15° \times \Delta T_{UTC}), \tag{2}$$

where lon is a longitude coordinate of specific location and ΔT_{UTC} is the difference of the Local Time (LT) from Universal Coordinated Time (UTC) in hours. After the local solar time has been defined, the hour angle can be calculated as follows:

$$HRA = 15° \times (LST - 12). \tag{3}$$

Before the solar position (azimuth and elevation) can be defined, the declination angle must be defined. The declination angle varies seasonally due to the tilt of the Earth on its axis of rotation and the rotation of the Earth around the Sun. There are a few formulas which can be used for the calculation of declination angle (δ). In this study, we used the following formula:

$$\delta = 23.45 \times \sin\left(\frac{360}{365} \times (d - 81)\right), \tag{4}$$

where d is a day number of the year. The difference between different formulas is relatively small (< 0.3°). To have more accurate estimation, we took into account the fact that d is changing over the day. Finally, elevation (α) and azimuth (β) angles of the Sun can be calculated. The elevation and azimuth angles are defined as follows:

$$\sin\alpha = \sin\delta \sin\varphi + \cos\delta \cos\varphi \cos(HRA); \tag{5}$$

$$\cos\beta = \frac{\sin\delta \cos\varphi - \cos\delta \sin\varphi \cos(HRA)}{\cos\alpha}. \tag{6}$$

2.1. Solar Radiation

After Sun's position has been defined, we can calculate the solar radiation at every point in time. The solar radiation (F) on arbitrary orientated and tilted surface can be calculated as follows:

$$F = \cos\alpha \sin\alpha_{tilt} \cos(\beta_{orien} - \beta) + \sin\alpha \cos\alpha_{tilt}, \tag{7}$$

where α_{tilt} is the photovoltage panel tilt angle and β_{orien} is the azimuth angle where the panel is pointed to.

We have estimated annual energy production so that we have calculated solar radiation in every 15 minutes in panel azimuth angles from 90° to 270° (with 2- or 5-degree steps) and panel tilt angles from 0° to 90° (with 2-degree steps). In each 15-minute step, hour, declination, and solar azimuth and elevation angles have been calculated separately. Finally, a daily average energy production with various angles (both azimuth and tilt) has been calculated for each azimuth and tilt angles on the basis of a 15-minute step. With this method, we have found optimal orientation angles from the energy production point of view. We have used this value (factor, F), presented here, in comparison with real solar panel energy production. The factor F varies between 0 and 1. The value 1 (one) means that the solar panel energy production is optimal (maximum) in the location under investigation. It is important to remember that simulation takes only into account direct solar radiation, which is facing to the panel. The isotropic radiation cannot be included in the simulation; thus, it depends on local conditions, such as shading and atmospheric stability.

3. RESULT

We have created a coloured contour map, which shows the photovoltage system energy production (colour scale) with different panel's tilt (y-axis) and azimuth orientation (x-axis) angles. In the current location (southern Finland), panel should be directed to the south ($\pm 10°$). In our study, the most energy effective angle is $186° \pm 1°$. The south is in the direction of 180. This can also be noticed in Fig. 1. The best tilt angle (elevation) should be $44° \pm 1°$ (optimal position). Previous studies gave somewhat smaller optimal tilt angle: 39° [1, 4]. The value 1 (one) for a factor F achieved in angles $186° \pm 1°$ (azimuth) and $44° \pm 1°$ (tilt). With these orientation angles, solar panel annual energy production is the most effective. However, the energy production does not drop drastically (less than 10 %) if the tilt angle is changing only $\pm 20°$. The energy production drops around 38 % if panels are oriented to the west. This is a major difference and reduction to the energy production. We can conclude that panels should be oriented to the south with an accuracy $\pm 40°$, if it is required that the energy production is still 90 % of the maximum. The result shows that energy production is still rather good even if orientation angles (azimuth and tilt) are some tens of degrees away from the optimal position. In the tilt angle, the allowed change is smaller. With a bigger change, the energy production drops drastically. In Fig. 2, the photovoltage system energy production close to the optimal orientation is shown. Figure 2 shows that the energy production is very effective when angle differences are $\pm 30°$ from the optimal angles. The result emphasises the matter that solar panels do not have to be orientated exactly to the south. Some difference is allowed, but not too large (> 60°).

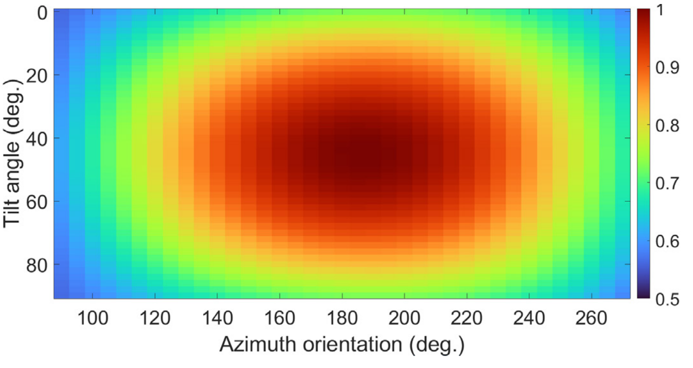

Fig. 1. Photovoltage (PV) system energy production with different tilt (0–90) and azimuth orientation angles (90–270). The south is in the direction of 180. Red colour (values close to 1) indicates that the energy production is optimal or close to optimal. A blue colour indicates efficiencies below 60 %.

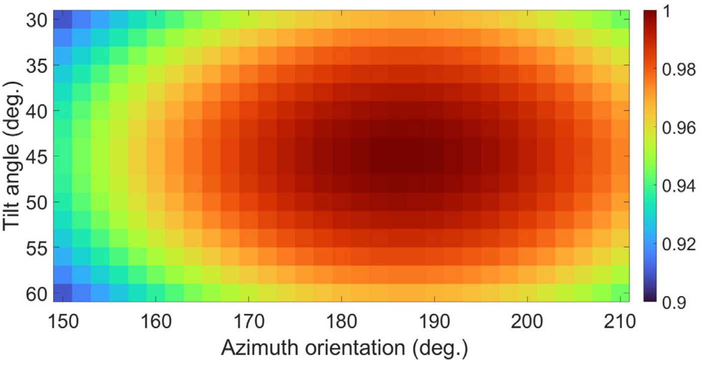

Fig. 2. Photovoltage (PV) system energy production with different tilt (30–60) and azimuth orientation angles (150–210). The south is in the direction of 180. Red colour (values close to 1) indicates that the energy production is optimal or close to optimal. The plot is made closer to optimal position. A blue colour indicates efficiencies below 94 %.

We have tested our model with a real solar panel. The panel nominal power is 30 W, so it is rather small. In Fig. 3, a test solar panel installation is shown. The solar panel is oriented close to the south 183° (±1°) with a tilt angle of 90° (±2°). We have measured the solar panel's open-circuit voltages during the fall, winter and spring seasons (from October 2023 to March 2024). Measured values have been recorded on days, when cloudiness level is moderate. This selection has been made using visual inspection. Besides, the ambient temperature has varied between -20 °C and +10 °C over the period of measurements. Since the temperatures have been rather moderate, we can assume that the efficiency of the panel is stable. The solar panel has the temperature correlation; high panel temperature means lower efficiency [6]. Totally 262 individual measurements have been collected. It has been shown that the open-circuit voltage increases with increasing irradiation with a linear dependency [7].

Fig. 3. The solar panel (30 W) under test, which has been used to confirm our calculation model. The panel is oriented close to the south 183° (± 1°) with a tilt angle of 90° (± 2°). On the right side of the panel there is a voltage meter (marked with a red circle), which shows the solar panel open-circuit voltage in real time. The picture has been taken on a cloudy winter day, and on that time energy production has been negligibly small and the voltage output has been zero.

Figure 4 shows the relationship between calculated panel efficiency and measurement. We have made a linear fit (a first-degree polynomial function) to obtain the measurement results. The correlation coefficient (R^2) between measurements and a fit model is 0.7. We have added an extra term to solar radiation (F) factor to present indirect radiation. It has been shown that the indirect radiation has a strong dependency with a solar elevation [8]. We chose a simple term for the indirect radiation: $a \times \sin \alpha$. Thus, the corrected solar radiation factor (F_{corr}) can be defined as follows:

$$F_{corr} = F + a \times \sin \alpha \, , \tag{8}$$

where a is an individual factor (a = 1.02), which only matches to this specific location and measurements.

This value is rather good by taking into account variable weather conditions over the long measurement period. The weather conditions are very critical for the energy production. This can be seen especially clear on times of low solar elevations, from the fall to the spring season. In addition, the solar panel under investigation is located in urban environment with some obstacles in front of it. This means that in some solar angles, there might be some losses or reflections, which affect debilitating to the open-circuit voltage. However, we can conclude that the measurement result also confirms that our calculation model is usable.

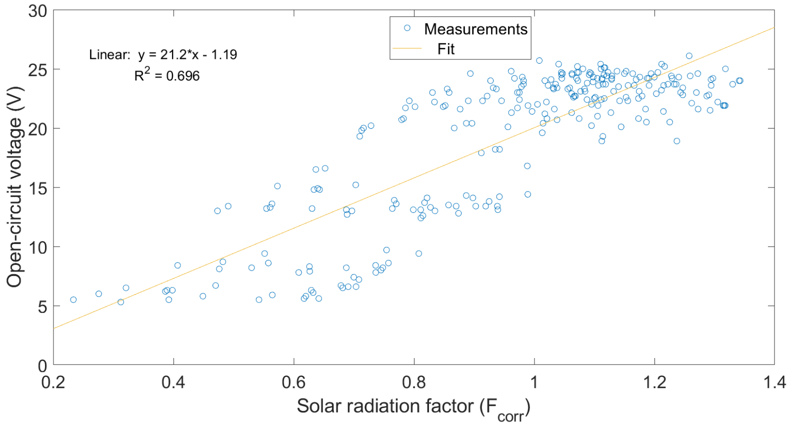

Fig. 4. The relationship between solar panel's open-circuit voltage and solar radiation factor (F_{corr}). The blue dots indicate individual measurements. The yellow line is a fit line (linear fit, a first-degree polynomial function), which is done on the basis of measurements. The correlation coefficient (R^2) between measurements and a fit model is 0.7.

4. CONCLUSIONS

We can conclude that the generated model works rather reliably and accurately. However, we could not test our model comprehensively since we could only use a single solar panel for verifying our results. The measurement should also be verified using other solar panels, which are installed with different orientation angles, and in other locations. In addition, the measurement should be repeated using different size solar panels, and also different manufacturer panels. The devolved model is simple and it can be used in any geographical locations. We did our measurement in the season from fall to spring; thus, the ambient temperature was moderate, and we could assume that the efficiency of the solar panel was stable. If the measurements are repeated in the summer season during hot summer days, the effect of the ambient temperature must be included in the analysis. In addition, we can conclude that local conditions (e.g., shading, panel temperature and atmosphere stability) have a major effect on the final energy production. The estimation of indirect radiation is challenging and the local conditions also contribute to this.

Results showed that energy production of solar panel decreased significantly if the tilt angle was more than 20 degrees from the optimal orientation, and in the azimuth direction, the angle could not be more than 40 degrees from the optimal orientation. This means that if the panels are installed in the east-west alignment, the energy production is far from the optimal. In this case, the energy production drops by 38 %, which is a major decrease for the production. If the solar panel, for instance, is installed on the east-west alignment, the investment decision should be made using careful consideration.

Our calculation and measurement also show that in the winter season, it is also possible to get some energy production from the solar panels if the panel orientation is made correctly. In Finland (north Europe), this means that tilt angle must be really high (between 70 and 80, and, on the opposite, in the summer season angle must be closer to 40. This means that there must be a possibility to adjust the tilt angle in different seasons. It can be technically rather challenging, at least in regular household installations. This is also increasing system total costs, and further the payback time. Usually, solar panel system's tilt angle is some sort of trade-off, which means that energy production is not very effective in the winter season. A common approach or aim is that the annual energy production will be maximised with a static azimuth and tilt angles. In addition, we have shown that the estimation of indirect radiation is rather challenging.

Calculations were made with a 15-minute step, so the efficiency factor, F, was calculated every 15 minutes. The time interval could be dense, but it required more calculation capacity. The calculation algorithm was made with Matlab. With a current simulation setup (15-minute step) and a standard laptop, it takes more than 12 hours to complete the whole simulation.

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