22nd International Conference on Renewable Energies and Power Quality (ICREPQ'24)
Bilbao (Spain), 26th to 28th June 2024

ISBN: 978-84-09-60656-6

Studying the Shading Effect of PV System on Energy Performances in Restricted Spaces

Sameer H. Khader[1], Abdel-Karim K. Daud[1], and Akram A. Abu-aisheh[2]

[1] Department of Electrical Engineering
Palestine Polytechnic University, Hebron,
PALESTINE, +970(2) 2233050

[2]Department of Electrical and Computer Engineering
University of Hartford, West Hartford, CT, USA
+1(860) 993-9757

Abstract. Shading has a considerable influence on solar cells' characteristics, temperature, and irradiation. Shading can be represented as partial or total shading over a few cells, panels, or even a set of modules. This study investigates the effect of shading rate on the PV panel's performance when used with modifies SEPIC converter. A mathematical model is performed and simulated on the MATLAB/Simulink platform. The investigation is conducted to study the effect of barrier height, tilt angle, and altitude angle changes for one day, one month, and the whole year. The results showed that the shadow factor depends on a set of parameters and varies from one system to another. Furthermore, the most affected months are the winter months, where the shadowing exceeds 28%, while in the summer months it falls to 10% at the highest barrier. The annual loss of energy is studied with and without obstacles, where results indicate that the loss of energy varies between 30% and 1% as the spacing from the closest PV row increases from 0.5m to 10m. This fact motivates designers to allow a certain rate of shadowing, especially in restricted and narrow spaces, keeping in mind that lost energy is negligible. Also, the energy gained is far greater than that when shading is completely eliminated by keeping enough spaces.

Key words: Modified SEPIC Converter, Photovoltaic Source, PWM, MPPT, and Inverters.

1. Introduction

Renewable energy (RE) resources are being progressively integrated into power systems to support a continuous increase in power generation due to the limitations of fossil fuel supply and to reduce negative environmental impacts [1]. Among the RE resources, the energy from the solar photovoltaic (PV) effect can be considered the most necessary and sustainable resource due to its ubiquity, large quantity, and sustainability [2]. This PV system consists of solar panels, a DC chopper, a smoothing unit, and a power management unit for operating the PV panels at maximum extracted power, called the Maximum Power Point Tracker (MPPT) [3, 4]. Usually, photovoltaic systems operate at a point near the point of maximum power, known as MPP, in order to obtain maximum system efficiency and extracted power.

Therefore, in order to extract maximum energy with reduced chopper switching losses and minimal total system losses at high efficiency, an MPPT system is a necessary step in the energy conversion process. The proper selection of the cell's materials, a clear and stable maximum achievable solar irradiation, stable temperature within an acceptable safe limit, tilt angle, and shade can all help to maximize the PV characteristics. To determine the loss of the PV outputs, the shading impact will be modelled [5, 6].

Recently, there have been great investments in building PV systems in urban and residential environments. Urban environments often include obstacles that could cast shadows on a PV system, badly affecting energy production [7]. In Germany, studies have shown that shading is one of the main causes of a lower energy yield [8]. Results from the German 1000 Roofs Program in 1990 revealed shading losses of up to 10% in more than half of their PV systems [9]. More recently, an analysis of more than residential PV systems in the United States showed that annual shading losses exceeded 20% [10]. Bayrak et al. [11] conducted an experiment where they applied different shading ratios to a single module. They analyzed three shading configurations: namely, shading of a single cell, horizontal shading of a row of cells, and vertical shading of a column of cells.

This paper provides a detailed investigation into the shading effect in three aspects:

- Studying the shading effect causes partial shadowing over a portion of the PV panel.
- Studying the shading effect causes complete shadowing over the complete surface of the PV panel for a predetermined time interval during the day, but with different shadowing rates from 0% to 90%.

- For a given shadowing rate and the same time interval, the investigations described the 21st of the month of all 12 months of the year in order to find which month is the most affected.

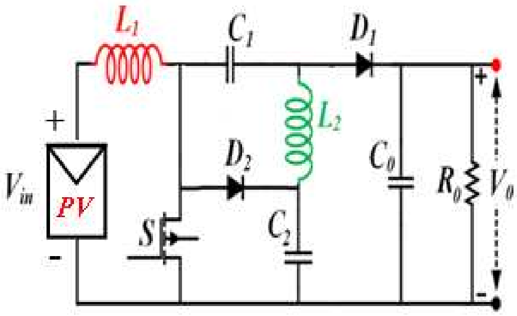

Figure 1: Modified SEPIC Converter

In this paper, a simulation model is built to detect the effect of various shadowing scenarios on the panels' main parameters. Taking into account the approach of [13], a direct detection of the maximum power at any value of solar irradiation and temperature during the daytime is realized.

Various DC-DC converters are applied, such as the single and modified single-ended primary-inductance converters SEPIC and MSEPIC, respectively. Figure1 illustrates the principle electrical circuit for MSEPIC, while figure 2 presents the control circuit with a partial shading condition. The proposed model is analyzed and simulated in MATLAB/ Simulink, and m-file code.

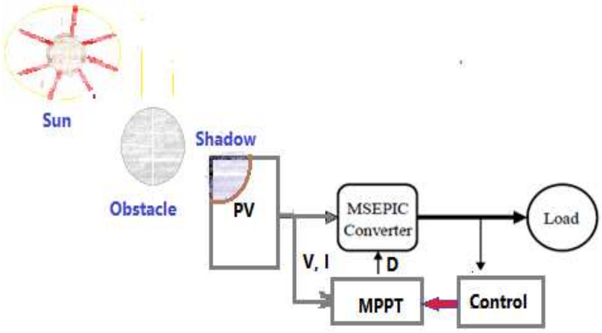

Figure 2: Block diagram of closed loop MSEPIC converter with partial shading.

2. Mathematical Modeling

2.1: The concept of shadow factor

Depending on the sun's position, the position of the PV panel, and surrounding objects, partial or complete shading can occur. The shading effect is defined as a change in the current-voltage characteristics (I-V) of the system, which in turn leads to a light or sharp reduction in the power output. Figure 2illustrates the sun's location with respect to the solar panel and related angles.

The sun position is defined as a function of the daytime, latitude, and longitude in order to determine the shaded area of the PV panel. The altitude of the sun as a function of latitude ϕ, solar declination δ, and angle ω subtended by the sun at a particular hour is given by [12] as follows:

$$\sin\alpha = \sin\emptyset \, \sin\delta + \cos\emptyset \, \cos\delta \, \cos\omega \qquad (1)$$

The direction of the irradiation beam striking the panel surface can be expressed as follows:

$$\begin{aligned}\cos\theta = {} & \cos\delta\cos\omega\,(\cos\gamma\,\cos\beta\,\sin\emptyset \\ & + \cos\emptyset\,\cos\beta) \\ & + \sin\delta\,(\sin\emptyset\,\cos\beta \\ & - \cos\gamma\,\cos\emptyset\cos\beta) \\ & + \sin\gamma\,\sin\beta\,\cos\delta\,\cos\omega\end{aligned} \qquad (2)$$

where β is the tilt angle, and γ is the angle measured from the direct south facing to the location of the sun with respect to the south.

The angle ω is the hour angle that presents the difference between noon and the desired time of day in terms of a 360° rotation in 24 hours. In other words,

$$\omega = \frac{12-T}{24} * 360^{\circ} = 15(12-T)^{\circ} \qquad (3)$$

where T is the time of day expressed in hours with respect to solar midnight on a 24-hour clock. By relating ω to the other angles, the sunrise and sunset angles can be expressed according to [14] as follows:

$$\omega_{sr} = \cos^{-1}(-\tan\emptyset * \tan\delta) \qquad (4)$$

and $\omega_{st} = -\omega_{sr}$ is the sunset angle.

For complete south-facing panels where γ=0°, eq. (2) becomes:

$$\cos\theta = \sin(\emptyset-\beta)\sin\delta + \cos(\emptyset-\beta)\cos\delta\cos\omega \quad (5)$$

This energy reduction can be calculated by using so-called shading factor. To do that, let's look out from the sun path and related angles as shown in figure 3 and the effect of shadowing for winter and summer time. Three rows of panels are presented with shading effects of 0%, 30%, and 60% due to hard-shaded objects or fixed barriers or obstacles such as building chimneys, water tanks for containers, trees, etc. Taking into account the panel dimensions of SPR-315E [15] with Lp=1.56m and Wp=1.05 m and the optimized tilt angle of β=27°with ground cover ratio GCR=51% [12], the distance between panels' rows can be obtained as follows:

$$d = Lp\,\frac{1-GCR\,\cos\beta}{GCR} = 1.67\ m \qquad (6)$$

Where Lp is the panel length and d is the safe distance to avoid panel's shading. According to eq. (6), the shadow effect due to adjacent PV rows is overcome while the shading due to above-mentioned obstacles cannot be crossed, but their effect can be reduced by keeping sufficient distance between the PV panel and the obstacle, and/or suggesting a movable mechanism that slides up or down according to the shadow rate that changes from point A to point B, according to figure 3 having in mind that the panel length faces the barrier width.

Furthermore, the shadow distances ds1 and ds2 for the first two PV rows also must be determined; d1 and d2 can be determined based on the panel length and the tilt angle; h and hs are the heights of the PV panel and the obstacles, respectively. For more details, let us describe figure 4, which illustrates the sun path and the resulting

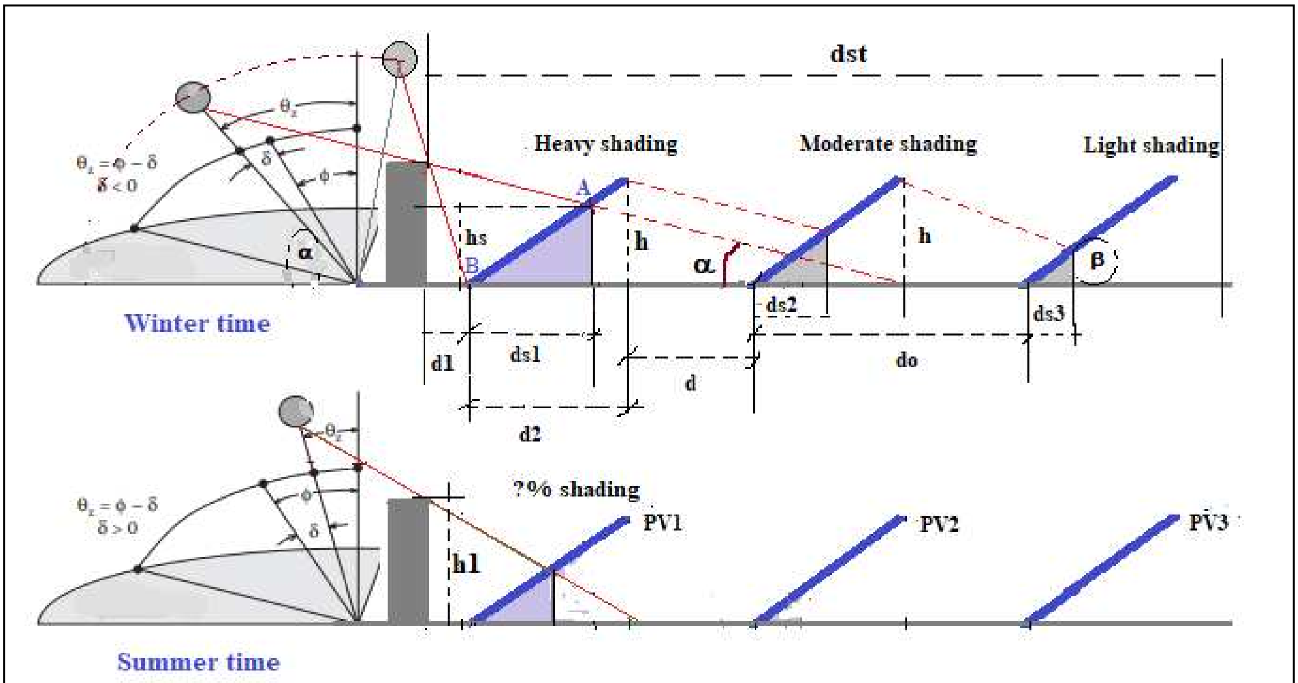

Figure 3: Sun path during summer and winter season with exiting hard barrier

shadow with the angles mentioned and their relations as follows:

At given angle α_2 the shadow occupies a portion of the panel surface with projection of ds_1, therefore this angle is:

$$\alpha_2 = \tan^{-1}\frac{h_S}{d_1} \tag{7}$$

Taking the trigonometrically ratio $\frac{h_S}{h} = \frac{d_{S1}}{d_2}$, the length of the occupied panel's portion L_{S1} is:

$$L_{S1} = \sqrt{{h_S}^2 + {d_{S1}}^2} = h_S\sqrt{1 + \left(\frac{d_{S1}}{h_S}\right)^2};$$

$$= d1.\tan\alpha_2\sqrt{1 + \left(\frac{d_2}{h}\right)^2} \tag{8}$$

Since *hs* and α_2 are unknown, a good starting point is to determine the angle α_3. The variations of the shadow range from 0% shadow to 100% shadow. The end limits of this angle are as follows:

The angle α_1 is known as the lower limit of the shadow range when the light strikes point B,

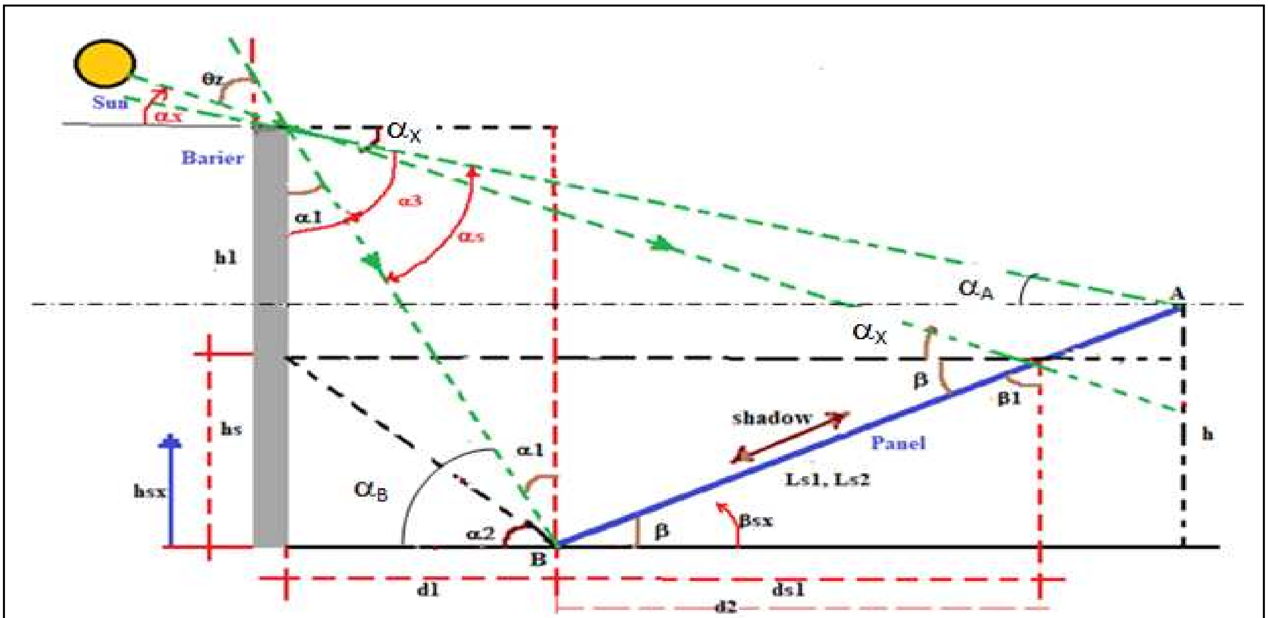

Figure 4: The shading change as altitude angle varies as well.

$$\alpha_1 = \frac{\pi}{2} - \alpha_B = \tan^{-1}\frac{d_1}{h_1}. \quad (9)$$

The angle α_A is known as the upper limit of the shadow range when the light strikes point **A.**

$$\alpha_A = \tan^{-1}\frac{h_1 - h}{d_1 + d_2};$$
$$0 \le \alpha_3 \le \frac{\pi}{2} - \alpha_A. \quad (10)$$

And the change in the striking angle α_S is:

$$\alpha_s = \alpha_3 - \alpha_1.$$

The range of the strike angle change is

$$\alpha_{SX} = \frac{\pi}{2} - (\alpha_X + \alpha_1) \quad (11)$$

Where $\alpha_1 \le \alpha_{SX} \le \alpha_s$, and

$$0 \le \alpha_X \le \alpha_B$$

Therefore, the shadow area depends on

$$\alpha_{SX} = \begin{cases} \alpha_3 = max;\ Ls = Lp \rightarrow \\ A_{sh} = L_s x W_p \\ \alpha_1 \rightarrow \min;\ Ls = 0 \rightarrow A_{sh} = 0. \end{cases} \quad (12)$$

Since α_{SX} depends on the sun's location, the shading area varies according to this angle. The following are concrete relations to Ash=f (α_{SX}) by using MATLAB platform [16] as follows:

1- When $0 \le \alpha_X \le \left(\frac{\pi}{2} - \alpha_3\right) = \alpha_A;$

$$A_{sh} = Lp\, xW_p = complete\ shadow; \quad (13)$$

2- When $\left(\frac{\pi}{2} - \alpha_3\right) \le \alpha_x \le \left(\frac{\pi}{2} - \alpha_1\right);$

$$d_{SX} = \frac{(h_1 - h_{sx})}{\tan\alpha_X - d_1} = \frac{(h_1 - d_1\tan\alpha_X)}{\tan\alpha_X + \tan\beta}$$
$$L_{SX} = \frac{d_{SX}}{\cos\beta};\quad A_{sh} = L_{SX}\, xW_p \quad (14)$$

3- When $\left(\frac{\pi}{2} - \alpha_1\right) \le \alpha_X \le \frac{\pi}{2};$

$$L_{SX} = 0;;\quad A_{sh} = 0. \quad (15)$$

4- The shaded factor according to [29,30] is

$$K_{sh} = \frac{A_{sh}}{A_c} = \frac{L_{SX}}{L_p} \quad (16)$$

5- The actual direct irradiation for PV1 is :

$$G_{actual}(PV1) = G_{1sun}(1 - K_{sh}) \quad (17)$$

2.2 The effect of shadowing over set of panels

Refer to figure 3, where a set of ordered panels in adjacent south-facing rows are exposed to shadowing due to an existing hard barrier. The rate of shading differs from one panel to another and can be determined as follow:

- The overall distance is

$$d_{st} = h_1 / \tan\alpha_X \quad (18)$$

- The number of rows, or rows in column panels is :

$$N_{st} = \frac{d_{st} - d_1}{d_o};\quad d_o = d_2 + d \quad (19)$$

- The obtained number is correlated to an integer number in both directions:

N_{p+}=Truncate (N_{st})+1;

and N_{p-}=Truncate (N_{st}); (20)

where $N_{st} > 1$.

- Comparing the actual distance of the light vector h_{pi} with respect to the horizon line at related panel height, then comparing both parameters and deciding whether it is fully shaded or partially shaded:

$$h_p(N_{p+} - i) = \big((d_{st} - d) - (N_{p-} - i).d_o\big).\tan\alpha_x$$
$$i = 1, \dots .N_{p-} \quad (21)$$

Then comparing both parameters:

$$\text{If } h_p(N_{p+} - i)\begin{cases} \ge h;\ K_s(N_{p+} - i) = 1; shade \\ < h;\ K_s((N_{p+} - i) = 0; unshade \end{cases} \quad (22)$$

- Having the distance of 4th panel which is around 1m, thus all panels located at the left of it will be completely shaded, therefore the fully shaded panels are N_{p-} as shown on figure 3.
- The completely unshaded (active) panels are:

$$N_{ac} = N_{tot} - N_{p-}; \quad (23)$$

- Calculating the shading factor in terms of the active PV unshaded area:

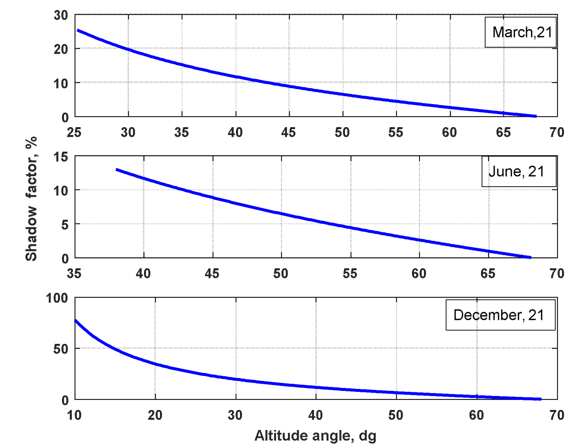

Figure 5 Shadow factor on 21st of various months.

$$A_{ac} = \big(N_{ac} - (N_{st} - N_{p-})\big) * A_{pv};$$
$$A_{tot} = N_{tot} * A_{pv} \quad (24)$$

where A_{ac}, A_{tot} are the active and total panels' area, respectively.

- The total shading factor of the whole PV system

$$K_{sht} = \frac{A_{sh}}{A_{tot}} = \frac{A_{tot} - A_{ac}}{A_{tot}} \quad (25)$$

To find the average daily shadow factor, it's necessary to calculate this factor various intervals of time every 10 minutes from sunrise until noon time i.e. $\alpha_A \le \alpha_X \le \alpha_B$. After that, the average value per day is determined by using the following arithmetical equation.

$$K_{sa} = \frac{\sum_1^{Nst} K_{sht}(Jx)}{Nst}; \quad (26)$$

where *Nst* is the maximum number of calculated shadow factor for various latitude angle α_X at given day.

Meanwhile, this procedure is repeated for 365 days, and the average annual shading factor can be expressed as follows:

$$K_{sa\_an} = \frac{\sum_1^{365} K_{sa}(j)}{365} \quad (27)$$

The annual energy without and with the shadow factor is:

$$E_{an} = G.P_{tot}.\eta_{con}.365;$$
$$E_{an\_sh} = E_{an}.K_{sa\_an} \quad (28)$$

Where G is the average annual irradiation, P_{tot} is the total generated PV power, and η_{con} is the coefficient of conversion with an average value of 75%.

3. Analysis and results discussion

In order to analyze the obtained results, concrete data is used as mentioned in Table 1, where the panel data, number of rows, barrier height, location, tilt angle, and spacing from the first row are changed.

3.1 Variation of shadow factor during single day

Let us describe the performance on March 21st, where the day number is **81** of the year, with sunrise at 5:47 and sunset at 17:47. The barrier height is **5m** and **2m** away

Table 1: Panels data and site coordination

Fixed parameters	Latitude	31.52°	Variable parameters	Tilt angle, β	10..65°
	Longitude	35.14°		Azimuth angle, Φ	0..180°
	Number of Rows	10		Barrier heigh h1, m	0…8
	Panel length, Lp, m	1.56		Spacing d1, m	1…10
	Panel width, Wp, m	1.04			
	Panel power, Pmp	315			
	Average irradiation Gav, h./day	5.2			

from the first panel, and a tilt angle of **27°**.

The obtained results are illustrated in figure 5, where the altitude angle varies between 25° to 67°and the shadow factor decreases from 25% to 0% at noon for March, 21st ,

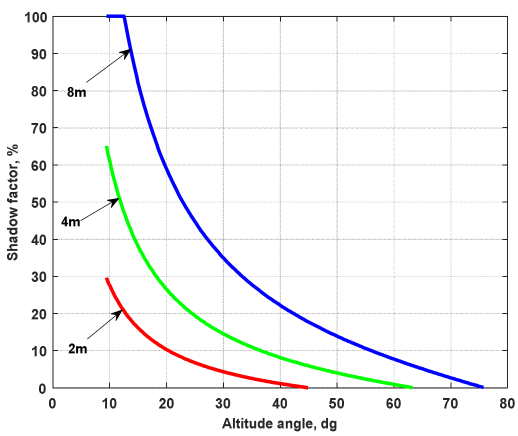

Figure 6: Shadow factor at various altitude angles and barrier height on March 21st.

while for December 21st it varies between 75% to 0%.

Figure 6 shows the variation of the shadow factor for various barrier heights (2m, 4m, and 8m), where the highest rate of this factor occurs for the highest barrier, which is correct.

3.2The variation of shadow factor for one year

Figure 7 displays the variation of the shadow factor for one year, where it's shown that for all cases of barrier height, the shadow rate is high during winter, while it goes down to its minimum value during the summer.

This indicator gives us the possibility to install the solar panel very close to the barrier, regardless of the amount of radiation loss. Of course, radiation in the winter is relatively weak, and thus we save more area and produce more energy, especially during the spring and summer, when the radiation loss is small due to shading.

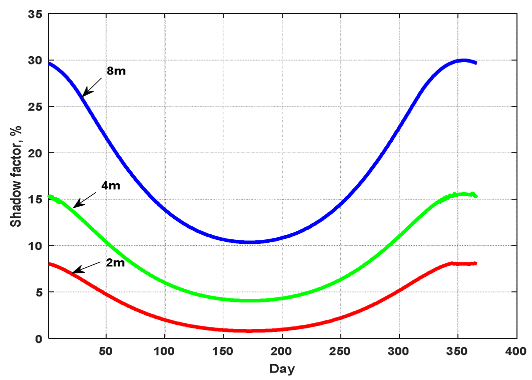

Figure 7: Shadow factor for various height during one year..

3.3The variation of shadow factor with tilt angle

As previously mentioned, the shadow factor directly depends on barrier height, sun location, and daytime, while the light depends on the tilt angle variation as well shown in Figure 8 at a barrier height of 4m, where there is no significant decrease in shadow rate when moving from 14° to 42°, which is quite a height for the installation of a PV panel with h=1.16m. This high is suitable for regions with a longer winter period.

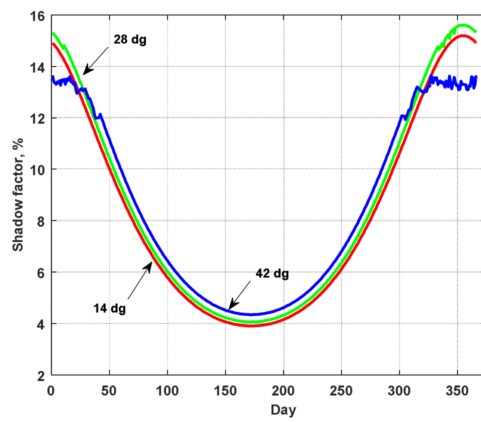

Figure 8: Shadow factor as function of tilt angle at d1=2m & h1=4m.

3.4 The annual energy change at various parameters

According to eq. (26), the simulation results of the gained annual energy for various design cases with respect to barrier height, tilt angle, and distance to the first panel's row are displayed as follows: The effect of spacing between the barrier and first panel is shown in figure 9, where the produced energy increases as the distance d1 increases.

Figure 10 shows the percentage decrease while distance d1 increases from 1m to 10m causing energy reduction in the range of 30% to 1% respectively. From this figure, Eao presents the energy produced when there is no shading either in the absence of a barrier or when a large number of rows are arranged. For example, at spacing of d1=5m from the barrier with a height of 5m, the energy decreases by 7.5% according to Figure 10. Let's say there are 3 panels per row and the barrier blocks the light for whole panels in that row. So, whether to decide to remove 1 row with produced energy of 1345 kWh/yr in order to realize zero shading or keeping this row existed and loosing no more than 100 kWh/yr. The acceptable solution is to allow shading with negligible energy loss rather than removing 3 panels and losing all the 1345kWhr/yr.

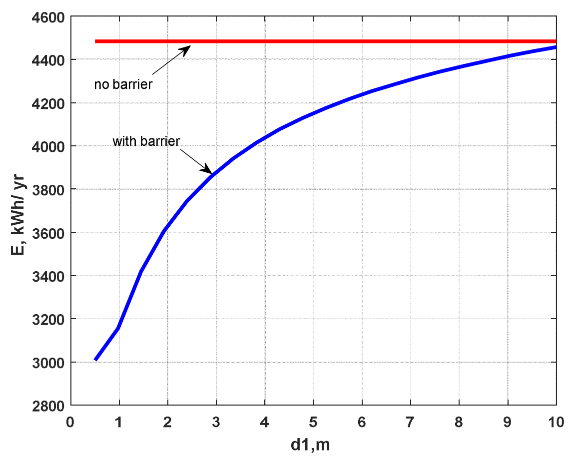

Figure 9: Energy increase versus the barrier distance.

4. Conclusion

This research proposes a mathematical model to simply calculate the effect of shadow over a set of panels south-facing and arranged in rows with specific data and spacing distances. As a result, the shadow factor depends on the solar data, barrier height, the number of rows facing the barrier, and the distance of the first row to the barrier. It decreases as the daytime increases presented in terms of solar altitude angle for any day of the year. For example, on March21st, it falls from 25% to about 0%. This factor is changed at different altitude angles, and depends on the years' months. With respect to shadow rate, the significant effect is observed during winter time at the highest barrier, while during the summer time, this effect is negligible. Due to this fact, installing the solar panels close to the barrier will not cause a significant energy decrease. When studying the lost annual energy due to shading, it's worth mentioning to estimate the shadow factor, then to decide whether to make enough spacing between the barrier and the PV system or to allow such shading. In the present study for the concrete PV system and site information with 5m spacing, 4m barrier height, and 10 rows arrangement the system just loosing 7.5% of its annual energy.

References

[1] Martin, S. S., Chebak, A., Barka, N., Development of renewable energy laboratory based on integration of wind, solar and biodiesel energies through a virtual and physical environment, 2015, *3rd International Renewable and Sustainable Energy Conference, Marrakech, 2015*, pp. 1-8. https://doi.org/10.1109/irsec.2015.7455086.

[2] Mahmoud, Y., Xiao, W., Zeineldin, H. H., A simple approach to modeling and simulation of photovoltaic modules, IEEE Trans. Sustain. Energy, vol. 3, no. 1, Jan. 2012, pp. 185–186. https://doi.org/10.1109/tste.2011.2170776.

[3] Mastromauro, R. A., Liserre, M., Dell'Aquila, A., Control issues in single-stage photovoltaic systems: MPPT, current and voltage control, IEEE Trans. Ind. Informat., vol. 8, no. 2, May. 2012, pp. 241– 254. https://doi.org/10.1109/tii.2012.2186973.

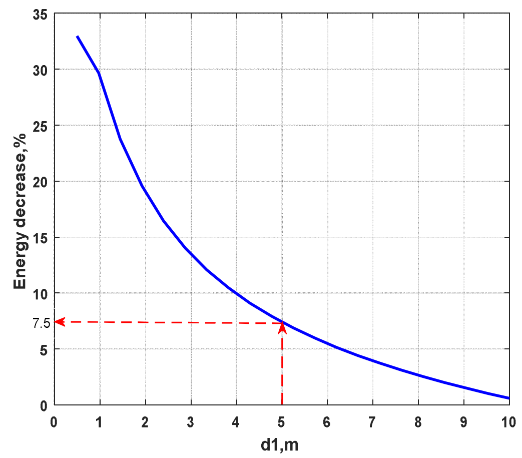

Figure 10: Percentage change of produced energy.

[4] Khader, S., Daud, A.K., Boost chopper behaviors in Solar photovoltaic system, Smart Grid and Renewable Energy , Vol.12, No.3, March 2021, https://doi.org/10.4236/sgre.2021.123003.

[5] Martín Silva, Justo Jose Roberts& Pedro Osvaldo Prado, " Calculation of the Shading Factors for Solar Modules with MATLAB", Energies 2021, 14(15), 4713; pp.1-23. https://doi.org/10.1051/matecconf/201821802004

[6] RusianaIskandar , Yuda Bakti Zainal, and Susanto Sambasr, "Study and Analysis of Shading Effects on Photovoltaic Application System", MATEC Web of Conferences 218, IVIEE,2018 ,https://doi.org/10.1051/matecconf/201821802004

[7] Ellabban, O.; Abu-Rub, H.; Blaabjerg, F. Renewable energy resources: Current status, future prospects and their enabling technology. Renew. Sustain. Energy Rev. 2014, 39, 748–764. https://doi.org/10.1016/j.rser.2014.07.113

[8] Decker, B.; Jahn, U. Performance of 170 grid connected PV plants in Northern Germany—Analysis of yields and optimization potentials. Sol. Energy 1997, 59, 127–133. https://doi.org/10.1016/S0038-092X(96)00132-6.

[9] Quaschning, V.; Hanitsch, R. Irradiance calculation on shaded surfaces. Sol. Energy 1998, 62, 369–375. https://doi.org/10.1002/pip.2884

[10] MacAlpine, S., Deline, C.; Dobos, A. Measured and estimated performance of a fleet of shaded photovoltaic systems with string and module-level inverters. Prog. Photovolt. Res. Appl. 2017, 25, 714–726. [CrossRef]

[11] Bayrak, F.; Ertürk, G.; Oztop, H.F. Effects of partial shading on energy and exergy efficiencies for photovoltaic panels. J. Clean. Prod. 2017, 164, pp. 58– 69 .https://doi.org/10.1016/j.jclepro.2017.06.108

[12] National Renewable Energy Laboratory (NREL). System Advisor Model (SAM). Available online: https://sam.nrel.gov/ (accessed on 1 January 2021).

[13] Boonraksa P., Chaisa-Ard T., et.al ," Design and Simulation of Fuzzy logic controller based MPPT of PV module using MATLAB/ Simulink", IEEE Xplore: 9 March 2022,

https://doi/ 10.1109/iEECON53204.2022.9741641. .

[14] Green, M., Third generation photovoltaics: Assessment of progress over the last decade, In Proc. 34th IEEE PV Spec. Conf., 2009.

[15] SUNPOWER PV Datasheet, SPR-315E https://www.solarfeeds.com/product/spr-p3-315-335-blk/

[16] MATLAB and Simulink (2016) The MathWorks, Inc., version R2016b.http://www.mathworks.com