

Economic Impact of Partial Shading on Solar PV System

A Real Case Study

Sameer Khader*, Abdel-Karim Daud

Department of Electrical Engineering-Palestine Polytechnic University

Abstract— This study examines the economic impact of shading on PV panel performance by studying the varying effects of the barrier's location, height, distance between the solar panels and the barrier, and the tilt angle variation. A mathematical model is derived in order to simulate the shading effect on the yield energy in various cases as mentioned above. The MATLAB/Simulink platform is used to simulate the shading process and to generate the results.

The analyses are conducted on the yield energy over a day, month, and year. Results show that shadowing varies with several factors, with winter months experiencing shadowing above 28% and summer months as low as 10%, depending on barrier height.

An economic study on a rooftop PV system at Palestine Polytechnic University (47 kWp, 164 panels) found it generates 67,545 kWh/year, yielding \$9,643/year in revenue. Allowing partial shading added 46 panels, producing an additional 88,826 kWh/year of energy. The gained extra revenue is \$11,098/year, equivalent to a 12.7% increase in the revenue with only a 9% shading loss. This approach boosts income by 24%, with extra revenue of ~\$59,000 over 20 years.

I. INTRODUCTION

Renewable energy resources, particularly solar photovoltaic (PV) systems, are increasingly adopted to address fossil fuel limitations and reduce environmental impacts [1,2]. PV systems consist of solar panels, a DC chopper, a smoothing unit, and an MPPT system for optimal energy extraction [3, 4]. Factors like material selection, solar irradiation, temperature, tilt angle, and shading significantly influence performance [5,6,7].

Shading, especially in urban settings with obstacles, greatly affects energy production. Studies in Germany and the U.S. highlight shading losses ranging from 10% to over 20% annually [8, 9, 10]. Experimental research further demonstrates that different shading patterns (single cell, row, or column) have varying impacts on energy output [11]. Modeling shading effects is crucial to optimizing PV system.

*Corresponding author:

Sameer Khader, Professor of electrical engineering- Power electronics, email: sameer@ppu.edu, cellphone: 00970599889623.

Wadi Hariya campus, Building B, Office B508.

II. MATHEMATICAL MODELING

A. Modeling related to previous study

Sameer Hanna and Abdel Karim Daoud [12] conducted a comprehensive study on the shading effects on SUNPOWER SPR415 solar panels (415 watts) over the course of a year. Their research focused on how different lengths of obstructing objects, referred to as solid obstacles, created shadows and impacted the energy production of the panels. The study also analysed the effect of varying the distance between the solar panel rows and these obstructing objects over a 365-day period. The findings revealed that the shading intensity was most significant during the winter months, reaching up to 24%, while in the summer, shading was minimal, dropping to as low as 5% in mid-July each year. This seasonal variation highlights the importance of considering both the height and position of obstacles when designing solar systems to optimize energy production throughout the year. Fig.1 illustrates a solar energy system that experiences partial shading, which reduces the overall energy production throughout the solar year, as detailed in Fig.2. To demonstrate the effects of shading on solar panels, the study examines the presence of a solid barrier positioned to the south of the solar panels. This barrier casts a shadow over a portion of the rows of panels that are connected in series. In Fig.3, the scenario is depicted with a concrete barrier that has a height of 4 meters and is positioned 2 meters away from the solar panel rows. The shadow cast by the barrier partially obstructs the sunlight that reaches the panels, thereby lowering the total energy produced by the system. The configuration of the shading effect is influenced by the height of the barrier and its distance from the panels, showing how such factors can significantly impact solar energy output.

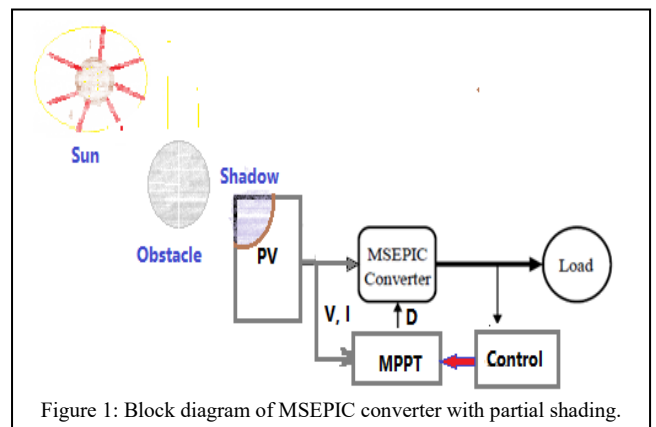
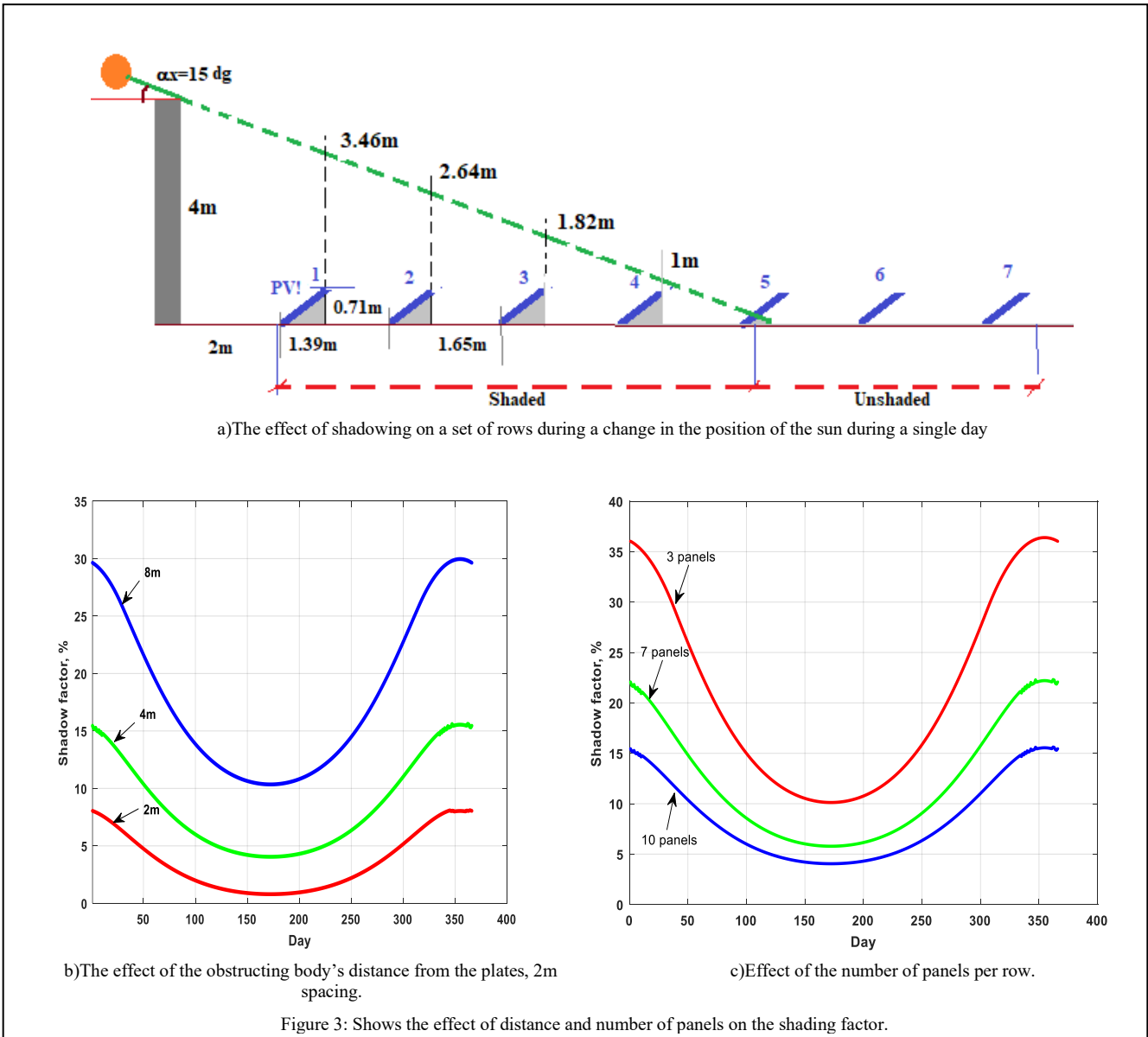
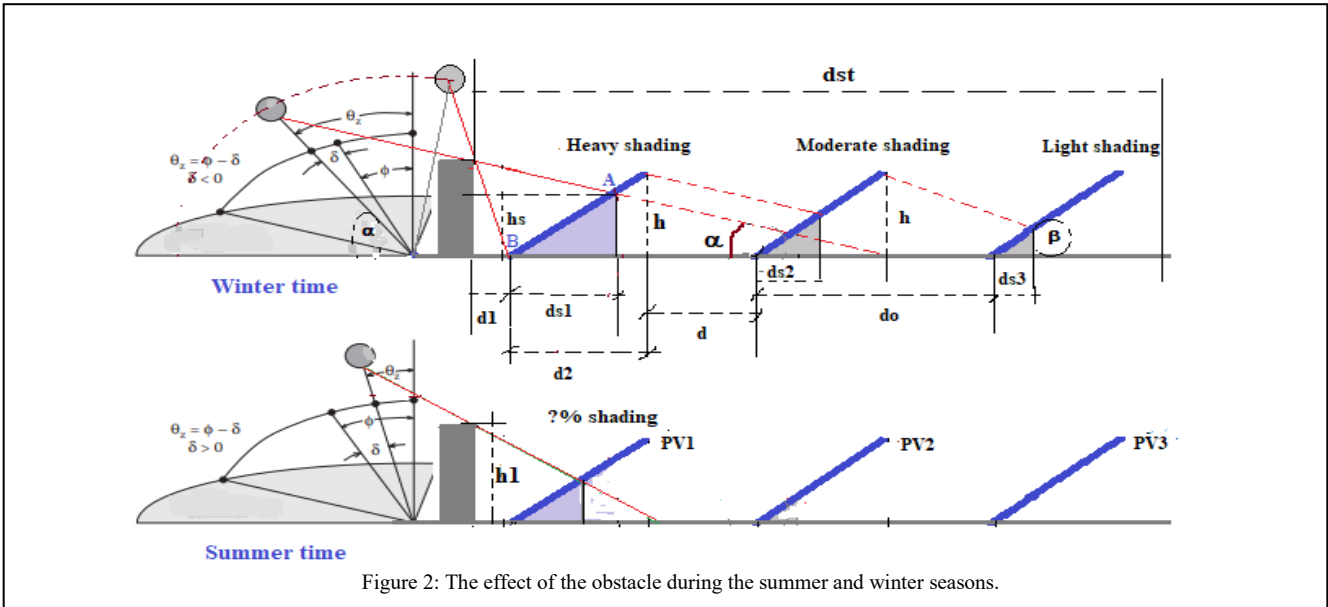


Figure 1: Block diagram of MSEPIC converter with partial shading.



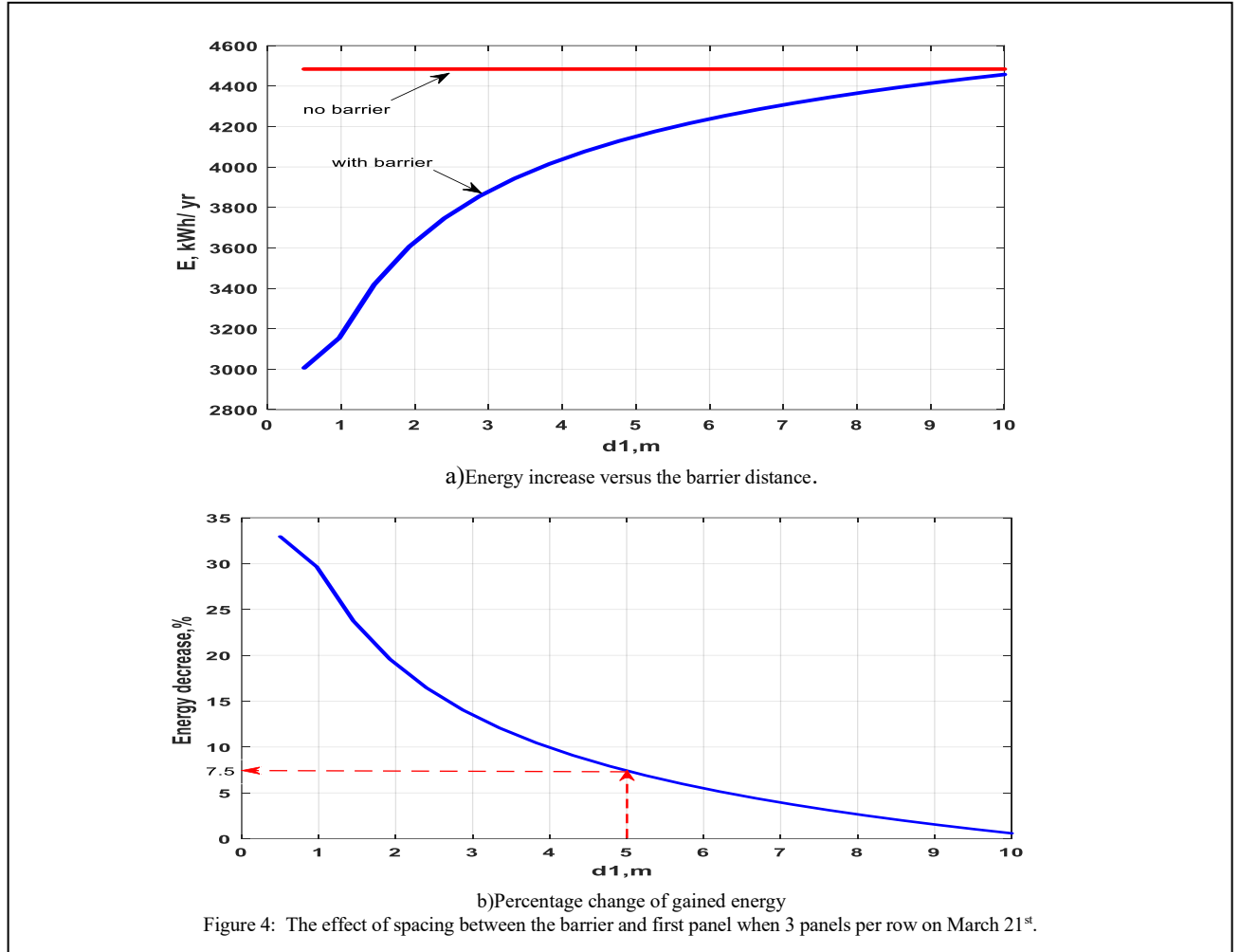


Figure 4: The effect of spacing between the barrier and first panel when 3 panels per row on March 21st.

B. Energy production

Refer to the system data regarding the number of panels, energy, and area of each panel, as shown in table (1), the annual energy produced can be calculated according to the following:

Fixed parameters		Variable parameters	
Latitude	31.52°	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, Watt	315		
Average irradiation G, h./day @ 1sun	5.2		

$$E_{anwo} = G \cdot P_{tot} \cdot \eta_{con} \cdot N_d; \quad (1)$$

Where, E_{anwo} - presents the annual energy, kWh/yr;

G- Hours of peak sun irradiation;

$\eta_{con}=0.75$ is a conversion efficiency;

$N_d=365$ days/yr;

$P_{tot}=N_{pv} \cdot P_{MPV}$; it presents the total maximum power of the solar panels at MPPT; and N_{pv} is the number of solar panels. In case of existing solid obstacles causing shadow, the produced energy is reduced according to (2):

$$E_{anw} = E_{anwo} (1 - K_{saan}); \quad (2)$$

Whereas K_{saan} is the average annual shading factor and can be calculated according to (3):

$$K_{saan} = \frac{\sum_1^{365} K_{sa}(j)}{365} \quad (3)$$

Fig.4 presents the shading factor throughout the year under various conditions, including different numbers of solar panels in a row and varying distances from the obstacle. The analysis shows that shading is most significant during the winter months, with the shading percentage peaking at 14% in early January when the distance between the solar panel and the obstacle is 4 meters. This highlights how the position and size of the obstruction can influence the shading effect on solar panels, especially during the low-sun months. Furthermore, the study indicates that the shading factor can become even more pronounced under certain configurations. For instance, when only one solar panel is placed in a row, the

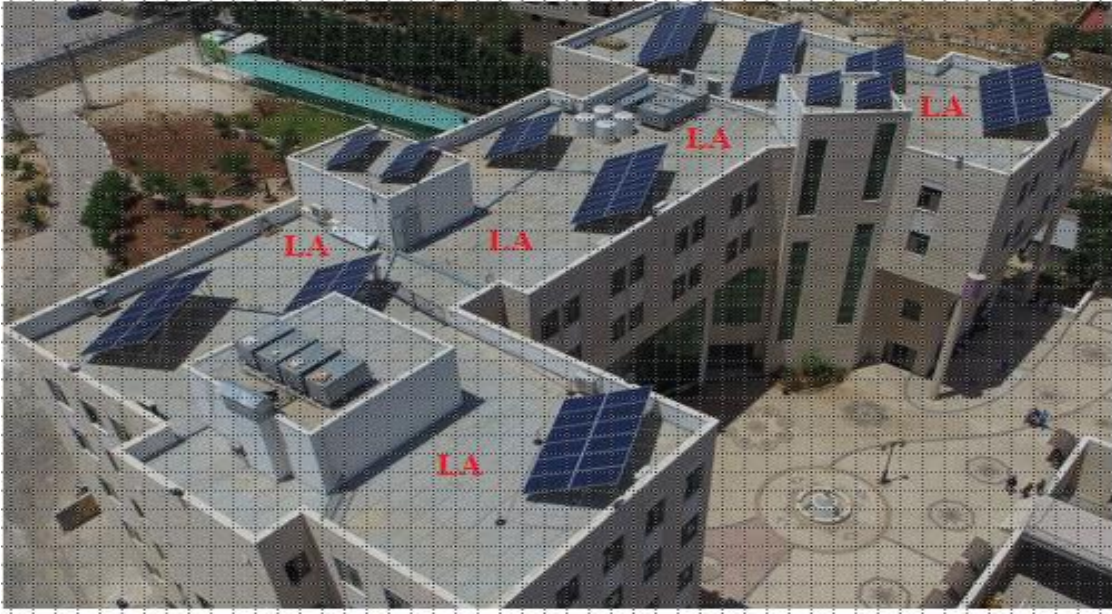


Figure 5: Rooftop of administrative building with installed PV system

shading percentage can rise to as much as 35%, demonstrating that fewer panels in a row are more susceptible to shading. The results underline the importance of considering both the number of panels and the distance from the obstacle to minimize shading and optimize energy production, especially during the winter when the sun's angle is lower and shading effects are more intense.

III. FINANCIAL EVALUATION

To conduct a financial analysis of the proposed energy system, one of the university buildings was selected, utilizing its roof to install a solar power station designed to serve the building's energy needs. While other university buildings were also considered, it was observed that the roof of this particular building had numerous obstacles. These obstacles significantly reduced efficiency, as larger spaces between PV rows were required to prevent shading, as illustrated in Fig.5.

The lost area (LA) resulting from these spacing adjustments, accounted for approximately 32% of the total available roof area. However, allowing partial shading could potentially increase the rate of energy production by utilizing this previously unused area. To ensure accurate evaluation and informed decision-making, the system's costs and revenues will be analyzed for both the existing configuration and the proposed new configuration. This comparison aims to determine the optimal balance between shading losses and energy production gains.

A. Project's data

The solar energy system installed on the rooftop of the administrative building is detailed in Table (2), which provides the system's technical and financial data. The actual cost per watt of generated AC power was determined based on local market prices as of June 5, 2024. This data serves as the foundation for analysing the system's economic feasibility and performance.

A.1 Project revenue _initial design

The total cost of 1 kWhr of energy, along with the annual revenue and the total revenue over the project's lifetime for the initial design before modification, can be calculated to [14, 15] and stated in (4).

$$C_{pvt} = N_{PV} P_{MPV} \eta_{con} C_{PV} = 32029 \$ \quad (4)$$

Where, N_{PV} is the number of panels = 146 panels ;

P_{MPV} is the power of one panel = 315W;

$\eta_{con} = 0.75$ is known derating factor;

$C_{PV}=900\$ / kWac.$ is the price of 1 kWac power.

The annual loan that to be paid is stated in (5).

$$A_{loan} = C_{pvt} CRF = C_{PV} \frac{i*(1+i)^n}{(1+i)^n - 1} = 3298\$/year \quad (5)$$

Where, i is the interest rate =6% for loan with 15 years span ($n=15$); $CRF=0.10296$ is the capital recovery factor.

The cost of 1kWhr energy produced by the PV system is (6).

$$\Delta C_{1kWh} = \frac{A_{loan}}{E_{pr}} = 0.04823 \$/kWhr \quad (6)$$

Where, $E_{pr} = 67545 \frac{kWhr}{yr}$ is the annual produced energy by this station.

The net annual revenue for the first year can be calculated in (7), having in mind that the actual cost of purchased ac energy from the grid is $\Delta C_{grid} = 0.191 \$/kWhr.$

Table 2: Project technical and financial data

PV panel's data	DC rated Power, W	325	Inverter data KACO	Capacity, kVA	2X 20 KVA
	Rated voltage, V	37.5		DC voltage range	70-200
	Rated current	8.67		Efficiency	98.4%
	Panel's size (cmxcm)	165x99		Phasing	3 phases
	Number of panels	146		Voltage range	211-410
	Panel's efficiency	16.7%		Harmonic distortion	<3%
	Derating factor	75%			
Rooftop data and produced energy	Total gross area, m2	1255	Financial data	Total cost, \$	32029
	Net area, m2	650		Interest rate	6%
	Location with respect to south	South faced		Loan's year	15
	Produced AC power, kWac	35.587		Cost of 1W ac power, \$	0.9
	Project lifetime, year	25		O& M	2%
	Number of total panels	146		Discount per /year	7%
	Produced annual energy, kWhr/yr	67545		-----	-----

$$P_{revenue} = E_{pr} (\Delta C_{grid} - \Delta C_{1kWh}) = 9643 \$/yr \quad (7)$$

Fig. (6) illustrates the project cost status in terms of payment, loan interest and net revenue among 20 years of the project years old. The net revenue after 25 years of project lifetime is ~295190 \$.

A.2 Project revenue _modified design

In order to reduce the lost area mentioned in Fig.5 as "LA" a partial shading is allowed by assigning 2m spacing between first PV's row and the barrier taking into account Fig.3b for 3 panels per row, 4m barrier height and 2m spacing on 21st of March (day# 81) the shading rate is Ksaan ≈ 8%. Now for 6 panels per row according to Fig.3c and Fig.4b the shadow factor is Ksaan = $\frac{18\%}{2} = 9\%$; so, the energy reduction according to (2).

$$E_{anw} = E_{anwo} (1 - K_{saan}) = 1466 \text{ kWh/yr} \quad (8)$$

Now, the lost area (LA) is reduced by adding additional panels closed to the barrier where the estimated number of added panels are $\Delta NPV = 46$ panels. So, the total system panels in accordance with Table 1 and (4) to (7).

- The total number solar panels is given in (9):

$$NPV_{new} = NPV + \Delta NPV = 146 + 46 = 192 \text{ panels} \quad (9)$$

- The new produced ac power is given in (10).

$$P_{acwtot} = P_{acw} \frac{NPV_{new}}{NPV} = 46.8 \text{ kWac} \quad (10)$$

- The new obtained energy is given in (11).

$$E_{anwtot} = E_{anw} \frac{NPV_{new}}{NPV} = 80831 \frac{\text{kWhr}}{\text{yr}} \quad (11)$$

- The cost of the system based on produced ac power according to (4) and given in (12).

$$C_{PV_{new}} = NPV_{new} P_{MPV} \eta_{conv} C_{PV} = 42200 \$ \quad (12)$$

- The annual loan that to be paid is given in (13).

$$A_{loan_{new}} = C_{PV_{new}} CRF = 4345 \frac{\$}{\text{year}} \quad (13)$$

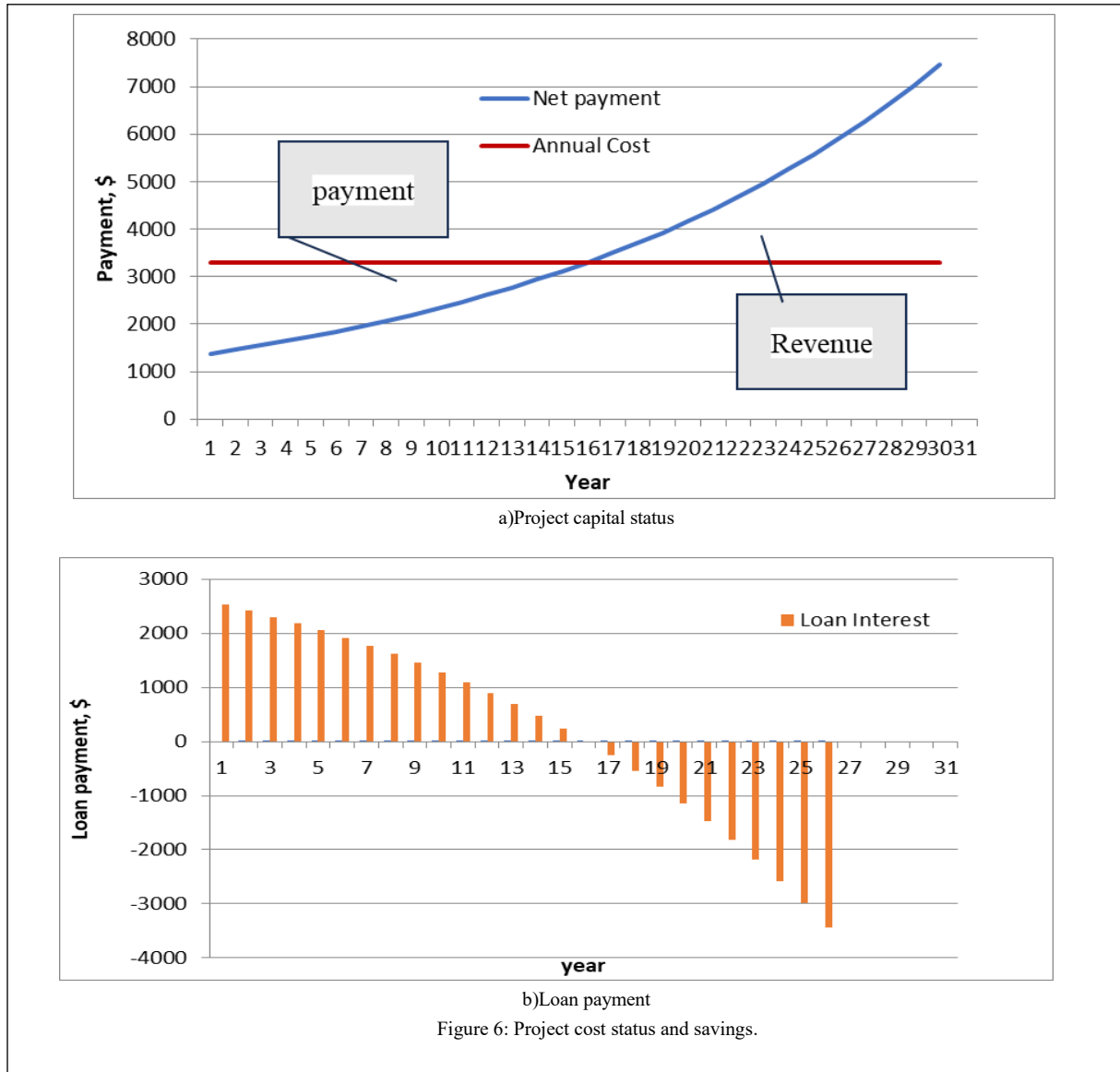
Where, i is the interest rate =6% for loan duration of 15 years span (n=15); CRF=0.10296 is the capital recovery factor .

- The cost of 1kWhr energy produced by the PV system is given in (14).

$$\Delta C_{1kWh_{new}} = \frac{A_{loan_{new}}}{E_{anwtot}} = 0.05375 \$/\text{kWhr} \quad (14)$$

- The net annual revenue for the first year can be calculated according to (15), taking into account the actual price of purchased energy from the local electricity network in 2024 year is equivalent to $\Delta C_{grid} = 0.19 \$/\text{kWh}$.

$$P_{revenue_{new}} = E_{anwtot} * (\Delta C_{grid} - \Delta C_{1kWh_{new}}) = 11098 \frac{\$}{\text{yr}} \quad (15)$$



- The extra benefit of allowing partial shadow with respect to no shadow is given in (16).

$$\Delta P_{revenue} = P_{revenue_{new}} - P_{revenue} = 1495 \$/\text{yr} \quad (16)$$

- The increase in the system cost according to (4) and (12) is given in (17).

$$\Delta COST = C_{pv_n} - C_{pvt} = 10180 \$ \quad (17)$$

Therefore, allowing partial shadow with spacing of 2m and 6 panels per row with total of 46 panels are added generates additional income of 1495\$/yr and for minimum 20 years project old the extra revenue will be 29900 \$ additional to the fixed revenue of 192860\$. By allowing partial shading and adding 46 new panels, the total revenue increases from \$192,860 to \$222,760. This translates to approximately 15% extra revenue over 20 years, which is a significant improvement, all while utilizing the same roof area.

Fig.7 illustrates the net revenue for project duration of 20 years when no shading and partial shading are allowed, where

allowing partial shading increases the installed panels to 192 PV panels, while if shading not allowed the total number of panels is 146 panels.

A .3 Levelized cost of energy

The levelized cost of electricity (LCOE) is used to evaluate the average cost of generating one unit of electricity (e.g., per kilowatt-hour or megawatt-hour) over the lifetime of a power generation facility. The LCOE provides a single value representing the cost-effectiveness of a power plant or technology, making it useful for comparing different energy generation methods (e.g., solar, wind, coal, nuclear) from an investor's perspective [16]. Referring [17,18,19], the LOCE is given in (18).

$$LCOE = \frac{NPV \text{ of total cost over lifetime}}{NPV \text{ of energy produced over lifetime}} = \frac{\sum_{j=1}^n \frac{(I_j + M_j)}{(1+r)^j}}{\sum_{j=1}^n \frac{E_{anj}}{(1+r)^j}} \quad (18)$$

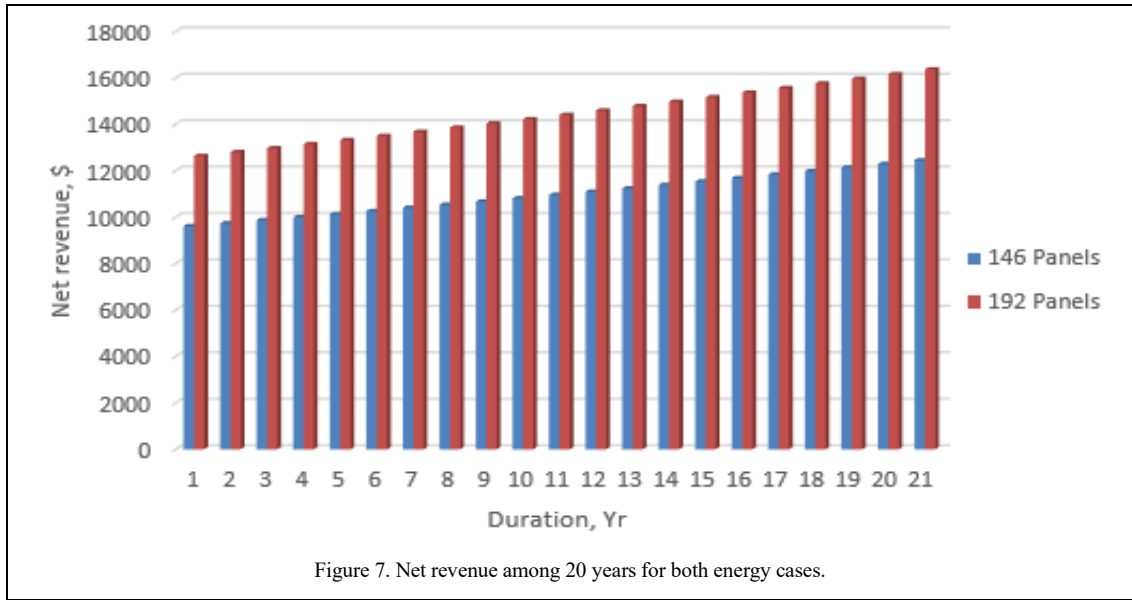


Figure 7. Net revenue among 20 years for both energy cases.

Where: I_j is the initial cost of the PV generator; M_j is the cost of operation & management expenditure of “j” year; “r” is the discount rate of the system; “n” is the life time of the PV generator in years and NPV determines the value of an investment or project by calculating the present value of all expected future cash flows, both inflows and outflows, discounted to the present using a discount rate. NPV can be calculated according to (19).

$$NPV = \sum_{j=0}^n \frac{C_j}{(1+r)^j} \quad (19)$$

Where: C_j is the cashflow at year “j”.

Table 3: Modified project data

Initial Investment Cost (\$)	42200
Operations and Maintenance Costs (\$)	900
O&M Growth Rate (%)	2.00%
Annual Electricity Output (kWhr)	80,831
Project Lifespan (years)	15
Discount Rate (%)	3.00%
Entry Date	1/1/2017
NPV_Expenditure	\$ 56,985
NPV_Energy	886,479 kWh
LCOE	\$ 0.06/kWh
Net revenue over 15 years	\$ 215,285

Table 3 states the project data and revenue with modified total number of panels. Refer to (14), where the cost of energy is calculated as $\Delta C_{l\text{kWh_new}}=0.0537$ \$/kWh and compare it

with the exact calculated $LCOE=0.06$ \$/kWh, we found that the results are reasonably accurate. The difference between these two values arises because maintenance and operational (M&O) costs, as well as the degradation rate are considered negligible in the calculations leading to (14).

IV. CONCLUSION

Shading significantly impacts solar system performance, requiring careful analysis to minimize energy losses. This research presents a mathematical model to calculate shading effects on south-facing solar panels arranged in rows. Key findings include:

- ✓The shadow factor depends on solar data, barrier height, number of rows, and distance from the barrier, furthermore, shading varies seasonally, with the greatest effect on December 21st. Adding more rows reduces shading effects
- ✓In this study, a 2m spacing and 4m barrier height results in only a 9% annual energy loss, suggesting partial shading is acceptable for optimized energy use.
- ✓Allowing partial shading by placing the first PV row closer to the barrier enables the installation of more panels and rows, resulting in a 12% increase in total revenue and profit return.
- ✓Over 20 years project old the net revenue is about \$222000 with 15.5% increase as partial shadowing is allowed.
- ✓According to the obtained LCOE, the conducted investment is deemed worthwhile and generates substantial revenue.
- ✓The conducted design and assessment focus on a small-scale PV system. However, if the system were scaled up to cover the entire institution's energy consumption, the resulting revenue and cost savings would be substantially higher.

REFERENCES

- [1] Martin, A. Chebak, and N. Barka, "Development of renewable energy laboratory based on integration of wind, solar and biodiesel energies through a virtual and physical environment" ,Proc. of 3rd Int. Conf. on Renewable and Sustainable Energy, Marrakech, Morocco, 2015, pp.1-8. <https://doi.org/10.1109/irsec.2015.7455086>.
- [2] W.-K. Chen, *Linear Networks and Systems* (Book style). Belmont, CA: Wadsworth, 1993, pp. 123–135.
- [3] H. Poor, *An Introduction to Signal Detection and Estimation*. New York: Springer-Verlag, 1985, ch.4.
- [4] B. Smith, "An approach to graphs of linear forms (Unpublished work style)," unpublished.
- [5] E. H. Miller, "A note on reflector arrays (Periodical style—Accepted for publication)," *IEEE Trans. Antennas Propagate.*, to be published.
- [6] J. Wang, "Fundamentals of erbium-doped fiber amplifiers arrays (Periodical style—Submitted for publication)," *IEEE J. Quantum Electron.*, submitted for publication.
- [7] C. J. Kaufman, Rocky Mountain Research Lab., Boulder, CO, private communication, May 1995.
- [8] Y. Yorozu, M. Hirano, K. Oka, and Y. Tagawa, "Electron spectroscopy studies on magneto-optical media and plastic substrate interfaces(Translation Journals style)," *IEEE Transl. J. Magn.Jpn.*, vol. 2, Aug. 1987, pp. 740–741 [*Dig. 9th Annu. Conf. Magnetism* Japan, 1982, p. 301].
- [9] M. Young, *The Technical Writers Handbook*. Mill Valley, CA: University Science, 1989.
- [10] J. U. Duncombe, "Infrared navigation—Part I: An assessment of feasibility (Periodical style)," *IEEE Trans. Electron Devices*, vol. ed-11, pp. 34–39, Jan. 1959.
- [11] S. Chen, B. Mulgrew, and P. M. Grant, "A clustering technique for digital communications channel equalization using radial basis function networks," *IEEE Trans. Neural Networks*, vol. 4, pp. 570–578, July 1993.
- [12] S. Khader, A. K. Daud, A. Abu Aisheh, "Studying the Shading Effect of PV System on Energy Performances in Restricted Spaces", 22th International Conference on Renewable Energies and Power Quality (ICREPQ'24) , Bilbao (Spain), 26th to 28th June 2024, ISBN: 978-84-09-60656-6, Volume No.22.
- [13] S. P. Bingulac, "On the compatibility of adaptive controllers (Published Conference Proceedings style)," in *Proc. 4th Annu. Allerton Conf. Circuits and Systems Theory*, New York, 1994, pp. 8–16.
- [14] G. R. Faulhaber, "Design of service systems with priority reservation," in *Conf. Rec. 1995 IEEE Int. Conf. Communications*, pp. 3–8.
- [15] W. D. Doyle, "Magnetization reversal in films with biaxial anisotropy," in *1987 Proc. INTERMAG Conf.*, pp. 2.2-1–2.2-6.
- [16] G. W. Juette and L. E. Zeffanella, "Radio noise currents n short sections on bundle conductors (Presented Conference Paper style)," presented at the IEEE Summer power Meeting, Dallas, TX, June 22–27, 1990, Paper 90 SM 690-0 PWRS.
- [17] J. G. Kreifeldt, "An analysis of surface-detected EMG as an amplitude-modulated noise," presented at the 1989 Int. Conf. Medicine and Biological Engineering, Chicago, IL.
- [18] J. Williams, "Narrow-band analyzer (Thesis or Dissertation style)," Ph.D. dissertation, Dept. Elect. Eng., Harvard Univ., Cambridge, MA, 1993.
- [19] N. Kawasaki, "Parametric study of thermal and chemical nonequilibrium nozzle flow," M.S. thesis, Dept. Electron. Eng., Osaka Univ., Osaka, Japan, 1993.
- [20] J. P. Wilkinson, "Nonlinear resonant circuit devices (Patent style)," U.S. Patent 3 624 12, July 16, 1990.