

GOCE DELCEV UNIVERSITY - STIP
FACULTY OF COMPUTER SCIENCE

The journal is indexed in

EBSCO

ISSN 2545-4803 on line

DOI: 10.46763/BJAMI

BALKAN JOURNAL
OF APPLIED MATHEMATICS
AND INFORMATICS
(BJAMI)



YEAR 2023

VOLUME VI, Number 2

AIMS AND SCOPE:

BJAMI publishes original research articles in the areas of applied mathematics and informatics.

Topics:

1. Computer science;
2. Computer and software engineering;
3. Information technology;
4. Computer security;
5. Electrical engineering;
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**BALKAN JOURNAL
OF APPLIED MATHEMATICS AND INFORMATICS
(BJAMI), Vol 6**

**ISSN 2545-4803 on line
Vol. 6, No. 2, Year 2023**

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The Appendix

The Faculty of Electrical Engineering at Goce Delcev University (UGD), has organized the Second International Conference Electrical Engineering, Informatics, Machinery and Automation - Technical Sciences Applied in Economy, Education and Industry-ETIMA on September, 27th-29th 2023.

ETIMA has a goal to gather scientists, professors, experts, and professionals from the field of technical sciences in one place as a forum for exchanging ideas, strengthening multidisciplinary research and cooperation, and promoting the achievements of technology and its impact on every aspect of living. Conference ETIMA was held as an online conference. More than sixty colleagues contributed to this event, from five different countries with more than thirty papers.

The Organizing Committee selected five papers that will be published in this number of the BJAMI.

COMPARATIVE ANALYSIS BETWEEN BIFACIAL AND MONOFACIAL SOLAR PANELS USING PV*SOL SOFTWARE

MLADEN MITKOVSKI AND VLATKO CHINGOSKI

Abstract. Traditional solar panels commonly used in today's solar power projects are monofacial, i.e., with solar cells only on one side of the panels. Recently, many solar panel producers have improved their panel designs by introducing the so-called bifacial solar panels which feature solar cells on both sides of the solar panel. Producers claim that bifacial solar panels, regarding energy generation, typically overperform the traditional monofacial solar panels by about 5.5%, with additional investment cost between 10% and 25%, which strongly depends on the producer and the size of the project. In this paper, the authors made a simulation and comparative analysis between bifacial and monofacial solar panels using PV*SOL simulation software. The simulation was done on a solar power project with an installed capacity of 1 MW using exact solar insolation values for the exact geographical location. Typical bifacial and monofacial half-cell solar panels available at the local market were used for the analysis. For enhancing the analysis, two common placements of the panels were utilized, ground placement, and rooftop placement parallel with the roof at the same inclination (pitch) and orientation (azimuth). The obtained results using PV*SOL simulation software for both panels and both placements are presented with accompanying discussion. For ground placement, bifacial solar panels resulted in increased energy generation of approximately 2.5%, while for rooftop placements the amount of the increased energy generation was negligible. Ground-placed bifacial solar panels have increased energy generation all year around, while rooftop bifacial solar panels provide larger energy generation only during summer months, from June to August. For the rest of the year the energy generation difference, although in favor of bifacial over monofacial solar panels, was still negligible.

1. Introduction

The technology for the production of solar power cells used for electric power generation has constantly been advancing and currently represents one of the most widely implemented renewable energy technologies around the world. There are two types of solar panels we will cover in the paper: monofacial and bifacial solar panels [1], [2].

With the continuous optimization of "*cost reduction and efficiency increase*" of photovoltaic (PV) power generation, monofacial solar panels (MFSP) and bifacial solar panels (BFSP) keep high attention and discussion in the PV industry. Thus, the main objective is to define what the main difference between these is - the MFSP and the BFSP. What are their advantages and disadvantages? Before we dive into this topic, let us define these two types of solar panels.

A MFSP only absorbs sunlight from the front surface of the solar panel while the BFSP, as its name suggests, features solar cells on both sides, as it is shown in Figure 1.

Keywords. Photovoltaics, monofacial solar panels, bifacial solar panels, PV*SOL, renewables

Accordingly, when a solar panel produces energy from both sides of the panel, the amount of electricity generated should be increased. Getting an increased amount of energy generated means more financial benefits for a solar system located in the same available space, which was the main driving force for solar panel manufacturers to introduce BFSP on the market.

MFSPs function just like normal solar panels. They convert solar sunlight from the front surface of the panel into direct current, which is turned into AC with an inverter and then can be used to power our building and home.

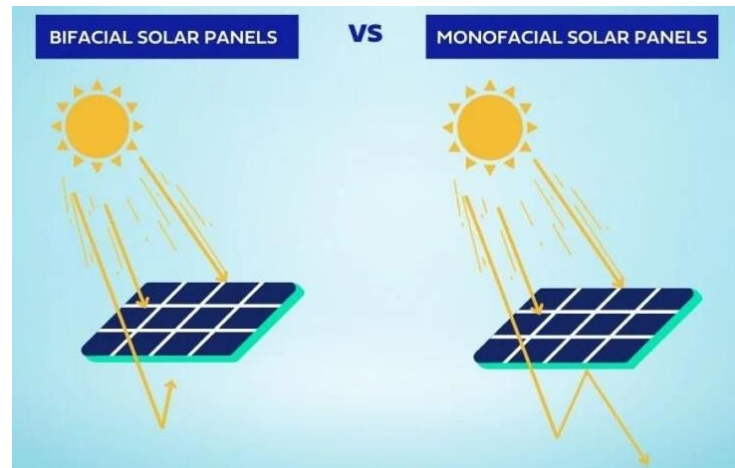


Figure 1. Schematic representation of BFSP and MFSP [2]

Instead of having a back sheet like monofacial, BFSPs have a transparent back sheet, thus both sides of the panel could capture the sunlight [1]. This allows the panels not only to absorb direct sunlight but also reflected light. Typically, BFSPs are also installed on the tiled racking system or the ground like the MFSPs. However, since BFSPs could capture the sunlight from both sides of the panel, from the front side direct sunlight and from the back side reflected sunlight, the solar mounting system that uses BFSPs could produce more energy. The higher the BFSP module is tilted, the more power it produces in comparison with the MFSP module. Accordingly, the type of surface on which the BFSPs should be installed is of paramount importance and should be as reflective as possible, as presented in Figure 2. When BFSPs are installed on a highly reflective surface, like a white roof or on the ground with high terrain clearance or a snowy area, the advantages of these solar panels come to the full extent.



Figure 2. *Quality-mounted BFSP on the high-reflective surface*

Solar mounting systems for BFSPs need to be specially designed to avoid shade from solar structures on the back sheet of panels. It is required that the beams or purlins of solar mounts should not cross the solar cell area. Besides, bifacial solar panels are not suitable to install on a single-axis solar tracking system with a single-row array, because the rotation axis of this kind of solar tracker will obscure the back side of the bifacial solar panels, thus decreasing the amount of generated energy.

2. Advantages of BFSPs Compared to MFSPs

Although slightly more expensive than MFSPs, the BFSPs have several important benefits. Among others, the following benefits compared to MFSPs, are the most relevant [2]:

- **BFSPs generate more power:** as they generate power from both sides of panels, BFSPs have higher efficiency per used space.
- **BFSPs are more durable:** BFSPs are covered by tempered glass that is UV resistant on both sides, and they can withstand high temperatures and strong winds.
- **BFSPs work well in diffused light:** The extra surface area (back side) provides that BFSPs perform better in diffuse light, making long-term costs lower than that of MFSP.
- **BFSPs have reduced Potential-induced Degradation (PID):** In the instance of a frameless bifacial panel, the solar cells are less likely to suffer from potential-induced degradation (PID), which, as a result, corrodes the solar panels. Furthermore, BFSPs without a metal frame do not require grounding, as there are no metal contacts on the exterior.
- **BFSPs have longer warranties:** BFSPs usually come with a long warranty of up to 30 years while monofacial only have a 25 year warranty.

In Table 1, some additional properties and differences between BFSPs and MFSPs are given.

Table 1. *Disadvantages of BFSPs compared to MFSPs*

Module Type	BFSPs	MFSPs
Initial Costs	10% higher	lower
Weight	heavier	lighter
Installation Costs	higher	lower
Flexibility	lower	higher

As major drawbacks of BFSPs in comparison with MFSPs we might consider the following:

- The price of the electricity generated by BFSPs is 5%-30% on average higher than the price of the generated electricity using conventional MFSPs.
- The amount of power output from the rear side of BFSPs strongly depends on the ground surface, such as grass, sand, cement, etc. The surface used for the installation of BFSPs should be as reflective as possible.
- Finally, MFSPs are easier to install because they are lighter and more flexible.

In conclusion, by comparing MFSPs and BFSPs, one can derive that the most important benefit of the BFSP is that it could generate more solar energy than MFSP with the same area. Therefore, to optimize the amount of electricity generated per square meter of space, BFSPs have the edge. Most trusted panel manufacturers offer warranties that last 25 years to 30 years, and the panels could still go on producing electricity long after the warranties expire providing a long-lasting way for low-cost and emissions-free electricity.

3. Introduction to the PV*SOL software package

PV*SOL is a simulation program for easy and quick design and economic efficiency forecast of grid-connected photovoltaic systems. It is meant for technical salespeople and PV plant installers who need a reliable tool to design accurately a PV system in the shortest time [3].

On the market, there are two versions of PV*SOL software: *PV*SOL basic* and *PV*SOL premium*. PV*SOL basic is used only for 2D simulations, while PV*SOL premium is used for both 2D and 3D simulations [4].

While PV*SOL basic is primarily used for rather small and/or medium size PV systems, PV*SOL premium is the industry standard PV design program that could be used for the design and simulation of all types of modern PV systems. From small and individual rooftop PV systems with a few PV modules, or medium-sized systems on commercial roofs, all the way to large PV parks, PV*SOL premium provides numerous tools for design and simulation. The unique 3D visualization capabilities are the highlight of PV*SOL premium. This enables the highest reliability for any project earnings forecast because, for an accurate income calculation, a realistic representation of the shading from surrounding objects is essential, whether calculating self-consumption, designing battery storage, or integrating electric vehicles, etc. [4].

4. Simulation models

The simulation aimed to compare energy generation obtained by a PV power plant with 1 MWp installed capacity utilizing MFSPs and BFSPs providing that the location, orientation, slope, and azimuth are kept the same for both types of panels.

As equipment for the simulation, the BFSPs from the manufacturer PIKCELL GROUP [5], type PiK550M(110) [6], with an installed power of 550 Wp were used in comparison with the MFSPs with half-cells, from the manufacturer PIKCELL GROUP, type PiK550M(144) [7], [8], with a power of 550 Wp, both connected to inverters from the manufacturer FRONIUS, type TAURO ECO 100-3-P [9]. Tables 2, 3, and 4 give the electrical, mechanical, and temperature characteristics of the photovoltaic panels.

Table 2. *Electrical characteristics - comparison*

Parameters	PiK550M(110)	PiK550M(144)
Maximum power [P_{max}]	550 W	550 W
Open circuit voltage [U_{oc}]	38.32 V	49.90 V
Maximum operating voltage [U_{mp}]	31.96 V	41.96 V
Short circuit current [I_{sc}]	18.23 A	14.00 A
Maximum operating current [I_{mp}]	17.22 A	13.11 A
Panel efficiency [η]	21.0 %	21.3 %
Power Tolerance	0 до + 5 W	0 до + 5 W
Coefficient of bifocality	0.7	0

STC: radiation 1000W/m², panel temperature 25°C, AM =1.5

Table 3. *Mechanical characteristics*

Parameters	PiK550M(110)	PiK550M(144)
Type of solar cells	BFSP	Half-cell MFSP
Weight	33 kg	28.6 kg
Dimensions	2,384 x 1,096 x 30 mm	2,279 x 1,134 x 35 mm
Number of cells	110 (5 x 11 + 5 x 11)	144 (12 x 6 x 2)
Junction box	IP 68	IP 68
Cable cross-section	4 mm ²	4 mm ²

Table 4. *Temperature characteristics*

Parameters	PiK550M(110)	PiK550M(144)
Temperature coefficient at U_{oc} (α)	-0.25 %/°C	-0.275 %/°C
Temperature coefficient at I_{sc} (β)	0.04 %/°C	0.045 %/°C
Temperature coefficient at P_{max} (γ)	-0.34 %/°C	-0.35 %/°C

Table 5. *Characteristics of the inverter*

DC parameters		AC parameters	
Max input power of the inverter	150 kWp	Rated output power	100 kW
Max input power PV 1	79 kWp	Max output power	100 kVA
Max input power PV 2	79 kWp	Max output current	151.5 A/220 V or 144.9 A/230 V
Max input voltage	1,000 V	Output voltage	380/220 V or 400/230 V
PV 1 peak current	100 A	Frequency	50 / 60 Hz
Max current of PV 2	100 A		
Max short circuit current PV 1	125 A		
Max short circuit current of PV 2	125 A		
Max inverter short circuit current	250 A		
Operating voltage range of MPPT	580V-930V		
Number of MPPT	1		

5. Simulation Data using PV*SOL

A comparison between MFSPs and BFSPs was done using PV*SOL software simulations. In the basic menu, the PV system connected to the grid was selected, with the geographical location in the vicinity of the city of Strumica, southeast of the country. The program itself has a database of climate conditions for the selected location for twenty years, from 1990 to 2010, thus calculations were done using average monthly insolation and temperature data providing an average expected annual electricity generation per plant. The initial PV*SOL starting menu page is given in Figure 3.

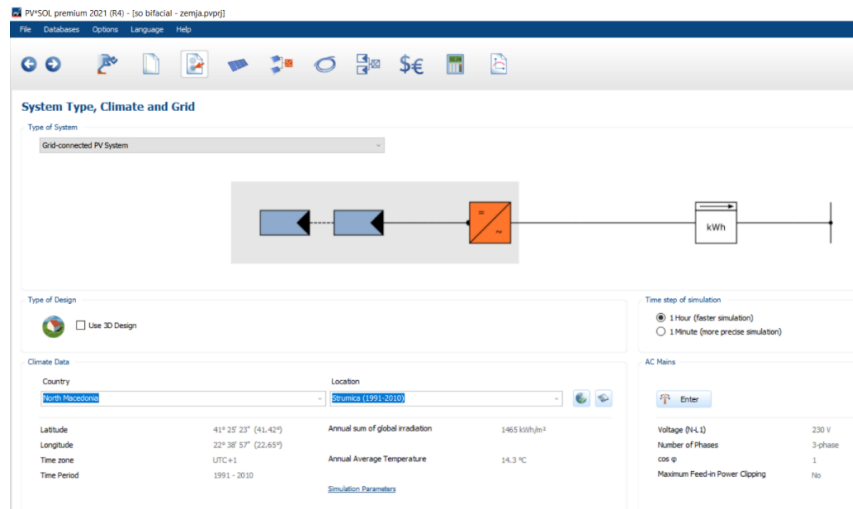


Figure 3. Starting menu page of PV*SOL program used for simulations

Two different simulations were done, one using BFSPs and the other using MFSPs. For the first simulation, 1818 BFSPs type PiK550M (110) [6] from the manufacturer PIKCELL Group were selected, placed on the ground under a slope of 30°, and oriented directly towards south. The second simulation was also performed using 1818 solar panels from the same manufacturer PIKCELL Group. However, these panels were MFSPs type PiK550M (144) [7] with half-cells [8], again placed on the ground under the same slope angle of 30° and oriented directly towards south. Both simulation models were constructed of two parallel branches, the first branch with 9 strings and 23 PV panels, and the second branch with 8 strings with 24 PV panels. Each simulated system had 9 inverters installed, type Tauro Eco 100-3-P, manufactured by FRONIUS, 6 for the first branch and 3 for the second branch [9]. Thus, the only difference between both simulations was only the type of solar panels, BFSP and MFSP, which was the main goal of the analysis. The schematic block diagram of both models as shown in the menu window of the PV*SOL software program is presented in Figure 4.

The same configuration of the above-presented and analyzed PV plant was used for the next two simulations. This time only the location of the PV plant was changed, thus instead of ground placement, the PV plants were located on the rooftop of a building. Again, two different types of solar panels were used, one with BFSPs and the other with MFSPs. All other data was the same as for the first two simulations that were done for on-the-ground solar panels. These simulations aimed to grasp the influence that the PV plant placement has on the amount of generated electricity.

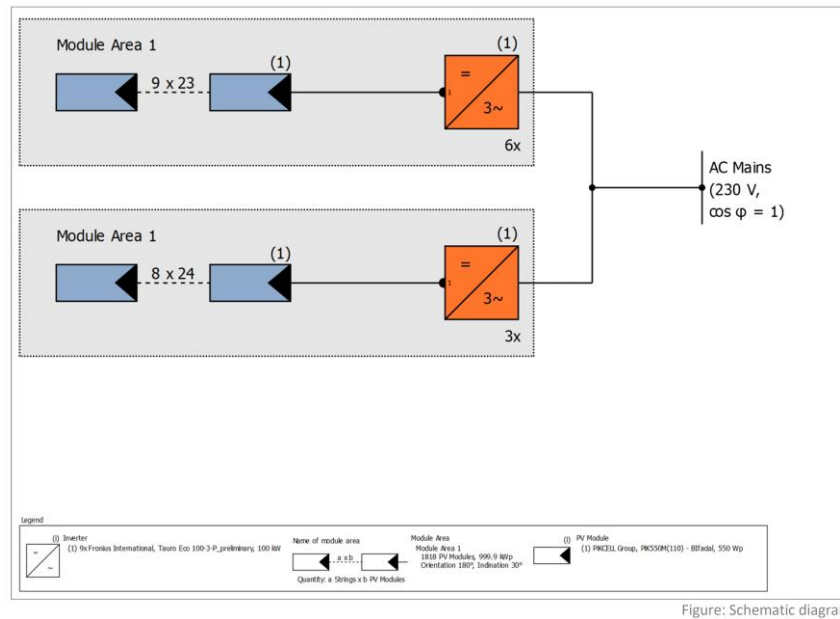


Figure 4. *PV*SOL* window menu with the PV plant connection block diagram

6. Simulation results and discussion

*PV*SOL* could present simulation results separately for each simulation, either as a separate MS WORD[®] or PDF[®] document. However, since the goal of our analysis was a comparison between generated electricity between two types of solar panels, BFSPs and MFSPs, and between two separated mounting positions, ground placement, and rooftop placement, the results will be presented using common tables and/or graphs. In the tables and graphs below, the following notations were used:

- A** – BFSPs placed on the ground;
- B** – MFSPs with half-cells placed on the ground;
- C** – BFSPs placed parallel to the rooftop;
- D** – MFSPs with half-cells placed parallel to the rooftop.

Figure 5 shows the expected monthly electricity production for each of the four simulated models using BFSPs and MFSPs with half-cells on the ground and the rooftop.

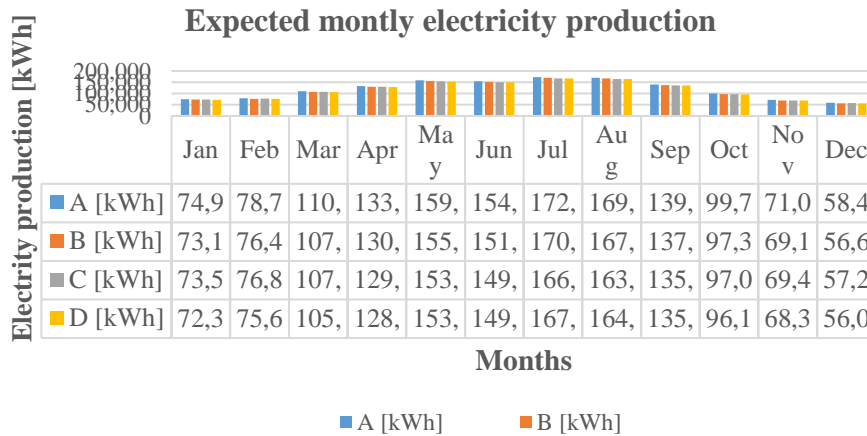


Figure 5. Expected monthly electricity production per model and per location

Figure 6 shows the expected annual electricity production for all four simulated models. Finally, in Table 6 one can observe the comparison between monthly and annual electricity production, as well as the difference between those productions depending on the type of solar panels and the PV plant placement – on the ground or the rooftop.

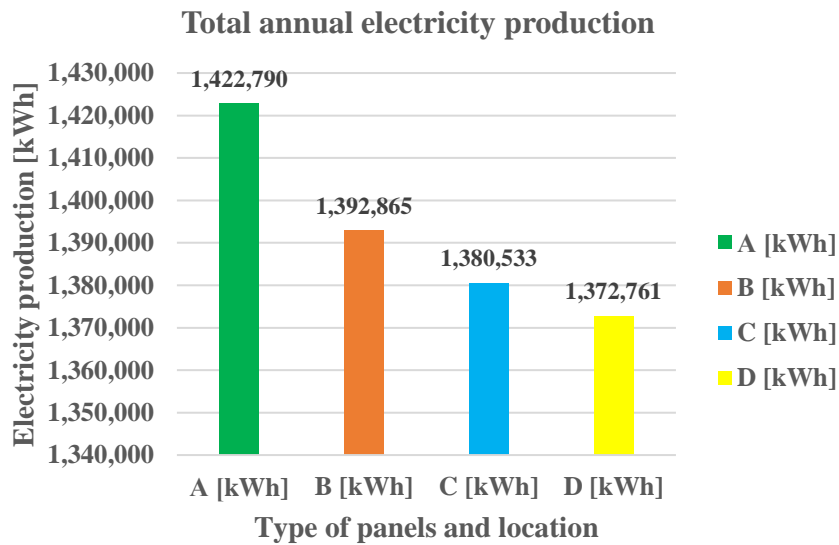


Figure 6. Total expected annual electricity production per model and location

Table 6. *Expected monthly electricity production*

	A [kWh]	B [kWh]	C [kWh]	D [kWh]	A-B [kWh]	C-D [kWh]
January	74,926.80	73,170.50	73,558.60	72,301.20	1,756.30	1,257.40
February	78,756.20	76,448.90	76,845.10	75,605.30	2,307.30	1,239.80
March	110,424.30	107,192.00	107,285.90	105,894.10	3,232.30	1,391.80
April	133,496.60	130,351.70	129,610.20	128,497.70	3,144.90	1,112.50
May	159,104.70	155,470.80	153,703.20	153,167.30	3,633.90	535.90
June	154,677.40	151,937.80	149,408.40	149,459.50	2,739.60	-51.10
July	172,898.80	170,562.70	166,988.60	167,631.60	2,336.10	-643.00
August	169,351.20	167,122.30	163,691.80	164,277.20	2,228.90	-585.40
September	139,879.00	137,518.20	135,689.70	135,399.50	2,360.80	290.20
October	99,794.00	97,336.80	97,049.20	96,151.80	2,457.20	897.40
November	71,080.00	69,122.50	69,467.40	68,341.40	1,957.50	1,126.00
December	58,401.10	56,631.10	57,235.20	56,034.30	1,770.00	1,200.90
TOTAL:	1,422,790.10	1,392,865.30	1,380,533.30	1,372,760.90	29,924.80	7,772.40

From Figures 5, and 6, and Table 6, it can be concluded that higher electricity production for the same installed capacity of 1 MWp, and under the same weather characteristic could be expected when:

- the panels are placed on the ground for better cooling and airflow through the space, and
- BFSPs that have the possibility of producing electricity from both sides of the panel are used.

When installing a PV plant on a rooftop, the difference in electricity production does not depend largely on whether the solar panels are BFSPs or half-cell MFSPs. The main reason behind this conclusion is that the rooftop reflection factors are very low in comparison with the ground floor, and the reflective sunlight is also very low. Regarding the monthly electricity generation, the half-cell MFSPs placed on the rooftop are more efficient only during the summer months of June, July, and August, while BFSPs are more efficient during the rest of the year.

7. Conclusions

In professional contexts, PV*SOL could be easily considered a standard analysis and design tool with a lot of auxiliary tools for calculations and simulations of PV systems. Therefore, in the PV industry, PV*SOL is a frequently used software tool for increasing productivity in the research, development, and analysis of various PV systems. Recently, much research is aimed at improving the efficiency of solar PV systems.

In this paper, we did several simulations using PV*SOL software to evaluate the difference in electricity production between PV plants built on the ground and the rooftop with BFSPs and half-cell MFSPs. For a single PV plant with an installed capacity of 1 MWp, the following conclusions were derived:

- For solar panels placed on the ground, due to better cooling conditions and air flow among them, the amount of expected electricity production is larger than that obtained by the same type of solar panels mounted on the rooftops for about 3% for BFSPs, and only 1.46% for MFSPs.
- BFSPs are superior to MFSPs for electricity production, especially when they are mounted on the ground. In the case of on-the-ground placement, they provide about 2.15% bigger electricity production, however, placed on the rooftop they provide a negligible increase of only 0.6%, which does not justify their utilization considering higher investment price.
- BFSPs could provide larger electricity production for rooftop mounted PV plants only during summer months, i.e., during June, July, and August, which does not make economic sense due to their higher prices.
- BFSPs have several manufacturing and exploitation benefits compared to MFSPs including longer life expectancy, that might somehow justify investments in BFSPs over MFSPs. However, for householders and small businesses, it is unlikely that BFSPs could support larger investments, especially if the PVs are planned to be installed on the rooftops.

To further confirm these conclusions, additional simulations are advisable based on different geographical conditions, especially those on higher elevation grounds and under various reflective surfaces, especially sandy and longer-term snowy surfaces.

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