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Research paper

PV Module Surface Area Maximisation for Enhancing Performance

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ABSTRACT

The amount of solar energy produced is directly proportional to the surface area of PV module exposed to solar irradiance. To increase the productivity of PV module, a number of techniques are proposed by curving the surface or protruding the PV module surface to maximise the surface area. The geometrical design analysis showed that, depending on the chosen surface curving method, the PV module can achieve a remarkable increase in surface area.

The system advisor model was used to assess a sample of solar cells with standard measurements of 6 by 6 inches that were organised in a zigzag pattern with different angles of curvation (10°, 15°, 20°, 25°, 30°, and 35°). Overall, the maximum power pump and annual AC energy performance increase by 1.4%, 4.2%, 6.8%, 10.8%, 14.9%, and 21.6%, respectively, over a one-year period of productivity. However, by applying the concept of solar PV module efficiency degradation due to tilting PV module at an angle by Mamun et al. (2022), for each 5° increase in tilt angle beyond the ideal 10°, the efficiency decreases by approximately 0.76%. In conclusion, the overall efficiency is greater than that of standard flat solar PV module, provided the curvation angle is within a reasonable range.

1. INTRODUCTION TO SOLAR PV MODULE TECHNOLOGY

Solar energy is a form of renewable energy derived from sunlight. Since there are no greenhouse gases produced throughout the process and fewer materials that could cause pollution are used, which could be harmful to our environment, as explained in an article by Ewim et al. (2023), it is therefore considered the cleanest type of renewable energy. Research and technological advancements are also driving growth in the renewable energy sector. Solar energy can be considered a basic human need that can be processed

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into secondary forms such as heat, light, and electricity, which has experienced considerable growth in Uganda, as well as worldwide as explained by Mugagga et al. (2019). In comparison, with other forms of renewable energy, solar and wind energy outperform other forms of renewable energy. Solar PV modules are a medium for converting solar energy into electricity using photovoltaic materials. This system is widely used in many fields, such as for powering rural schools, homes, etc, according to Behera et al. (2017) and Samad et al. (2013), for space-based fused deposition modelling (FDM) 3D printers powered by solar photovoltaics, according to Wong et al. (2015), and for solar-powered vehicles, according to Khan et al. (2018). This is generally because it is easily engineered and ecologically friendly and can reduce consumer dependence on state power companies. Further application of solar energy can be found in Parvez et al. (2024) on the energy, exergy, economic, and environmental evaluation of a trigeneration system for integrated power, cooling, and desalinating water fuelled by solar energy and in Hasan et al. (2019), who designed and built a solar thermal hybrid variable refrigerant flow (VRF) air conditioning system, estimated the system's energy savings, and contrasted it with a standard VRF system.

Despite advancements in technology, the most significant problem in solar energy systems is the rate at which sunlight is absorbed by solar PV module. The amount of sunshine that the solar PV module absorbs determines the amount of electricity that it can generate.

The relationship between sunlight energy and solar PV module design needs to be studied to increase the absorption rate of sunlight energy into solar PV modules. The simplest example of ensuring that a solar PV module absorbs sunlight is by considering the angle of installation, as explained by Zhong et al. (2020) and Chen et al. (2005). The best angle for solar PV module installation is important for maximum energy production. In addition to the angle, solar PV module design also covers the types and sizes of solar PV modules and solar PV module components. Different types of solar PV modules work perfectly in the same or different ways. Solar PV module components mainly determine the lifespan of the PV modules (Sodhi et al., 2022; Nehme et al., 2021). Proper solar PV module components can increase the absorption of sunlight (Eze et al., 2024; Majdi et al. 2021) and the longevity of solar PV modules e.g. advanced materials, cooling techniques, and smart solar PV modules tracking systems are used.

For the installation, after studying the relationship between solar PV module design and sunlight energy absorption, the angle is chosen by considering the environmental aspect and electricity requirements.

Optimisation techniques explained in Okello (2021), especially in solar energy, enables increased performance of solar PV modules and thermal collectors, such as those presented by Qazi et al. (2019).

Many high-quality solutions provide high solar yields in places such as shadow areas or non-optimal spatial conditions. Currently, the standard solar PV module installation angle is placed completely perpendicular to the ground, but at low latitudes, such as the equator, this assumption is sometimes incorrect.

El-Khozondar et al. (2024) conducted an analysis of different off-grid solar PV system architectures for the lighting of the Kuwaiti roundabout. They solve critical issues like power consumption, space constraints, and network load issues. They also provided novel solutions, such as dual-voltage lights and charge controllers, which identified optimal design techniques for roadway applications and have significance for sustainable urban illumination models.

Ubando et al. (2022) explored the idea of concentrated solar power, which is a form of sustainable energy that uses a solar concentrating device and a solar receiver to transform solar energy into electricity. They applied computational fluid dynamics to simulate concentrated solar power. They went on to thoroughly examine the optical models of solar concentrators such as hyperbolic and parabolic discs, as well as solar receivers.

Visa et al. (2015) designed an optimum solar thermal absorber for facade integration. The collector's isosceles trapeze design allows for a multicoloured absorption PV module. They investigated inside in steady-state settings and revealed an approximate performance of 62.38%, whereas the initial outdoor examination yielded a collector performance of 62%.

Cox et al. (1985) investigated many potentially beneficial characteristics in the conceptualisation of photovoltaic/thermal (PV/T) devices to establish their efficacy and interaction. Their research focused on air-type collectors with single-crystalline silicon photovoltaic cells. This research focuses on two major areas: improving solar absorptance and decreasing infrared emittance. The simulation results were then stated as follows. When combined with a gridded-back cell, a selective absorber affects the thermal efficiency of PV cells, which cover more than approximately 65% of the total collector area. The low-emissivity coating required an infrared radiation emissivity below 0.25 and a solar transmissivity of at least 0.85. The best combination for airborne PV/T was determined to be gridded-back PV cells, a nonselective tertiary absorber, and a high-trans-emissivity/low-emissivity covering across photovoltaic cells.

A computational model aimed at optimising the layout of polymer solar collectors with flat plates by Do Ango et al. (2013) revealed that solar energy absorbers are often constructed of copper or aluminium, and while they provide excellent efficiency, they are also expensive. In contrast, utilising polymers can increase the financial viability of solar collectors. They presented a numerical assessment of an innovative solar power collector construction to determine how the design variables (air gap thickness and collector length) and operational variables (mass flow rate, incident solar energy, and inlet temperature) affect efficiency. Their research showed the major trends in the key parameters that influence the efficiency of polymer flat plate solar collectors.

The electrical and thermal efficiencies of the PV/T system were superior to those of standard separated systems. According to Khare & Bunglowala (2020), the formula for calculating the power output of solar PV modules module is given as follows:

$$P = \eta V_m(t) I_m(t) \tag{1}$$

where P is the maximum power produced by a solar PV module with η solar modules and the maximum voltage V_m and maximum current I_m over time t.

If we maximise the surface area of the PV module, more modules can fit in the same PV module; therefore, an increase in η means that more power can be produced by the same solar PV module occupying the same space with the given fixed dimensions. This is especially useful for a confined space in which the demand for the maximum is high. For example, in a densely populated area in some parts of Africa, in an urban setting where people live in apartments or have small plots of land, they need electricity to drive their daily home activities, but often there are constant electric grid power outages, or in some parts of Africa, some areas are without electricity connected to the central grid supply. Therefore, the entire area is without electricity, rendering them reliant on alternative electricity sources such as solar energy due to its cost-effectiveness.

The amount of solar energy produced is directly proportional to the surface area of the solar PV module exposed to the solar irradiance, so challenges arise for the space required to install solar PV modules to achieve maximum coverage of solar radiation energy absorption in constricted spaces such as vehicles powered by solar or small residential apartments. The challenges with solar energy are that once a plate is installed, the space under it or above it cannot be used for another solar PV module installation. This is because the shadow cast by the above solar PV module or structure prevents solar irradiance from reaching the below solar PV module. The introduction of flexible solar PV modules that can take on any shape has given us the opportunity to explore the possibility of maximising the solar plate surface area using surface curving techniques. In this optimisation study, the constraint is that we have a space with fixed dimensions (length, width, and height), and the objective is to maximise the top surface area of the PV module within the given dimensions to maximise the solar PV module surface for sun energy absorption. This optimisation approach is possible due to the introduction of thin fabric printable and foldable solar PV modules, such as the one that was recently developed by MIT researcher "Paper-thin solar cells can turn any surface into a power source" by Adam Zewe (2022).

2. PV MODULE SURFACE AREA MAXIMISATION

In this paper, a number of mathematical techniques to maximize solar PV module surface area by curving it are presented. This is based on the proven concept that many scholarly works demonstrated that non-flat surfaces, such as on buildings (Tian et al., 2022) and on vehicles like buses (Adefila et al. 2025) and many more, when solar PV modules are placed on them, improve solar PV module productivity by a significant amount, as presented in their article.

Problem Definition: Given the constricted space (frame) shown in Figure 1, whose length, width, and height are fixed, a PV module that can fit in such a space with the maximum top surface area can be designed:

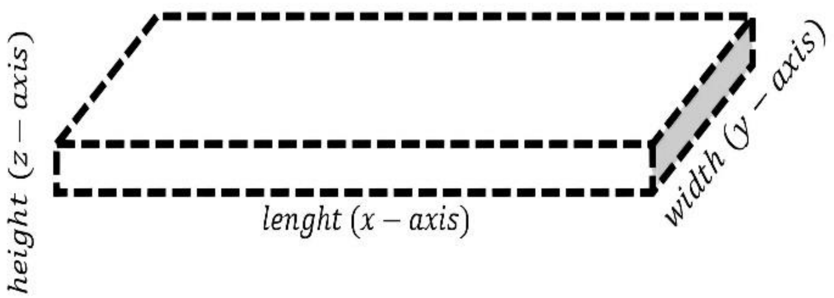
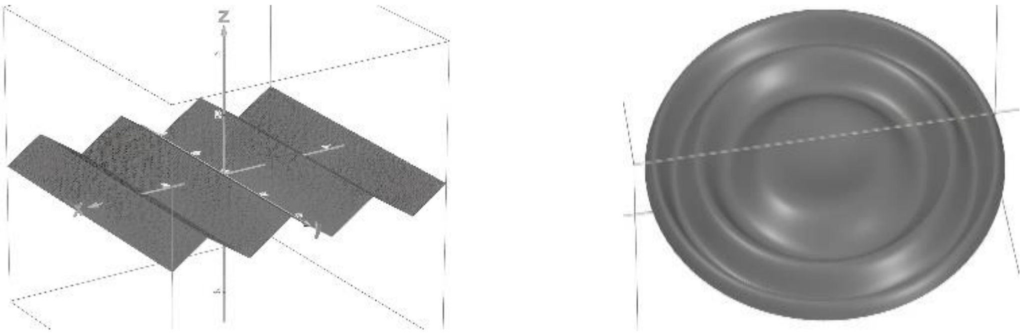


Fig 1. Dimensions of the flat PV module before surface curving

2.1 Curving surface (along x or y axis and radius r for a circle)

In this type of surface curve, one side of the plate, i.e., x-axis, is curved using either a wavy (2-i) or zigzag (2-ii) curve, as shown in Figure 2. However, y-axis is left straight (uncurved) treated as constant value. λ is the wavelength, and δ is the wave amplitude, which is an extension of the zigzag and wavy lines of Zhang & Hua (2024) into a surface curving. Given that z=f(x), or z=f(y), the curvation can be given as in (2): for circle whose radius is r function is described as z=f(r), range of the radius is from zero to c, and for circumscribing the circle is θ is between 0 to 360o or in radian is between 0 to 2π.

$$\begin{cases} Rectangle \begin{cases} f(x) = \frac{\delta}{2}\sin\left(\frac{2\pi}{\lambda}x\right) & (i) \\ f(x) = \frac{\delta}{\pi}\sin^{-1}\left(\sin\left(\frac{2\pi}{\lambda}x\right)\right) & (ii) \end{cases} \\ Circle \begin{cases} f(r) = \frac{\delta}{2}\sin\left(\frac{2\pi r}{\lambda}\right) \quad \forall\,(0<r<c);(0<\theta<2\pi) & (iii) \\ f(r) = \frac{\delta}{\pi}\sin^{-1}\left(\sin\left(\frac{2\pi r}{\lambda}\right)\right) \forall\,(0<r<c);(0<\theta<2\pi) & (iv) \end{cases} \end{cases} \quad (2)$$



Eqn (2-ii) Eqn (2-iii)

Fig 2. Sample 3D geometry design of eqn (2-ii) and eqn (2-iii)

To determine the surface area of the above equation (2), see equations (4) and (5).

2.2 Surface Curving (along x-axis and y-axis)

Another approach is to extend the above surface curving from the x-axis only to both the x-axis and y-axis. See equation (3), where z=f(x,y), and refer to figure 3, where uniform surface curving is presented in the equation. k is a constant value to ensure δ is the exact amplitude hight. k=2 for (5-i) and (2-ii). For (3-vi) k≈1.635. The value can be calculated separately for each equation. For equation in (2), k=1.

$$\begin{cases} f(x,y) = \frac{\delta}{2k}\left(\sin\left(\frac{2\pi}{\lambda}x\right) + \sin\left(\frac{2\pi}{\lambda}y\right)\right) & (i) \\ f(x,y) = \frac{\delta}{k\pi}\left(\sin^{-1}\left(\sin\left(\frac{2\pi}{\lambda}x\right)\right) + \sin^{-1}\left(\sin\left(\frac{2\pi}{\lambda}y\right)\right)\right) & (ii) \\ f(x,y) = \frac{\delta}{2k}\left(\sin\left(\frac{2\pi}{\lambda}(x+y)\right) + \sin\left(\frac{2\pi}{\lambda}(x)\right)\right) & (iii) \\ f(x,y) = \frac{\delta}{k\pi}\left(\sin^{-1}\left(\sin\left(\left(\frac{2\pi}{\lambda}(x+y)\right)\right) + \sin\left(\sin\left(\frac{2\pi}{\lambda}x\right)\right)\right)\right) & (iv) \\ f(x,y) = \frac{\delta}{k\pi}\left(\sin^{-1}\left(\sin\left(\left(\frac{2\pi}{\lambda}(x+y)\right)\right)\right) + \sin^{-1}\left(\sin\left(\sin\left(\frac{2\pi}{\lambda}x\right)\right)\right)\right) & (v) \\ f(x,y) = \frac{\delta}{k\pi}\left(\sin\left(\frac{2\pi}{\lambda}x\right) + \sin^{-1}\left(\sin\left(\frac{2\pi}{\lambda}y\right)\right)\right) & (vi) \end{cases} \quad (3)$$

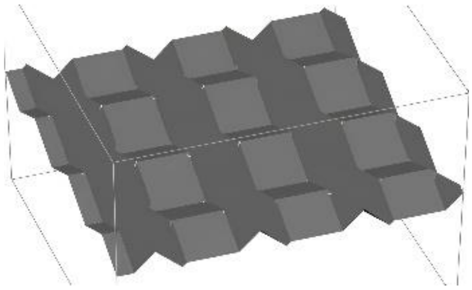


Fig 3. Sample 3D geometry design of equation (3-v)

2.3 Solution for determining the surface area

The surface area "S" of the above surfaces produced by curving along either or both the x-axis and y-axis from the equations (1) and (2) can be obtained by using the equation below.

Supposed the parameterization is define as as $R(x, y)$, where (x, y) varies in some region w in the plane.
Given a graph of $z = f(x, y)$. We can use scaler approach to find the equation for the surface area. Defining $R = (x, y, z)$ and substituting z, so that $R = \left(x, y, f(x, y)\right)$ and by taking partial derivative:

$$\frac{dR}{dx} = \left(1{,}0, \frac{df(x,y)}{dx}\right) \text{ and } \frac{dR}{dy} = \left(0{,}1, \frac{df(x,y)}{dy}\right)$$

Therefore, the surface integral is given as the magnitude of the cross product of the two partial derivatives:

$$S = \iint_w \left\| \left(1{,}0, \frac{df(x,y)}{dx}\right) \mathrm{X} \left(0{,}1, \frac{df(x,y)}{dy}\right) \right\| dxdy$$

$$= \iint_w \left\| \det\left(\begin{bmatrix} \hat{\imath} & \hat{\jmath} & \hat{k} \\ 1 & 0 & \frac{df(x,y)}{dx} \\ 0 & 1 & \frac{df(x,y)}{dy} \end{bmatrix} \right) \right\| dxdy$$

$$= \iint_w \left\| \left(-\frac{df(x,y)}{dx}\hat{\imath}, -\frac{df(x,y)}{dy}\hat{\jmath}, \hat{k} \right) \right\| dxdy$$

$$S = \int_{y_1}^{y_2} \int_{x_1}^{x_2} \sqrt{1 + \left(\frac{df(x,y)}{dx}\right)^2 + \left(\frac{df(x,y)}{dy}\right)^2}\, dxdy \qquad (4)$$

We can modify the above double integral for surface area (4) to a single integral along x-axis or y-axis, as shown below since one side either along x-axis or y-axis is a straight line which is a constant, therefor, partial derivative of the constant side is zero i.e. i.e. $\frac{df(x,y)}{dy} = 0$, and $f(x, y) = f(x)$ for straight line along y-axis or $\frac{df(x,y)}{dx} = 0$ for straight line along x-axis and $f(x, y) = f(y)$.. Overall, for both x-axis and y-axis is:

$$S = \int_{y_1}^{y_2}\int_{x_1}^{x_2}\sqrt{1+\left(\frac{df(x)}{dx}\right)^2}\,dxdy \quad \text{or} \quad S = \int_{y_1}^{y_2}\int_{x_1}^{x_2}\sqrt{1+\left(\frac{df(y)}{dy}\right)^2}\,dxdy \tag{5}$$

Or alternatively, we can just integrate one side (line integration) which is curving and multiply with the flat one side to find the surface area since it's a rectangle with curving one side. Supposed the curvation is along x-axis, y -axis is flat, so by defining $y = f(x)$ and $R = (x, y)$. Therefore, $R = \left(x, f(x)\right)$ So that by taking partial derivative, $\frac{dR}{dx} = \left(1, \frac{df(x)}{dx}\right)$. And by integrating the scaler over x, see below:

$$S = (y_2 - y_1)\int_{x_1}^{x_2}\left\|\left(1, \frac{df(x)}{dx}\right)\right\| dx = (y_2 - y_1)\int_{x_1}^{x_2}\sqrt{1+\left(\frac{df(x,y)}{dx}\right)^2}\,dx \tag{6}$$

More details of vector product in R² space is included an article by Walter, (1996). Furthermore, the surface area of a curve along the radius of a circle r can be calculated as follows:

Similar to the way of finding (5), Defining $R = \left(r, f(r)\right)$ So that; $\frac{dR}{dr} = \left(1, \frac{df(r)}{dr}\right)$.

$$S = \pi\left(\int_0^r \sqrt{1+\left(\frac{df(r)}{dr}\right)^2}\,dr\right)^2 \tag{7}$$

Further details can be found in an article by Feldman et al. (2017). This solution can be obtained numerically using MATLAB or any other numerical solver.

3. SOLAR PV MODULE PERFORMANCE USING SYSTEM ADVISOR MODEL

In this subsection, an analysis using the System Advisor Model is provided based on a simplified geometry. The SAM has been extensively used to simulate solar energy by many scholars, for instance, by Salem et al. (2004), because it provides real-world solar energy data. Here, concentrated solar energy is used. Equation (1-ii) is used for this simulation. See Figure 7 for solar cell setup which arranged in zigzag pattern at an angle θ of elevation.

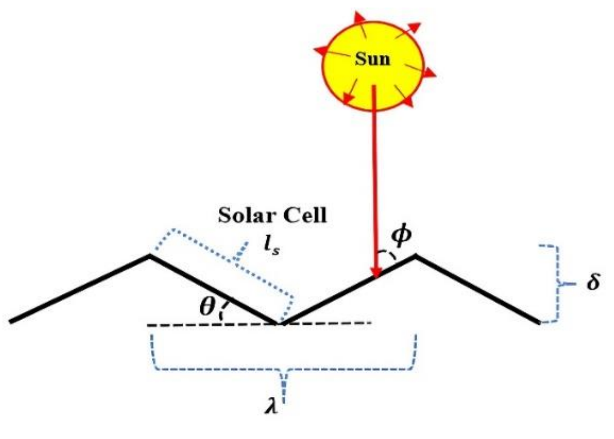


Fig 4. Alignment of solar cells within a solar module following the zigzag equation (1-ii) in Fig 2

The size of solar PV module varies depending on the brand, but typically a residential PV module is 5.5 feet by 3 feet (167.64 cm by 91.44 cm), and a commercial PV module is 6.5 feet by 3 feet (198.12 cm by 91.44 cm), which is roughly a foot longer. However, for this study, commercial solar PV module dimension is used having roughly 72 cells

The standard dimensions of a solar cell are approximately 6 by 6 inches, which is approximately (15.6 cm by 15.6 cm) surface area 243.36 cm^2. So, the length and width of the solar cell are *ls*=15.6 cm, *ws*=15.6 cm.

$$\lambda = 2l_s \cos\theta \qquad \forall\ 0^o \le \theta < 90^o \tag{8}$$

where θ is the angle of elevation of the solar cell, as shown in Figure 4.

$$\delta = l_s \sin\theta \quad \forall\ 0^o \le \theta < 90^o \tag{9}$$

By substituting (8) and (9) into 2-ii) we get (10).

$$f(x) = \frac{l_s \sin\theta}{\pi}\left(\sin^{-1}\left(\sin\left(\frac{\pi x}{l_s \cos\theta}\right)\right)\right) \qquad \forall\ 0^o \le \theta < 90^o \tag{10}$$

Solution of the above equation when $\theta = 10^o, 15^o, 25^o, 30^o, 35^o$, $x_1 = 0, x_2 = 198.12\ cm$, and $y_1 = 0, y_2 = 91.44\ cm.$

Solution

The first approach is to use the integration approach provided in equation (6) using the equation (10). The floor function ⌊x⌋ is to remove any decimal point number to ensure that we have an exact number that accommodates solar cells not having half or less than one solar cell. So total number of solar cells Nη in a given solar module is given as below.

$$N_\eta = \left\lfloor \frac{\int_{x_1}^{x_2}\int_{y_1}^{y_2}\sqrt{1+\left(\frac{d}{dx}\left[\frac{l_s \sin\theta}{\pi}\left(\sin^{-1}\left(\sin\left(\frac{\pi x}{l_s \cos\theta}\right)\right)\right)\right]\right)^2}\,dy\,dx}{l_s w_s} \right\rfloor \quad \forall\ 0^o \le \theta < 90^o \tag{11}$$

However, we can use direct calculation without using integration for solving equation (11) to find the total solar cells that fit within a given space. Please note that solution (12) is specifically for solving equation (10) and (11) shown in figure 7, any other function apart from (10) will require different solution design.

$$N_\eta = \left\lfloor \frac{(x_2 - x_1)(y_2 - y_1)}{l_s w_s \cos\theta} \right\rfloor \qquad \forall\ 0^o \le \theta < 90^o \tag{12}$$

According to Table 1, the calculated solar PV module having flat surface area is 18,116 cm^2, with 74 solar cells having a maximum power pump of about 338 kW dc and an annual AC energy 1-year for flat surface solar PV module of 2155 GWh. According to an article by Mamun et al. (2022), the overall solar PV module efficiency is downgraded when tilted at an angle to the source radiation, i.e., the sun; it decreases by approximately 0.76% for every 5° increase in the angle of the solar tilted for an outdoor solar PV module from 15o. Therefore, in Table 1, the Annual AC Energy kWh is decreased by 0.76%

for every 5° increase in the solar curved angle θ to determine the approximate solar efficiency decrease in performance. In Table 1, $\phi = 90^o - \theta$. For angle θ < *15°* is considered insignificant to affect solar PV module productivity for solar mounted on tracker. Given initial flat solar PV module Annual Energy $A_0 \approx 2155$ GWh. For this case the angle is incremented by 5o, such that (θ+=*5°*).

$$A_j = \frac{A_{j-1}(100-0.76)}{100} \qquad \forall\ 1 \le j < \left\lfloor \frac{\theta - 10^o}{5^o} \right\rfloor\ , (\theta > 10^o) \tag{13}$$

Table 1. Increase in the Maximum Power Pump and Annual AC Energy of Zigzag Solar PV modules from Figure 4

θ	ϕ	Surface Area cm^2	Number of cells	Max Power Pump Wdc	Annual AC Energy kWh	Percentage Increase before efficiency issue	Approximate Percentage Increase after efficiency issue
10º	80º	18395.56	75	342729.350	2184022016	1.4%	1.4%
15º	75º	18755.16	77	351868.800	2242262272	4.1%	3.26%
20º	70º	19278.74	79	361008.249	2300503040	6.8%	5.14%
25º	65º	19988.90	82	374717.423	2387863808	10.8%	8.31%
30º	60º	20918.66	85	388426.597	2475224832	14.9%	11.41%
35º	55º	22115.66	90	411275.221	2620826368	21.6%	17.07%

This is done repeatedly for all value of j to find the final approximate Productivity after efficiency issue has been removed which is $A_{\left\lfloor \frac{\theta-10^o}{5^o} \right\rfloor}$.

Figure 5, show sample figure taken from the SAM simulation software using the system advisor model SAM when the total number of cells in a module was set to 122; this was calculated using equations (11) and (12) when the angle $\theta = 35^o$.

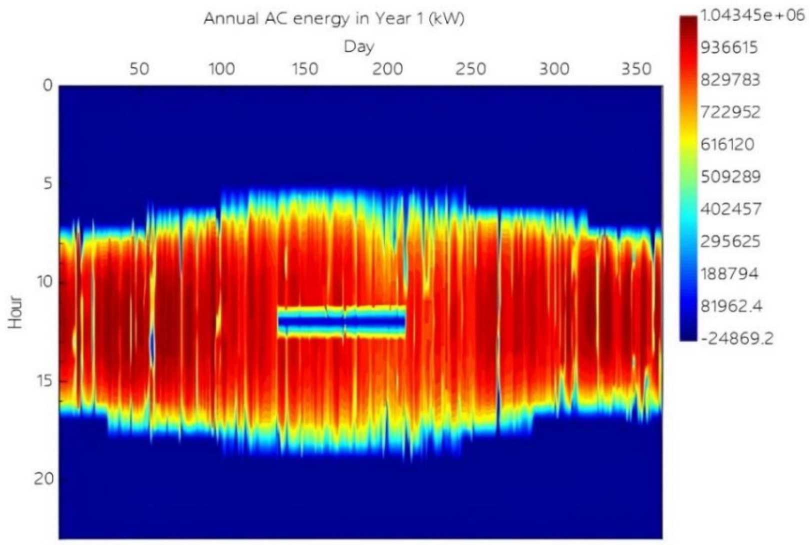


Fig 5. Annual AC energy in one year in KW for the total cell in a module is 90, θ=35° and single cell surface area is 243.36 cm².

By using the above equation (8) and (9), we can substitute all of the equations in (1) and (2). See sample of zigzag PV module on both x and y axis from equation (2-ii), see the modification below (14).

$$f(x,y) = \frac{l_s \sin\theta}{2\pi}\left(\sin^{-1}\left(\sin\left(\frac{\pi x}{l_s\cos\theta}\right)\right) + \sin^{-1}\left(\sin\left(\frac{\pi y}{l_s\cos\theta}\right)\right)\right) \quad \forall\ 0^o \leq \theta < 90^o \qquad (14)$$

By using the angle approach given above, we can design the scenario from figure 4 for zigzag to wavy curve like in figure 6 below where $\varphi = (180^o - 2\theta)$ and $(\phi = 90^o - \theta)$.

This wavy curvation means not all parts are inclined to the sun's rays at an angle θ, like the top or bottom, which receives direct sunlight. So overall, this design experiences less efficiency problems due to curvation than the design in Figure 4 using zigzag. Regions of curved solar PV module in figure 6 dotted with red received solar irradiance angle ≈ϕ while for other region receive at angle >ϕ. On top and bottom region of curve when $\frac{df(x)}{dx} = \theta = 0;\ \phi = 90^o$.

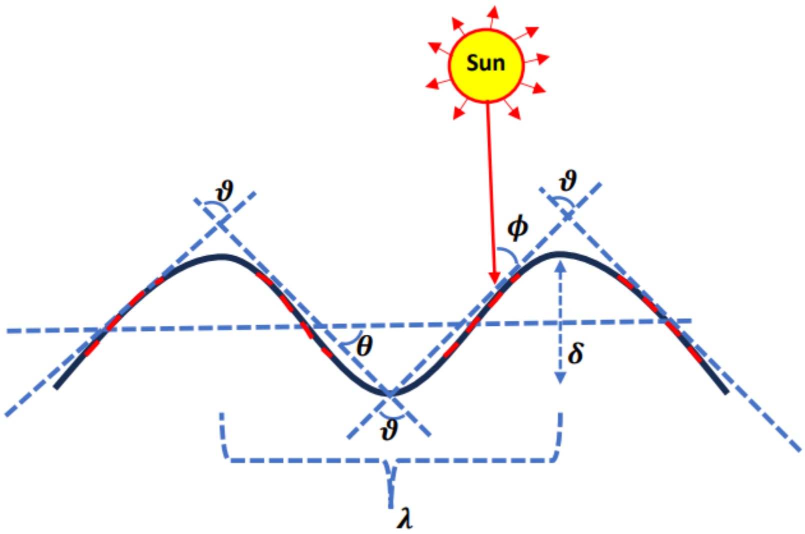


Fig 6. Wavy Curved Solar Surface based on Equation (2-i) when tangential angle θ of inclination is applied in (8) and (9) Just like in Figure 4.

4. DISCUSSION

Although having a curved surface increases the surface area of a given plate and maximises solar energy output, it should be noted that the solar plate angle of inclination to the source of solar energy (the sun) for maximum energy output varies, but mostly solar rays from the sun should be perpendicular to the plate surface, i.e., when ϕ=90°.

This presents a problem with the proposed method in that, due to the curved surface, for some parts of the curved surface, even if the entire solar plate is set facing the sun directly using a tracker, some parts of the curved surface will be tilted at an angle to the solar irradiance, i.e., ϕ<90^o, which may cause reflection and cast shadows on the neighbouring curved surface parts, reducing the energy absorption rate and efficiency of the solar PV module. A protruding surface with a sharp pointing surface may not be good because it can be prone to breakage when hit, for instance, cone, pyramidal, or zigzag curved solar PV module surface. Therefore, a gentle, curved protruding surface, such as a hemisphere or wavy curve, is a better choice.

4.1 Comparison of the Proposed Solar Design to a Flat Solar PV module

The proposed method enables solar PV module to gain more surface area that is exposed to the sun's rays, hence increasing their absorption rate and, consequently, their entire solar energy production efficiency.

For a conventional flat-surface solar PV module, the surface area of the PV module is exactly the same as the surface area exposed to the sun; hence, it has a smaller surface area in comparison to the proposed method of curving the surface of the solar PV module.

On the other hand, curving the surface of the solar PV module reduces the efficiency and productivity of the PV module because some parts of the surface are not directly exposed to the sun. This in turn causes a decrease in solar efficiency, although overall, the decrease does not affect overall performance, which may still outperform that of the conventional flat solar PV module design. This is evidenced in Tian et al. (2022) and Adefila et al. (2025) where they presented studies on the curved solar surface which provide better productivity than flat surface solar PV module.

4.2 Impacts of the research results on the economy, environment, and society

Solar power plants, compared to other energy sources, are not harmful to the air, water, or greenhouse gas emissions. Solar power plants can contribute to society and the environment by replacing harmful, non-renewable energy sources. Furthermore, economically, it reduces the cost of being dependent on non-renewable energy sources that are expensive, such as oil, coal, and the nation's power grid, since solar energy is abundantly available at zero cost except for purchasing equipment.

4.3 Challenges and future research extensions

The immediate challenge of this proposed method is that a curved solar surface means that the angle at which solar irradiance hits the solar plate surface is not uniform. Therefore, based on the work of Mamun et al. (2022), the overall solar PV module efficiency decreases when tilted at an angle to the source radiation, i.e., the sun; it decreases by approximately 0.76% for every 5° increase in the angle of the solar tilted for an outdoor solar PV module. This means that some parts of the curved solar surface may experience efficiency issues due to the lower angle ϕ, which subsequently decreases its performance. Overall, solar PV module with curved surfaces having larger angles ϕ and smaller angles θ will have greater efficiency than those with flat surfaces.

The curvature angle θ should be small, or else the solar PV module efficiency will decrease to less than that of a flat solar PV module. And this type of solar needs to be mounted on a tracker to keep it upright, following the sun, to maintain efficiency. Furthermore, maximum θ beyond which the solar PV module efficiency Is equal to or less than that of flat solar PV module need to be determine in future research practically. In addition, the solar PV module needs to be mounted on a tracker to maximise efficiency under maximum curvation.

5. CONCLUSION

A solar PV module with a curved surface can have a remarkable increase in surface area relative to its original flat surface area, depending on the chosen curvature method, as demonstrated in Tables 1, 2 & 3. This increases its surface area for maximising sunlight energy absorption, resulting in an increase in overall solar PV module productivity.

Samples of solar cells with standard measurements of 6 by 6 inches set in zigzag patterns with varying inclination angles of 10°, 15°, 20°, 25°, 30°, and 35° were analysed using a system advisor model. The performance measurements of the maximum power pump and annual AC energy for 1 year achieved overall productivity increases of 1.4%, 4.2%, 6.8%, 10.8%, 14.9%, and 21.6%, respectively. However, by applying the concept of solar PV module efficiency degradation due to tilting solar PV modules by Mamun et al. (2022), for each 5° increase in tilt angle beyond the ideal of 10°, the efficiency decreases by approximately 0.76%. In conclusion, the overall efficiency is greater than that of standard flat solar PV modules provided the tilt angle is within a reasonable range.

COMPETING INTERESTS

The authors declare no conflicts of interest. This work initially was published in MDPI Preprint (Okello, 2024).

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