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# Solar harvesting through multiple semi-transparent cadmium telluride solar panels for collective energy generation

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ABSTRACT

Among major energy conversion methods, photovoltaic (PV) solar cells have been the most popular and widely employed for a variety of applications. Although a PV solar panel has been shown as one of the most efficient green energy sources, its 2D surface solar light harvesting has reached great limitations as it requires large surface areas. There is, therefore, an increasing need to seek solar harvest in a three-dimensional fashion for enhanced energy density. In addition to a conventional 2D solar panel in the x-y area, we extend another dimension of solar harvesting in the z-axis through multiple CdTe solar panels arranged in parallel. The high transparency allows sunlight to partially penetrate multiple solar panels, resulting in significantly increased solar harvesting surface area in a 3D fashion. The advantages of the 3D multi-panel solar harvesting system include: i) enlarged solar light collecting surface area, therefore increased energy density, ii) the total output power from multiple panels can exceed that of the single panel, and iii) significantly reduced surface area needed for densely populated cities. With five CdTe solar panels of different transparencies in parallel, the multilayer system can produce collective output power 233% higher than that of the single solar panel under the same surface area when arranged in descending (i.e., PV panel with the highest transparency on top and lowest at bottom). The PCE of the multi-panel system has also increased 233% in descending order indicating the viability of 3D solar harvesting. The multi-panel system will dimensionally transform solar harvesting from 2D to 3D for more efficient energy generation.

## 1. Introduction

To address critical energy issues, utilization of solar energy has emerged as a primary approach to produce clean energy, offering numerous technical, environmental, and ecological advantages [1–9]. Among the various energy conversion methods available, photovoltaic (PV) solar cells have gained significant popularity and have been widely employed for diverse applications. However, despite the proven efficiency of PV technology as a green energy source, its two-dimensional (2D) surface solar harvesting is confronted with significant limitations. One of the key limitations of 2D solar harvesting is the considerable amount of land required for large-scale implementation. According to the National Renewable Energy Laboratory, meeting the entire electricity demands of the United States solely through photovoltaic solar energy would necessitate approximately 1,948 square feet per person [10]. This vast land requirement poses challenges, particularly in densely-populated areas and megacities where suitable land for solar cell installations is limited. The scarcity of available land inhibits the widespread adoption of PV technology, hindering its potential to fully address the energy needs of highly populated regions.

Furthermore, the flat configuration of 2D solar panels restricts the amount of solar energy that can be harnessed. Solar panels have a fixed orientation, typically aligned with the sun's azimuth and elevation angles, to optimize sunlight absorption. However, this design limits the panels' exposure to sunlight, as they can only capture solar radiation during specific hours of the day when the incident angle matches the optimal alignment [11]. Consequently, the energy yield from 2D solar harvesting systems is subject to daily and seasonal variations, leading to inefficiencies and reduced overall energy output. To overcome these limitations, there is an increasing need to explore solar harvesting in a three-dimensional (3D) fashion to enhance energy density and address land constraints. By utilizing the vertical space available, 3D solar harvesting enables the installation of solar panels on building facades, rooftops, and other vertical surfaces. This approach not only maximizes

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solar energy utilization but also optimizes land usage, making it particularly suitable for densely-populated urban areas. Implementing 3D solar harvesting technologies would greatly expand the potential for solar energy generation and help meet the increasing energy demands of modern societies. Embracing 3D solar harvesting technologies would not only enhance energy density but also promote the widespread adoption of photovoltaic solar cells in densely-populated regions, leading to a more sustainable and efficient energy future.

Building Integrated Photovoltaics (BIPV) is a rapidly emerging technology that combines solar energy generation with architectural design, allowing buildings to generate electricity while maintaining a visually appealing appearance [12–15]. By integrating transparent PV panels into various building elements such as windows, skylights, facades, and roofs, BIPV systems effectively convert sunlight into electricity while still allowing natural light to pass through. The transparent solar panels used in BIPV systems are typically thin-film solar cells that possess transparency to visible light. When these transparent PV panels are arranged in parallel, several advantages are realized. Firstly, the enlarged solar harvesting surface area allows for capturing a greater amount of sunlight, increasing the overall energy generation potential of the BIPV system. The parallel arrangement ensures that the panels collectively receive sunlight from various angles throughout the day, maximizing the solar energy conversion. Secondly, the parallel arrangement of transparent PV panels helps in optimizing the energy generation efficiency. Although light power density may decrease across several transparent solar panels, multiple outputs of electricity will exceed that by the single panel. The parallel arrangement of transparent solar panels also allows for better integration into the building design. Architects and designers can have greater flexibility in incorporating these panels, whether as windows, skylights, or as part of the building's facade. This flexibility ensures that BIPV systems can seamlessly blend with the overall aesthetics of the structure, promoting the adoption of solar energy generation in architectural projects. Building Integrated Photovoltaics with multiple transparent solar panels arranged in parallel holds great potential for revolutionizing the way we generate and utilize solar energy. By combining energy generation with architectural design, BIPV systems can help create sustainable, energy-efficient buildings while reducing reliance on fossil fuels and contributing to a cleaner and greener future.

Transparent solar cells have gained significant attention in recent years as a promising technology for integrating solar energy harvesting into various applications while maintaining transparency [16–20]. Among the various materials explored for transparent solar cells, cadmium telluride (CdTe) has emerged as a noteworthy candidate due to its unique structure, desirable properties, and high photon conversion efficiency (PCE) [21–26]. The structure of transparent CdTe solar cells typically involves a thin-film configuration. CdTe, a compound semiconductor, is deposited as a thin layer onto a transparent substrate such as glass or plastic. The thin-film structure enables the transmission of visible light while simultaneously capturing and converting solar energy into electricity. To enhance the performance of CdTe solar cells, various strategies are employed, including the incorporation of transparent conducting oxide (TCO) layers and optimizing the CdTe film thickness [27–30]. The processing procedure for making laminated window glass using CdTe involves modifying standard CdTe panels with two additional steps: laser ablation and modified lamination [27]. These steps are implemented to achieve semi-transparency and enhance the aesthetics of the panels, while also providing protection to the thin-film semiconductor and ensuring the safety and robustness of the module structure.

Fig. 1 schematically illustrates the concept of solar harvesting via multiple transparent/semi-transparent solar panels. As shown in this figure, these solar panels can be arranged in parallel, significantly enlarging the solar light harvesting area. If the average visible transmittance (AVT) can be kept at a level on the order of 40–80 %, substantial solar light can penetrate all solar panels, reaching the one at bottom for collectively generating electricity [31]. In this fashion, all solar panels can generate electricity under the limited surface area only from the top solar panel enabling solar harvesting vertically for enhanced overall energy generation. If successful, this multiple solar panel assembly will dimensionally transform solar harvesting from 2D to 3D, effectively increasing energy density within a finite volume. The combined electricity from multiple solar panels will exceed that of the single layer, reaching magnitude of increase in output power. In this study, we carried out I-V curve measurements on five commercial CdTe solar panels with different transparencies: 40 %, 50 %, 60 %, 70 %, and 80 %. These CdTe solar panels were arranged in parallel (Fig. 1) with descending and ascending of transparency for determining their I-V characteristics including maximum output power and PCE.

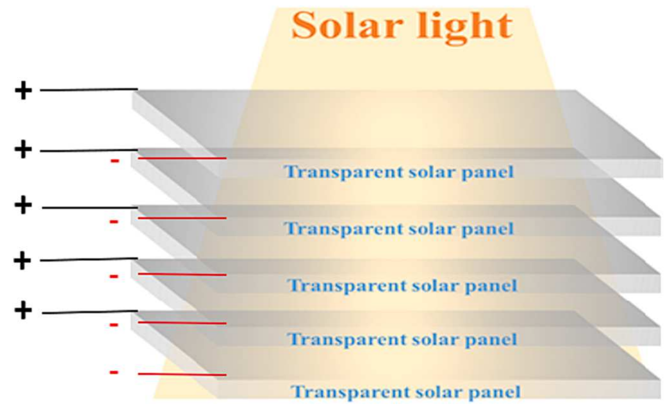


**Fig. 1.** Schematic diagrams showing the concept of 3D solar light harvesting via multiple transparent solar panels.

## 2. Experimental details

Five commercial CdTe solar panels (Solar First Technology Co) with 150 × 150 $mm^2$ dimensions were used in this study for I-V measurements. These five solar panels have different average visible transmittance (AVT): 80 %, 70 %, 60 %, 50 %, and 40 %, respectively. The SourceMeter instrument was connected to the Device Under Test (DUT), which in this case refers to the CdTe panels. The sourcing mode was configured as a voltage source to enable voltage sweeping for the purpose of obtaining an I-V curve. The voltage sweep range started from 0 V and concluded at 20 V. The SourceMeter measures the current flowing through the DUT at each voltage step, with a total of 400 steps performed throughout the experiment.

The resulting dataset generated from the voltage sweep was utilized to calculate important parameters such as Voc (Open-Circuit Voltage), Isc (Short-Circuit Current), $P_{max}$ (Maximum Power), F.F (Fill Factor), and PCE (Photon Conversion Efficiency). It is important to note that not all of the data points from the voltage steps were utilized for analysis. Only the data ranging from Isc to Voc was considered. For plotting purposes, the absolute values of the current data points falling between Isc and Voc were considered. Fig. 2 shows the I-V curves obtained from these CdTe solar panels and the I-V parameters are summarized in Table 1. As shown in Table 1 and Fig. 2, all CdTe panels exhibit consistent PCE values according to their AVTs. These experimental data are also consistent with data sheet provided by the company.

Following the analysis of the individual panels, the five CdTe panels were stacked in two different orders: Ascending and Descending. An optical power meter was positioned beneath the panel being tested to determine the light power density that reached the panels positioned below it. This setup allowed for the measurement of I-V curves and light power density for all the panels within the stack. Furthermore, a thermal camera was used to monitor the temperature of the CdTe panels.

Fig. 3a shows a photograph of the 80 % CdTe solar PV panel. As

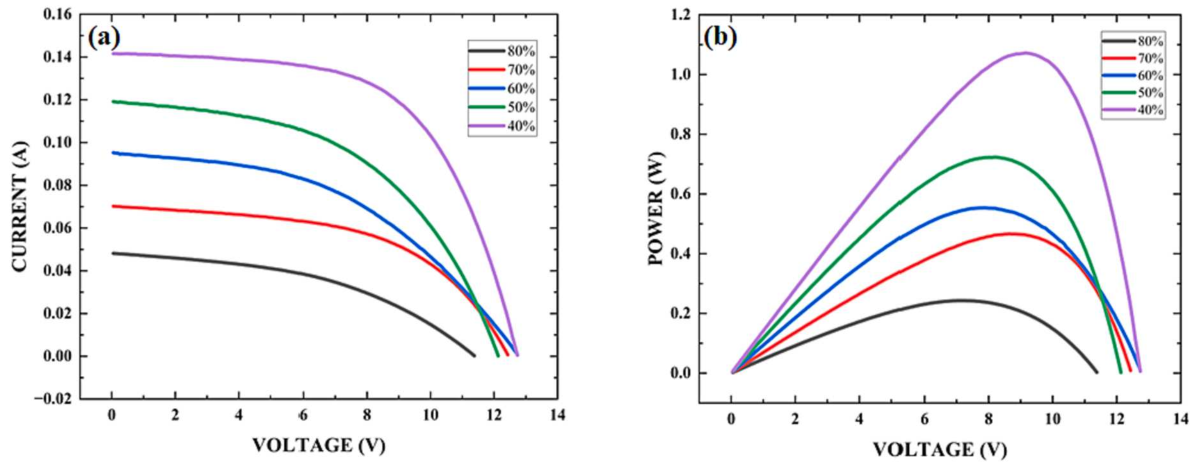


**Fig. 2.** (a) I-V curves and (b) output power of CdTe solar panels with different transparencies.

**Table 1**
I-V parameters of CdTe solar panels with different transparencies.

| Solar Panel AVT | $V_{OC}(V)$ | $I_{SC}(A)$ | $P_{MAX}(W)$ | F.F | P.C.E | Light Power Density (mW/cm$^2$) |
|---|---|---|---|---|---|---|
| 40 % | 12.732 | 0.141 | 1.072 | 0.594 | 8.60 % | 55.4 |
| 50 % | 12.130 | 0.119 | 0.723 | 0.500 | 5.80 % | 55.4 |
| 60 % | 12.732 | 0.095 | 0.553 | 0.456 | 4.44 % | 55.4 |
| 70 % | 12.431 | 0.070 | 0.466 | 0.534 | 3.74 % | 55.4 |
| 80 % | 11.378 | 0.048 | 0.242 | 0.443 | 1.94 % | 55.4 |

shown in this figure, the 80 % panel exhibits high transparency. These CdTe solar panels are stacked on top of each other with transparency in descending order: 80 %, 70 %, 60 %, 50 %, and 40 % which is denoted as descending order (Fig. 3b). In this fashion, the top 80 % panel harvests most of the photons and passes them to the next one with 70 % transparency. The bottom one has the lowest transparency (40 %) but the highest PCE. We also measured the I-V curves with a different transparency in ascending order, i.e., 40 %, 50 %, 60 %, 70 %, and 80 % (Fig. 3c). In this fashion, the 40 % panel is placed on the top which has the highest PCE. The measurement setup for I-V characterization is shown in Fig. 3d. The I-V measurements were conducted in open air under sunny weather on June 26, 2023, at 13:00, on the main campus of University of Cincinnati (Location: outside of Rhodes Hall). The power density was measured by using an optical power meter (Newport Inc. Model 1919-R). The I-V curve measurement was performed by using Keithley 2400 Source Meter.

Although there has been extensive research on I-V measurement of solar panels, few was conducted by using the multiple transparent solar panels stacked in parallel as shown in Fig. 3. It is highly possible to harvest solar light via multiple transparent solar panels for further increasing the system output power with the same incoming light power per unit area. By stacking multiple solar panels together, energy will be generated collectively.

The photon conversion efficiency (PCE) of solar panel can be calculated using the following equation:

$$\eta_{PV} = \frac{P_{out}}{P_{in}} = \frac{I_{SC}V_{OC}FF}{P_{in}} \quad (1)$$

where $P_{out}$ is output power, $P_{in}$ is input power, $I_{SC}$ is short − circuit current, and $V_{OC}$ is open − circuit Voltage. We denote $I_{MP}$ the current density at maximum power, $V_{MP}$ the voltage at maximum power, $P_{max}$ is the maximum output power, and FF is fill factor. It should be noted that $P_{in}$ used to determine PCE is the light power density on each PV panel. Due to multiple solar panels, the light power density on the PV surface also varies. Nonetheless, there will be additional output power from the PV panels beneath the top one giving an overall $P_{out}$ exceeding that of the single PV panel.

## 3. Experimental results

As some of these CdTe solar panels are only semi-transparent, there will be considerable light attenuation after passing through different panels. We therefore first determined light powder density at each solar panel by using an optical power meter. Table 2 enlists the light power densities at different solar panels. As shown in this table, in descending order, on the top solar panel, the light power density (LPD) reaches 55.4 mW/cm$^2$. LPD decreases considerably on the second solar panel,

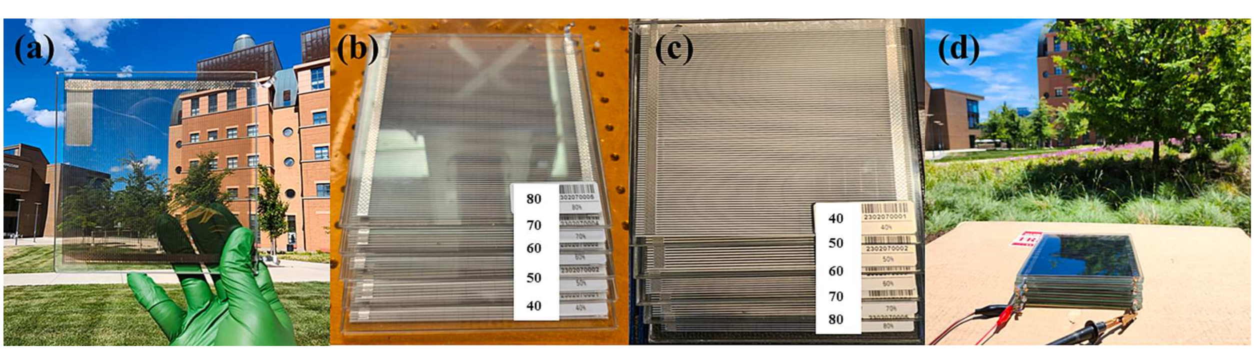


**Fig. 3.** Photographs of (a) 80% CdTe solar panel on campus; (b) five CdTe solar panels stacked in parallel with descending transparency: 80%,70%,60%,50%, 40%, (c) five CdTe solar panels stacked in parallel with ascending transparency: 40%,50%,60%,70%, 80%, (d) I-V measurement set for five CdTe solar panels stacked in parallel (experimental date: June 26, 2023, location: outside of Rhodes Hall on the main campus of University of Cincinnati).

**Table 2**
Light power densities of parallel solar panels in descending and ascending orders.

| Solar Panel | Light Power Density (mW/cm$^2$) |
|---|---|
| PANEL 1 (80 % AVT) | 55.40 |
| PANEL 2 (70 % AVT) | 44.32 |
| PANEL 3 (60 % AVT) | 31.02 |
| PANEL 4 (50 % AVT) | 18.61 |
| PANEL 5 (40 % AVT) | 9.31 |
| **Solar Panel** | **Light Power Density (mW/cm$^2$)** |
| PANEL 1 (40% AVT) | 55.40 |
| PANEL 2 (50% AVT) | 22.16 |
| PANEL 3 (60% AVT) | 11.08 |
| PANEL 4 (70% AVT) | 6.65 |
| PANEL 5 (80% AVT) | 4.65 |

however, remains an appreciable value at 44.32 mW/cm$^2$. On the 3rd and 4th layers, LPD decreases to 31.024 mW/cm$^2$ and 18.614 mW/cm$^2$, respectively. On the 5th (the bottom) solar panel, LPD can still register 9.307 mW/cm$^2$. This data indicates that the natural sunlight can penetrate all panels underneath, reaching the one at the bottom. In ascending order, due to placing the 40 % panel on the top, LPD decreases more rapidly, but remains appreciable values at all panels underneath, responsible for producing electricity collectively at different levels.

The I-V curves and output powers obtained from descending order are shown in Fig. 4. As shown in this Fig. 4a, the I-V curves are consistent with the light power densities on each solar panel with panel 1 (the top panel) at 55.4 mW/cm$^2$. $I_{SC}$ then decreases from each solar panel underneath in a descending order, but all remain appreciable values. Fig. 4b shows the output powers from each panel as calculated using Equation (1). These values are summarized in Table 3 based on the I-V measurements shown in Fig. 4.

Due to considerable transparency of these solar panels, each one can register appreciable numbers of photons as indicated in Table 3. As shown in Table 3, the light power density under the given condition can reach 55.4 mW/cm$^2$ on the top panel. It drops to 44.3 mW/cm$^2$ at the second panel, a reduction of only 20 %. It then decreases to 31.024 mW/cm$^2$ and 18.614 mW/cm$^2$ on the 3rd and 4th panel, respectively. On the 5th panel, the light power density remains at 9.307 mW/cm$^2$. However, despite considerable light power intensity reduction, the maximum output powers appear to remain at considerable levels as shown in Table 3. As shown in Table 3, the maximum output power has reached 0.235 W on the top panel with 80 % AVT which is consistent with the single layer measurement (Fig. 1 and Table 2). Interestingly, on the second panel (70 % AVT), $P_{max}$ is 0.302 W, higher than that of the top panel under considerably reduced light intensity (44.32 mW/cm$^2$). This can be explained by the higher PCE of the 70 % panel (3.74 %) compared

**Table 3**
The I-V curve parameters of multiple CdTe solar panels in descending order.

| Solar Panel AVT | $V_{OC}(V)$ | $I_{SC}(A)$ | $P_{MAX}(W)$ | F.F | P.C.E | Light Power Density (mW/cm$^2$) |
|---|---|---|---|---|---|---|
| 80 % | 10.977 | 0.047 | 0.235 | 0.452 | 1.89 % | 55.400 |
| 70 % | 10.928 | 0.048 | 0.302 | 0.880 | 3.02 % | 44.320 |
| 60 % | 10.927 | 0.019 | 0.110 | 0.511 | 1.57 % | 31.024 |
| 50 % | 9.223 | 0.019 | 0.090 | 0.508 | 2.16 % | 18.614 |
| 40 % | 9.624 | 0.007 | 0.047 | 0.664 | 2.24 % | 9.307 |

to that of the 80 % panel (1.94 %).

On the 3rd (60 %) and 4th (50 %) panel, the $P_{max}$ is reduced to about ~ 0.1 W. On the 5th (40 %) panel under only 9.307 mW/cm$^2$ light intensity, $P_{max}$ has dropped to 0.047 W. Although the $P_{max}$ decreases due to reduced incoming light power intensity, each panel can yield finite output power, the net power output of the entire stack has reached 0.786 W. This means that with the same solar harvesting surface area, a stack of CdTe solar panels arranged in descending order can produce 233 % more output power than that of the single solar panel with AVT of 80 %, indicating the viability of 3D solar harvesting via multiple transparent/semi-transparent panels, capable of much more efficient energy generation.

The I-V curves and output powers obtained from solar panels in ascending order are shown in Fig. 5. As shown in Fig. 5a, the I-V curves are also consistent with the light power densities on each solar panel with the 40 % panel on the top having the largest PCE. Since the 40 % panel has the highest PCE (9.60 %), $P_{max}$ has reached 1.197 W (Table 4), greater than that of the 80 % panel on top (0.235 W) under the same light power density (55.40 mW/cm$^2$). However, due to the lowest transparency at 40 %, Isc values of all panels underneath drastically decrease to much lower levels as shown in Table 4. Accordingly, the corresponding $P_{max}$ values are also much lower as shown in Fig. 5b. These results are consistent with the lowered light power densities (Fig. 4). Interestingly, the net $P_{max}$ of five solar panels in ascending order has reached 1.440 W, even higher than that of the descending order (0.786 W). A stack of CdTe solar panels arranged in ascending order can produce 20 % more output power compared to a single solar panel (AVT: 40 %).

## 4. Discussion

The experimental results presented in this study highlight the potential of solar harvesting and energy generation using multiple transparent/semi-transparent solar panels. The considerable transparency of these panels enables them to each register a significant number of photons, indicating their ability to effectively capture sunlight via multiple surfaces. Although the power output of each panel

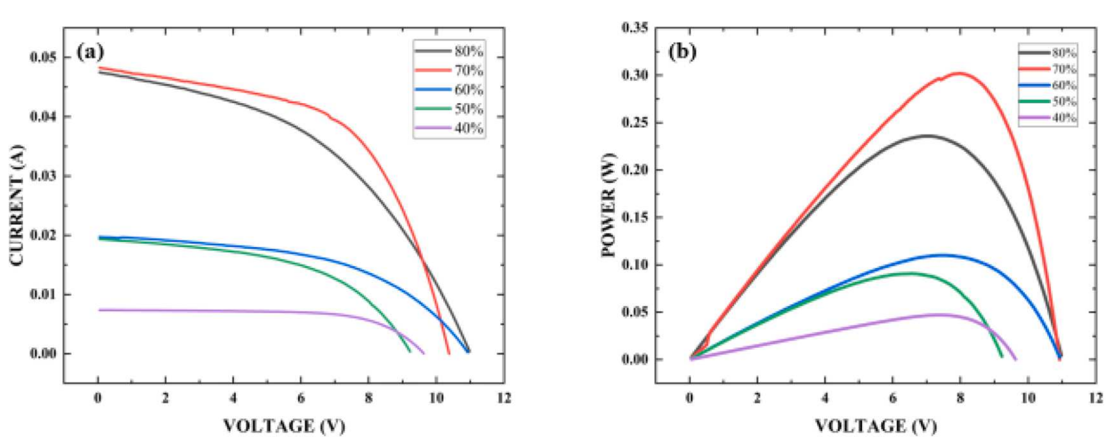


**Fig. 4.** (a) I-V curves and (b) output power of CdTe solar panels with different transparencies that are arranged in descending order (Fig. 2b).

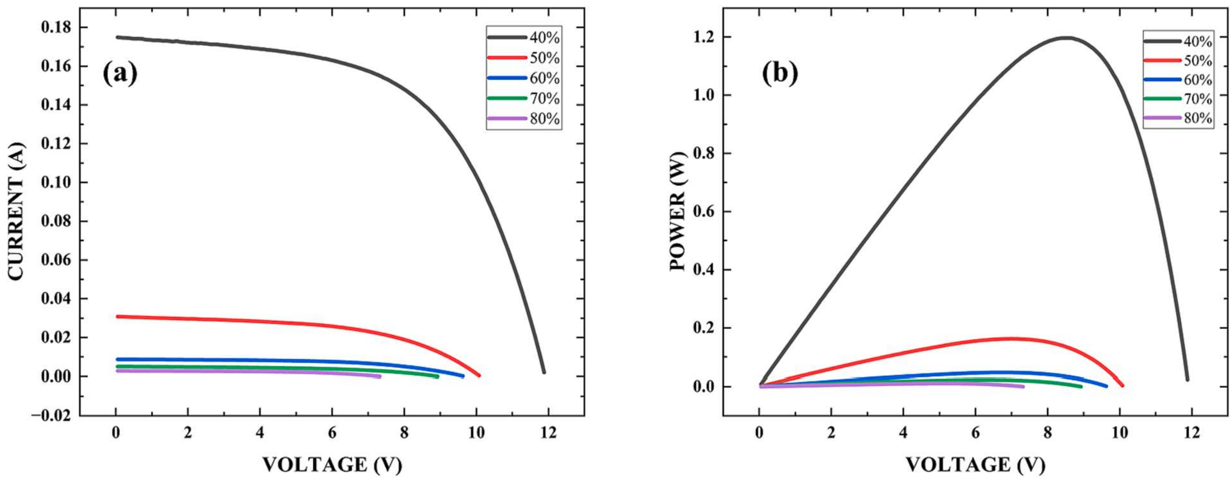


**Fig. 5.** (a) I-V curves and (b) Output power of CdTe solar panels with different transparencies that are arranged in ascending order (Fig. 2c).

**Table 4**
The I-V curve parameters of multiple CdTe solar panels in ascending order.

| Solar Panel AVT | $V_{OC}(V)$ | $I_{SC}(A)$ | $P_{MAX}(W)$ | F.F | P.C.E | Light Power Density (mW/cm$^2$) |
|---|---|---|---|---|---|---|
| 40 % | 11.880 | 0.174 | 1.197 | 0.576 | 9.60 % | 55.400 |
| 50 % | 10.075 | 0.030 | 0.162 | 0.522 | 3.25 % | 22.160 |
| 60 % | 9.624 | 0.008 | 0.046 | 0.557 | 1.87 % | 11.080 |
| 70 % | 8.922 | 0.005 | 0.022 | 0.505 | 1.52 % | 6.648 |
| 80 % | 7.319 | 0.002 | 0.011 | 0.538 | 1.05 % | 4.653 |

decreases due to reduced incoming light power density, they can yield finite output power, demonstrating the viability of solar harvesting in a 3D configuration (Z-direction). Increased solar harvesting surface area through the use of multiple transparent solar panels can significantly enhance solar energy generation. In a 3D fashion, the key is to add more transparent/semi-transparent solar panels underneath the top panel, while maintaining the same 2D surface area. This arrangement allows all panels to harvest solar light and collectively generate electricity, resulting in a net output power which can surpass that of a single panel configuration.

Based on the definition of PCE in Eq. (1), we can calculate the PCE of each solar panel in the multiple system (Fig. 1) in both descending and ascending orders. As shown in Table 5, when the solar panels are arranged in descending or ascending orders, each solar panel with a given transparency exhibits a PCE value. For ascending order, the top 40 % panel has the highest PCE of 9.60 %; and PCEs of others drop significantly due to reduced light power densities. However, if we can calculate the PCE of the entire system with all five solar panels, the PCE of the multi-panel system yields a PCE of 11.53 % which is a 20 % increase. This scenario indicates that with five solar panels stacking together, we are able to increase PCE from 9.60 % to 11.53 %. For descending order, the top 80 % panel yields a PCE of 1.89 %. The PCE of the entire system with all five solar panels reaches a PCE of 6.3 %. This is a 233 % increase via multiple layers, a significant improvement.

**Table 5**
PCE value of each CdTe solar panel in both ascending and descending orders. The PCE values of the multiple PV system with all five solar panels are also presented in both orders.

| Solar Panel AVT | PCE Ascending | Solar Panel AVT | PCE Descending |
|---|---|---|---|
| 1$^{ST}$ 40 % | 9.60 % | 1$^{ST}$ 80 % | 1.89 % |
| 2$^{ND}$ 50 % | 3.25 % | 2$^{ND}$ 70 % | 3.02 % |
| 3$^{RD}$ 60 % | 1.87 % | 3$^{RD}$ 60 % | 1.57 % |
| 4$^{TH}$ 70 % | 1.52 % | 4$^{TH}$ 50 % | 2.16 % |
| 5$^{TH}$ 80 % | 1.05 % | 5$^{TH}$ 40 % | 2.24 % |
| **NET PCE** | **11.53 %** | | **6.3 %** |

These experimental data indicate an important strategy of enhancing PCE by adding multiple transparent/semi-transparent solar panels. This approach is straightforward, economic, and practical without complications in PV materials design, synthesis, and device engineering.

Transparent solar cells are developed using various deposition methods for the active material, including screen-printing, dye-sensitized solar cell (DSSC), electrophoretic deposition (EPD), and dip-coating a thin film of on FTO/ITO glass [16,22–31]. In semi-transparent CdTe solar panels, in addition to use of a transparent top electrode, reducing the CdTe thickness is the key to achieve high AVT. However, thinning of CdTe under 400 nm suffers loss in Voc, Isc and hence PCE [32–34]. As shown in Table 1, PCE of the CdTe solar panel drops from 8.60 (40 %) to 1.94 (80 %), while Isc decreases from 1.141A to 0.048A. Isc majorly depends on the area of the solar cell; the number of photons (i.e., the light power density), and the spectrum of the incident light. With all given conditions in this study, Isc is consistent with the incoming photon intensity as shown in Tables 2, 3, 4. Despite the decreasing light power density, the maximum output powers of the solar panels underneath the top one remain at appreciable values. This highlights the accumulative effect of multiple panels, and the overall power generation can be expected by adding even more transparent/semi-transparent solar panels.

There have been extensive studies in the synthesis and characterization of transparent thin film and bulk energy materials for solar harvesting for a variety of energy applications such as efficient building skins and optically thermal-insulated windows [35–41]. In PV solar harvesting, by adding more transparent/semi-transparent solar panels underneath with the same top 2D surface area, it is possible to harvest solar light from all panels and collectively generate electricity. The net output power of the multi-panel system surpasses that of a single panel, due to the collective and accumulative effects. It is highly possible to further increase system PCE (i.e., PCE of the multi-panels) by considering arrangements with transparent/semi-transparent solar panels in different AVT configurations for optimum output power. Despite the decreasing light power density at each layer, the maximum output powers of all panels remain significant, indicating the feasibility and potential of this approach for solar energy generation.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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