Stretchable micro-scale concentrator photovoltaic module with 15.4% efficiency for three-dimensional curved surfaces

Daisuke Sato, Taizo Masuda, Kenji Araki, Masafumi Yamaguchi, Kenichi Okumura, Akinori Sato, Ryota Tomizawa & Noboru Yamada

Stretchable photovoltaics are emerging power sources for collapsible electronics, biomedical devices, and buildings and vehicles with curved surfaces. Development of stretchable photovoltaics are crucial to achieve rapid growth of the future photovoltaic market. However, owing to their rigidity, existing thin-film solar cells based predominantly on silicon, compound semiconductors, and perovskites are difficult to apply to 3D curved surfaces, which are potential real-world candidates. Herein, we present a stretchable micro-scale concentrator photovoltaic module with a geometrical concentration ratio of 3.5×. When perfectly fitted on a 3D curved surface with a sharp curvature, the prototype module achieves an outdoor power conversion efficiency of 15.4% and the daily generated electricity yield improves to a maximum of 190% relative to a non-concentration stretchable photovoltaic module. Thus, this module design enables high areal coverage on 3D curved surfaces, while generating a higher electricity yield in a limited installation area.
According to a recently reported scenario regarding the growth of the photovoltaic (PV) market, it is projected that the global cumulative installed PV capacity will be 40 TW by 2040, even though it is presently below 1 TW. The highest recorded power conversion efficiency of crystalline silicon (Si) solar cells, which have been the most predominant PV technology for decades, is 26.7%, and this record efficiency is very close to the theoretical efficiency limit, which is 29.4%. Si modules, which accounted for ~90% of all commercially available PV modules produced in 2013, have been primarily installed on flat roofs of residential buildings and on vast expanses of land, often referred to as mega-solar power plants. To realize the aforementioned 2040 scenario, further diversification of PV applications—specifically, overcoming the limitations of the installation features—is becoming increasingly important. One of the most advantageous installation features of PV modules is coverage on curved surfaces, and PV modules that incorporate flexible and thin-film solar cells, including thin-film Si, CIGS, CdTe, perovskite, and III-V compounds, could be suitable candidates. These modules can easily cover 2D curved surfaces (e.g., toroidal surfaces); however, their ability to fit perfectly on 3D curved surfaces (e.g., spherical surfaces), especially those with sharp curvature, is limited because they are inherently brittle and non-stretchable. The surfaces of walls/roofs, wearable devices, artificial satellites, and small mobiles, including automobiles and flying vehicles, which are promising applications for PV modules, have 3D curved surfaces with sharp curvatures owing to considerations related to appearance and/or aerodynamics. Thus, the availability of PV modules that can fit perfectly on such 3D curved surfaces and require a relatively small installation area to generate higher electricity yields, as independent power sources, are highly desired.

The development of stretchable electronics is crucial as this technology is required for the manufacture of PV modules that can completely cover the arbitrary 3D curved surfaces that are characterized by sharp curvatures. Rapid and significant progress has been made in the development of stretchable circuits and in the mounting processes of micro/nano-sized semiconductor devices on stretchable materials. This has stimulated considerable research interest in flexible displays, curvilinear digital cameras, bio-integrated systems, and other such applications. As an example of a PV-related technology, stretchable organic solar cells have garnered significant attention because they show great potential for large-area manufacturing. However, compared with semiconductor-based inorganic solar cells, such as Si and III–V compounds, they are associated with several drawbacks, including lower power conversion efficiencies (at most ~10%) and inferior durability. Another example of a PV-related technology is the integration of micro/nano-sized inorganic solar cells onto soft and stretchable substrates. Although inorganic solar cells show higher power conversion efficiencies, they are inherently rigid and brittle. Hence, to ensure stretchability, they need to be arranged such that gaps are left between adjacent solar cells, providing an elastic area and/or space for electrical wiring. However, leaving such gaps deteriorates electricity yield per module area. Previous studies have primarily highlighted high stretchability in the axial direction, stating that even in the stretched state, solar cells did not show any decrease in conversion efficiency (not generated power per module area). However, the power-generation performance per module area when they are attached to actual 3D curved surfaces has not yet been investigated in detail. Additionally, a trade-off relationship between power generation per module area and stretchability is associated with this technology, because an increase in the gaps between the solar cells, i.e., a decrease in the area occupied by the solar cells, enhances stretchability.

Concentrator photovoltaics (CPV) could be a solution to this drawback. In CPVs, inexpensive concentrator optics collect sunlight into small-area solar cells so that high power generation can be obtained with relatively low solar-cell usage. In this architecture, the solar-cell area is necessarily smaller than the module aperture area because the solar cells are arranged with some gaps between them. If the module components (e.g., concentrator, cell mounting substrate, etc.) are made from stretchable materials, more of the sunlight incident on the module aperture can be collected via concentration, while ensuring high areal coverage on 3D curved surfaces. Originally, CPV systems were developed for large-scale power plants, in which high-concentration CPV modules with geometrical concentration ratios $C_g$ ranging from several hundreds to one thousand were mounted on big-bonded sun-tracking systems. Subsequently, some of the authors proposed low-concentration static CPV ($C_g \leq 4x$), and clarified that optimally designed concentrators have wide acceptance operation angles of several tens of degrees without sun-tracking.

In this study, a stretchable micro-scale CPV module with $C_g = 3.5x$ for static (non-sun-tracking) operation is designed and developed. The designed module (32 mm × 40 mm) consists of stretchable materials, including a silicone concentrator lens and a thermoplastic polyurethane sheet, and a rigid III–V triple-junction solar cell. When perfectly fitted on a 3D curved surface with a sharp curvature, a prototype module achieves an outdoor power conversion efficiency of 15.4% and the daily generated electricity yield improves to a maximum of 190% relative to a non-concentration stretchable PV module.

**Results**

**Module design and prototyping.** Photographs and a schematic top side view of the stretchable micro-scale CPV module are shown in Fig. 1. In addition to being flexible (Fig. 1a), the prototype module was also stretchable (Fig. 1b). Thus, it could fit perfectly on a 3D curved surface, such as a spherical surface with a curvature radius, $R = 100$ mm, without wrinkling, as shown in Fig. 1c. The curvature radius, $R$ of the sharpest curve in the roof of most passenger vehicles is ~1000 mm, and the stretchability of the prototype module permitted it to fully cover car roofs without gaps, enabling high areal coverage. It is worth noting that a smaller curvature radius implies a sharper curved surface. Additionally, the prototype module could be fitted on a motorcycle helmet (see Supplementary Fig. 1a), which has a non-spherical 3D curved surface (this could be one of its possible applications, i.e., supplying energy to the interior cooling systems of helmets); moreover, the module could fit perfectly on an airfoil-shaped surface (see Supplementary Fig. 1b), which has sharper and more complex curves, with curvatures that vary by position; it could also fit perfectly on a concave surface (see Supplementary Fig. 1c). As shown in Fig. 1d, with the exception of the solar cells that were rigid (i.e., the GaInP/GaInAs/Ge triple-junction cells), the prototype module consisted of stretchable materials, namely, the thermoplastic polyurethane (TPU) sheet with the screen-printed electrode pattern and the silicone lens array. The triple-junction cells were encapsulated by the stretchable silicone lens, and the structure of the modules was basically the same as those of light-emitting diode (LED) packages, to which large-scale mounting technologies can be applied. The lens-encapsulating design is advantageous because it reduces the number of lens-air interfaces penetrated by sunlight, implying a lower Fresnel reflection loss at the interfaces between dissimilar materials.

In applications that require the covering of curved surfaces, the module should be as thin and as light weight as possible. This is
particularly crucial with respect to appearance, the ease with which it is carried (i.e., for wearable devices), and the improvement of the power consumption ratio (for small mobiles). Therefore, a micro-scale CPV design, which is a state-of-the-art CPV technology, involving the use of miniaturized lenses (in the order of ~1–10 mm) and solar cells (in the order of ~0.1–1 mm) were employed. Miniaturizing the concentrator and the solar cell offers the advantages of less absorption loss owing to the thinner concentrator, better heat dissipation from the solar cells, and a thinner module thickness, i.e., a lighter module weight, owing to the shorter focal length\textsuperscript{42,43}. The thickness and weight per unit area of the prototype module were 4.1 mm (silicone lens, 4.0 mm; TPU sheet, 0.1 mm) and 2.84 kg m\textsuperscript{-2} (almost the same as that of a 1.2-mm thick glass substrate), respectively. The geometrical concentration ratio was determined as, $C_g = \frac{A_{\text{lens}}}{A_{\text{cell}}} = 3.5\times$, where $A_{\text{lens}}$ represents the unit lens aperture area (8.0 mm $\times$ 8.0 mm) and $A_{\text{cell}}$ represents the active power-generation area of the triple-junction cell (4.05 mm $\times$ 4.47 mm). The triple-junction cells with a total area of 4.10 mm $\times$ 4.95 mm, including the electrode area were arranged with 3.05 and 3.90 mm gaps between them in the $x$ and $y$ directions, respectively, forming a $4 \times 5$ array. The ratio of the total cell area to the active power-generation area of the module (32 mm $\times$ 40 mm) was 31.7%, and the ratio of the active cell area to the active module area was 28.3%. Several micro-scale CPV modules employing submillimeter-scale solar cells have been recently reported\textsuperscript{44–46}. Such miniaturized solar cells can also be applied to the present module design. To ensure equivalent power-generation performance and its incidence-angle dependency to those of the present design, the solar cells need to be downscaled while maintaining $C_g$ and the similarity of the optical system. In that case, because the unit-lens side length, lens thickness, and interval between the active lens islands decrease in proportion to the downsampling degree, the rigid active lens islands are subdivided, which would improve the flexibility of the module. As the silicone lens is soft and flexible, it is supposed not to impede the module flexibility as much as the solar cell. It is important to note that although the concentrator lens itself is scalable, power-generation performance and its incidence-angle dependency can vary with changes in the ratio of the lens aperture area to the solar-cell area (i.e., $C_g$).

The non-axisymmetric aspheric lens designed in our previous study\textsuperscript{39} was used in this module. The concentrator lens was designed taking into consideration the incidence-angle characteristics of the annual solar irradiance on a car roof. In the lens design, the optimal lens-geometry parameters that maximized the annual irradiance concentrated on the triple-junction cell were determined via optical analysis using ray-tracing simulation. In the present lens design, the active area loss—that is, the 1-mm-thick flat area formed between the active lens islands that does not contribute to sunlight concentration on the solar cell—occupied 28.9% in the active module area (i.e., 32 mm $\times$ 40 mm shown in Fig. 1d). This proportion depends on the lens design method and $C_g$. Although in the lens design method used in this study, the smaller $C_g$ can decrease the proportion of the active area loss (eventually becoming zero for $C_g = 1.5\times$), the flexibility of the module would be degraded.

The module prototyping process was as follows: (1) a stretchable conductive paste was screen-printed on the TPU sheet, forming the electrode pattern; (2) the triple-junction cells were mounted on the electrode pattern via die-bonding and wire-bonding; (3) the silicone lens was formed on the cell-mounted TPU sheet via injection molding.

**Stretch dependency of power-generation performance.** Photographs of the prototype module under relax and asymmetrical...
stretching states are shown in Fig. 2a, b, respectively. The maximum strain of the uppermost string consisting of five series-connected triple-junction cells was 10% (39.4 mm → 43.2 mm). In the maximum stretch state, strains in the thinner part (i.e., the trench formed between the active lens islands) and in the thicker part (i.e., the active lens island) were 50% (0.6 mm → 0.9 mm) and 8.1% (7.4 mm → 8.0 mm), which was smaller than that of the thinner part, respectively. This relationship is consistent with the deformation mechanism of stretchable PVs reported in previous studies30,31. The maximum strain of 10% is smaller than that of the record value (95%)32. This is because the overall module stretchability is restricted by the solar cells, in which the stress concentration occurs near the vertices of the rigid solar cells, while the stress occurring at the interface between silicone lens and TPU sheet is much smaller than the maximum stress (see Supplementary Fig. 2b). The stress concentration at the vertices of the solar cells can be expected to be mitigated by employing the structured stretchable substrate instead of the flat TPU sheet, based on the outcome of prior studies30,31. As another approach, rounding the solar-cell vertices (i.e., employing circular solar cells) can contribute to a significant reduction in the maximum stress (see Supplementary Fig. 3). The current-voltage (I-V) and power-voltage (P-V) characteristics under relax and maximum stretch states were measured for uppermost string in (a) and (b) at indoor 1 sun (1000 W m⁻²) irradiation and room temperature (~25 °C). The module conversion efficiency was calculated as the ratio of P_max per active module area (one string: 8 mm × 8 mm × 5 lenses) to irradiance (1000 W m⁻²).

**Fig. 2** Power-generation characteristics under stretch state. Photographs of the prototype module under (a) relax and (b) maximum stretch (10% strain) states (Unit: mm). The right-side photographs are magnifications of the region marked by red-colored rectangle in the left-side photographs. c) Current-voltage (I-V) and power-voltage (P-V) characteristics under relax and maximum stretch states. I_sc, V_oc, P_max, and FF are short-circuit current, open-circuit voltage, generated power, and fill factor, respectively. d) Cycling test showing the module conversion efficiency and FF when stretched by 10% up to 300 cycles. The I-V and P-V characteristics were measured for uppermost string in (a) and (b) at indoor 1 sun (1000 W m⁻²) irradiation and room temperature (~25 °C). The module conversion efficiency was calculated as the ratio of P_max per active module area (one string: 8 mm × 8 mm × 5 lenses) to irradiance (1000 W m⁻²).
below by the outdoor power-generation performance, the present CPV is advantageous in the fixed installation on a 3D curved surface with sharp curvature over the existing technologies.

Outdoor power-generation performance on a 3D curved surface. To evaluate the power-generation performance when attached to a 3D curved surface, the prototype module was attached to a hemispherical dome with a curvature radius, \( R = 100 \text{ mm} \). Thereafter, outdoor tests were performed at Nagaoka University of Technology (Nagaoka city, Japan; latitude, 37.42°; longitude, 138.78°). During the outdoor tests, the power-generation performance of the three strings, each consisting of five series-connected triple-junction cells as shown in Fig. 3a, were measured, and the cell-lens pair located at the center of the measured 3 × 5 array was positioned at the zenith of the hemispherical dome.

As a fundamental power-generation performance indicator, \( I\)–\( V \) characteristics were first measured under the condition that the zenith of the hemispherical dome on which the prototype module was attached was facing the sun (i.e., the differences in the generated power, \( P_{\text{max}} \)), short-circuit current, \( I_{\text{sc}} \), open-circuit voltage, \( V_{\text{oc}} \), fill factor, \( \text{FF} \), and \( \eta_{\text{GNI}} \) were short-circuit current, open-circuit voltage, generated power, fill factor, and GNI-based module conversion efficiency, respectively. \( \eta_{\text{GNI}} \) was calculated as the ratio of \( P_{\text{max}} \) per active module area (one string: 8 mm × 8 mm × 5 lenses) to GNI. (w/ lens, with lens; w/o lens, without lens).

Figure 3c, d shows the \( I\)–\( V \) curves of string 2 (center string) under a clear-sky condition with and without lens, respectively. When the prototype module was fitted on the spherical surface, the outline of the active module area shown in Fig. 1d (i.e., 32 mm × 40 mm) was elongated by \( \sim 1 \text{ mm} \) in directions both parallel and orthogonal to the string directions, which corresponds to \( \sim 3\% \) strain and is smaller than 1/3 of the maximum value (10%). Consequently, although the ohmic resistance of the printed electrode pattern on the TPU sheet somewhat increased, that had a minor effect on the \( I\)–\( V \) characteristics even under the possible best irradiance (i.e., highest current output) condition. The FF of the CPV module (w/ lens) was slightly lower than that of the non-concentration module (w/o lens) owing to the degradation of irradiance uniformity in the cell area caused by non-uniform concentration. On the other hand, enhancing the short-circuit current \( (I_{\text{sc}}) \) and the open-circuit voltage \( (V_{\text{oc}}) \) contributed to an increase in the generated power, \( P_{\text{max}} \), up to 1.88 times; consequently, a GNI-based module conversion efficiency, \( \eta_{\text{GNI}} \), of 15.4% was realized, and it is worth noting that \( \eta_{\text{GNI}} \) is defined as the ratio of \( P_{\text{max}} \) per active module area to GNI. Additionally, the \( I\)–\( V \) characteristics of strings 1 and 3 were basically the same as those of string 2, even though the incidence angles for the unit lenses in the string were a little larger (see Supplementary Fig. 4). In the case of the static CPV module (non-sun-tracking), the incidence angle varied with time. Furthermore, the incidence angles for the unit lenses were different when the module was attached to 3D curved surfaces. To clarify the daily power-generation performance potential of the prototype CPV module, prototype modules (w/ lens and w/o lens) attached to the hemispherical domes (\( R = 100 \text{ mm} \)) were installed on horizontal and 30°-inclined surfaces (simulating attachment on different
positions on the spherical surface), and I–V characteristics were continuously measured throughout the day (~7:00–17:30) on clear-sky days. Figures 4a, 5a show magnifications of the modules attached to the hemispherical dome in the test setups. The other setups were the same as shown in Fig. 3b. To compare the effect of string direction on power-generation performance, the string direction was changed by 90° at the culmination time (approximately 12:00), i.e., the series-connected strings were oriented from east to west until 12:00, and thereafter, from north to south. String 1 lay on the northern side in AM and on the western side in PM; string 2 lay on the center line of the hemispherical dome; and string 3 lay on the southern side in AM and on the eastern side in PM. For the solar altitude, 90° corresponded to the zenith, and for the solar azimuth, −90°, 0°, and 90° corresponded to the east, south, and west, respectively.

Fig. 4 Outdoor power-generation performance at representative times (prototype modules atop the hemispherical domes were installed on a horizontal surface). a Magnifications of the prototype modules in the experimental setup. b, c Measured $P_{\text{max}}$ and irradiances (direct horizontal irradiance (DHI), diffuse irradiance) as a function of the sun’s position on May 17, 2019 (Nagaoka city, Japan). String directions were (b) east–west in AM and (c) north–south in PM. String 1 lay on the northern side in AM (black bar referred to as “N”) and on the western side in PM (black bar referred to as “W”); string 2 lay on the center line of the hemispherical dome (blue bar referred to as “C”); and string 3 lay on the southern side in AM (yellow bar referred to as “S”) and on the eastern side in PM (yellow bar referred to as “E”). For the solar altitude, 90° corresponded to the zenith, and for the solar azimuth, −90°, 0°, and 90° corresponded to the east, south, and west, respectively. (w/ lens, with lens; w/o lens, without lens).
lens to that w/o lens) was 1.8–2.0 times during the daytime, and early in the morning or in the evening, it was significantly lower (e.g. 7:00 in Fig. 4b and 16:30 in Fig. 5c). This is because the incidence angles to some or all the lens apertures were greater than the acceptance half angles of the optics\(^5\), resulting in a reduced concentration of sunlight on the solar cells. By attaching the prototype module to the hemispherical dome (3D curved surface), the acceptance half angle of each string became smaller relative to horizontal surface installation. Nevertheless, the peak optical efficiency could be maintained provided the incidence angle to the zenith of the dome is below 50° (see Supplementary Fig. 7).

**Discussion**

From the outdoor testing results, the accumulated generated electricity per module area (for the three strings: 8 mm × 8 mm × 15 lenses) during the measurement period was calculated assuming that the three strings investigated were connected in series and in parallel, i.e., the overall current and voltage at each time was limited to the minimum value associated with the three strings. To compare the generated electricity based on the different positions on the spherical surface (i.e., between horizontal and 30°-inclined installations), the calculated electricity was normalized using the total GHI energy accumulated over the corresponding measurement period. Additionally, for the stretchable PV module (w/o lens), a practically impossible and ideal configuration, in which the module area was fully covered by an active solar-cell area, i.e., no interval between the solar cells, was assumed (hereafter referred to as gapless case). For the gapless case, the accumulated generated electricity was approximated as the product of that generated by the stretchable PV module (w/o lens) and the geometrical concentration ratio.

---

Fig. 5 Outdoor power-generation performance at representative times (prototype modules atop the hemispherical domes were installed on a 30°-inclined surface). a Magnifications of the prototype modules in the experimental setup. b, c Measured \(P_{\text{max}}\) and irradiances (direct horizontal irradiance (DHI), diffuse irradiance) as a function of the sun’s position on May 19, 2019 (Nagaoka city, Japan). The string directions were (b) east–west in AM and (c) north–south in PM. String 1 lay on the northern side in AM (black bar referred to as “N”) and on the western side in PM (black bar referred to as “W”); string 2 lay on the center line of the hemispherical dome (blue bar referred to as “C”); and string 3 lay on the southern side in AM (yellow bar referred to as “S”) and on the eastern side in PM (yellow bar referred to as “E”). For the solar altitude, 90° corresponded to the zenith, and for the solar azimuth, −90°, 0°, and 90° corresponded to east, south, and west, respectively. (w/ lens, with lens; w/o lens, without lens).
Figure 6 shows the accumulated electricity per module area / accumulated GHI ratio (ζ) for each of the cases shown in Figs. 4, 5. The time ranges of the integral were 7:00–12:00 and 12:30–17:30 for the string directions oriented east–west (AM) and north–south (PM), respectively. For the series- and parallel-connected cases, ζ varied in the range 8.6–16.0% and 9.7–16.3%, respectively, depending on the dome inclination angle (i.e., the position on the spherical surface) and the string direction. Basically, the current output of the solar cells was directly proportional to the received irradiance; hence, the effect of current mismatching was more significant in the series-connected cases. Nevertheless, comparing both connection cases, ζ practically showed the same values for the same installation modes, and it was obviously different with respect to the different installation modes (i.e., horizontal and 30°-inclined surface installations) for the same string directions (W–E or N–S). However, comparing the w/ lens and w/o lens cases, the improvement factor of ζ, defined as ζ (w/ lens) / ζ (w/o lens), was approximately constant (1.63–1.89), i.e., the difference between the ζ of the different installation modes was mainly caused by the irradiance distribution on the spherical surface rather than the performance of the concentrator optics. It is important to note that the concentrator lens was designed so that the annual electricity yield can be maximized in the horizontal installation case (see “Lens design optimization and ray-tracing simulation” in the “Methods” section and Supplementary Fig. 8); therefore, to compare fairly the electricity yield between the installation modes, it needs to be verified throughout the year. Considering the above-mentioned sun-tracking condition, where the differences among the incidence angles to the unit lenses are minimum, the improvement factor was 1.88, indicating that the prototype module could maintain more than 86.7% of the performance associated with the sun-tracking case, even under the unique condition that the time variation of the incidence angle to the module aperture and the differences among the incidence angles to the unit lenses were combined. Furthermore, the ζ of the prototype CPV module (w/ lens) showed a performance that was 46.6–54.0% that of the ideal gapless case, i.e., with the prototype module, the daily generated electricity yield was maintained at ~50%, even though the solar-cell usage had decreased by 71% relative to the gapless case, demonstrating better cost per unit of electricity yield. Furthermore, the additional advantage would be obtained by effectively utilizing the sunlight that is not concentrated on the solar cells. For example, although in this study, we used the less transparent TPU sheet because the electrode pattern can be easily formed by screen-printing, substituting highly transparent and stretchable materials (e.g., polydimethylsiloxane: PDMS) improves the module transmittance to the sunlight; consequently, unutilized sunlight for power generation can be transmitted under the module while generating the power comparable to the Si module. Therefore, also given the stretchability to be fitted to 3D curved surfaces with sharp edges.
curvature, this upgraded concept would be a promising technology for efficient dual-land use (i.e., semi-transparent CPV module\textsuperscript{[1–3]}).

The relative importance of the module cost and the power-generation performance are determined by considering the quantity of electricity required and the constraint of the installation area. As another design example, a CPV module with $C_L = 2.0 \times$ and the same lens aperture area as the present design (8.0 mm × 8.0 mm per unit) was considered. A ray-tracing simulation showed that the optical efficiency for normal-incident light as well as the acceptance half angle increased by 21.3%abs and 7.5°, respectively, compared with the present design (see Supplementary Fig. 6b). Consequently, this module, for example, can collect 73.3% of the annual irradiance on a car roof onto the solar cell (cf. 46.6% for the present design of $C_L = 3.5 \times$, 100% for gapless case). Therefore, even though decreasing $C_L$ from 3.5× to 2.0× resulted in a 1.75-fold increase in cell usage, the annual generated electricity on a car roof increased 1.57-fold (see Supplementary Fig. 6c).

This module concept can be applied to various curved surfaces. The sizes of the solar cells and the gaps between them can be arbitrarily selected based on the shape of the curved surfaces, i.e., the required stretchability. The optical characteristics of the concentrator lens can be tailored for an angular irradiance distribution on the target attachment surfaces, offering a large degree of freedom for the module design. Considering the proposed module design, basically any type of solar cell, regardless of the material from which it is made, can be applied. In this study, commercially available III-V triple-junction cells optimized for high-concentration (500–1000×) CPV (HCPV) were employed because the present design required the use of small-size solar cells. Under one-sun irradiation, the determined power conversion efficiency of the triple-junction cell was 29.8%; thus, the same level of performance would be obtained even if the Si cells with the highest reported efficiency (26.7%)\textsuperscript{[3]} were used. Additionally, given that the heat generation density of the solar cells is smaller than that of conventional HCPVs by more than two orders of magnitude, and that the aspherically shaped lens contributes to better heat dissipation owing to a larger surface area as with the fins, the temperature rise of the solar cells could be mitigated to the same level as that in conventional flat PV modules (~80 °C even under possibly higher temperatures, see Supplementary Fig. 9). Furthermore, with respect to weather durability, solar cells could be effectively utilized by integrating this lens-encapsulating design, and the use of thin-film solar cells would enable adaptation to more complicated curved surfaces.

In summary, in this study, a stretchable micro-scale CPV module ($C_L = 3.5 \times$), which allows high areal coverage on 3D curved surfaces with sharp curvature for static (non-sun-tracking) operation, was developed and investigated. The results showed that the prototype module could fit perfectly on spherical surfaces with a curvature radius of 100 mm, and under outdoor one-sun irradiation, the module showed a power conversion efficiency of 15.4%. Additionally, relative to the non-concentration stretchable PV module, the CPV module yielded an enhancement of the total daily generated electricity by a factor of 1.63–1.89, which depended on the position of the spherical surface and the mode of electric connection (i.e., series or parallel). The solar-cell usage associated with this CPV module decreased by 71%, which is indicative of a lower cost per unit of electricity generated, while the electricity yield throughout the day was ~50% that of the ideal gapless case, in which the solar cells fully occupy the module aperture. Nevertheless, there is still room to improve the module efficiency and daily generated electricity to achieve cost competitiveness.

Our future studies will focus on a more detailed examination of the prototype module with respect to practical use and further optimization of the module design for enhancement of power generation and stretchability. For module-size expansion, the large-area module can be divided into submodule operational units with appropriate sizes so as to minimize the current mismatching loss resulting from irradiance distribution on the curved installation surface; thus, an optimal circuit design and control strategy are important. Additionally, given the importance of long-term reliability and lifetime issues, their consideration is also important. The effect of the periodic thermal deformation of the lens material on the mechanical stress of the encapsulated electrical components, such as bonding wires, needs to be clarified. It is also necessary to investigate the durability of the lens material against humidity, soiling, and debris. Finally, the development of coatings that do not degrade transmittance in the power-generation sensitive spectral range is an option to improve the resistance of the module to such negative factors.

**Methods**

**Lens design optimization and ray-tracing simulation.** The concentrator lens was designed considering the incidence-angle characteristics of annual solar radiation on the horizontal surface, modified by assuming a car-roof-specific environment. The reported angular irradiance model\textsuperscript{[38]} was used in the simulation (see Supplementary Fig. 8a), referred to as “car roof”. To obtain this angular irradiance model, the average 20-year (1990–2009) solar irradiance of 47 major Japanese cities extracted from a meteorological database (METPV-11, New Energy and Industrial Technology Development Organization (NEDO)), including both direct and diffuse sunlight on a horizontal flat surface, was modified by statistically accounting for the car-roof specific shading condition resulting from surrounding objects. For car-roof specific conditions, the following assumptions were made: the heights of the shading objects are distributed in accordance with a function in which the probability linearly decreases from 100% (at 5°) to 0% (at 60°); the angular irradiance is independent of the orientation angle, i.e., the car direction.

An optimum lens was defined as that which can maximize the annual solar energy reaching the solar cell, and its geometric parameters were determined via optical analysis using ray-tracing simulation and an in-house macro program with an optimization algorithm, which are both incorporated in a commercial software (LightTools 8.4.0, Synopsys, Inc., California, USA). Supplementary Fig. 8a shows the 3D ray-tracing simulation model. To facilitate the consideration of the cross-talk effect resulting from adjacent lenses, a 3 × 3 lens array was employed, and the solar cell was placed at the center of the array. The light irradiation area (16 mm × 16 mm) was irradiated using AM1.5G standard spectrum rays (300–2000 nm)\textsuperscript{[74]} and a divergence angle of the rays emitted from the hemispherical light source was ± 0.26° (half angle of solar disc). The angular intensity of the ray was weighted based on the above-mentioned angular irradiance distribution on a car roof. The chromatic dispersion of the optical properties of the module components was considered, and the solar cell was assumed to be a black body (ideal absorber). The Fresnel reflection loss at the interface between dissimilar materials and the absorption loss in the lens materials were also considered. Details regarding the resultant lens geometry have been presented in the literature\textsuperscript{[39]}.

**Module prototyping.** A step-by-step module prototyping process is illustrated in Supplementary Fig. 10. (Step 1) A stretchable conductive paste (XIE81A, NAMICS Corp., Niigata, Japan) was screen-printed on a 0.1-mm thick thermoplastic polyurethane (TPU) sheet (TPILION® ES85, Okura Industrial Co., Ltd., Kagawa, Japan) to form the electrode pattern. (Step 2) Commercial GaInP/GaInAs/Ge triple-junction solar cells (High Efficiency 4×4 CPV Solar Cell, TaiCrystal International Technology Co., Ltd., Taoyuan City, Taiwan) were mounted on the female mold with the designated position on the female mold and placed; (3) the integrated module was carved via machining; (2) the CPV receiver was aligned into the male mold and placed; (3) the integrated module was cured at room temperature (23 °C), Copper pieces with dimensions of 1.0 mm × 2.0 mm (area) × 0.1 mm (thickness), which were coated with Ni/Au thin films to improve the bondability with the wire, were also mounted on the printed electrode pattern by using the same process for the triple-junction cells. (Step 3) The electrode pads on the triple-junction cells and the copper pieces on the printed electrode pattern were electrically connected via wire bonding. An aluminum wire with a diameter of 25 μm containing 1% Si was used, and the wire bonding was performed at room temperature (23 °C). (Steps 4–6) The silicone lens concentrator was applied and the cell-mounted TPU sheet (i.e., CPV receiver) via injection molding as follows: (1) well mixed and deformed liquid-state addition-curing RTV-2 silicone resin (ELASTOSIL® RT 601; Wacker Asahikasei Silicone Co., Ltd., Tokyo, Japan) was poured into a polypropylene polymerurethane (PPMA) female mold, on which the geometry of the designed lens was carved via machining; (2) the CPV receiver was aligned into the designated position on the female mold and placed; (3) the integrated module components were cured at 20 °C for 24 h in a thermostatic chamber; (4) after
The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. Haegel, N. M. et al. Terawatt-scale photovoltaics: transform global energy. Science 364, 836–838 (2019).
2. WEBER, E. R. Photovoltaics moving into the terawatt age. In SPIE Opt. Eng. + Appl. (SPIE, 2017), https://doi.org/10.1117/12.2277978
3. YOSHIKAWA, K. et al. Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%. Nat. Energy 2, 17032 (2017).
4. Richter, A., Hermle, M. & Glunz, S. W. Reassessment of the limiting efficiency for crystalline silicon solar cells. IEEE J. Photovolt. 3, 1184–1191 (2013).
5. Lewis, N. S. Research opportunities to advance solar energy utilization. Science 351, 1a9120 (2016).
6. Cashmore, J. S. et al. Improved conversion efficiencies of thin-film silicon tandem (MICROMORPH™) photovoltaic modules. Sol. Energy Mater. Sol. Cells 144, 84–95 (2016).
7. Sugimoto, H. High efficiency and large volume production of CIS-based modules. In 2014 IEEE 40th Photovoltaic Specialist Conf. (PVSC) (PVSC-40) 2767–2770 (IEEE, 2014), https://doi.org/10.1109/PVSC.2014.6925503
8. First Solar. First Solar achieves world record 18.6% thin film module conversion efficiency. https://investor.firstsolar.com/news/press-release-details/2015/First-Solar-Achieves-World-Record-186-%C2%A0-Thin-Film-Module-Conversion-Efficiency/default.aspx (2015).
9. Toshiba Corporation. NEDO and Toshiba develops world’s largest film-based perovskite photovoltaic module —703 cm² module achieves 11.7% power conversion efficiency. --. https://www.toshiba.co.jp/prd/rc/rd/detail/e/1806_03_.html (2018).
10. Higuchi, H. & Negami, T. Largest highly efficient 203 × 203 mm² CH3NH3PbI3 perovskite solar modules. Ipn. J. Appl. Phys. 57, 08RE111 (2018).
11. Mattos, L. S. et al. New module efficiency record: 23.5% under 1-sun illumination using thin-film single-junction GaAs solar cells. In 2012 IEEE 38th Photovoltaic Specialist Conf. (PVSC-38) (IEEE, 2012), https://doi.org/10.1109/PVSC.2012.6318255
12. New Energy and Industrial Technology Development Organization (NEDO). Solar cell module with world’s highest conversion efficiency of 31.17% achieved – lightweight, flexible prototype created. --. https://www.nedo.go.jp/english/news/AA5en_100070.html (2016).
13. Ostfeld, A. E., Gaikwad, A. M., Khan, Y. & Arias, A. C. High-performance flexible energy storage and harvesting system for wearable electronics. Sci. Rep. 6, 26122 (2016).
14. Jokic, P. & Magno, M. Powering smart wearable systems with flexible solar energy harvesting. In 2017 IEEE Int. Symp. on Circuits and Systems (ISCAS) (IEEE, 2017), https://doi.org/10.1109/ISCAS.2017.8050615
15. Byron Bay Railroad Company. Solar power. http://byronbayrailtrain.com.au/sustainability/ (2020).
16. Araki, K., Ii, L., Kelly, G. & Yamaguichi, M. To do list for research and development and international standardization to achieve the goal of running a majority of electric vehicles on solar energy. Coatings 8, 251 (2018).
17. Rogers, J. A., Somera, T. & Huang, Y. Materials and mechanics for stretchable electronics. Science 327, 1603–1607 (2010).
18. Kim, D. H. et al. Materials and noncoplanar mesh designs for integrated circuits with linear elastic responses to extreme mechanical deformations. Proc. Natl. Acad. Sci. 105, 18675–18680 (2008).
19. Kim, D. H. et al. Stretchable and foldable silicon integrated circuits. Science 320, 507–511 (2008).
20. NAM, J. et al. Transfer printed flexible and stretchable thin film solar cells using a water-soluble sacrificial layer. Adv. Energy Mater. 6, 1601269 (2016).
21. Nam, J., Seo, B., Lee, Y., Kim, D. H. & Jo, S. Cross-buckled structures for stretchable and compressible thin film silicon solar cells. Sci. Rep. 7, 7575 (2017).
22. Park, S. II et al. Printed assemblies of inorganic light-emitting diodes for deformable and semitransparent displays. Science 325, 977–981 (2009).
23. Ko, H. C. et al. A hemispherical electronic eye camera based on compressible silicon optoelectronics. Nature 454, 748–753 (2008).
24. Kim, D. H. et al. Dissolvable films of silk fibroin for ultrathin conformal bio-integrated electronics. Nat. Mater. 9, 511–517 (2010).
25. Kim, D. H. et al. Epidermal electronics. Science 333, 838–843 (2011).
26. Lipomi, D. J., Tee, B. C. K., Vosgueritchian, M. & Bao, Z. Stretchable organic solar cells. Adv. Mater. 23, 1771–1775 (2011).
27. Li, L. et al. A solid-state intrinsically stretchable polymer solar cell. ACS Appl. Mater. Interfaces 9, 40523–40532 (2017).
28. Jinno, H. et al. Stretchable and waterproof elastomer-coated organic photovoltaics for washable electronic textile applications. *Nat. Energy* 2, 780–785 (2017).
29. Hsieh, Y. T., Chen, J. Y., Shih, C. C., Chueh, C. C. & Chen, W. C. Mechanically robust, stretchable organic solar cells via buckle-on-elastomer strategy. *Org. Electron.* 53, 339–345 (2018).
30. Lee, J. et al. Stretchable GaAs photovoltaics with designs that enable high area coverage and strain-limiting behavior: Demonstration in high efficiency dual-junction GaInP/GaAs photovoltaics. *Small* 8, 1851–1856 (2012).
31. El-Atab, N., Qaiser, N., Bahabry, R. & Hussain, M. M. Corrugation enabled asymmetrically ultrastretchable (95%) monocrystalline silicon solar cells with high efficiency (19%). *Adv. Energy Mater.* 9, 1902883 (2019).
32. Luque, A. L. & Arendse, V. M. *Concentrator Photovoltaics* Ch. 1 (Springer, 2007).
33. Wiesenfarth, M., Philippis, S. P., Bett, A. W., Horowitz, K. & Kurtz, S. Current Status of Concentrator Photovoltaic (CPV) Technology (Fraunhofer ISE and National Renewable Energy Laboratory, 2017), http://www.isc.fraunhofer.de/en/publications/veroeffentlichungen-pdf/dateien-en/studien-und-konzeptpapiere/current-status-of-concentrator-photovoltaic-cpv-technology.pdf.
34. Kinsey, G. S. et al. Advancing efficiency and scale in CPV arrays. *IEEE J. Photovolt.* 3, 873–878 (2013).
35. Ghosal, K. et al. Field results and progress in system development. *IEEE J. Photovolt.* 4, 703–708 (2014).
36. Steiner, M. et al. FLATCON® CPV module with 36.7% efficiency equipped with four-junction solar cells. *Prog. Photovolt. Res. Appl.* 23, 1323–1329 (2015).
37. Masuda, T. et al. Static concentrator photovoltaics for automotive applications. *Adv. Mater.* 29, 523–531 (2017).
38. Sato, D. et al. Design of low-concentration static III-V/Si partial CPV module with 27.3% annual efficiency for car-roof application. *Prog. Photovolt. Res. Appl.* 27, 501–510 (2019).
39. Feher Helmets. Air conditioned motorcycle helmets. https://feherhelmets.com/ (2020).
40. Yamada, N. et al. Development of silicone-encapsulated CPV module based on LED package technology. In *2013 IEEE 39th Photovoltaic Specialist Conf.* (PVSC-39) 0493–0496 (IEEE, 2013), https://doi.org/10.1109/PVSC.2013.6744197.
41. Domínguez, C., Jost, N., Askins, S., Victoria, M. & Antón, I. A review of the promises and challenges of micro-concentrator photovoltaics. *AIP Conf. Proc.* 1881, 080003 (2017).
42. Ritou, A., Vearino, P. & Raccurt, O. Does micro-scaling of CPV modules improve efficiency? A cell-to-module performance analysis. *Sol. Energy* 173, 789–803 (2018).
43. Lee, K.-T. et al. Concentrator photovoltaic module architectures with capabilities for capture and conversion of full global solar radiation. *Prog. Natl. Acad. Sci.* 113, E8120–E8128 (2016).
44. Price, J. S. et al. High-concentration planar microtracking photovoltaic system exceeding 30% efficiency. *Nat. Energy* 2, 17113 (2017).
45. Li, D. et al. Wafer integrated micro-scale concentrating photovoltaics. *Prog. Photovolt. Res. Appl.* 26, 651–658 (2018).
46. Rusad, C. J., Price, J. S., Fisher, R., Wang, R. & Giebink, N. C. Lightweight monolithic multicell CPV for space. In *The 7th World Conf. on Photovoltaic Energy Conversion (WCPEC-7)* (IEEE, 2018), https://ieeexplore.ieee.org/document/8548170.
47. Lumb, M. P. et al. A micro-concentrator photovoltaic module incorporating a bifacial silicon solar cell for direct and diffuse light capture. In *2019 IEEE 46th Photovoltaic Specialist Conf.* (PVSC-46) (IEEE, 2019), https://doi.org/10.1109/PVSC40753.2019.8980829.
48. Herrero, R. et al. Concentration photovoltaic optical system irradiance distribution measurements and its effect on multi-junction solar cells. *Prog. Photovolt. Res. Appl.* 20, 423–430 (2012).
49. Algera, C. & Rey-Stolle, I. *Handbook of Concentrator Photovoltaic Technology* Ch. 4 (John Wiley & Sons, Ltd, 2016).
50. Sato, D. & Yamada, N. Design and testing of highly transparent concentrator photovoltaic modules for efficient dual-land-use applications. *Energy Sci. Eng.* 8, 779–788 (2020).
51. Insolight SA. THEIA (Translucency & High Efficiency in Agrivoltaics). https://insolight.ch/agrivoltaics-insolight/. (2020).
52. Askins, S. et al. Performance of hybrid micro-concentrator module with integrated planar tracking and diffuse light collection. In *2019 IEEE 46th Photovoltaic Specialist Conf.* (PVSC-46) (IEEE, 2019), https://doi.org/10.1109/PVSC40753.2019.8980519.
53. National Renewable Energy Laboratory (NREL). Reference air mass 1.5 spectra. https://www.nrel.gov/grid/solar-resource/spectra-am1.5.html (2020).
54. Yamada, N. & Hirai, D. Maximization of conversion efficiency based on global normal irradiance using hybrid concentrator photovoltaic architecture. *Prog. Photovolt. Res. Appl.* 24, 846–854 (2016).

**Acknowledgements**

The authors would like to thank T. Ogihara of NAMICS Corporation for providing the stretchable conductive paste and technically supporting screen-printing to form the electrode pattern on the stretchable sheet.

**Author contributions**

D.S. performed theoretical simulations (lens design optimization, ray-tracing simulation, FEM simulation), module prototyping, and performance evaluation (indoor/outdoor tests). T.M. conducted marketing survey and supported the understanding of the concept of coverage on 3D curved surfaces. K.A. and M.Y. proposed the idea of low-concentration static CPV and supported discussions regarding the module design. K.O., A.S., and R.T. contributed to analyses of the concepts. N.Y. developed the concept of stretchable micro-scale CPV and supervised the project. All authors contributed to the discussions and to improvements of this manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

Supplementary information is available for this paper at https://doi.org/10.1038/s43246-020-00106-x.

**Correspondence**

and requests for materials should be addressed to D.S.

**Peer review information**

Primary handling editor: John Plummer

Reprints and permission information is available at http://www.nature.com/reprints

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

---

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.