Supplementary Information

Increasing efficiency of Perovskite solar cells using Low Concentrating Photovoltaic systems

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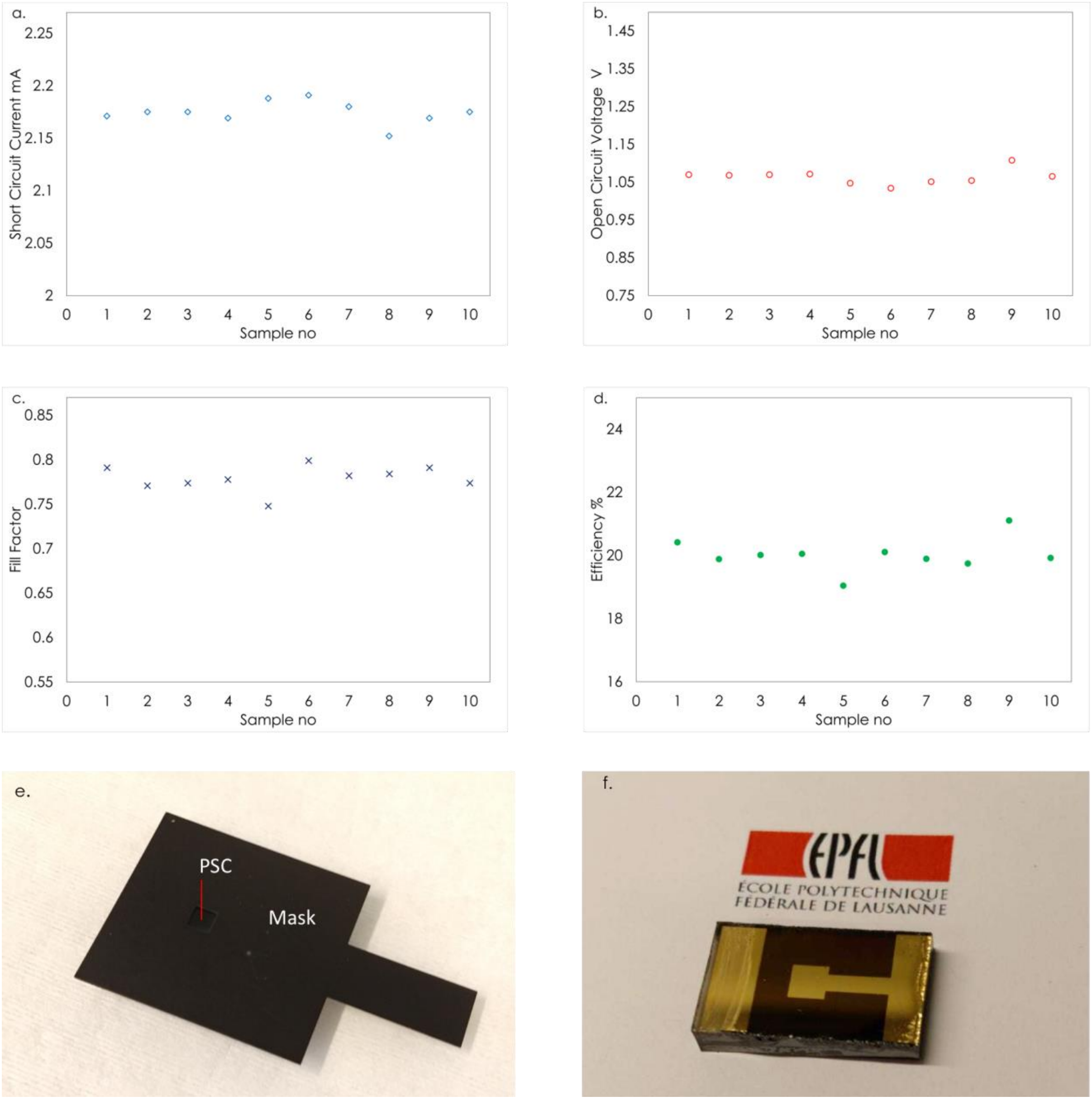
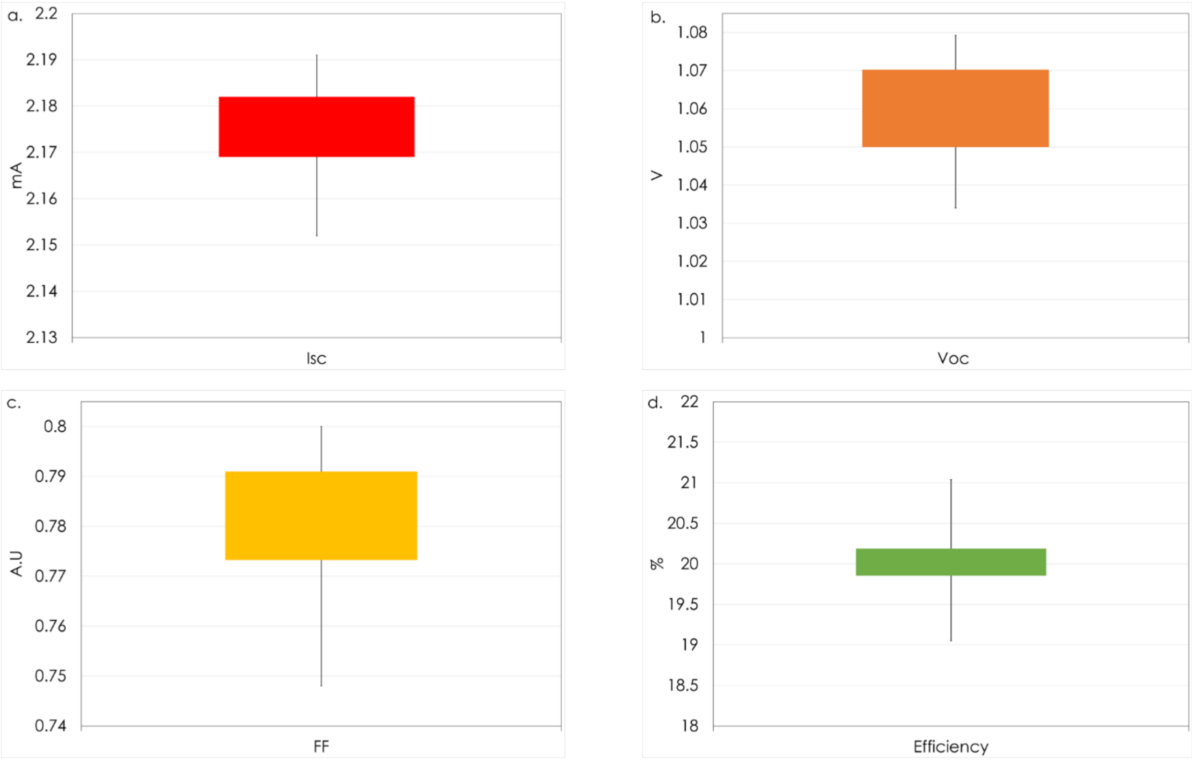
Supplementary Note 1. We start by first evaluating the performance of several samples and identify a good representative that could be utilised for our study. In Supplementary Figure 1 below we showcase the key parameters extracted from the I-V characteristics of ten different samples of the perovskite solar cells (PSC). The summary of the PV metrics of the same are shown in Supplementary Figure 2.

The n-i-p structured devices are made using triple cation perovskite absorber, with a mesoporous titanium oxide/SnO_2 layers as an electron transporting layer, and Spiro-OMeTAD as a hole transporting material. All the tests are performed on unsealed cells in the ambient air under a 4-wire, source and sense mode. The active area of the cells is 9 mm^2, this is achieved using a mask on top of the PSC.



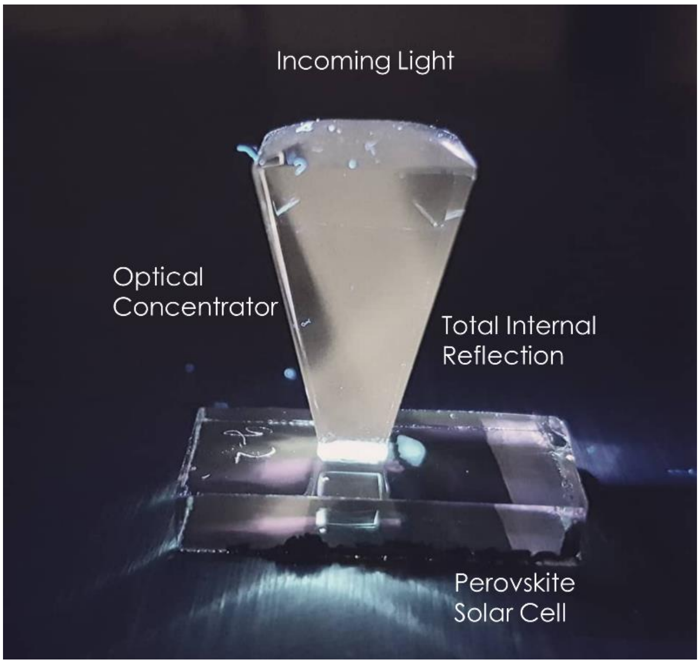
Supplementary Figure 1 of (a) Short Circuit current Isc (b) Open Circuit Voltage Voc (c) Fill Factor FF and (d) power conversion efficiency η for ten different samples (e) Mask placed on top of the PSC with an active area of 9 mm^2 (f) rear side of the PSC.



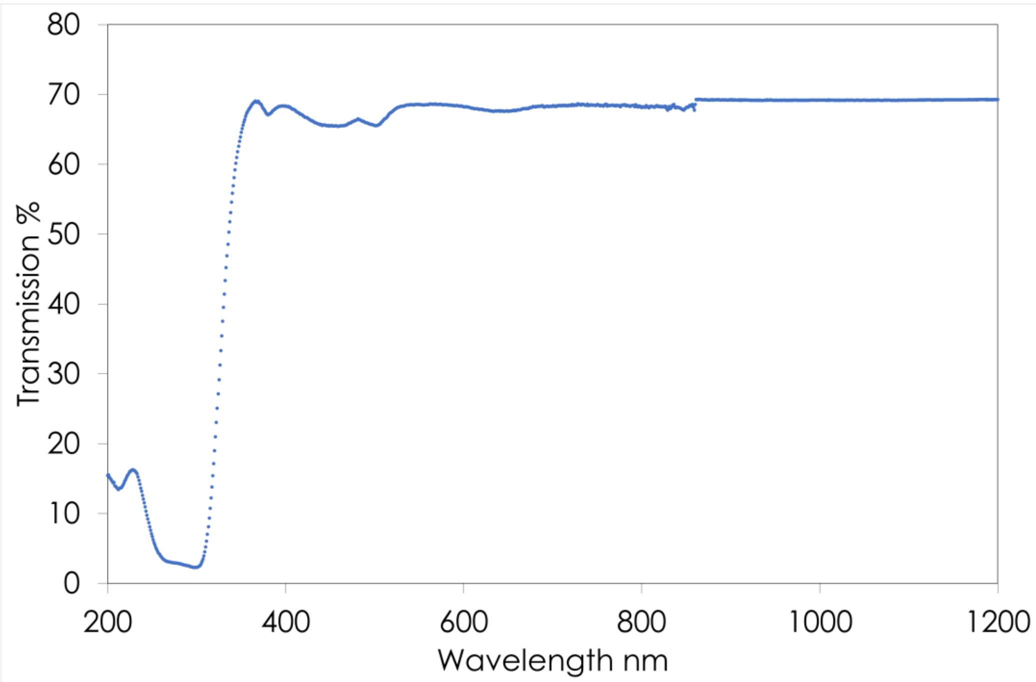
Supplementary Figure 2 Photovoltaic metrics obtained from the 10 samples of PSC tested at AM1.5G, and 1000W/m2 (a) Short circuit current (b) Open Circuit voltage (c) Fill factor (d) Power conversion efficiency

Supplementary Note 2. Light absorption inside the concentrating optic:

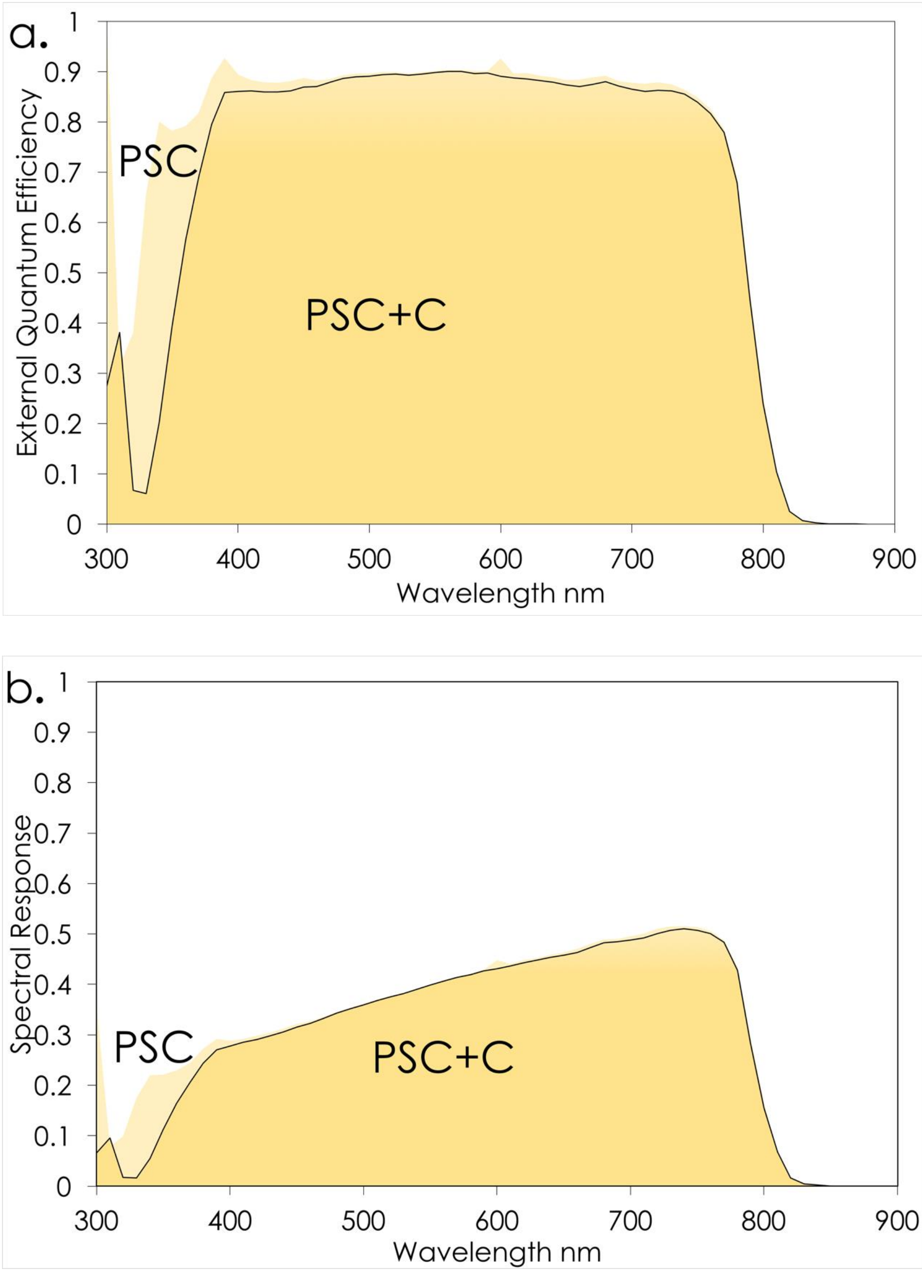
The key requirement of the concentrator material is to have excellent transmission properties. Different solar cell technologies have different spectral response ranges, so the transmission properties of the concentrating optic are important whilst considering the range of spectral response of the solar cell to maximise the electrical output. Equally important is the transmission of adhesive used for bonding the concentrating optic to the PSC. In the present study we used commercially available LOCTITE® AA 350 UV cure adhesive. The viscosity of the UV adhesive used in this work is low making it easy to spread and bonds quickly with the PSC. It is suitable for bonding glass and metals and can also be used on plastics and ceramics. Tack-free time is 20 secs and fixture time 15 secs. The light incident at an angle on the concentrating optic refracts through it and is redirected towards the PSC via total internal reflection as shown in Supplementary Figure 3. We show this image only to demonstrate the effect of total internal reflection occurring inside the concentrating optic. In Supplementary Figure 4 we show the transmission results of the optical concentrator using a Perkin Elmer Lambda 900 UV-Vis spectrometer. A light beam from a light source can pass through a monochromator and filters before reaching the sample. The monochromatic light reaches the detector after passing through the sample to measure the transmittance or absorption properties of the material. The sample is placed in a sample holder and the transmittance is measured with reference to air. This gives us a good understanding of the spectrum of the light that is absorbed essentially between 300-400nm before reaching the PSC. The spectral response and quantum efficiency are properties, which are used to understand the current generation, recombination and diffusion mechanisms in a solar cell. The spectral responsivity (SR) is measured in units of current produced per unit incident power. ORIEL IQE 200B was used to carry out the EQE experiments. Supplementary Figure 5 (a) shows the External Quantum Efficiency and (b) the spectral response of the PSC with and without the concentrating optic. Integrating the AM1.5G photon flux spectrum of the simulator over the cell quantum efficiency leads to expected current densities of 24.85 mA/cm2. This is comparable with the average of the measured ten samples 24.16 mA/cm2.



Supplementary Figure 3 Total internal reflection occurring in the optical concentrator element before reaching the perovskite solar cell



Supplementary Figure 4 Transmission data of the optical concentrator element

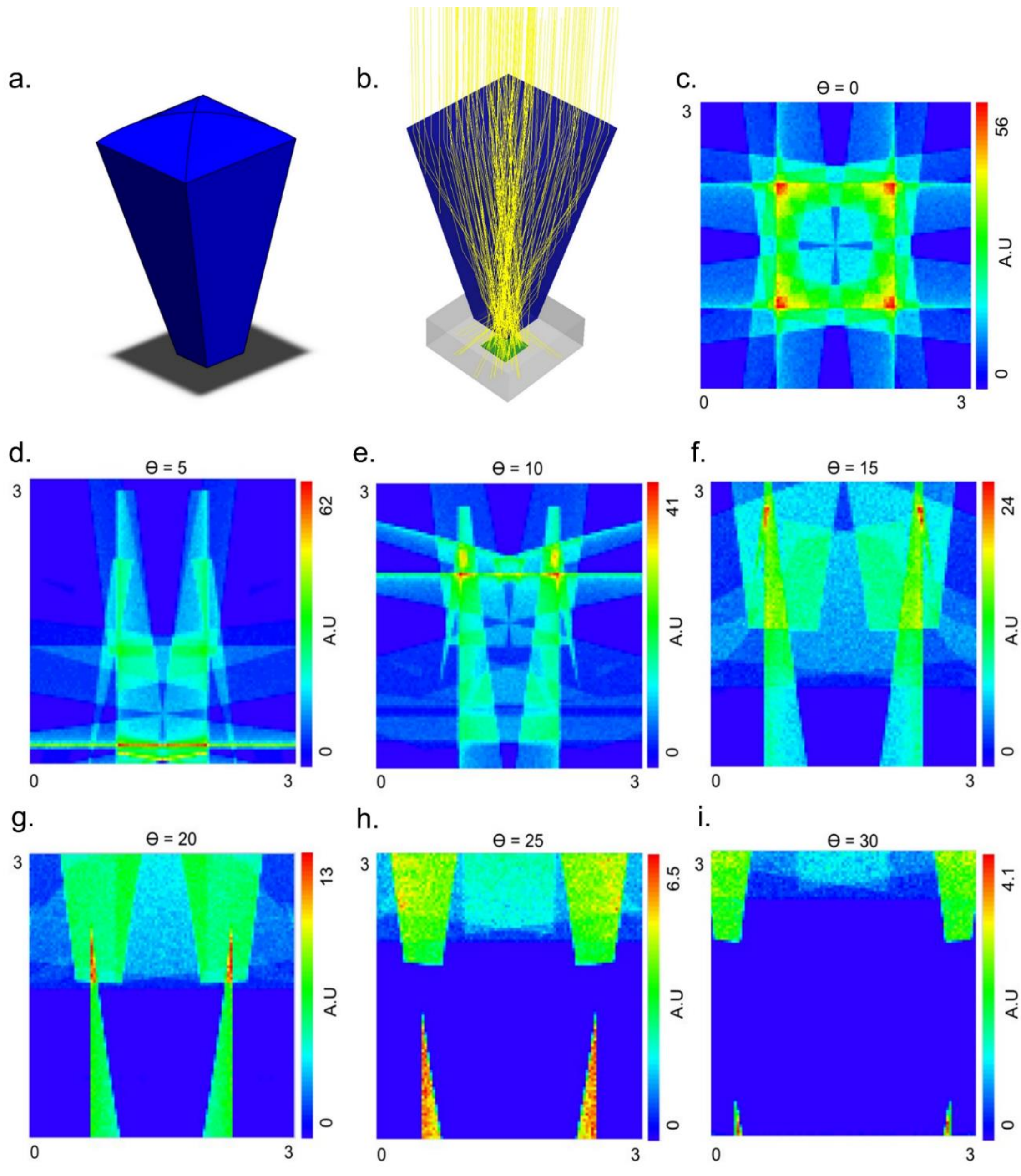


Supplementary Figure 5 (a) An EQE analysis of the bare perovskite solar cell (PSC) and the CPV (PSC+C) has been undertaken to understand the change in spectral response of the module. Due to the absorption of the concentrator material, the EQE of the CPV module drops between 300- 400nm (b) Spectral response indicating the ratio of the current generated by the solar cell to the power incident on the bare perovskite solar cell (PSC) and the CPV (PSC+C).

Supplementary Note 3. Ray tracing

Ray-trace simulations were carried out using the APEX® software package[1]. The optical properties of the dielectric material used for making the optical element and the spectrum of the incoming solar radiation were kept in accordance with the experimental setup. Air mass 1.5G spectrum was utilised for the source that produces collimated light. Once the light rays are incident on the optical geometry, they are refracted, reflected and scattered at the entry aperture and are ultimately transmitted towards the exit aperture via total internal reflection. A portion of the rays also escape the concentrator through its sides or bounce back from the top surface. It's very important that the optical properties of the material be defined as close as possible to the actual material in order to get consistent results. Use of wavelength dependent refractive index material property is made for the concentrator to ensure accuracy of results.

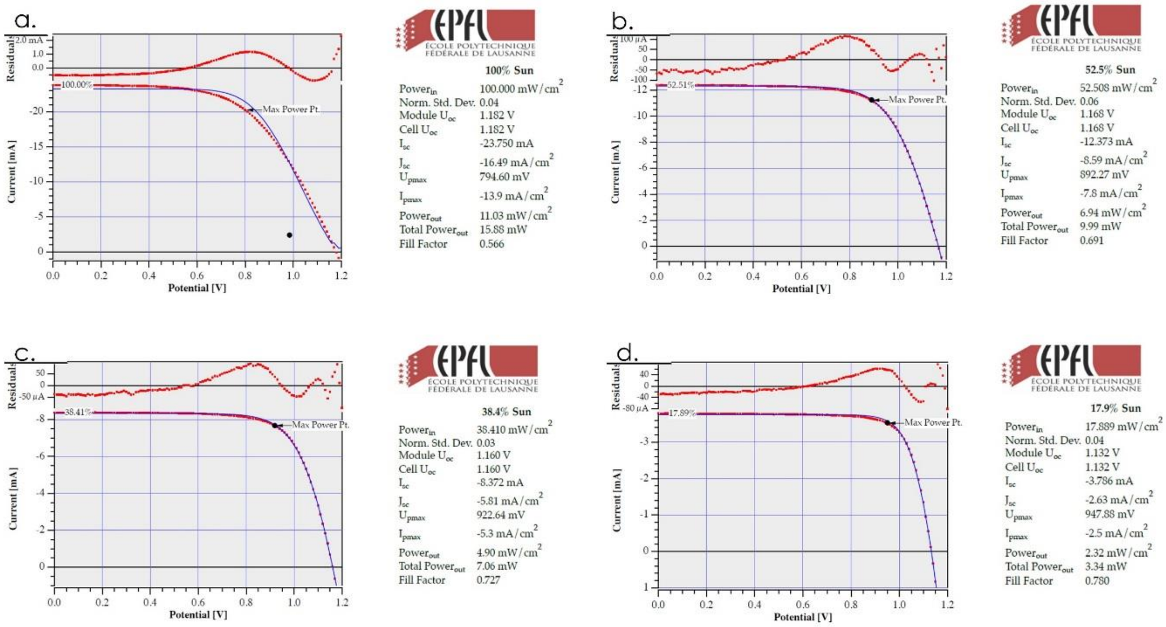
A given number of rays can be traced to represent direct and diffuse solar radiations on the optical unit subjected to appropriate material properties and boundary conditions to predict its performance. In the present study the ray trace analysis was carried out assuming all the incident rays to be parallel and carrying an equal amount of energy. The rays follow basic principles of reflection and refraction (Snell's law) and reach the PSC absorber surface. The results from the optical modelling form a crucial part of our analysis. A square shaped power source is chosen which generates one million parallel rays with an incoming power of 1000 W/m^2 and AM1.5G spectrum. The size of the source is large enough to cover the entirety entrance aperture of the optical element at all angles of incidence. The refractive material causes total internal reflection and traps the incoming rays. The CAD model of the optical element is placed at 20 cm from the source and a PSC is attached at the exit aperture of the optical element. Supplementary Figure 6 shows the optical concentrator, the ray tracing and the illumination flux profiles obtained at different angles of incidence.



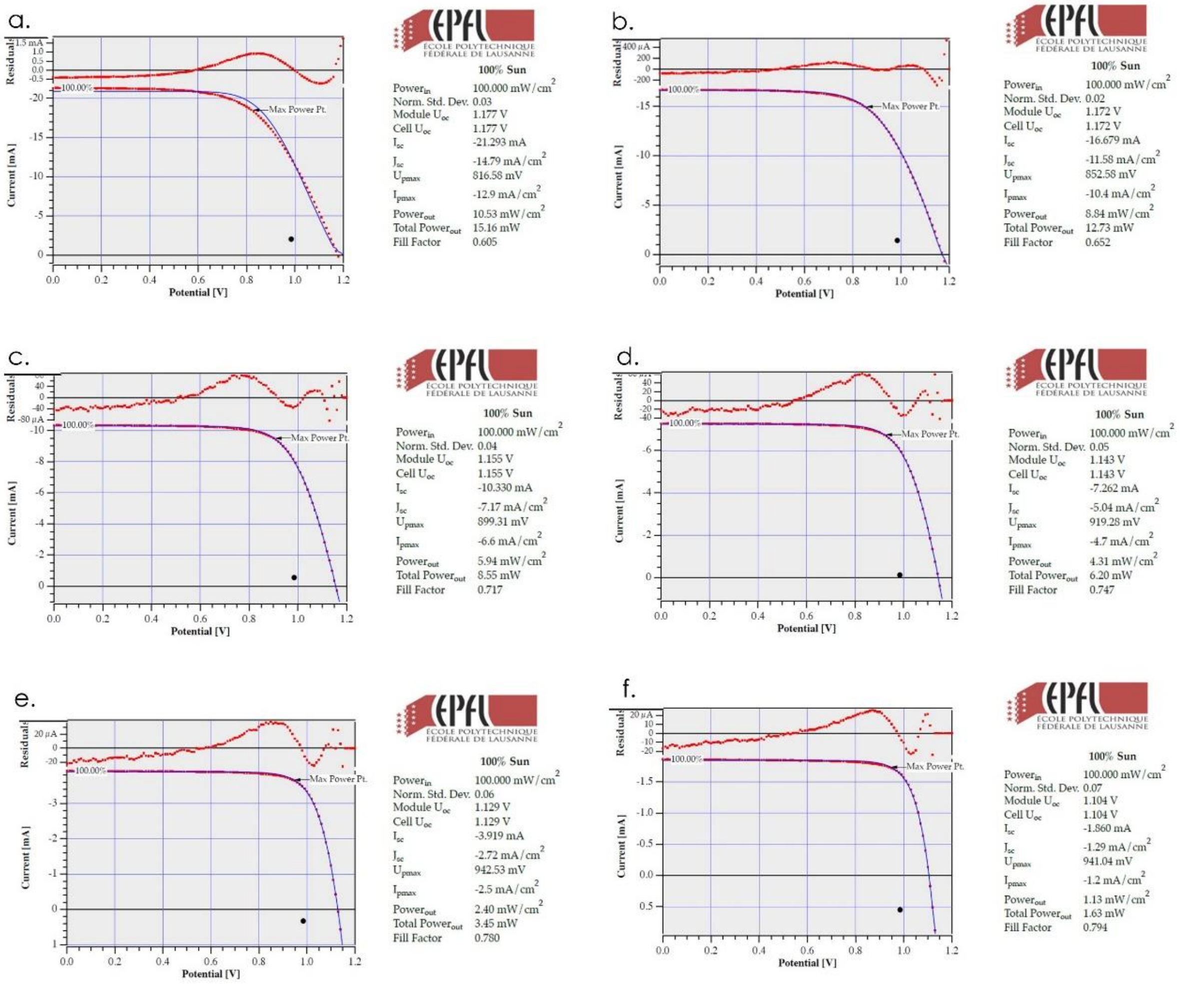
Supplementary Figure 6(a) Optical element (b) ray tracing of the concentrator showing the refraction and focussing of incident light on the PSC (c),(d),(e), (f), (g), (h) and (i) flux profiles at 0,5,10,15,20,25 and 30degree angle of incidence.

Supplementary Note 4. Impact of incident radiation on the PSC performance.

We now proceed to test the PSC coupled with the concentrating optic under different irradiance levels. This is achieved first by changing the intensity levels of the solar simulator using filters. The filters used reduce the intensity of the light incident on the concentrating optic and ultimately the PSC. Supplementary Figure *7* shows the I-V characteristics obtained at the respective irradiance levels. Further, we also tilt the unit at different inclination angles with steps of 5° intervals to investigate the performance of the PSC as shown in Supplementary Figure *8*. The sun concentration incident on the PSC is then calculated based on the equivalent 1 Sun short circuit current density.



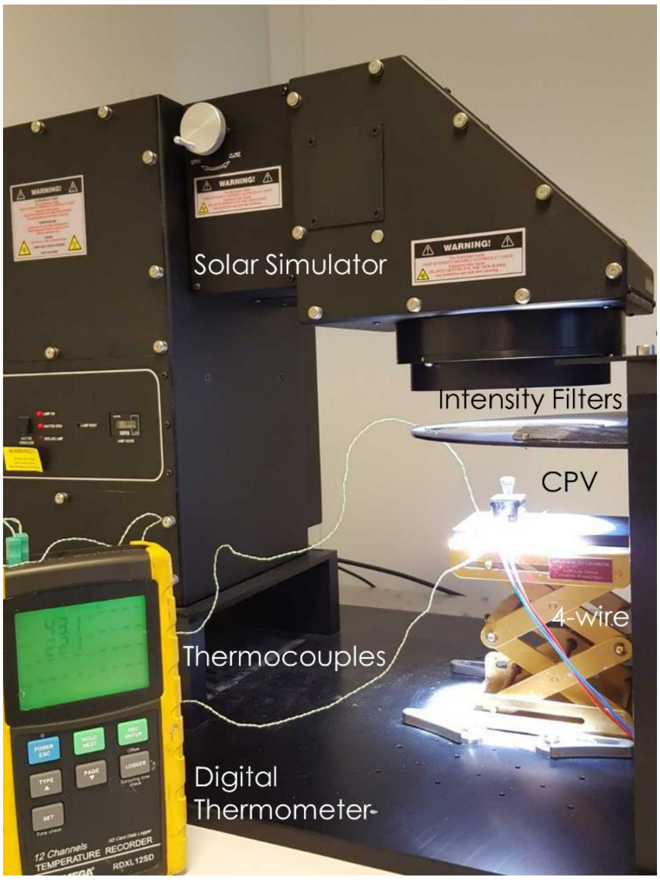
Supplementary Figure 7 Current-density voltage (J–V) characteristics of the perovskite solar cells with concentrator, measured from forward bias (FB) to short-circuit (SC) and back again with a scan rate of 50mV s−1 under simulated AM 1.5 G solar irradiance at (a) 1000W m−2 (b) 525 W m−2 (c) 384 W m−2 and (d) 179 W m−2 with four-wire connections under source mode through filters with respective optical densities.



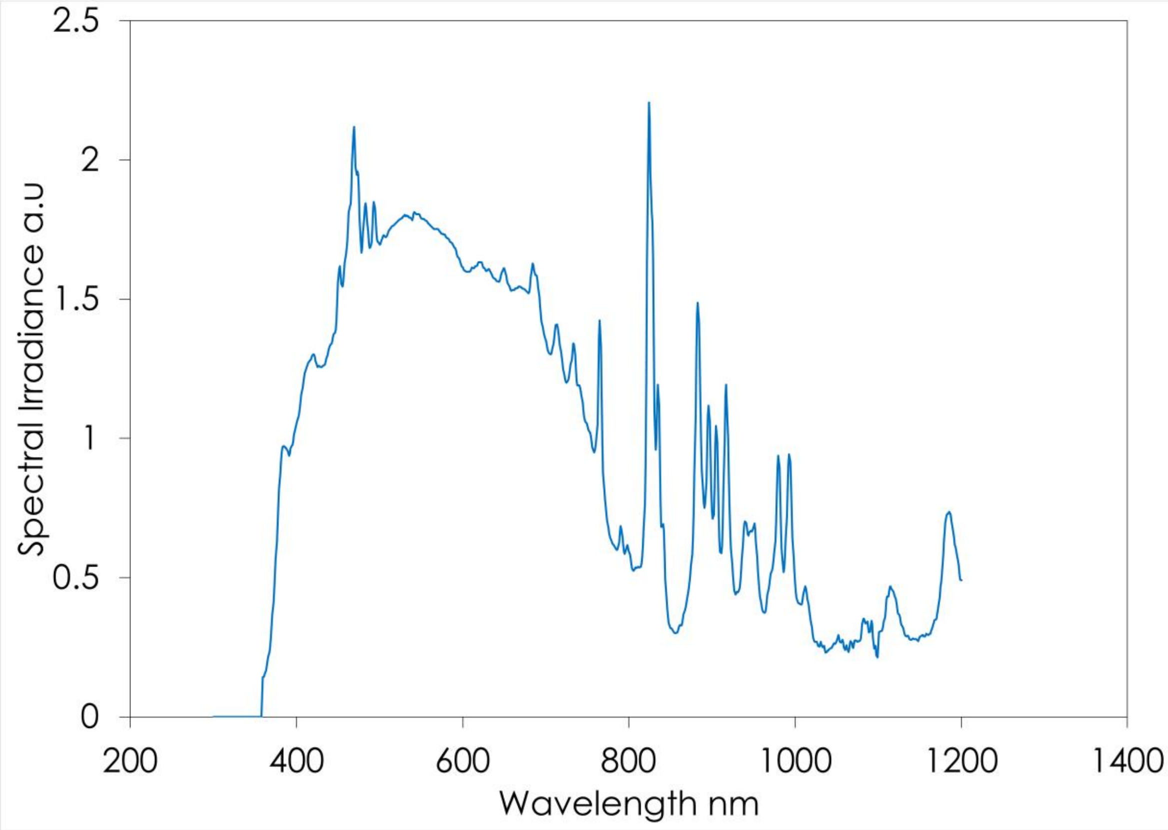
Supplementary Figure 8 Current-density voltage (J–V) characteristics of the perovskite solar cells with concentrator, measured from forward bias (FB) to short-circuit (SC) and back again with a scan rate of 50 mV s−1 under simulated AM 1.5 G solar irradiance at (a) 5° (b) 10° (c) 15°(d) 20° (e) 25° and (f) 30°with four-wire connections under source mode under different angles of incidence.

Supplementary Note 5. Impact of temperature and solar concentration

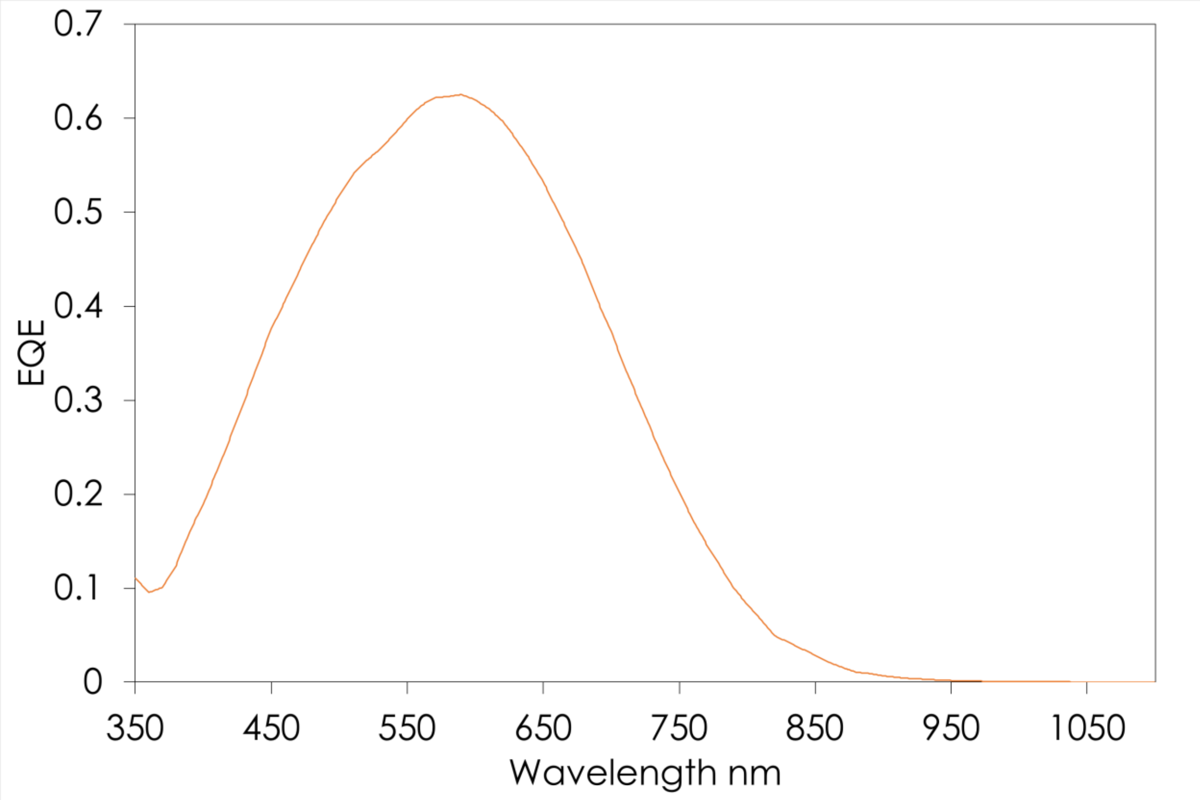
The PSC with the concentrating optic (CPV) device was initially characterised using flash measurements. To further investigate the impact of the continuous exposure to sunlight the device was continuously exposed for a period of approximately 2 hours. During this the temperature of the PSC was monitored closely and the I-V characteristics recorded for every 5°C increase. The experimental setup for carrying out these measurements can be seen in Supplementary Figure 9. The spectrum of the solar simulator is shown in Supplementary Figure 10 and the EQE of the silicon solar cell reference used for calibration is shown in Supplementary Figure 11.



Supplementary Figure 9 Experimental setup for device I-V measurement and temperature under AM 1.5G and 1000 W m−2



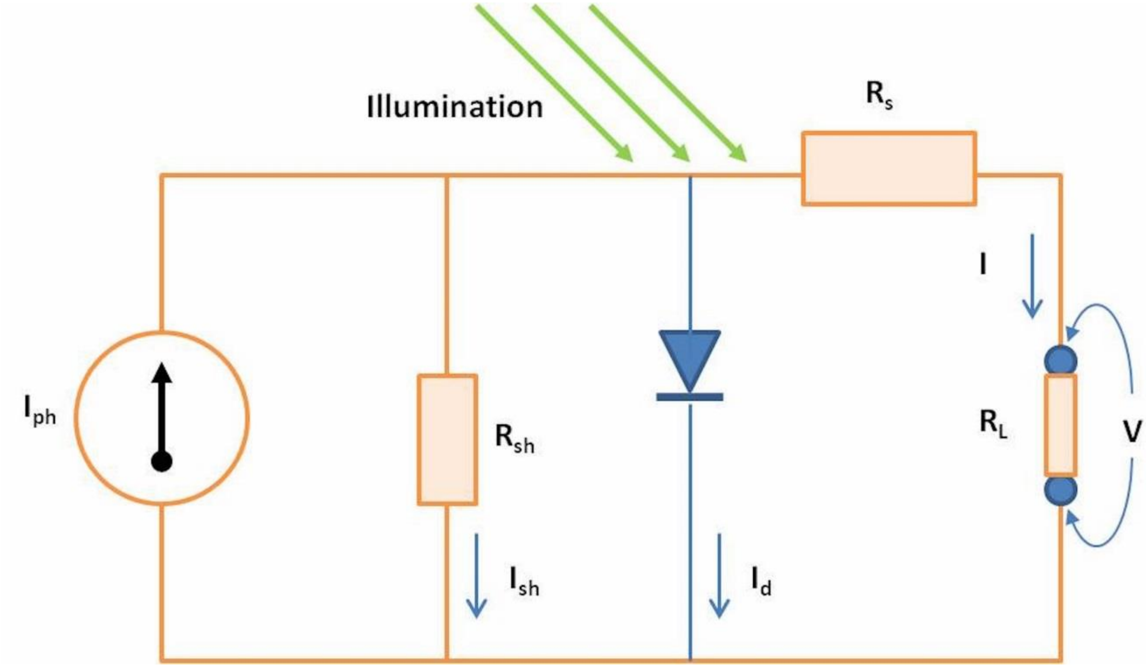
Supplementary Figure 10 Spectrum of the Solar Simulator used for carrying out experiments



Supplementary Figure 11 EQE of the KG3 filtered Si reference cell

Supplementary Note 6. Calculation of solar cell parameters using I-V curves

The solar cell can be modelled using the one diode model[2] as shown in Supplementary Figure 12. The total current flowing in the external load R_L is given by Equation (1) and (2) respectively.



Supplementary Figure 12 Equivalent circuit of solar cell with one diode. The term I_D represents the diode current and the term I_{ph} represents the photo-generated current.

$$I = I_{ph} - I_D \tag{1}$$

$$I = I_{ph} - I_0\left[\exp\left[\frac{V_j}{nV_T}\right] - 1\right] - \frac{V_j}{R_{sh}} \tag{2}$$

$$V_T = k_B T / q_e \tag{3}$$

$$V_j = V + IR_s \tag{4}$$

The term I_0 represents the reverse saturation diode current corresponding to the diffusion and recombination of electrons and holes in the p and n sides of the cell, V is the mean cell voltage across the external load resistance R_L and V_T is the thermodynamic voltage, V_j is the junction potential, k_B is the Boltzmann constant, q_e is the electron charge and n is the ideality factor which is usually greater than 1. R_s and R_{sh} are series and shunt resistances respectively. Fitting is carried out using a custom fitting program based on a nonlinear least square's method.

Supplementary Note 7. Calculation of the optimum solar concentration for a given series resistance

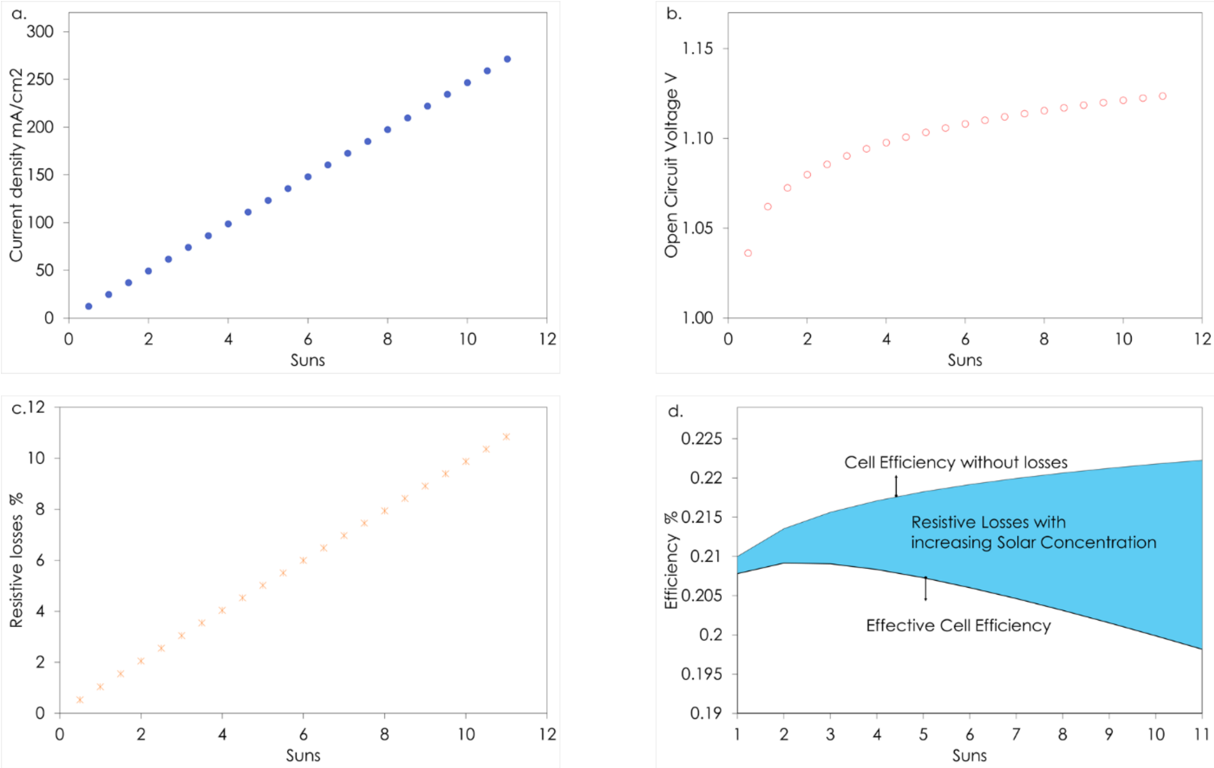
The current flowing through the cell is proportional to the amount of irradiance incident on the PSC. The power dissipated by the PSC can be expressed as

$$P_{loss} = (I_{sc}^{*})^2 * \ R_s$$

$$P_{loss} \cong \left(C_{opt} * I_{sc}\ \right)^2 * \ R_s$$

The power loss will grow very swiftly as the optical concentration ratio (Copt) increases because of the exponent factor. Increasing the optical concentration endlessly would not make any sense as the losses occurring within the solar cell would also increase. Hence an optimum solar concentration would exist for a given series resistance of the cell. Previous studies[3] indicate this optimum to be

$$C_{opt} \ \cong \frac{kT}{q_e} * \frac{1}{I_{sc} R_s}$$



Supplementary Figure 13 Modelled performance of the PSC at a fixed Rs=4.67Ω (a) increasing current density as a function of solar concentration (b) Open circuit voltage with increasing solar concentration (c) the contribution of resistive losses as a % of the maximum power produced (d) the impact of the resistive losses with increasing solar concentration

References

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