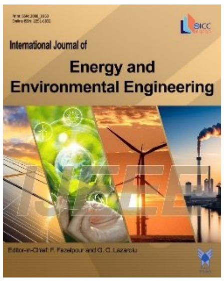

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Energy production and future perspectives of active photovoltaic materials

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Original Research

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Abstract

The rapid growth of the photovoltaic device market is imperative for meeting global sustainability goals, such as reducing chlorofluorocarbon emissions to improve air quality, fulfilling the increasing public energy demands, and ultimately lowering the cost of electricity production. The development and application of advanced energy materials are gaining significant attention within the scientific and industrial communities. In this context, recent research has focused on exploring various photophysical mechanisms that can be integrated into photovoltaic devices to achieve conversion efficiencies theoretically surpassing the Shockley-Queisser limit. This limit, which represents the maximum theoretical efficiency for single-junction solar cells, has long been considered a fundamental constraint. However, innovative strategies such as multi-junction architectures, down-conversion and up-conversion layers, hot carrier extraction, and plasmonic enhancements are being investigated to overcome these limitations. It is noteworthy that approximately 55% of incident photon energy is lost, predominantly due to sub-bandgap losses, where photons have insufficient energy to excite electrons across the bandgap, and thermalization losses, where excess photon energy above the bandgap is dissipated as heat. Addressing these intrinsic loss mechanisms is crucial for the development of next-generation photovoltaic technologies capable of delivering higher efficiencies and supporting a sustainable energy future.

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Keywords: Ultrathin solar cells, Plasmonic resonance, Downconversion layer, Concentrating solar cell

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1. Introduction

Nikola Tesla stressed the importance of alternative energy sources, stating that *"our stores of coal and oil will eventually be used up, and there is not enough waterpower to supply our needs* [1]*."* Obtaining motive energy from atoms or elemental modification once seemed illusory and unquestionable. However, the underlying reasons are becoming clearer with time. The overconsumption of energy resources worldwide has not only led to the depletion of energy sources but has also contributed to the increase in Earth's temperature. This heavy dependency on fossil fuels has resulted in a global temperature rise of approximately 2°C since the pre-industrial era [2]. Renewable energy is increasingly dominating over fossil fuels, with an expected growth of 15.2% by 2030 [3]. This milestone can be achieved by reducing the cost of solar cell components and enhancing their efficiency.

Besides cost and efficiency, intermittency is another significant challenge preventing solar energy from fully replacing fossil fuels. Weather conditions, dust accumulation, and the absence of sunlight at night are major limitations for solar technologies and must be addressed to reduce fossil fuel dependence. Intermittency can be overcome by incorporating storage capabilities, such as thermal or electrical energy storage, as backup sources. Recently, sand batteries have gained popularity as a promising solution to overcome energy intermittency, and they are expected to be highly productive in achieving the required energy yield.

To enhance the output parameters of photovoltaic technology, various techniques have been employed to achieve optimized solutions. The main parameter limiting solar cell efficiency is the Shockley–Queisser (SQ) limit, which was established by Shockley and Queisser through theoretical calculations. Different experimental innovations have been applied to overcome these limitations, and it has been observed that the output efficiency of monocrystalline single-junction solar cells is now approaching their maximum theoretical SQ limit. However, it is important to note that the SQ limit is not a fixed value; it varies depending on the material properties and bandgap (see Figure 1).

The first limitation to the advancement of photovoltaic is approaching the SQ-limit through material engineering. It requires optimal material engineering to tolerate real-world conditions with minimum degradation. Although many laboratory experiments report outstanding results, they often fail to maintain performance under practical conditions [5]. Stunning results have been achieved for perovskite solar cells by PV's research community predicting to reach closer into the QS limit. The best perovskite solar cell efficiency reported by UNIST under standard test conditions, is 25.7%. It is noted that the efficiency of the perovskite solar cell has increased rapidly, with a 12.2% rise over the past 10 years, compared to only a 1.6% increase for silicon solar cells [6]. This improvement is primarily attributed to better light management and carrier dynamics. This rapid advancement of perovskite materials positions them to compete with all other commercialized photovoltaic materials in the near future. The improved light management in perovskite solar cells enhances their electrical performance far beyond that of silicon solar cells.

Despite stability concerns, Perovskite-based solar cells are emerging as highly promising photovoltaic devices with great potential for solar energy conversion [7]. Improvement in the stability can be achieved through the use of double perovskite solar cell, which exhibit enhanced resistance against oxygen and moister, thereby improving the efficiency of the solar cell [8,9]. However, the efficiency gains observed at the laboratory scale for perovskite solar cells have yet to be realized at the industrial scale, where large-scale manufacturing is essential for commercialization [10].

In contrast, the efficiency of silicon solar cells remains approximately 4% below the Shockley–Queisser limit, primarily due to their low radiative recombination rate and significant Auger recombination losses [11].

Another important concept for enhancing the output characteristics of a solar cell is the integration of additional features such as solar concentration, light reflection, and downconversion [12]. While these techniques may add additional structures to the photovoltaic device, they can significantly improve overall performance. We present an overview of these processes and their microscopic understanding, which contribute to enhancing solar cell efficiency. The objective of this study is to discuss advanced photovoltaic systems, including ultrathin-film and polymer solar cells, their operation and recent advancements, as well as their integration with downconversion layers and concentrated light to enhance output parameters.

Process Overview

Solar cell operation involves several key processes, including light absorption, exciton generation within the active material, and photocurrent generation [13]. A pivotal aspect influencing these processes is material architecture, which facilitates the efficient generation of free excitons, minimizes recombination losses and enables effective charge collection at the electrodes. Each exciton generated within the photovoltaic material has a finite escaping probability. This probability is idealized for a blackbody but is significantly lower for real photovoltaic devices. The dynamics of incoming and outgoing electron-hole pairs adhere to the principle of detailed balance, which governs the equilibrium between generation and recombination processes.

The conservation of particles under steady-state conditions is governed by Kirchhoff's current law, as given in Equation 1.

$$J_{sun}\text{-}J_{recom}\text{-}J_{ext} = 0 \qquad (1)$$

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Where J_{sun} is the photocurrent density, J_{recom} is the recombination current and J_{ext} is the output current density generated during solar irradiance AM1.5G given in equations (2), (3) and (4) [14].

$$J_{sun} = q\int_{E_g}^{\infty} \frac{\lambda}{hc} I_{AM1.5G}\, dE \tag{2}$$

$$J_{recom} = \frac{q f_{esc}}{\eta_{rad}} \int_{E_g}^{\infty} \frac{4\pi E^2}{h^3 c^2} \frac{1}{\left[e^{\frac{E-qV}{KT}}-1\right]} dE \tag{3}$$

$$J_{ext} = \int_{E_g}^{\infty} \frac{q\lambda}{hc} I_{AM1.5G}\, dE - \frac{q f_{esc}}{\eta_{rad}} \int_{E_g}^{\infty} \frac{4\pi E^2}{h^3 c^2} \frac{1}{\left[e^{\frac{E-qV}{KT}}-1\right]} dE \tag{4}$$

Whereas

q	Elementary charge
λ	Wavelength
h	Plank constant
E	Photon energy
E_g	Bandgap of the absorber material
K	Boltzmann constant
f_{esc}	Probability of escape for luminescent photon
T	Temperature of the solar cell
η_{rad}	efficiency of the radiative recombination

The only potential material among the available photovoltaic materials is GaAs solar cell which achieves an efficiency of 29.1% with AM 1.5G illumination [15]. The solar spectrum plays an important role in the output characteristics of the solar cell. The solar spectrum is defined by the American Society for Testing and Materials (ASTM International Standard), which defines three spectral distributions, (i) the direct normal AM 1.5D (ii) hemispherical on 37° tilted surface 1.5G and (iii) extraterrestrial irradiance distribution AM 0 just outside the earth's atmosphere as shown in figure 2. Where AM is defined as 1/cos(θ) and stands for air mass. The 2-micron thick GaAs absorbing layer, as reported by Alta Devices and Green et al., [16,17] represents the highest achieved efficiency to date. This exceptional efficiency for GaAs is possible because the growth substrate does not affect the device's performance. Unlu Xu et al. reported single-junction nanostructured solar cells with a maximum theoretical efficiency of 42% under AM 1.5 solar irradiance. This is the highest efficiency achieved for a non-concentrating planar device, although it remains lower than the Shockley–Queisser limit for a planar device with optical concentration [18].

Ultrathin solar cells

Ultrathin solar cells are characterized by an absorbing layer that is at least ten times thinner than that of conventional solar cells. These structures offer several advantages, including significant material savings, enhanced carrier collection, and reduced optical reflection. Furthermore, their ability to support advanced light-trapping structures increases the optical path length, leading to more effective light absorption and, consequently, higher power conversion efficiency [19]. Ultrathin photovoltaics offer the advantage of reduced capital investment due to shorter material deposition times thereby saving both energy and resources. The lower thickness of the active layer also enhances carrier collection efficiency, as it reduces the overall defect density. Liu et al. [20] Liu et al. reported that reducing the thickness of silicon absorbing layer in solar cell by 31% makes low-cost synthesis techniques more attractive for high-throughput production. Furthermore, advanced light-trapping strategies, such as plasmonic resonance, textured surface, and photonic structures, are more easily integrated into ultrathin solar cells, further improving their performance [21]. Parasitic losses in conventional solar cell including optical, thermal, electrical, Auger recombination, etc. are the consequences of lower material quality in the thick absorber layer, preventing these solar cells from approaching efficiency well below SQ limit [22]. It is reported that the transition from conventional solar cells to ultrathin solar cells corresponds to thicknesses below 20 µm for crystalline silicon and below 400 nm for arsenide and chalcogenide based thin-film solar cell materials [23,24]. A 28.8% increase in efficiency has been reported for 10 µm thin amorphous silicon solar cells, attributed to the incorporation of increase in light trapping structures [23,25]. These different light trapping structures such as plasmonic or photonic crystals have already been implemented in perovskites, organic photovoltaics, or colloidal quantum dot solar cells. In an ultrathin solar cell, the appealing features are advanced light-trapping strategies based on unique patterning techniques at the nanometer scale. GaAs has been found to be very efficient among other absorber layers, with significant potential for light trapping via plasmonic resonance. The material can be made more appealing by boosting the V_{oc} via photon recycling effect by the integration of a highly reflective back mirror [26]. Hung-Ling Chen et al [27] reported a 19.9% efficient, 205 nm ultrathin solar cell based on a GaAs absorber and a silver nanostructured back mirror serving as a perfect reflector. The previous achievements for GaAs ultrathin and thick solar cell have been presented in table 1. It shows that efficiency is low for the thinnest GaAs-based solar cells, but in terms of material usage, the progress is quite intriguing.

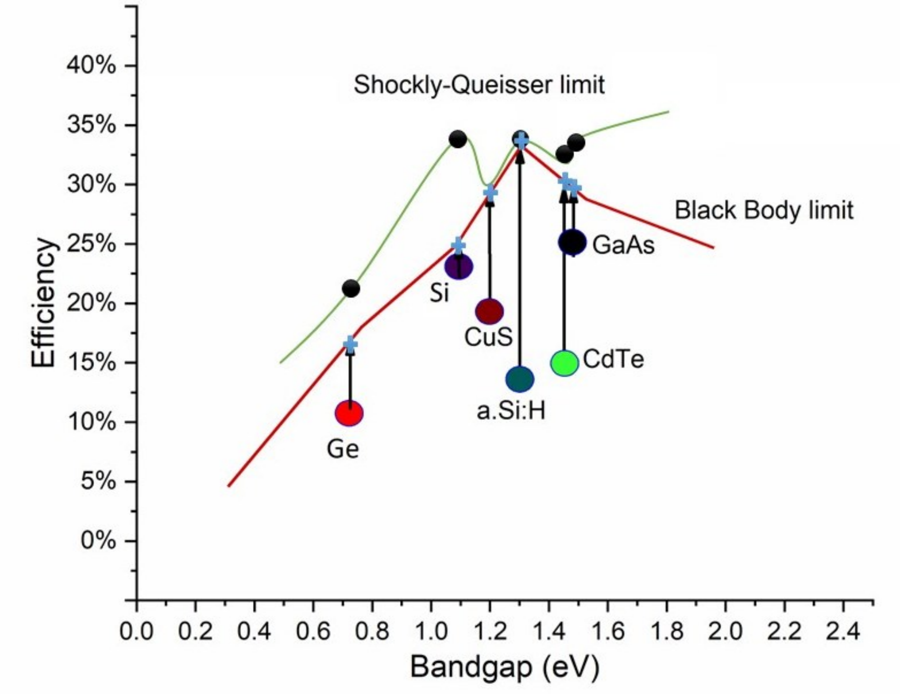

Figure 1. Record solar cell efficiency of different materials against their bandgap, comparison with SQ limits and black body radiation limit. The green line represents the QS limit for each material, while the red line shows the black body radiation limit

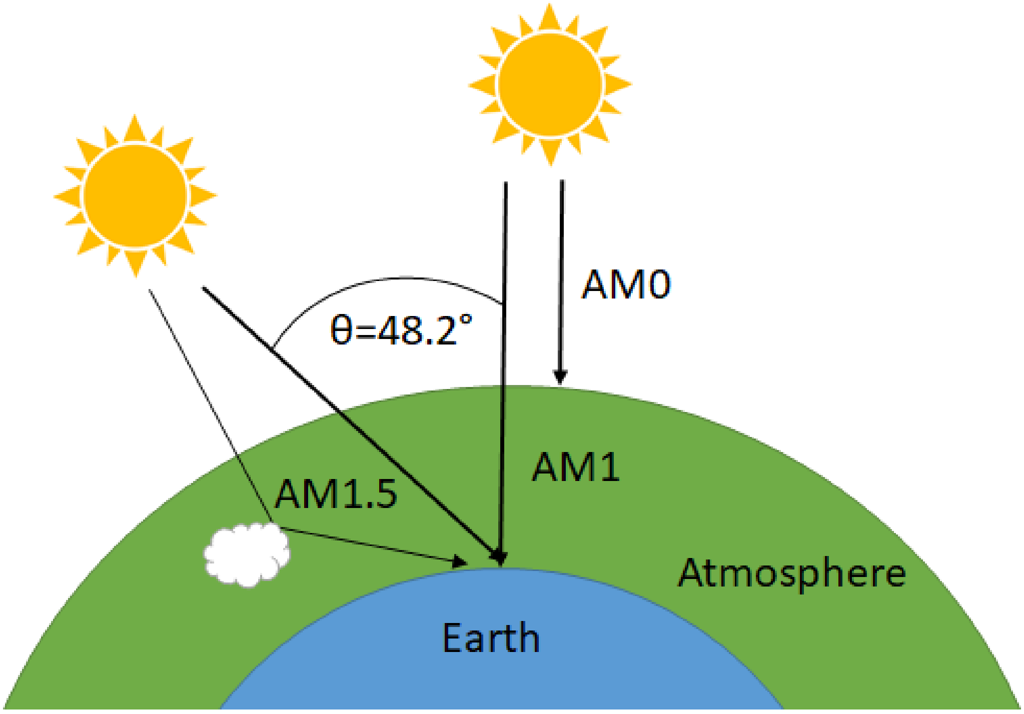

Figure 2. (a) Schematic representation of the solar spectrum outside the earth atmosphere (AM 0) and on the earth surface (AM 1.5D), the direct sunlight along with the scattered radiation from atmosphere integrated over a hemisphere (AM 1.5G) and the direct solar irradiance without concentration inside atmosphere (AM 1)

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Table 1. Record solar cell performance of ultrathin GaAs solar cell with variable thickness

Thickness (nm)	J_{sc} ($mAcm^{-2}$)	J_{sc}/double-pass absorption	V_{oc}(V)	FF	Efficiency(%)	Reference
200	21.96	0.94	0.942	0.78	16.2	[28]
205	24.64	1.05	1.022	0.792	19.9	[27]
300	24.5	0.94	1.000	0.778	19.1	[29]
~1000	29.68	0.94	0.122	0.865	29.1	[30]
>1000	29.46	-	1.101	0.857	27.8	[31]
800	36.91	-	0.95	85.87	30.26	[32]

It is important to note that each material type requires a critical thickness to operate effectively as an ultrathin solar cell.

The structural design of the ultrathin solar cell has significant features compared to the conventional solar cells. The compensation of light escape from the ultrathin structure is carried out by light trapping structure [33]. Light trapping is accomplished using a nanostructured Ag back mirror (in combination with Ni/Ge/Au Ohmic contacts to minimize resistive losses), which serves as a highly reflective layer [34]. This periodic pattern installed as a back contact and reflector intensifies the absorption via multiple guided mode resonance. This will increase the number of resonances with period “p” but destructive diffraction losses for shorter wavelengths at normal incidence induces optical losses in free space. This loss is compensated by the nanostructured reflective surface installed at the back of the device. The rationale of the device is accomplished in such a way that the active absorbing layers are kept absolutely flat to avoid degradation triggered by improved surfaces. Figure 3 (A, B) shows a schematic of the ultrathin solar cell design with spectral irradiance and the actual ultrathin solar cell inside a soap bubble in order to realize the thickness of the solar cell.

Plasmonic resonance in ultrathin solar cells

In an ultrathin solar cell, the active absorbing layer can be made up to 100 times thinner than that of conventional thin-film solar cells. While this reduction in thickness improves economic competitiveness thereby significantly diminishes optical absorption. To compensate the absorption losses, plasmonic resonance phenomena in metal nanostructures are employed for light trapping and increased generation of charge carriers in the adjacent semiconductor material [36]. The idea in the plasmonic resonance lies in their potential to condense the conduction electron oscillator strength into the required spectral frequency range required for efficient photovoltaics. The reduction in thickness (up to 10 nm) will also give rise to high open circuit voltage and short circuit current due to concentrated absorption via plasmonic resonance [37]. Yinan Zhang et al. [38] carried out a theoretical study on metallic nanoparticles within the silicon wafer to maximize absorption in the photovoltaic devices. It was noted that the plasmonic resonance achieved in metallic nanoparticles significantly reduces the thickness of silicon wafer up to 1 nm. Figure 4 is a schematic layout of silicon solar cell with and without metallic nanoparticles. The figure shows how the thickness is dramatically reduced with the inclusion of nanoparticles leading to surface plasmonic resonance.

The primary mechanism behind the unique optical properties of metallic nanoparticles in surface plasmon resonance involves dipole oscillation, enhanced photonic absorption, photon coupling, and scattering. Gold and silver nanoparticles are particularly known for exhibiting strong plasmonic resonance due to their specific size and morphology [39]. This strong light-trapping capability, facilitated by plasmonic effects, significantly improves light absorption in the active layer, thereby enhancing solar cell efficiency. Moreover, the output power of the solar cell is highly dependent on the localized plasmonic interactions at the interface [40]. The underlying physics of surface plasmon resonance lies in the condition that the nanoparticle size must be smaller than the wavelength of the incident photon [41]. In solar cells, an additional layer of plasmonic nanoparticles can generate secondary excitons through radiative and non-radiative effects, primarily by utilizing the phenomenon of hot electron injection [41]. Among other nanoparticles, the use of silver (Ag) and gold (Au) NPs has been extensively reported in the literature for solar cell applications due to its unique resonance potential [42-44]. Fei Zhao et al. reported the use of Ag nanoparticles and TiO_2 inverted triangular prism in c-Si heterojunction solar cells for potential absorption. The TiO_2 inverted triangular prism is installed at the top in photonic mode to enhance short wavelength absorption in the active layer while Ag nanoparticles installed at the bottom increases the longer wavelength absorption via surface plasmonic resonance [45]. In the literature, extensive work has been devoted to gold (Au) and silver (Ag) nanoparticles for surface plasmon resonance despite their high cost. The plasmonic resonance generated by Au nanoparticles helps enhance the electrical properties of solar cells, especially an increase in short-circuit current [46-53]. The nanoparticles incorporated at different locations of the device have a significant impact on the performance of the solar cell. The most impressive results are obtained for polymer solar cells via gold nanoparticles with graphene shells positioned in between the active and hole transport layer. The incorporation of nanoparticles induces a plasmonic response in the solar cell, enhancing its efficiency by 100%, which is a major breakthrough in polymer photovoltaics [54]. It has been observed that the integration of metallic nanoparticles in a buffer layer maximizes the plasmonic resonance, enables greater light absorption in the active layer by optimizing field coupling and reducing electrical losses at the interface [55,56].

Further results demonstrating plasmonic responses for efficiency enhancements in various solar cell devices are presented in Table 2.

Polymer solar cell

Polymers are employed in photovoltaics as versatile materials to help circumvent reliance on fossil fuels and other non-renewable technologies. Their various uses include: (i) as a templates for the synthesis of mesoporous materials, (ii) as a polymeric matrices in solid-state electrolytes, (iii) as a counter electrode materials, (iv) as a substrates in dye-sensitized solar cells, (v) as a photoanodes in dye-sensitized solar cells, (vi) as a composite electrolyte materials in dye-sensitized solar cells, (vii) as a hole transport layers in dye-sensitized solar cells, and (viii) as a interlayers in layered device structures, among others [67]. The most important use of polymer in photovoltaic devices is its exclusive use as active layer.

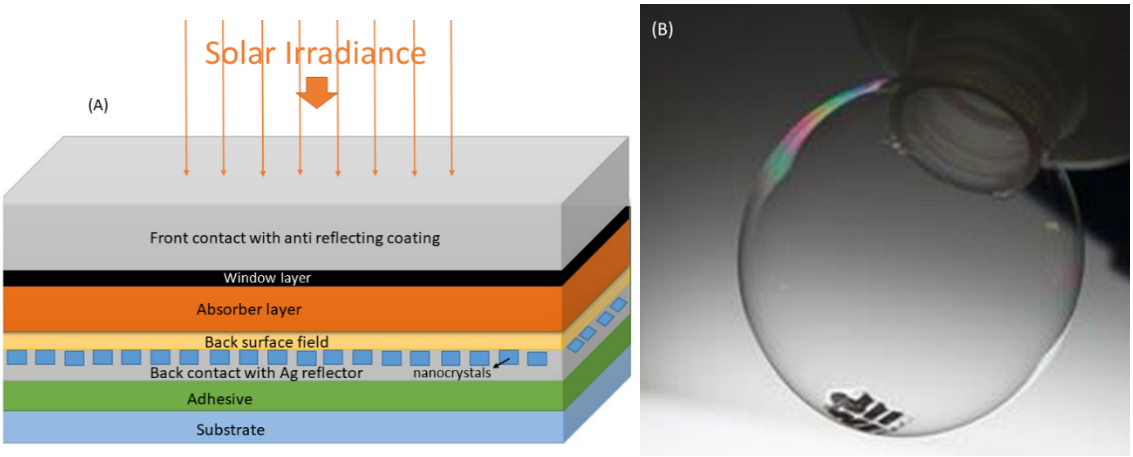

Figure 3. (A) Schematic of ultrathin solar cell in substrate structure nanostructured back mirror and front contact with anti-reflecting coating. (B) Image of the actual solar cell placed in a soap bubble for comparison as light than a soap bubble. Copyright @ Elsevier and copyright clearance center under license number 5342360289231[35]

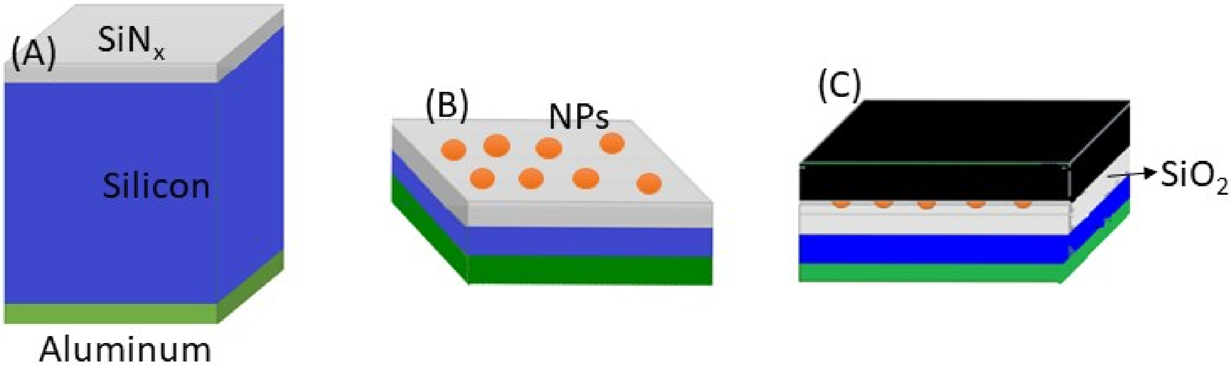

Figure 4. (A) 180 mm thick standard silicon solar cell with 75 nm with antireflection coating layer, the silicon layer and aluminum layer as back reflector. (b) Ultra-thin solar cell with the spherical nanoparticles positioned on top front surface of the anti-reflecting layer and (c) the hemispherical nanoparticles implanted in a silicon dioxide layer between the silicon and aluminum layer

Table 2. Plasmonic nanostructures of gold (Au) and/or sliver (Ag) used to increase PSCs/OSCs efficiency

Plasmonic structure	Position in device	Efficiency enhancement	Ref
Ag NPs	At two different locations	15%	[57]
Ag NSs	Buffer layer	39.5%	[58]
Au NSs	Buffer layer	24%	[59]
Au NSs	Buffer layer	18%	[60]
Au NSs	On the ITO	15.6%	[61]
Au@SiO_2 NP	Buffer layer	16.3%	[62]
Au@TiO_2 NP	ZnO buffer layer	17.3%	[63]
Au:Ag NPs	MnO_3 buffer layer	22.5%	[64]
Au:Ag NPs	In the active layer	55.9%	[65]
Au:Ag NPs	Buffer layer	74%	[66]
Au@Gr NPs	HTL & active layer	100%	[54]

In 1980's, the 1st polymer solar cell with 0.04% efficiency was reported [68] using monochromatic light. A couple of years later in 1982, Weinberger et al. explored a new polymer solar cell with a structure Al/polyacetylene/graphite with an open circuit voltage of 0.3 V and was 0.3% efficient [69]. A major development came in 1986 when Tang discovered a 1% efficient solar cell by bringing a donor and an acceptor together in one cell [70]. The recently reported efficiency of the organic polymer solar is 18.2% with significant stability and green processing [71]. This highly efficient polymer solar cell was achieved by replacing the inorganic components with semiconducting polymer. The output cell performance (such as exciton diffusion lengths and electron/hole mobilities) was further enhanced by replacing the existing morphology with nanostructured. The nanostructured morphology will not only increase the surface to volume ratio but will also give rise to the plasmonic resonance effect. This development of bulk heterojunction and synthesis of solvable fullerene has substantially improved the efficiency of the polymer-based device. The polymer serves as an electron donor (D) while the modified fullerene serves as an electron acceptor (A). The combination of both solutions resulted into a modified film solution with multiple donor/acceptor interfaces where charges are generated after photoexcitation [72]. The replacement of electron acceptor materials with fullerene sharply rises the efficiency above 18% which is a major advancement in the field of polymer photovoltaics [72,73]. The architecture of the device as an active layer is shown schematically in figure 5 [72]. The optoelectronic properties of polymers can be tuned through molecular and chemical engineering, copolymerization, and controlled doping. These modifications enable the polymer to tailor its HOMO-LUMO energy levels, absorption spectrum, and charge carrier mobilities. Such tuning effectively facilitates exciton generation and enhances the stability and mechanical flexibility of the material, which are essential for high-performance photovoltaic applications [74].

The optical absorption is accomplished in the polymer active layer, as a result, the electron overcomes the energy of the bandgap. The band gap corresponds to the energetic leap from the occupied molecular orbital of higher energy (HOMO) to the lower energy unoccupied molecular orbital (LUMO), forming a spatially located electron-hole pair (exciton) attracted by Coulomb's force [75].

It has been reported that metallic nanoparticles and their derivatives are key enablers for enhancing the efficiency of solar cells by leveraging the principles of plasmonic resonance [76]. These plasmonic metal nanoparticles act as local light-trapping centers, induce multiple scattering, and increase the optical path length [77]. Although metallic and metallic alloy nanoparticles can be embedded in various layers of the solar cell for plasmonic resonance, studies have shown that embedding them in the active layer yields the highest efficiency improvements. The plasmonic materials help reduce reflection losses in the active layer through wave-guiding effects [78-80]. The role of different nanoparticles in the performance of the polymer solar cell has been tabulated in table 3.

Downconversion layer for maximization of carriers in active layer

The maximum efficiency for an optimal bandgap of 1.1 eV was calculated to be approximately 31% by Shockley and Queisser in 1961 [4]. This limit has already been surpassed in solar cells through theoretical modeling and computation. The use of new materials in solar cell technology has extended beyond the traditional limits of conventional modules. However, for cost-effective modules, maximum efficiency can be achieved within the existing framework by controlling thermalization losses in the active region. This approach will reduce the price of solar modules and facilitate the transition to a sustainable global economy. Numerous concepts have been proposed over the last 50 years to achieve this fundamental efficiency limit close to the QS limit. These concepts have included multijunction solar cells, plasmonic resonance, interband transitions, concentrator, and up-conversion (uc) and down-conversion (dc) techniques [83]. Both dc and uc are two rigorous techniques for photon management, thereby enhancing the exciton generation process.

The DC mechanism is possible in organic dyes, rare earth ions, and quantum dots, and is particularly preferable in quantum dots due to their tunable size, which allows precise control over emission and absorption bands. Organic dyes, on the other hand, have a small Stokes shift, resulting in significant absorption losses, while rare earth ions suffer from a low absorption coefficient [84]. The DC layer acts as a photon management layer, maximizing the number of controlled photons reaching the active layer for photovoltaic conversion. Photons must pass through several layers (e.g., window layer, CdS, buffer layer, ZnO, front contact, ITO) before reaching the active region (as shown in figure 6a). In the visible spectrum, CdS absorbs wavelengths $\lambda < 500$ nm and ZnO absorbs wavelengths $\lambda < 390$ nm in the active region, while the remaining spectrum is lost as parasitic losses [85]. In order to utilize the spectrum more effectively, the DC layer can leverage quantum dots or rare earth ions with suitable energy levels to convert high-energy photons into low-energy photons that align with the bandgap of the active medium, maximizing the exciton generation process and improving power conversion efficiency of the device [86].

The DC phenomena was 1st reported by Trupke et al. in solar cell as a separate layer to split high energy photons into two intermediate photons matched with solar cell bandgap [87]. The dc layer integrated with the conventional thin film solar cell is schematically shown in figure 6-(a) [88]. The 1st attempt to increase the efficiency of dye sensitized solar cells (DSSC) using dc layer integration was reported by Shan and Demopoulos with the addition of Yb^{3+}-Er^{3+} co-coped LaF_3 into the TiO_2 [89]. The dc layer converted 980 nm of unabsorbed light into visible wavelength 510 nm-700 nm enhancing the efficiency by 13.6%. The mechanism responsible for dc phenomena is the incorporation of rare earth (RE) element acting as a p-type dopant raising the fermi level of the electron and the redox potential in the electrolyte thus increasing the photovoltage of the DSSC. In the dc mechanism, an ultraviolet (UV) photon is absorbed in a single ion, exciting an electron to the higher excited state, the electron is de-excited into an intermediate state by emitting two near infrared (NIR) photons. The three possibilities in dc mechanism via resonant energy transfer between two distinct ions as shown in figure 6-b. A reverse co-operative energy transfer is induced upon photon absorption leaving the ions in an excited state. These excited states simultaneously decay into a lower state emitting two low energy photons. It is also noted that the dc process is independent of the light intensity [90].

The literature shows that the downconversion (DC) layer has not yet been fully optimized, and further work is needed to achieve optimal conditions. Previously, Lucile Dumont et al. reported an efficiency increase from 16.48% to 16.53% for silicon solar cells with $SiNx:Yb^{3+}/SiNx:Tb^{3+}$ DC multilayers deposited by reactive magnetron co-sputtering. The deposition parameters were adjusted to position both rare-earth ions optimally for enhanced light management. The V_{oc}, J_{sc}, and FF were also improved to 0.595 V, 33.61 $mA \cdot cm^{-2}$, and 0.82 [91]. Wen-Jeng Ho et al. reported an 18.77% enhancement in efficiency by incorporating a Eu-doped silicate phosphor luminescent downconversion layer in combination with a silicon solar cell [92]. B.S. Richards [93] reported the utilization of a downconversion (DC) layer in conjunction with silicon solar cells, resulting in approximately a 38.6% increase in efficiency. Olfa Maalej et al. [94] demonstrated a 1.4% efficiency improvement in silicon solar cells using a DC encapsulation glass with an optimal Tm^{3+} doping concentration of 1 mole %. Taylor Uekert et al.[95] reported enhancements in short-circuit current density and power conversion efficiency of 3.2–4.3% by employing nanostructured organosilicon luminescent down-shifting layers in thin-film solar cell applications. Jinbiao Jia et al. [96] observed a 6% increase in the photovoltaic performance of perovskite solar cells through the use of down-conversion $NaYF_4:Eu^{3+}$ nanophosphors.

Concentrating photovoltaic (CPV) systems

CPV has the ability to replace costly solar cells with inexpensive optics. It consume less materials and space but introduces additional complications. The price of the solar cell will rises considerbly, which will specifically affect the large scale utilization [97]. The dailly and annual rotation of the sun will require some additional challenges in maintaining full light concentration on the junctions [98]. CPV systems are notably complex to implement due to their precise tracking requirements. Additionally, conversion losses, including absorption and non-uniformity losses can reduce overall efficiency by up to 16%. Furthermore, CPV systems are often inefficient at fully utilizing the available radiation on the aperture.

These losses are largely avoided in non-concentrating systems. As a result, CPV units require a much larger aperture area to achieve comparable output, leading to increased costs and maintenance challenges [99]. Besides these limitations, the CPV unit is very helpful in cost and space constraints by increasing the development of concentrated technology.

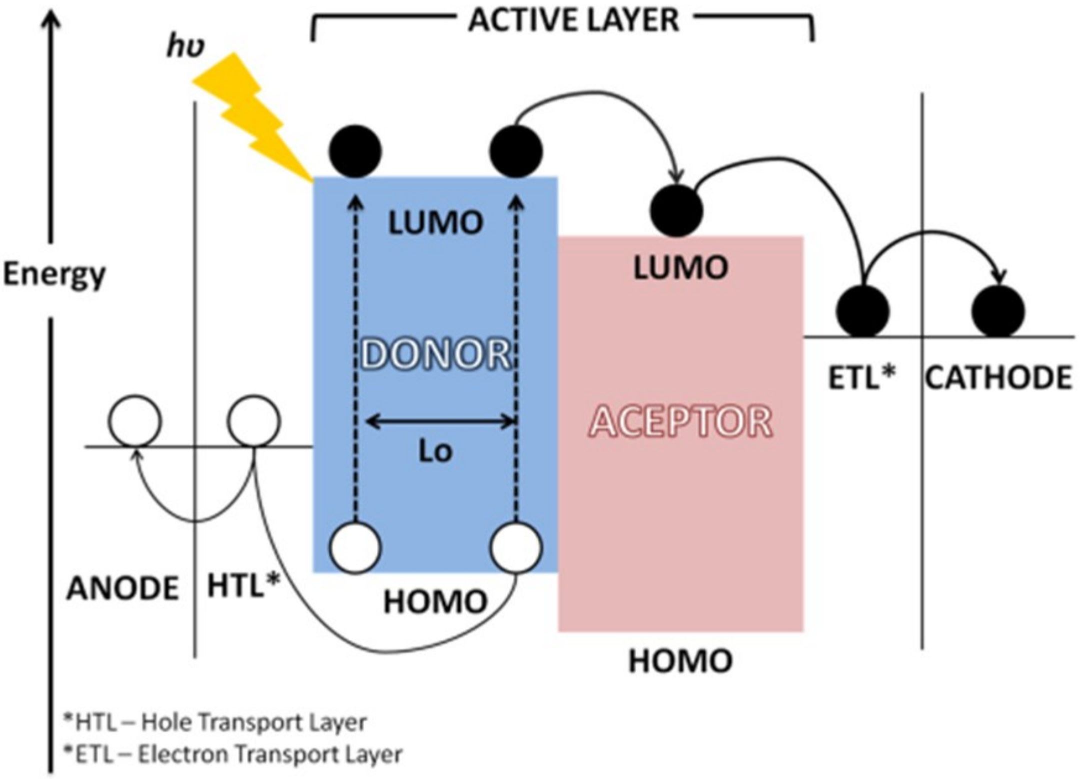

Figure 5. Schematic for photon conversion in polymer based PV cells, copied from reference [72] (AIMS Press are Open Access under the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0)

Table 3. Main results of plasmonic nanostructures of Au, Ag, Al, and In used to increase solar cell parameters

Dopant	Condition	Fill factor (%)	Short circuit current (mA.cm^{-2})	Efficiency (%)	Reference
Au	Without nanoparticles	50.1	7.59	2.37	[81]
	With nanoparticles	51.8	9.05	2.91	
Ag	Without nanoparticles	69.9	27.08	3.47	[76]
	With nanoparticles	76.6	31.43	7.61	
Al	Without nanoparticles	35	27.43	11.35	[82]
	With nanoparticles	39	31.87	13.72	
In	Without nanoparticles	__	27.38	11.52	[82]
	With nanoparticles	__	33.59	14.18	

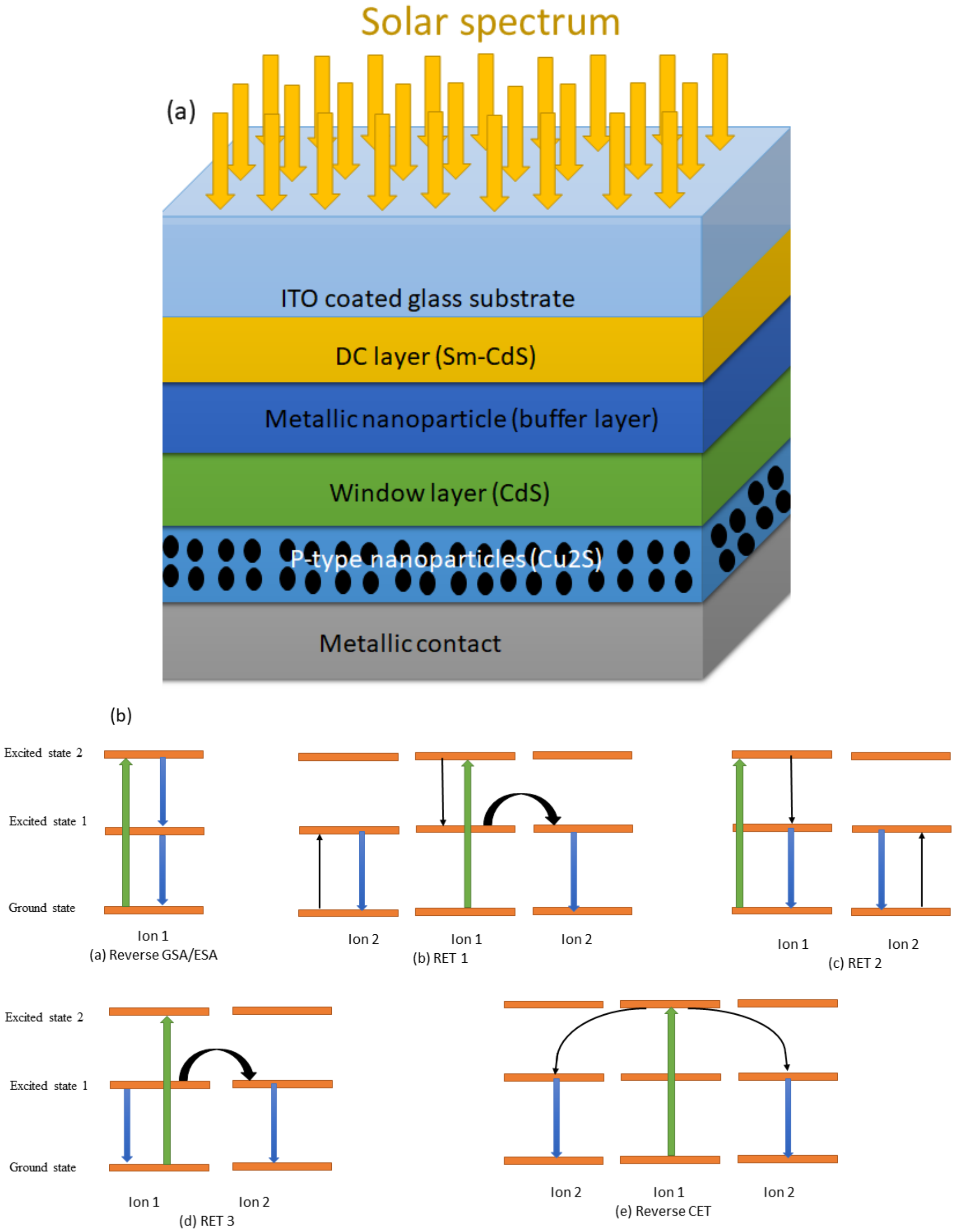

Figure 6. Schematic of ultrathin plasmonic solar cell with Downconversion (Sm-CdS) layer (b) Diagram for downconversion mechanism: (a) Excited State Absorption in reversed direction (b), (c) and (d) The resonant energy transfer between two ions and (e) Co-operative Energy Transfer

The concentrated photovoltaic technology uses Fresnel lenses, parabolic troughs, dishes, luminescent glass, and a compound parabolic concentrator. CPV systems are classified on the basis of concentration levels as low (<10 suns), medium (10-100 suns), and high (100-2000 suns) concentration systems [100]. Ahmadi et al. reported his analysis based on CPV and non-concentrated photovoltaic. It was found that the CPV system is 2% more efficient than the non-concentrated PV system. It was also established that the concentrator solar panel has better results than the Fresnel lens concentrator in terms of efficiency and temperature [101]. Algora & Rey-Stolle reported that, for the generation of 1 watt of output power, a 40% efficient multijunction photovoltaic system operating under normal conditions (1 sun) would require 2666 times more area than a 15 % efficient solar cell operating under 1000 suns radiation power [102]. The National

Renewable Energy Laboratory (NREL) efficiency chart for 2025 shows that the maximum solar cell efficiency reached 47.6%, achieved with four or more junction concentrator cells [103]. Concentrators are used to focus light on the photovoltaic device, aiming to enhance efficiency and reduce costs. Energy demand is increasing day by day due to the rapid growth of the population. Photovoltaic energy systems are expanding in production to help reduce the burden on global energy resources. Maximum photovoltaic generation capacity for various years is presented in table 4 [104-107].

Solar PV systems are often criticized for their low mass production density, primarily due to their low power density, intermittent nature, and limited photovoltaic conversion efficiency. To address this, small cells are combined with mirrors and low-cost lenses to concentrate solar radiation, which impacts reliability, cost, and complexity. Nonetheless, multi-junction photovoltaic cells continue to set new records in efficiency, particularly when operated under concentrated sunlight. The flat-plate Si-based photovoltaic cell, with a plateaued efficiency of around 25%, holds the record for single-junction, non-concentrated solar cells and dominates the solar energy market as well as the annual increase in installed MWp capacity. Concentrated multi-junction photovoltaic (CPV) devices remain the only alternatives for achieving higher efficiencies. However, CPV systems are not only costly but also more complex to operate under concentrated sunlight due to their tracking mechanisms and optical components. Additionally, CPV structures typically require cooling systems, such as integrated steam turbines, organic Rankine cycles, water circulation, or Stirling engines, to manage thermal loads [108].

There is significant potential for CPV modules to achieve higher efficiencies in the future, offering a viable path to reduce system costs beyond what traditional flat-plate technology can provide. However, the main challenge today is the lack of funding for research and production of new CPV modules due to economic difficulties. A promising solution involves novel module architectures that reduce cell size. As an alternative to conventional CPV, micro-CPV miniaturizes the cell area to about 1 mm². The micro-CPV concept aims to maximize benefits despite the added manufacturing challenges. High-tech companies such as Semprius and Panasonic are among the first to achieve efficiencies of around 35% in micro-HCPV modules [109]. Micro-CPVs can be further improved by reducing heat concentration on each cell through decreasing the module thickness, which promotes more homogeneous heat distribution across the backplane. This approach allows the solar module to operate without a heat sink, thereby reducing bulkiness and enhancing the cell's thermal dissipation [109,110]. Figure 7 is a representation of uniform concentration through edge ray mapping Fresnel concentrator. The solar spectrum incident at an optimal angle spread evenly over the entire cell, providing additional radiation to improve its output parameters.

On the other hand, micrometer-scale manipulation and micro-optics precision remain major challenges, resulting in high cell assembly costs. A cost-effective synthesis method could be transfer printing, which is already used in commercial LED devices. Conventional CPV technology only utilizes direct radiation and is not cost-effective under AM1.5 diffuse radiation conditions (W/m²) [97]. Therefore, new CPV technologies have been developed recently to capture diffuse radiation. For example, Yoon et al. (2006) reported a novel plano-concave CPV system serving as a secondary optical element (SOE), combined with multi-junction solar cells encapsulated by additional low-cost Si solar cells to capture diffuse radiation [112]. Simulation results showed that the optical power ratio of this theoretical model increased by nearly 17.12% compared to CPV without additional treatments, with no extra cost incurred. Such systems are generally integrated together and are thus called hybrid CPV. The increased number of intersections in hybrid CPV systems enhances efficiency up to 46% [97,109].

Conclusion

In this review, we highlighted solar cells with leading efficiencies and explored various methods to enhance their performance parameters. A major constraint for the commercialization of single-junction solar cells is the Shockley–Queisser (SQ) limit, which stands at approximately 33.5%. This limit is higher for multi-junction solar cells, which were discussed in detail, including ultra-thin solar cell, quantum dot solar cell, polymer solar cell and concentrated solar cells. It was found that a combination of anti-reflective coatings, plasmonic resonance, multi-junction architectures, size reduction, and solar concentration can lead to solar cells with significantly enhanced efficiencies. It was also found that the proper absorption of solar radiation has significant impact on the output parameters of the solar cell which can be effectively enhanced by DC mechanism and plasmonic resonance. These advancements hold great promises for addressing future energy challenges effectively.

Table 4. Year wise solar cell generation capacity

Year	Capacity (TW)	Increase (%)
2022-2023	1.6	33.9
2023-2024	2.2	37.5
2024-2025	2.8-2.9	27-32
2030	3.725	30.7
2040	6.678	79.3

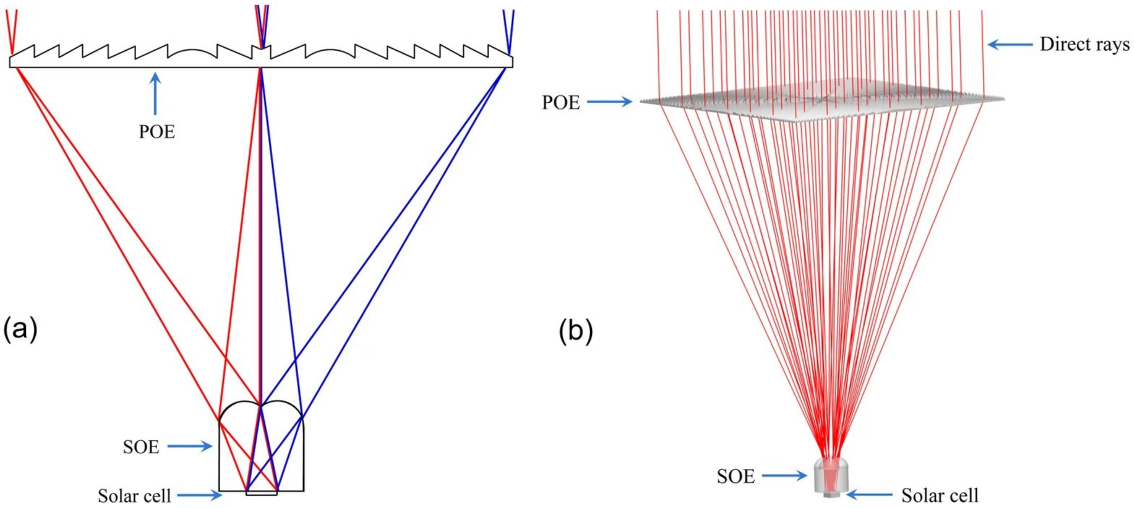

Figure 7. (a) Schematic diagram describing edge-ray mapping in Fresnel concentrator. (b) Outline of the CPV system with raytracing uniformly to the solar cell[111]. (Open Access under the Creative Commons Attribution License https://creativecommons.org/licenses/by/3.0/)

Future prospects

The future challenges for achieving highly efficient solar cells can be summarized as.

Photon management is the only available method to overcome SQ limit. This is possible by the proper integration of DC layer and metallic quantum dots for plasmonic resonance.

For the DC layer, the available mechanism of rare earth metal can be replaced by effective QD DC layer system, which will not only reduce the pressure on rare earth metal but also effectively manage the photons properly for photovoltaic operation.

An optimized metallic quantum dot must be integrated for the plasmonic resonance to effectively absorb all the incoming photons for photovoltaic operation. It is important that proper size and proper position of the metallic nanoparticle must be optimized in the device for maximum output.

For increasing the photons concentration on the existing photovoltaic devices, the coupling of non-imaging photovoltaics must be considered for the effective operation of the already installed photovoltaic devices.

Simulation tools and machine learning can be effectively employed to minimize experimental challenges. These approaches can be seamlessly integrated to optimize research parameters, thereby enabling the development of highly efficient devices.

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Authors Contribution
All authors have contributed equally to prepare the paper.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Conflict of interests
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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