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Optics for concentrating photovoltaics: Trends, limits and opportunities for materials and design

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ABSTRACT

Concentrating photovoltaic (CPV) systems are a key step in expanding the use of solar energy. Solar cells can operate at increased efficiencies under higher solar concentration and replacing solar cells with optical devices to capture light is an effective method of decreasing the cost of a system without compromising the amount of solar energy absorbed. However, CPV systems are still in a stage of development where new designs, methods and materials are still being created in order to reach a low levelled cost of energy comparable to standard silicon based PV systems. This article outlines the different types of concentration photovoltaic systems, their various design advantages and limitations, and noticeable trends. This will include comparisons on materials used, optical efficiency and optical tolerance (acceptance angle). As well as reviewing the recent development in the most commonly used and most established designs such as the Fresnel lens and parabolic trough/dish, novel optics and materials are also suggested. The aim of this review is to provide the reader with an understanding of the many types of solar concentrators and their reported advantages and disadvantages. This review should aid the development of solar concentrator optics by highlighting the successful trends and emphasising the importance of novel designs and materials in need of further research. There is a vast opportunity for solar concentrator designs to expand into other scientific fields and take advantage of these developed resources. Solar concentrator technologies have many layers and factors to be considered when designing. This review attempts to simplify and categorise these layers and stresses the significance of comparing as many of the applicable factors as possible when choosing the right design for an application.

From this review, it has been ascertained that higher concentration levels are being achieved and will likely continue to increase as high performance high concentration designs are developed. Fresnel lenses have been identified as having a greater optical tolerance than reflective parabolic concentrators but more complex homogenisers are being developed for both system types which improve multiple performance factors. Trends towards higher performance solar concentrator designs include the use of micro-patterned structures and attention to detailed design such as tailoring secondary optics to primary optics and vice-versa. There is still a vast potential for what materials and surface structures could be utilised for solar concentrator designs especially if inspiration is taken from biological structures already proven to manipulate light in nature.

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1. Introduction

1.1. The benefits of concentrator photovoltaics and review objectives

The sun delivers 120 petajoules of energy per second to the Earth. In 1 h the sun delivers more energy to Earth than humanity consumes over the course of a year. The ability to harvest this solar energy efficiently and cost effectively however is challenging. For this reason, there is a growing interest in concentrating photovoltaic (CPV) technologies which are systems made up of optical devices that focus light towards decreased areas of photovoltaic (PV) material. In this way the expensive PV material is replaced by more affordable mirrors and/or lenses, reducing the overall cost of the system but maintaining the area of energy captured and the efficiency at which it is converted. Not only can CPV systems be the answer to reducing the cost of solar power but they are more environmentally friendly than regular flat plate PV panels. This is due to two reasons; CPV technology uses less semiconductor components which are made from heavily mined and relatively rare metals, and CPV technology has a smaller impact on the albedo change in an area than flat plate PV panels [1,2]. Burg et al. [1] and Akbari et al. [2] explain this further. Aside from this, the two main advantages of concentrating photovoltaics (CPV) are their ability to reduce system costs and to increase the efficiency limits of solar cells [3].

However, at present it is difficult to produce cost competitive CPV systems in comparison to those of flat plate photovoltaic (PV) [4–6]. More reliable optics of higher concentration levels and lower dependencies on expensive tracking and cooling systems need to be designed. This requires novel structures and materials to be investigated. Secondary optics in particular hold a vast potential for improving the acceptance angle and optical tolerance of a CPV system and there are many more designs and materials yet to be tested.

This literature review aims to identify new routes to developing high performance and reliable optics for solar concentrator applications. To do this, the subject of solar concentrators must first be explained as it stands, and then broadened to justify novel design opportunities. One objective of this review is to give a basis of the most established methods of solar photovoltaic concentrating and group them where possible. By categorising designs effectively, development trends can be seen more clearly and routes for improved devices substantiated. This also requires presenting the advantages and disadvantages of each group of devices which can become very complicated as a solar concentrator's performance depends on multiple factors (Fig. 1). We also aim to outline the design considerations and in particular emphasis the importance of surface structure and material on a concentrator optics performance as shown in Fig. 1. This area of research hence requires us to branch into the materials science where inspiration can often be taken by structures found in nature. Overall, this results in a rather extensive review but one which is necessary to fully appreciate the potential for solar concentrator designs and guide them towards a more comprehensive capacity.

1.2. Concentrator design categorisation

Concentrating photovoltaic systems can be categorised in a variety of ways as shown in Fig. 2. We will provide a simple grouping of these different designs in order to aid the comparison of different research areas and literature. The concentration of a system or optic can be classed as low (<10 suns), medium (10–100 suns), high (100–2000 suns) and ultrahigh (>2000 suns) due to the different solar tracking requirements outlined by Chemisana et al. [7]. The main methods of concentration are; reflective, refractive, luminescent, and total internal reflection (TIR) although the latter is included within the refractive and luminescent types. This paper focuses on reflective and refractive photovoltaic systems. Each type of concentrating photovoltaic system has advantages and disadvantages and it is important to know the application and location to choose the most appropriate design. A concentrator characterisation table is given in Table 1 to help visualise the different basic systems and the many combinations possible.

2. Primary optics

The most common and widely adopted primary design concepts are the Fresnel lens and parabolic mirror (Table 1). These two concentrators differ in a number of ways, allowing them to suit different applications. One important characteristic is their range of concentration. Under normal incidence the maximum concentration ratio achievable on earth is 46,000 × [8]. Languy et al. [9] investigated the concentration limits of Fresnel lenses and found the concentration limit to be around 1000 × due to

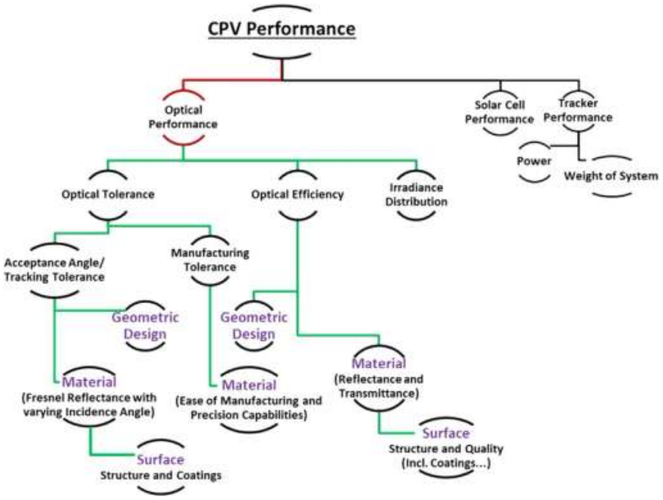


Fig. 1. Factors affecting CPV performance.

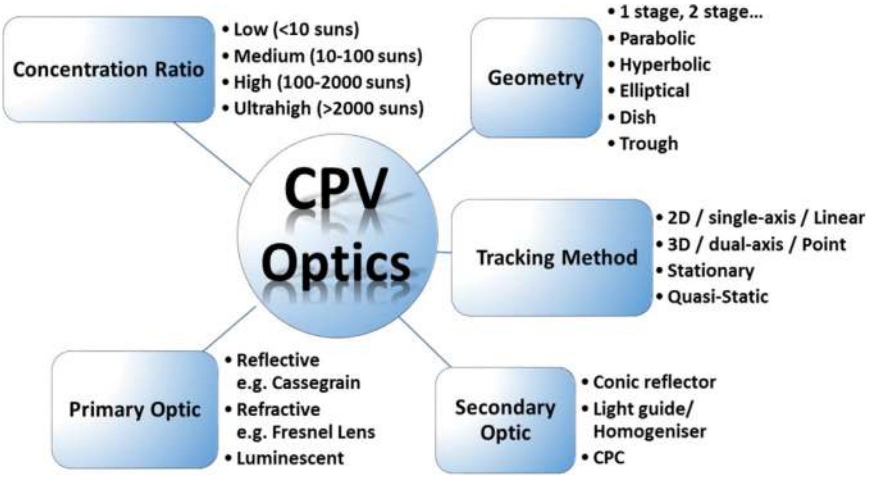


Fig. 2. Concentrator dissemination chart.

chromatic aberration but this could be increased by combining a diverging polycarbonate (PC) lens and a converging PMMA lens to achieve up to ~8500× concentration [8]. Canavarro et al. [10] suggest a singular parabolic trough (with no secondary optics) is suited to concentrations of only ~70×, above which the optical efficiency, acceptance angle and irradiance distribution begin to compromise each other. Various research in this field has extended the concentration of parabolic troughs to ~200× [11–15]. These singular optic designs however still have a severe dependency on optical tolerance, which includes: acceptance angle, solar tracking, manufacturing accuracy, wind load effects and the optical finish quality (see Fig. 1). By matching receiver size to concentrated beam radius, the optical tolerance can be increased for high concentration optics, but not without lowering the topical efficiency due to the Gaussian shape of solar light [16,17]. The use of a second concentrator element is needed to bring the concentration value as close to the limit as possible and relax the demand on the system accuracy. This is the case for both point focus and line focus systems [18]. Due to the increasing importance and complexity of the optical tolerance and acceptance angle of CPV systems, this area is reviewed on its own in section 2.3.

Brunotte et al. investigated the design of a primary parabolic trough with a secondary crossed standard CPC, reaching 214× concentration and concluded ratios exceeding 250× were possible [19]. Canavarro et al. [10] similarly later proposed the use of a new ZZ SMS secondary optic to increase the 70× limit to 213× and achieve an increased acceptance angle. More recently Canavarro et al. [12] have proposed a number of potential parabolic trough concentrator designs with larger aperture areas but still of only medium concentration levels to maintain acceptable acceptance angles.

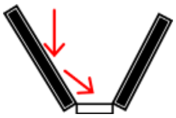
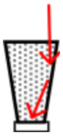
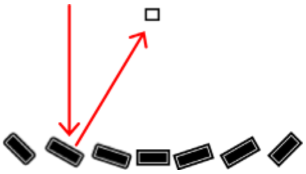
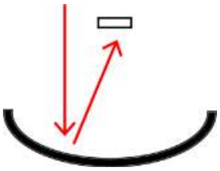
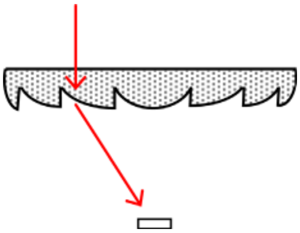
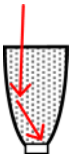
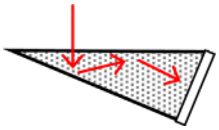
Fresnel lens designs seemingly can cope better without the aid of a secondary optic in comparison to parabolic mirrors. There are a number of reports describing Fresnel lens systems with somewhat enhanced irradiance uniformity, optical tolerance, efficiency and concentration. This however could be due to the broader interest in Fresnel lenses, accompanied by more ongoing research and ingenuity in designs. Gonzalez et al. [20] proposed a curved cylindrical Fresnel lens with good uniform irradiance but with significant manufacturing problems. Pan et al. [21] designed a Fresnel lens where each pitch focused to a different area upon the receiver, improving uniformity without the aid of a secondary optic. The design however lacked a good acceptance angle (only ~0.3°) [21]. Benitez et al. [22] and Jing et al. [23] have also both designed their own unique Fresnel lenses to focus the light rays to different 'entry' areas of the secondary which has also been tailor designed. Both systems had an improved irradiance distribution, an optical efficiency of >80% and an acceptance angle of ~1.3°. This suggests fitting secondaries and primaries to complement each other is important and that CPV technologies would benefit more from many unique designs, than a few 'standards'. Although moving towards new designs, solar concentrators, especially in a commercial sense, are currently largely in the standards phase. This is however understandable as the technology is still relatively new and the conventional Fresnel lens and parabolic concentrators are the most tested and proven.

Zhenfeng Zhuang et al. [24] more recently also redesigned the ring structure of a Fresnel lens; rearrangement of the rings resulted in a significantly improved irradiance uniformity as shown in Fig. 3. This attention to surface structure again protrudes, this time for a singular optic, as a strong method to improve concentrator performance. By tailoring the macro- or micro-structure (rings in these scenarios) and avoiding continuous surfaces on reflectors, high optical efficiencies and improved irradiance distributions are achievable. Zanganeh et al. [25] developed a solar dish concentrator based on ellipsoidal polyester membrane facets which could reach an optical efficiency of 90% while maintaining a good optical tolerance, and V-groove reflectors have shown optical efficiencies of >80% within systems [26] and helped surpass 2D concentration limits [27]. Nilsson et al. [28] proposed a stationary asymmetric parabolic solar concentrator with a micro-structured reflector surface. Three different microstructures were tested, the highest optical efficiency obtained was 88% and all distributions had reduced irradiance peaks in comparison to the non-micro-structured counterpart. The optical surface, and hence material, structure and quality evidently plays a key role in concentrator design and performance but expands extensively into the areas of materials science. The subject is hence discussed later in Sections 5 and 6.

3. Secondary optics

The compound parabolic concentrator (CPC) (Fig. 4) is the most studied stationary and secondary optic and is said to be an ideal concentrator in that it works perfectly for all rays within the designed acceptance angle (in 2D geometry) [13,29]. The 3D CPC is also very close to ideal [13]. CPC's can theoretically be used for higher concentration ratios than Fresnel lenses and match the theoretical concentration limit of purely reflective optics at 42,000× [30,31] but their very high aspect-ratio makes them impractical for implementation at >40× [30]. There have been

Table 1
Concentrator characterisation table.

Type	Characterisation by mechanism				Concentration			Shape
	Refractive	Reflective (Coating)	Reflective (TIR)	Luminescent	Low	Medium	High	Key: ▭ Receiver/Cell ▬ Reflector — TIR surface ▤ Lens → Light Ray ▩ Luminescent
Flat reflector [26,164]		X			X	X		
V-trough [42]		X			X	X	X	
Light funnel/homogeniser [13,39-44]	X		X		X			
Linear Fresnel reflector [165-167]		X				X	X	
Parabolic dish/trough [10-15]		X				X	X	
Fresnel lens [9,22]	X		X			X	X	
Compound parabolic concentrator [67]	X				X			
Wedge prism [109]	X	X	X		X			
luminescent/quantum dot [168]	X	X	X	X	X			

variations in the CPC design to improve different aspects such as concentration ratio and irradiance distribution. Some of these designs include the crossed CPC (CCPC) [32] and similarly the 3D CPC [33], as well as the polygonal CPC designs [34] and the lens walled CPC [35–37] (all shown in Fig. 4). The CPC and many of its variations commonly lack a good irradiance distribution as described by Victoria et al. [38] who compared different secondaries for a primary lens, and by Sellami et al. [32] for the CCPC.

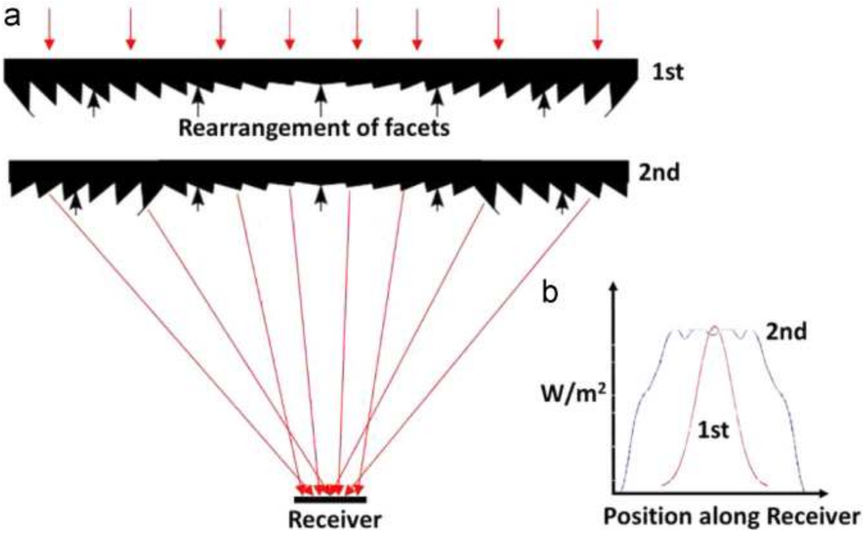


Fig. 3. Improved irradiance distribution of Fresnel lens. By rearranging, or horizontally 'flipping' the Fresnel lens rings (a) an improved, more uniform irradiance distribution is obtained as shown in (b) [4,24].

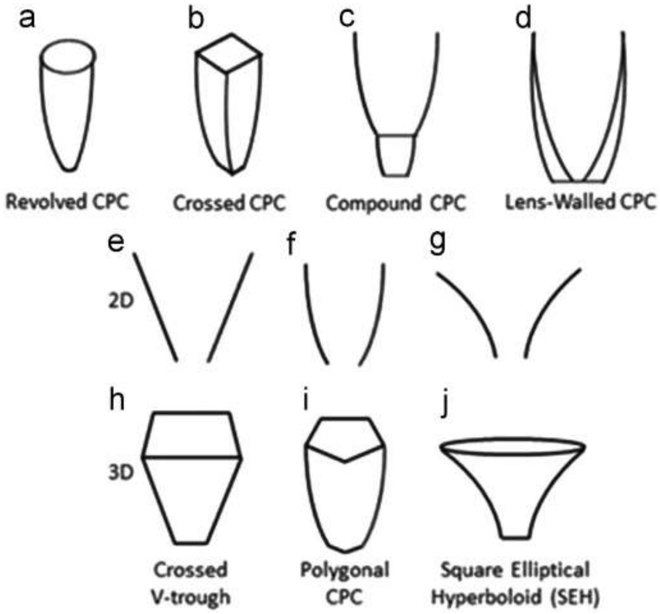


Fig. 4. Variations of CPC: (a) The revolved CPC. (b) The Crossed CPC. (c) The Compound CPC. (d) The Lens-Walled CPC. Examples of 2D profiles and possible 3D transformations: (e) V-trough. (f) CPC. (g) Compound Hyperbolic Concentrator. (h) 3D square aperture V-trough. (i) Polygonal aperture CPC. (j) Hyperboloid with an elliptical entry aperture and square exit aperture [4].

Cooper et al. [34] investigated polygonal CPCs with a varying number of sides and concluded that the cubic CPC was best suited when low reflectance materials are being utilised. This is one example of when the true optimum concentrator design will be an amalgamation of multiple factors, in this case of the efficiency and available resources. The lens-walled CPC reduces the amount of material required and hence has a lower weight than the filled dielectric CPC. It has been proven to have an improved acceptance angle and irradiance distribution than the mirror CPC but has a lower maximum optical efficiency [35–37].

The significance of these differing characteristics is that the location, incident sunlight conditions and tracker options would decide which CPC type suited best. Again, this reinforces the idea that no one design will be absolutely better than another and specific adaptation, although not the easiest, is likely to be the most beneficial procedure in concentrator development. The irradiance distribution uniformity of the CPC seems to be an inherent flaw which again suggests more novel optics need to be investigated. It is however recognised that for many systems this inhomogeneous light and heat distribution has either little effect or is manageable depending on concentration ratio, solar cell specifications and cooling methods. Solar cell structures and cooling technologies are beyond the scope of this review but can influence optic design as significantly as any other factor already discussed.

Light funnels and homogenisers (Fig. 4) have been utilised by many to improve the acceptance angle and irradiance distribution of a system [13,39–44]. These typically take on the shape of an inverted cone or pyramid but there are also elliptical and hyperbolic shapes possible [45–48] such as the square elliptical hyperboloid (SEH) designed by Nazmi et al. [49–51]. Some examples of geometries are shown in Fig. 4. The square elliptical hyperboloid (SEH) based on the ideal trumpet concentrator has an elliptical entry aperture connected to a square exit aperture via hyperbolic curves [49]. Nazmi et al. concluded a concentration ratio of 6 × for the SEH is the optimum for use as a stationary solar concentrator despite its low optical efficiency of 55% but the main use of this type of concentrator is for building integrated photovoltaic applications and its performance as a final stage light funnel has still to be tested. The 4 × concentration ratio SEH design has however a higher optical efficiency of 68% [49] and may be more suited in HCPV optical systems if it can improve optical tolerance significantly.

The dome lens typically uses less material than a filled dielectric CPC and can be easier to manufacture [38]. The dome lens and ball lens have proven to have higher acceptance angle values than even the CPC and with improved irradiance distributions [38,52]. Due to the ball lens 3D symmetry, any expansion due to heat should not affect the performance of the ball lens to redirect the light rays to the intended destination. However the weight and support of the ball lens is more difficult to accommodate and may need another optic at the receiver [52]. More research is needed to find the full potential of the ball and dome lenses as secondary optics but there is growing interest in similar geometries for secondary optics [22,23].

Simple plane mirrors can be used to homogenise the distribution of solar flux on to the receiver as discussed by Chong et al. [53] but it has been shown that V-groove reflectors are more effective as mentioned earlier and investigated by Uematsu et al. [54–56] and Weber et al. [26].

4. Overall optical tolerance and acceptance angle

The acceptance angle for high concentration devices such as parabolic dishes and Fresnel lenses, without additional optics is very low [29,57,58] as depicted in Fig. 5. Akisawa et al. [29] proposed a dome-shaped non-imaging Fresnel lens. The tracking tolerance of the proposed lens held efficiencies of ~90% up to an incident angle of 0.4°, then dropped to 80% at 0.6° and then to 10% at 1°. Recently, more focus is given to the acceptance angle and overall tolerance of a CPV system and higher acceptance angles are being achieved. Dreger et al. [59] obtained an acceptance angle of 0.75° without the need of a tertiary optic such as a homogeniser but by instead reducing the path length. ISFOC and Green-Mountain studies have HCPV modules with acceptance values of 1.2 degrees and 1.4° respectively [60]. Opsun Technologies claim to have a HCPV system of 380 × with an acceptance angle of 3.2° and an optical efficiency of 87% [60]. They also propose they can design a CPV system of 1000 × with an acceptance angle 1.9° [60]. This would be a significant achievement in CPV technology if the system has a similarly high optical efficiency and acceptable irradiance distribution as well.

Low concentration optics (LCO) are not as dependent on solar tracking as high concentration systems due to the principle of etendue [41,58]. LCO's can be static or quasi-static and due to their typical high acceptance angle they can often gather direct and diffuse radiation [49,61–63]. This eliminates the need for continuous sun tracking systems and reduces the overall system cost [42,64–66]. For a V-trough concentrator, Tang et al. [42] suggests a concentration less than 2 for a fixed position but for concentrations > 2 several tilt adjustments should be made to significantly increase annual solar gain and take full advantage of the systems capabilities. Similarly Li et al. [67] compared a 3 × and 6 × truncated mirror CPC where the 6 × CPC needed adjusted five times a day but the 3 × did not. For higher concentrations, the frequency and accuracy of the tracking must increase which tends to lead to very expensive solar trackers for HCPV technologies. New concentrator optics with improved optical tolerance could thus be vastly beneficial to developing high and ultra-high concentrator photovoltaics. There is always an inevitable trade-off required between acceptance angle, optical efficiency and irradiance distribution but recent novel designs are extending when this compromise is required (Fig. 5). Truncation can increase the acceptance angle of a mirror CPC but it also reduces the geometrical concentration ratio [10]. This could be the condition for most optics [27,40,61,68–70] and explains why Fresnel lenses, truncated convex lenses, typically have a higher acceptance angle than parabolic concentrators of a similar concentration ratio. Truncation can also be thought of as a method to reduce the light ray path length within an optical system which has already been said to increase the acceptance angle [4,59]

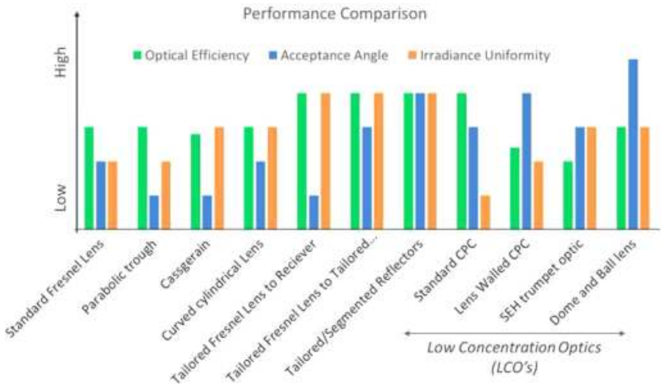


Fig. 5. Performance comparison of various CPV designs on optical efficiency, acceptance angle and irradiance uniformity upon receiver.

Larger opening angles are another option to improve the optical tolerance and reduce the effect of wind induced deviations, manufacturing errors and sagging as reported by Canavarro et al. [10]. This method however can also reduce the optical efficiency and concentration ratio of a system. The acceptance angle, optical efficiency and irradiance uniformity are interlinked and hence systems usually prioritise optical efficiency as shown in Fig. 5. As mentioned earlier the lens walled CPC has an improved acceptance angle in comparison to the refractive CPC but a lower optical efficiency (Fig. 5). There are studies however that suggest a decrease in optical efficiency, to gain higher acceptance angles will still produce more yearly energy output [60,71,72] but this will depend on the specific application and location.

5. Materials

5.1. Reflective

The optical performance of a CPV system is equally dependent on chosen material and surface structure as well as geometrical design. Reflective concentrators for example do not suffer from selective wavelength absorption and dispersion associated with dielectric lenses [73–75]. In terms of the overall desired criteria of a CPV system and its individual components, reflectors technically use less material than conventional lenses as they are not “filled”. They are however said to be more prone to manufacturing errors and are less tolerant to slope error than lenses [30]. The advantage of reflective secondary optics is they tend to have increased flux uniformity and colour mixing effects. Dielectric secondaries utilise TIR and can withstand more internal reflections without much loss [76]. For both reflective and refractive optics fewer reflections and stages are always preferred.

The simple polishing of metal can result in a reflective mirror finish but such polished surfaces are very heavy and specific curved shapes are difficult and therefore expensive to manufacture [77,78]. Reflective film mirrors is a second option but this setup often has low reflectivity when also applied to complex surfaces [78]. Polymer mirror films are a more recent third method to gain reflectance values of >90% but require specially designed structures to gain the appropriate shapes for a given application [25,79]. Vacuum metalizing is therefore the current best option but this process is highly dependent on the material and surface quality it is bonded with in order to ensure a high quality mirror finish [77,80]. Due to the limitations of all these materials and processes it can be concluded that further research into effective reflective materials for CPV applications is required.

Yin et al. [81] studied the surface qualities of different brittle materials used for the nano-abrasive fabrication of optical mirrors. They found that surface roughness in ultra-precision grinding increased with brittleness and hence brittle materials gave a lower reflectance after processing. The principal means of shaping and finishing ceramic optics is abrasive machining with abrasive tools involved with grinding, lapping and polishing. Laser-assisted machining is also an option [81–85]. The high hardness of these materials as well as the inherent brittleness and associated susceptibility to fracture, makes abrasive machining response an important issue in the fabrication of optical mirrors. In general, material responses to machining depend strongly on microstructure and mechanical properties [81].

Options for reflectors include mirrored (silvered) glass, aluminized or polished metals or plastics, including silvered polymers, aluminized polymers and anodised aluminium. Examples of polymer films used include polymethlmethacrylate (PMMA) researched by Schissel et al. [86] and polyethylene terephthalate (PET) film researched by Kennedy et al. [87]. Schissel et al. [86] demonstrated the environmental durability of silvered-PMMA reflectors which have an un-weathered solar reflectance as high as glass reflectors at 97%. The reflectance of freshly deposited silver is roughly 97% (Fig. 6) dropping to 84% after 3 years due to weathering. Soiling appears not to be a major issue affecting the long-term performance of silvered-PMMA reflectors but regular contact (abrasive) cleaning is required to retain efficiencies up to about 93%. Fend et al. [88] researched cheaper lighter high reflectance aluminized sheets which also had good mechanical properties. Fend et al. [89] then later compared various samples of reflectors for optical durability in outdoor weather conditions. SolarBrite 95, a silvered UV-stabilized polyester film, had an un-weathered reflectance of ~92% which dropped below 90% after 2 years. Thin glass mirrors have better durability but are more costly and difficult to handle. Their un-weathered reflectance was 93% to 96% and can last as long as 5 years with 5% reflectance loss. A graph of the standard reflectance spectra of the most common metals is given in Fig. 6 however reflectance spectra will depend on specific manufacturing process, composition of metal and any coatings applied. Reflectance Measurements for a hand polished aluminium dish and a vapour metalized acrylonitrile butadiene styrene (ABS) semi-sphere are also shown in Fig. 6 to show example reflectance spectra for these materials and methods of manufacturing.

Fend et al. [89] also confirmed that different locations and environments affect durability by as much as 2 years difference. Front surfaced aluminized reflectors exhibit adequate optical durability in non-industrial/urban environments but corrode rapidly in atmospheric pollutants. Their un-weathered reflectance was ~90% and dropped by ~4% in 4 years depending on location [89]. Flabeg thick glass mirrors have excellent durability to scratches and surface damage but are still fragile if strained and heavy. Curvature is also difficult and requires slumped glass that is expensive and in some cases can break due to high winds. The un-weathered reflectance was reported as 88–92% and dropped by ~2% depending on location for up to 4–5 years [89].

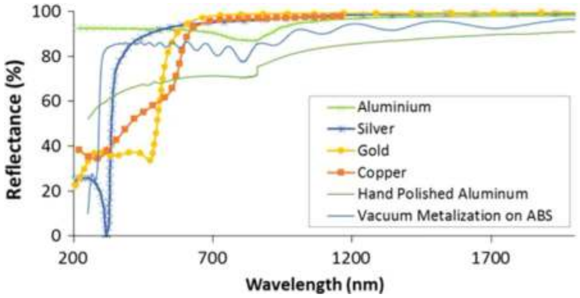


Fig. 6. Standard reflectance spectra for aluminium, silver, gold and copper metal [169]. Graph also shows measured reflectance spectra for a hand polished aluminium dish and a vacuum metalized acrylonitrile butadiene styrene (ABS) semi-sphere.

Mallick et al. [90] designed and experimentally tested a non-imaging asymmetric compound parabolic concentrator with a self-adhesive multi-layer polymer film, which had a quoted specular reflectance of 98% in the visible region. The material was also non-corroding and non-conductive due to it being metal free and also thermally stable up to a continuous temperature of 150° with low levels of shrinkage. The designed system was of 2 × concentration however and its performance under higher concentrations and temperatures needs to be tested. Higher concentration optics as mentioned have a reduced optical tolerance and hence require higher accuracy of optical shape and surface smoothness. Given the limitations of all existing systems, materials and manufacturing processes, further study into possible reflective materials and structures is important.

5.2. *Refractive*

Fresnel lenses have traditionally been manufactured out of poly (methyl methacrylate) (PMMA) which due to the dispersion curve causes longitudinal chromatic aberration (LCA). The manufacturing processes can include hot-embossing, casting, extruding, laminating, compression-moulding, or injection-moulding thermoplastic PMMA [91]. Sources for refractive lenses and materials are abundant but not all have been tested for CPV applications. Optical or mirror-grade PMMA material may come from the automotive, lighting or skylight industries. Optical-grade poly (dimethyl siloxane) (PDMS), another material increasingly being used, has applicable formulations shared with the aerospace, electronics, and light-emitting diode industries. A heavier lens technology consists of acrylic or silicone facets patterned onto glass as researched in the late 1970s by Egger [92] and Lorenzo et al. [93] in 1979. PMMA and PDMS are at present the preferred medium to be adhered to glass and patterned as a Fresnel lens. Polycarbonate (PC) is sometimes suggested as an alternative to PMMA due to its significantly greater toughness which prevents mechanical fracture and fatigue. However PC is less scratch resistant [94] and has a smaller spectral bandwidth, optical transmittance [95] and suffers more from optical dispersion, chromatic aberration and solar-induced photo oxidation [96–99].

One of the advantages of Fresnel lens designs is that they double as the top cover encasing of the system. In reflective systems a cover glass of high transmittance is used to seal and protect the optics inside but still adds loss to the system. Refractive lens systems effectively eliminate this stage and save around 5–10% light loss. Using the primary lens as the boundary to the outside weather however, adds other demands. PMMA has a transmittance of ~95% (Fig. 7) but high temperature treatments such as calcination, which is a preparation method of antireflective and antifogging coatings, cannot be used on PMMA material. To achieve an anti-reflective

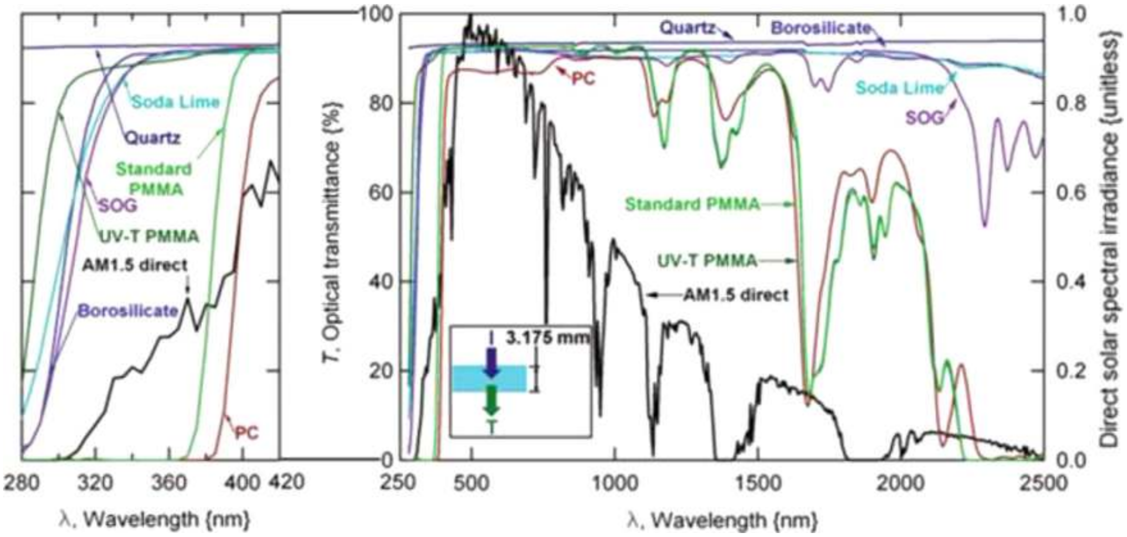


Fig. 7. Optical transmittance spectra of various refractive materials for CPV as measured by Miller et al. [95]. The results for flat-panel PV (soda lime glass) as well as the normalised direct solar spectral irradiance (AM1.5 in ASTM G173) are provided for reference [95].
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property on PMMA (refractive index = 1.49) one method is to layer coatings of lower refractive indexes. Finding suitable sources of high transmitting but low refractive index materials however is also challenging. Zhou et al. [100] overcame both these difficulties and successfully fabricated antifogging and antireflective coatings on Fresnel lenses while achieving a transmittance of 98.5%. By spin-assembling solid and mesoporous silica nanoparticles, which have voids and result in a lower refractive index, Zhou et al avoided high temperature treatments and produced coatings with a refractive index between 1.32 and 1.40. This reinforces the importance of researching new materials and structures to overcome current CPV challenges and limitations.

Chromatic aberration is a common problem in refractive lenses. Chromatic aberration can be reduced if a domed Fresnel lens geometry is used as carried out by Akisawa et al. [29]. As discussed earlier, Languy et al. [9,30] designed and manufactured an achromatic Fresnel doublet which combines the advantages of plastic lenses without being affected by chromatic aberrations. The achromatic Fresnel doublet is tolerant of manufacturing errors and the dispersion uncertainty of the refractive index, making it suitable in conditions where the temperature can alter the refractive index and shape of the lens. However, a redesign was required to avoid soiling of the outward patterned lens [8]. In the latter study, PMMA and PC were suitable materials at minimising the longitudinal chromatic aberration (LCA) down to 0.1% with a wavelength range of 380–1680 nm along the visible and near-infrared regions [8].

For refractive materials under concentrated light conditions there can be significant temperature and ultraviolet (UV) exposure effects. Miller et al. [95] investigated the photo degradation of CPV modules via accelerated UV testing and analysed the optical transmittance spectra of various CPV refractive materials as shown in Fig. 7. There is however still a great need for research into material durability and performance with time in different environments.

6. Novel optics and materials

6.1. Novel optics

Due to the developing state of CPV technology, a variety of novel designs are still being created and tested. Laine et al. [73] investigated a transmissive non-imaging Fresnel type reflector concentrator made of a continuous reflective spiral (shown in Fig. 8). Stefancich et al. [101] proposed a spectral splitting primary optic which dispersed different wavelengths to different single junction solar cells arranged along the focus plane. This was an alternative to focusing the light to one multijunction solar cell but still obtaining similar overall conversion efficiencies. This has also been proposed elsewhere [102,103].

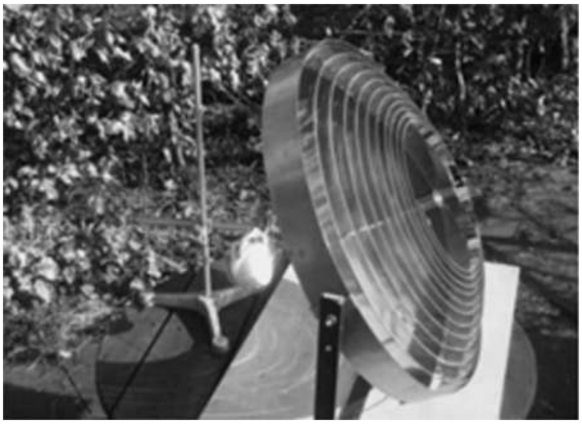

Fig. 8. Photograph of transmissive solar concentrator designed and tested by Laine et al. [73].
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Jing et al. [23] coupled the design of a novel Fresnel lens with a novel secondary optic with specific 'entry' points. This attention to detailed design and matching primaries with secondaries can yield simultaneous benefits in concentration ratio, optical efficiency, acceptance angle and uniform distribution which is otherwise very difficult to do effectively. Liu et al. [104] use a novel channel waveguide as a secondary which collects focused light rays from a Fresnel lens array primary. At each focal point there is a microstructure which couples the light into the waveguide. This structure can reach 800 × concentration at 89.1% optical efficiency and a 0.7° acceptance angle. Similar designs have been tried and tested by many other researchers [66,105–108]. Jung et al. [70] designed a novel metal slit array Fresnel lens for wavelength scale coupling into a nano-photonic waveguide. Although aimed at a different application, this paper demonstrates the flexibility of concentrator optics. Waritanant et al. [109] was able to obtain a maximum collection efficiency of 54% for a wedge prism concentrator coupled with a diffraction grating. Huges et al. [110] found that a wedge shaped Luminescent Solar Concentrator (LSC) is able to produce a larger average power density year round under direct illumination than a planar LSC but unusually its optimum orientation was when tilted away from the sun and for this reason may be more suited to latitudes further from the equator. These are just some examples of the novel designs being explored within CPV technologies and how they can vary.

6.2. *Novel materials*

Some applicable concepts for solar concentrators include: spectrally selective coatings [111–113]; switchable optics which can change from transparent to reflective; anti-reflective and reflective enhancing coatings [111,113]; water filled optics; nanocrystal materials, graphene layers [114,115] as well as other organic and inorganic materials. Much of this technology is researched extensively in the glazing and window industry but less so in the application of CPV's due to the associated high costs of such materials. These materials however hold a lot of potential for advancing solar concentrator technologies, some more than others for specific applications such as building integrated concentrator photovoltaics (BICPV).

Hybrid organic–inorganic (O–I) materials are nano-composite materials with both an inorganic and organic (bio-organic) component. These O–I materials often have impressive characteristics. For example, the Maya Blue pigment is the incorporation of a natural organic dye within the channels of micro-fibrous clay. This hybrid material is of a strong blue colouring which lasts against weathering and bio-degradation to the extent that 12 century old vestiges are still appreciable today [116]. The hybrid materials processed by Avnir et al. [117–120] provided many advances in many diverse fields including optics. There are now many industrially developed hybrid materials including films, membranes, fibres, powders, monoliths and micro (and nano) patterns [121–125]. Graphene has found many uses in a variety of applications due to its tenability and unique properties. It has a very promising optical transparency of 97.7% but more research is required into its use in solar concentrator materials [126].

Nature has a vast range of advanced complex structures which have been studied by many to be replicated and adapted for our own use [127–132]. A clear example is the application of light trapping microstructures, inspired by moth eye facets and other natural light trapping structures, imprinted upon solar cells to enhance light collection and conversion efficiencies [132–134]. Nature has created these structures over billions of years and optimised their functions through evolution. A process which will forever exceed any 'trial and error' optimisation routine carried out by ourselves. Structures within nature often must fulfil multiple functions and hence are usually a complex hierarchal multi-scale system. Such structures may hence appear random to us but are in fact a controlled balance of compositions [135–144]. Smith et al. [144] discuss the importance of quasi-random nanostructures found in nature and more recently now also in engineering applications such as blue-ray discs due to their ability to manage photons efficiently. This reinforces the importance of surface structures on optical components and why microstructures significantly effect: reflectance, distribution and acceptance angle [21–24,28,64,100,134,145–147]. Siddique et al. [148] has discovered butterfly wings which have a reflectance of only 2–5% over a range of viewing angles. This high transparency at multiple incidence angles could be very useful for solar concentrator optics, in terms of the cover glass encasing and for lens surfaces to increase the optical efficiency and acceptance angle. The Pieridae butterfly achieves the opposite; it has an interesting grooved tiling upon its white wings with an underlying nipple pattern of pterin beads as shown in Fig. 9. These wings have a surprisingly high reflectance of 78.9% over the 400–950 nm range and are used to concentrate light onto the butterflies' body to help it heat its flight muscles faster [149]. Shanks et al. [149] suggest these wing structures (Fig. 9) can be the basis of a new lightweight, highly reflective materials for concentrator photovoltaics to greatly improve the power to weight ratio of solar concentrator technologies as demonstrated in Fig. 10 [149]. In both cases, the wing structures have a very interesting 'random' or 'chaotic' structure but as mentioned earlier, this may have some underlying complex coherence to it that we have yet to understand.

There are numerous studies into how natural structures, especially insect membranes, can affect light [130,131,150–156]. There are also various bio-replication reviews covering a range of applications [157–160]. However, at present it is an untapped area of research for CPV applications.

6.3. *Future outlook and discussion*

For concentrator photovoltaic technologies to continue to develop there are some key factors that should and likely will be focused upon in ongoing research. One of these is increasing the concentration ratio. High and ultrahigh concentration ratio systems have a vast potential for increasing efficiencies and reducing cost. This is relatively well known and discussed elsewhere [8,60,161]. From the literature reviewed here, other methods to be highlighted which improve CPV performance include: (1) The use of secondary/homogenising optics; (2) Reducing the path length of light rays; and (3) Tailored surfaces structures. Out of these, the attention to optical surface structure (3) is the most promising with the resulting systems being able to simultaneously achieve improved optical efficiency, tolerance and irradiance uniformity (Figs. 5 and 11). Most CPV systems have to make compromises in one area or another when trying to attain higher concentration ratios but the segmented reflectors described here are able to challenge or at least extend this trade-off which is inevitably encountered. The most noteworthy designs are those with ingenuity and careful geometric design (Fig. 5). Matching the primary output light to input sections of the secondary optic or to illuminate the receiver in a more effective and reliable manner. Ultimately, future CPV optical systems will become larger in concentration ratio but require the use of modular surfaces, facets, truncation and more acute design. This will also increase the dependency on the materials available and their properties. It can be seen from Fig. 5 even in the brief milestones section that one of the breakthroughs for solar concentrator technology was the discovery of PMMA and its application for Fresnel lenses. Fresnel lenses were available before this but only became popular in CPV technology when they became affordable and practical due to PMMA [4,5,162,163]. It is hence not an unusual notion that further breakthroughs in the optics for concentrator photovoltaic applications will be largely due to the development of new materials for its purpose. The combined balance between reducing path length, utilising secondary optics and tailoring surface structures will see the way to ultrahigh concentrator photovoltaics (Fig. 11).

7. Conclusion

An extensive review of solar concentrator research and technologies has been carried out, comparing different materials and the optical performance of different designs. There is not enough consideration into the durability of designs and their performance

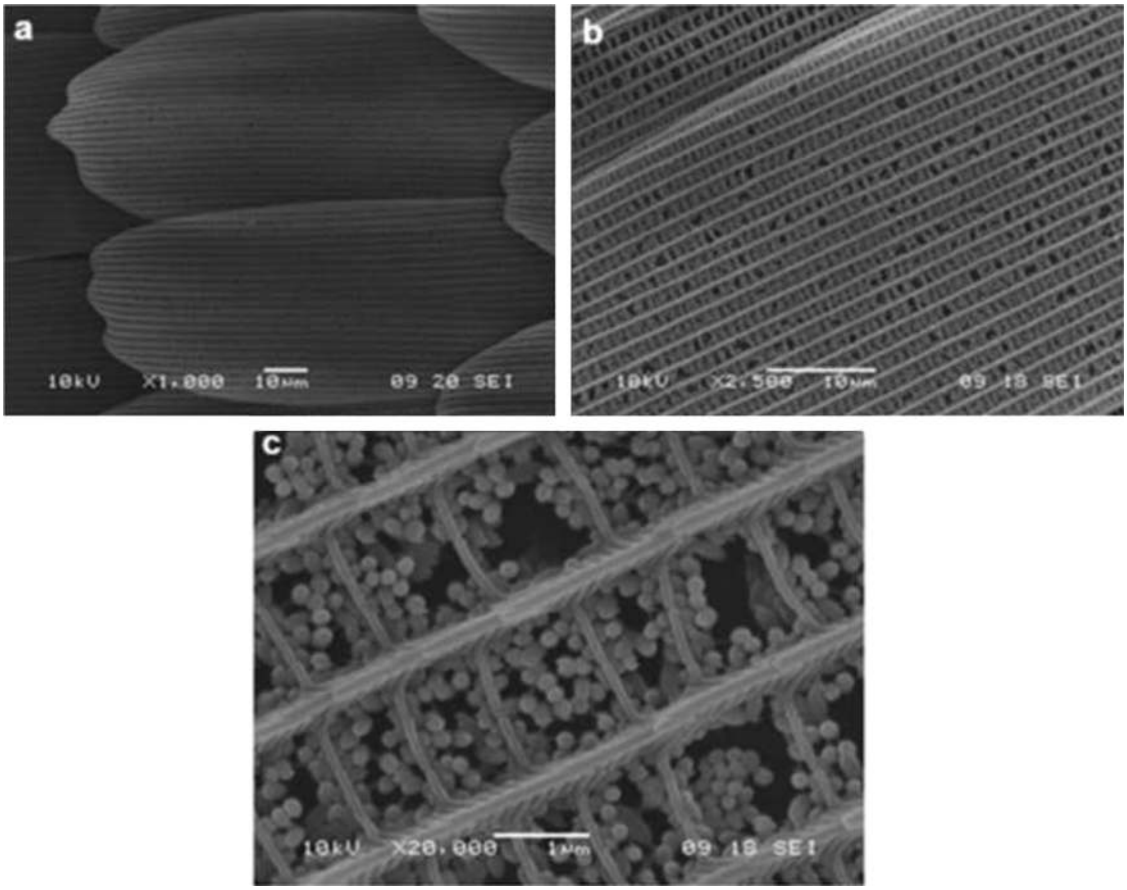

Fig. 9. Large white Pieridae wing structures at increased magnification.

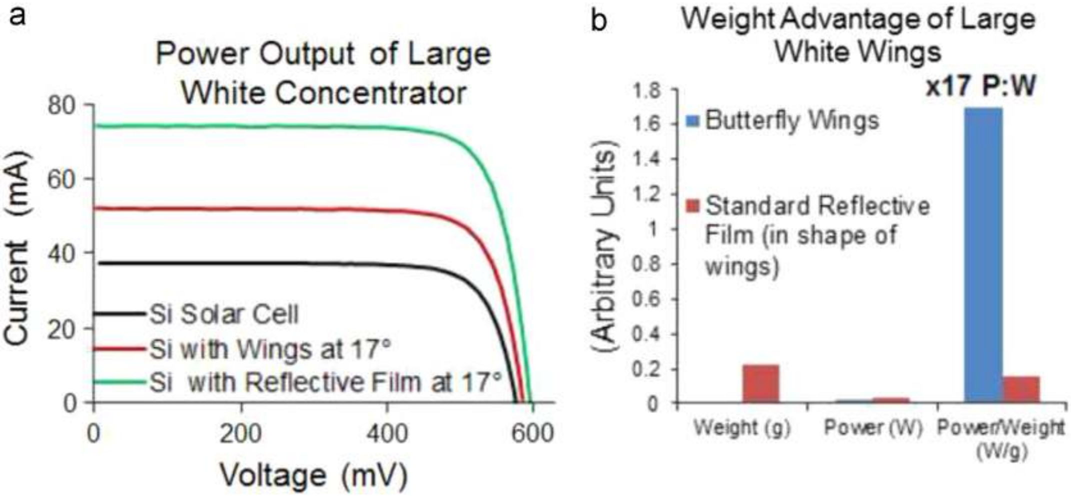

Fig. 10. Butterfly wings increase both the output power and the final power to weight ratio of solar cells. (a) Power output of a mono-crystalline silicon (Si) solar cell either alone, or with large white wings versus reflective film held at the optimal angle of 17°. (b) Histogram representing the relative changes in power, weight and the subsequent power to weight ratio of large white butterfly wings versus reflective film [149].

over years of use, especially for concentrators utilising refractive optics. Recurring challenges and trends in the designs of CPVS have been highlighted.

The above review gives examples of how solar concentrators can be designed in a variety of unique ways boasting different characteristics for different applications. In order to make the necessary leaps in solar concentrator optics to efficient cost effective PV technologies, future novel designs should consider not only novel geometries but also the effect of different materials and surface structures. Trends towards higher performance solar concentrator designs include the use of micro-patterned structures and attention to detailed design such as tailoring secondary optics to primary optics and vice-versa. There is still a vast potential for what materials and hence surface structures could be utilised for

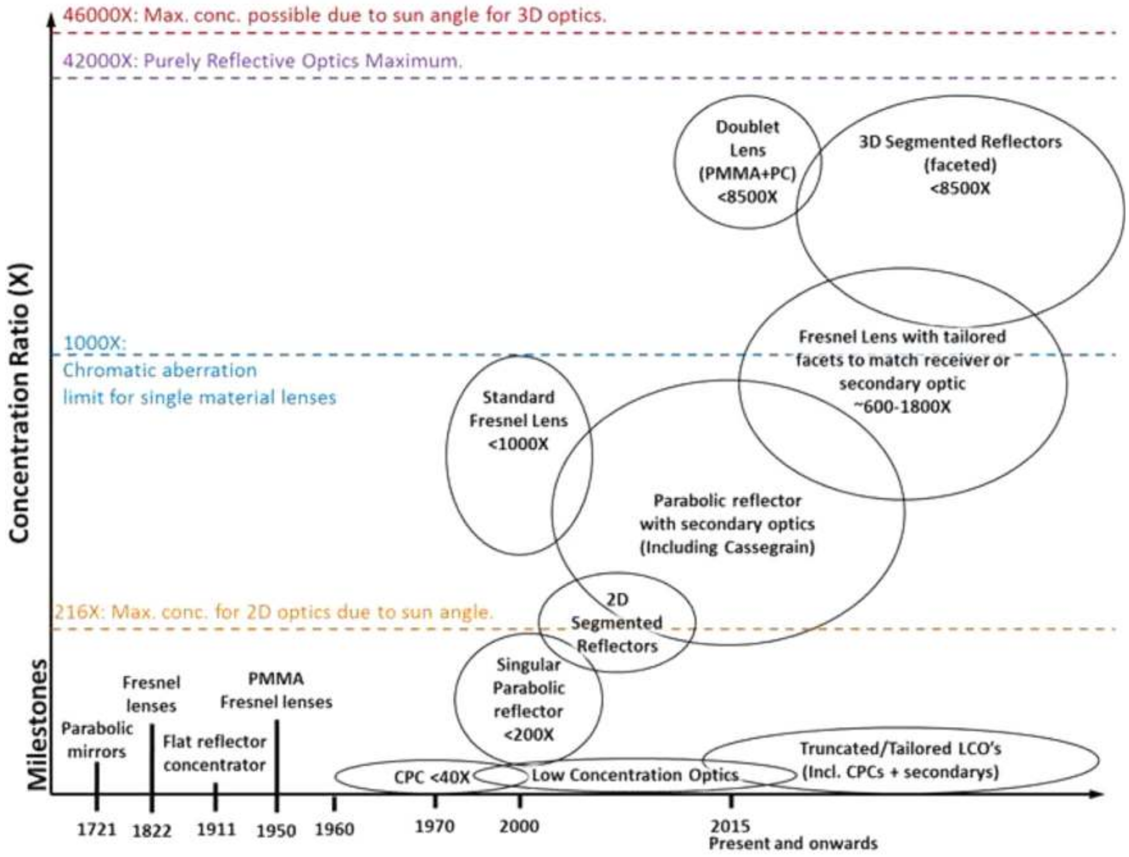

Fig. 11. Timeline of CPV designs and predicted future trends towards high and ultrahigh concentration ratios. Within each CPV types range, the most reliable versions will be in the bottom half of the circles whereas the upper half designs will require high accuracy manufacturing and quality materials.

solar concentrator designs especially if inspiration is taken from biological structures already proven to manipulate light.

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