High-Concentration Optics for Photovoltaic Applications

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Abstract The concept of a high-concentration optical system is introduced detailing the various design types and focusing only on those aimed at photovoltaic (PV) applications. This will include point focus, line focus, imaging, nonimaging, and the classical cassegrain set-up. The theory of high-concentration optics is explained in terms of idealised concepts and maximum limits for each concentrator type and combination. The optical system is broken down into the different stages and materials possible in a high-concentration configuration. The physics of reflective and refractive optics are described, and their associated errors, advantages and a brief overview of past milestones, and recent research trends in the area of high-concentration PVs are presented. Current primary and secondary optics are geometrically explained covering Fresnel, parabolic, heliostat, compound parabolic, hyperboloid, v-trough, and dome-shaped optics. This chapter also covers examples of new secondary optics, such as the three-dimensional crossed-compound parabolic concentrator and the square elliptical hyperboloid concentrator. The aim of this chapter is to provide the basic optical behaviour of high-concentration designs aimed at PV applications considering their geometry, materials, and reliability.

1 Introduction

1.1 Concentrator Concepts

High-concentration optics are in the range of 100–2000 suns [1], a recently modified definition due to their need for dual axis tracking. The development of solar concentrator technology over the years has included improvements in concentration solar cells, cooling systems, and optical accuracy. The concentration ratio

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definition also lacks conformity because this can be linked to the geometrical concentration ratio, optical concentration ratio (similar to optical efficiency), or intensity concentration ratio (flux concentration ratio) [2]. Care should be taken when a concentrating system is being described what is being used, although often it is the designed geometrical concentration ratio quoted along with an optical efficiency, which, when multiplied, should give the flux concentration ratio.

In terms of a concentrator PV (CPV) system, multiple concentrator optics (including low concentration devices <10 suns) can be involved. In this way a high-concentrator PV (HCPV) system can be classified as a single-stage, two-stage, or greater-stage system, although fewer stages are desired to decrease complexity and additional uncertainties. The preferred outline of a high-concentration optical system within an HCPV system consists of primary and secondary optics. The primary optics initially collect incident light, and typical examples include the Fresnel lens and the parabolic reflector. The secondary optics are of medium to low concentration and can be referred to as "receiver optics" when in optical contact with the PV. These secondary optics can increase the concentration of the system but are used more often with the aim of improving the system's acceptance angle and the irradiance distribution on the PV. Receiver optics introduced to a concentrator design which improve the irradiance distribution are also suitably referred to as homogenisers. Two examples of different HCPVs are given in Fig. 1.

CPV systems can be categorised in a variety of ways such as concentration ratio, primary optic type, tracking method, geometry, and number of stages. Figure 1a could be described as a two-stage refractive concentrator consisting of a primary

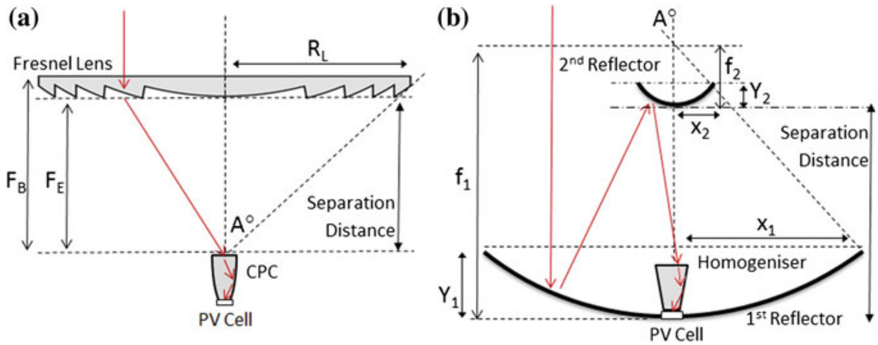


Fig. 1 **a** Primary Fresnel lens with secondary compound parabolic concentrator (CPC). Parameters that may be considered during the design of such a system are given: radius of the Fresnel lens R_L, back focal length F_B; effective focal length F_E; and separation distance and maximum angle of incident rays on the secondary, A. **b** A classical cassegrain set-up of a primary parabolic dish reflector with a hyperoboloid secondary reflector and crossed V-trough dielectric filled homogeniser as a receiver optic. Example of design parameters to be considered in a cassegrain are shown: primary paraboloid's radius x_1; depth of the paraboloid y_1; and focal length f_1. Similarly, examples for the secondary are hyperboloid radius x_2; depth y_2; and focal length f_2. The separation distance between the two reflectors is again displayed as is the maximum incidence angle of light on the secondary A, which can relate the two reflectors' geometry

Fresnel lens and secondary CPC. Figure 1b shows the classic cassegrain set-up, which typically consists of a parabolic primary reflector, a secondary paraboloid or hyperboloid secondary, and a tertiary crossed V-troughed dielectric filled homogeniser. In both of these, if the original two-dimensional (2D) geometries were translated linearly, then they would be described as “line-focus systems.” Figure 1a would become a linear Fresnel lens with a linear (or 2D) CPC focusing on a line of solar cells, and Fig. 1b would become a parabolic trough similarly focusing on linear optics and receivers. A line-focus CPV system, also referred to as a 2D design, is normally used for solar thermal concentrator systems where the receiver may be a transparent pipe carrying water or another liquid medium to be heated. There is often a point-focus version to every line-focus geometry and vice versa, where by way of rotational or translational symmetry the original 2D design is transformed into a three-dimensional (3D) one. Terms such as “crossed” or “rotated” could be used to describe how a 2D profile has been transformed into a 3D optic. A point-focus collector can be deliberately designed not to be symmetrical across any obvious axis, but an uneven irradiance distribution on the cell would be expected. Due to the popularity of line-focus systems with thermal heating, and the rareity of high-concentration linear optics [3], point source systems will be addressed more than linear systems in this chapter. It should also be obvious that with point-focus optics, a dual-axis tracking system is preferred for maximum performance, and a line-focus optical concentrator would require a single-axis tracking system.

Optics can also be classified as imaging or nonimaging where the former describes an optic that refracts light from an object in such a way as to maintain the image but produce a smaller form at the focal plane [4]. Nonimaging optics, such as the CPC and the nonimaging Fresnel lens, were designed later and tailored specifically for the collection of solar rays. This means that they were designed specifically to obtain high optical efficiencies and highly uniform flux distribution output and to cope with the characteristics of solar light [4]. This list of aims, however, does not necessarily require the same image to be replicated at the focal plane, and thus typically the image is distorted at the focal plane, and the term “nonimaging optics” was given. Nonimaging concentrators with very large numerical apertures (small aperture ratio or *f*-number) would have very large aberrations if used as image-forming systems [2]. Geometrical aberrations in the classic sense cause imaging optics to perform at a nonideal level. Image-forming concentrators must treat each ray in a similar fashion to replicate the image at the receiver.

This means all rays that pass through an imaging optic will be reflected once or pass through a refractive boundary only once along with all of the other rays. In this way, rays at varying angles or different incident positions, which would be lost, cannot be treated differently in an attempt to keep them within the system. Nonimaging concentrators such as the CPC, however, can apply different conditions to different rays and obtain ideal performance. Purely imaging optics are, however, capable of approaching the thermodynamic limit and even possibly attaining flux levels greater than a nonimaging one; for both types, careful and tailored design decides which is optimum [5].

The ideal solar concentrating optical system would have 100 % optical efficiency, an output of uniform irradiance distribution (matching in shape and size to the PV receiver), maximum acceptance angle, high optical tolerance, and durability (hence high reliability). It would also preferably be cheap to manufacture, lightweight, and easy to install. Each type of CPV system has advantages and disadvantages, and it is important to know the application and location to choose the most appropriate design.

1.2 Optical Physics Basics

1.2.1 Concentration Ratio

The concentration of an optic or system of optics can be defined as low (<10 suns), medium (10–100 suns), high (100–2000 suns), or ultrahigh (>2000 suns) concentration [1]. Under normal conditions, the maximum concentration ratio ($C_{\max}$) achievable on Earth due to the divergence of light from the Sun is 46,000× for a 3D system (full tracking) and only 216× for a 2D system (single-axis tracking) as calculated from the Sun's diameter [2, 6]. The resulting Eqs. (1) and (2) consider that the concentrator is immersed in refractive index, n, (for air this becomes 1) and θ_i as the input angle (i.e., effective solar angular radius: 4.7 mrad or 0.267°) [2, 6]:

For a linear concentrator, the maximum concentration equation is shown:

$$C_{\max} = \frac{n}{\sin \theta_i} \tag{1}$$

and for a point-focus concentrator:

$$C_{\max} = \left(\frac{n}{\sin \theta_i}\right)^2 \tag{2}$$

If we now use θ_o to represent the output (absorber) angle and NA to denote the numerical aperture ($NA = n \sin \alpha$), then the above can be written [7]:

$$C_{\max} = \left(\frac{n \sin \theta_o}{n \sin \theta_i}\right)^2 = \left(\frac{NA_o}{NA_i}\right)^2 \tag{3}$$

The previous equation can be used to calculate the maximum concentration possible of an optic by using the maximum acceptance angle as θ_i. Fresnel-reflective losses from the absorber can be avoided by limiting the θ_o to $<\pi/2$ [2, 7], but some antireflective coatings of solar cells can still have greater reflectance values for off-axis incident light rays. The concentration ratio of a linear concentrator is usually given as the ratio of the transverse input and output dimensions [2]. As expected, the point-focus equivalent of a line-focus concentrator will always have an increased geometrical concentration ratio, but it is much easier to achieve an ideal concentrator design in 2D geometry such has been performed for the CPC. An ideal concentrator works perfectly for all rays within the acceptance angle.

The current concentration ratio range for commercial HCPV is 100–1000 suns [8]. Specific concentration limits for each type of concentrator is discussed in later sections.

1.2.2 Ideal Conditions and the Classic Cassegrain

Most optical concentrators are initially based on, or initially designed on, idealised concepts and conditions, and then they are developed to consider more accurately the practical environment. First assumptions may include the condition of incoming radiation from the Sun to be parallel and a specific irradiance value (e.g., 1000 W/m^2). The optical components are also idealised, assuming 100 % specular reflectance for mirrors, all wavelengths to be fully refracted for lenses, and no thermal effects on shape [9]. It would be difficult to include all uncertainties in the first steps of optical design, but some are essential and can significantly alter results. One must consider that these practical uncertainties are especially important at greater concentration ratios (which are more sensitive to error) and when incorporating multiple stages (errors build on each other) where these uncertainties intensify (see Fig. 2).

The line and spot in line- and point-focusing optics can only ever be realised in an idealized mathematical model. Manufacturing uncertainties (surface roughness and slope errors) and alignment errors (tracking error and component misalignment) give an effective distribution of errors for the system, which contribute to the Gaussian diameter seen in real measurements [3]. Parabolic reflectors are concentrators intended for distant sources (parallel light sources) where all incident light is reflected into the focal point. In this way, parabolic mirrors are popularly used in telescopes. The Sun is an extended source, not a point light source, with a light divergence of 4.7 mrad (0.27°) and where solar rays are not exactly parallel, but instead each ray can be described as a cone. This effect is amplified by multiple stage concentrators [10–12].

The classical cassegrain (shown in Fig. 1b) uses a primary parabolic-shaped reflector and a hyperboloid secondary. Other conic curves have been tried for the primary and secondary, but a hyperboloid secondary is preferred to allow greater optical tolerance. A cassegrain consisting of a parabolic primary and secondary is based on the theory of parabolas: Any parallel light incident on a parabolic dish will be reflected at such an angle as to pass through the focal point of that parabola. In this way, with a parabolic primary and secondary of coincident focal points, the

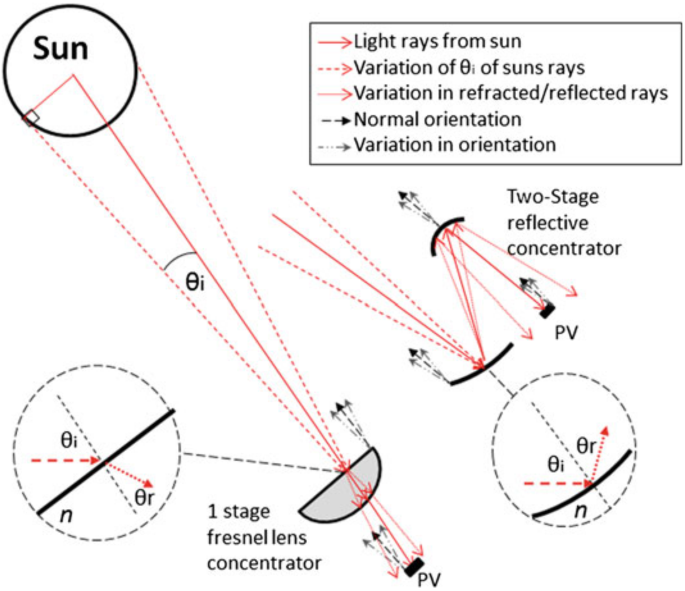


Fig. 2 Light rays from the Sun are shown to not be parallel, incident on a single-stage refractive concentrator and a two-stage reflective concentrator. Focus is given to the variation of incidence angle of a light ray from the Sun after refraction or reflection, which can cause final light rays missing the PV receiver. Magnifications of the incident rays undergoing refraction and reflection are also shown and labelled

parallel light would be concentrated and reproduced, thus giving a uniform irradiance distribution on a solar cell placed in the base of the first reflector. As mentioned, light from the Sun is not parallel, and so the paraboloids would need to be positioned off focus (afocal) to compensate, or another design such as the parabolololoid-hyperboloid one could be used instead. Many have researched and commercialised the cassegrain design, and it holds the advantage of an upward-facing receiver. This can be easier to cool and structure without extensive shadowing on the primary. For HCPVs, shadowing within the cassegrain causes the loss of 1 sun, which is not significant compared with the hundreds of suns an HCPV is designed to produce. The dark image produced on the PV receiver may, however, affect the PVs efficiency. The shadow is $1/C$ of the total area where C is the geometrical concentration ratio.

Low optical tolerance is associated with the cassegrain design because it uses two reflective stages, thus compounding the reflective error and the uncertainty in incidence angle of the light rays (see Fig. 2). It often requires a tertiary optic to improve the acceptance angle, but there are methods to avoid this such as decreasing the path length of light rays within the system. This decreases the effect of error on the final light ray position [13]. The cassegrain reflector arrangement allows the PV receiver to be mounted below the main reflector. This geometry gives easy access to the receivers during replacement and thus drastically lowers maintenance costs. Furthermore, the whole optical geometry can be designed using ray tracing and is usually considered a compact solar concentrator. The minimum aspect ratio of the cassegrain design has been calculated as one fourth [2], but the same has yet to be proven for a cassegrain design with a nonimaging (hence different ray path lengths) primary and/or secondary [10].

The final hurdle in any concentrator optic development is manufacturing and practical testing. Unless the design has a sufficiently high optical tolerance then errors in geometry replication and alignment will decrease the performance. Practical considerations—such as fluctuations in temperature, moisture, wind, and shadowing—can also affect results as expected.

1.2.3 Optical Tolerance, Etendue, and Solar Tracking

One of the main challenges of concentration optics is the decrease in acceptance angle as concentration ratio is increased due to etendue. Optical tolerance refers to all possible alignment uncertainties within the optical system including component misalignment, cell position uncertainty, and tracking error. For high and ultra-high concentrator optics, this is difficult to overcome without compromising another attribute such as optical efficiency or irradiance distribution. Conventionally, the acceptance angle of an optical system is taken to be the offset angle from normal solar incidence, which achieves 90 % of the normal incidence power. This value may be different for $\theta > 0$ and $\theta < 0$ in an asymmetric concentrator (or one with asymmetric errors). If the acceptance angle is maximised, then it decreases the need for highly accurate and more expensive optics, structure, and tracking. A minimum requirement for the angular tolerance, θ_t, and hence the acceptance angle of a system, is to exceed the effective solar angular radius, θ_i. Assuming that $\sin\theta_t \approx \theta_t$, the following equation is formed [14]:

$$\theta_t \leq \frac{n \sin\theta_o}{\sqrt{C_g}} - \theta_i \tag{4}$$

The acceptance angle or optical tolerance for high-concentration devices, such as parabolic dishes and Fresnel lenses, without additional optics can be expected to be very low ($\pm \approx 0.5^\circ$ or less) [15–17]. However, there are exceptions to this with increasing focus on improving acceptance angles for HCPVs [13].

High-concentration optics have the limitation of requiring continuous tracking. The acceptance angle can be determined from the variation of optical efficiency as a function of the incident angle of the input light rays. However, there is slight variation in the value at which to measure the acceptance angle (e.g., 95–80 % of the normal incidence maximum). During practical testing, the short circuit current or power output can be used to measure acceptance angle, but each gives slightly differing results [18].

During the day the Sun is viewed as having a daily rotation about its north-south axis. It then also has a seasonal north-south motion of $\pm 23^{\circ}27'$ away from the equator [19]. Due to the Earth's axial tilt and elliptical orbit, the Sun's noontime position also slightly changes. Jagoo [19] give the derivation for the Sun's position equation as well as a comparison of the theoretical azimuth and theoretical altitude with measured values at different times of the day. Single-axis trackers follow the east–west motion of the Sun during the day but are unable to fully consider the seasonal variation. Dual-axes trackers give optimal performance year-round. However, trackers introduce their own error and cost and are less resistant to natural extremes, which could permanently damage the system. Dynamic trackers use sensors to generate a differential signal when the device is not positioned optimally for available incident light. Although easy to build and maintain, these devices fail to discriminate between the obscured Sun and a bright spot in a broken cloud [19]. The chronological tracker maintains the receiver normal to the Sun using a built-in clock and is typically single-axis. This type of tracker requires frequent manual adjustments, thus making it difficult to accurately follow both daily and seasonal variations and only works over a portion of the time because it rotates 15°/h.

1.2.4 Reflection and Refraction

Snell's law of refraction dictates that any ray travelling through a medium with refractive index n_1, which is then incident on the surface of another medium of refractive index n_2, will have a path described by:

$$n_1 \sin \alpha_1 = n_2 \sin \alpha_2 \tag{5}$$

where α_1 and α_2 are the angles the ray makes with the normal of the surface before (angle of incidence) and after refraction (angle of refraction). Snell's law can also be applied to the case of reflection where the refractive medium is replaced by a mirror. In this scenario, the ray will continue to stay in the same medium of refractive index n_1, and so Eq. (5) becomes Eq. (6) where α_2 is referred to as the angle of reflection:

$$\begin{aligned} n_1 \sin \alpha_1 &= n_1 \sin \alpha_2 \\ \alpha_1 &= \alpha_2 \end{aligned} \tag{6}$$

Total internal reflection (TIR) occurs when a light ray comes into contact with a less optically dense medium (lower refractive index) than the medium it is currently travelling in and if the angle of incidence is greater than the critical angle for TIR. The critical angle for TIR can be calculated using Snell's law by letting $\theta_2 = \frac{\pi}{2}$ and rearranging for θ_1, which now represents the critical angle θ_c:

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \tag{7}$$

When a mirror is placed against the surface of a lens (n_2 now > n_1), TIR is lost, and the rays will be reflected with the mirror's reflectance properties (approximately 90 %). By leaving an air gap between the two materials both the TIR and refracted rays, which do not meet the TIR criteria (otherwise lost), are kept within the optical system.

The surface of both reflective and refractive surfaces must be smooth to avoid the scattering of light. The previous equations assume optically smooth interfaces between two lossless media, but light can be partially or fully absorbed, refracted, and reflected. For lenses, a rough finish will decrease TIR or alter the refraction direction intended; for mirrors, a greater proportion of the light will be diffusely reflected (scattered) instead of specularly reflected (direct). On a very smooth surface, lines normal to neighbouring points along that surface are parallel to each other, and multiple light rays reflect specularly, all with the same definite angle pertaining to Eq. (6). In diffuse reflection, all of the reflected rays still behave in accordance with the law of reflection, but the roughness of the surface means normals along the surface vary. Because the angle of incidence depends on the normal line at the exact point a ray hits, the incident angles for a set of parallel rays will not be the same, and each reflected ray will have a different angle of reflection, hence scattering occurs.

Gaussian scattering can be applied to optical surfaces using Eq. (8) within simulations to produce more accurate irradiance distributions, which will be affected by nonideal factors in the optics [20].

$$R(\alpha) = R_0 \exp\left[-0.5(\alpha/\sigma)^2\right] \tag{8}$$

where R_0 is the radiance in the specular direction, and σ is the SD of a Gaussian distribution in degrees (0.2).

High-concentration optics very rarely will be able to use any diffuse irradiance. Most materials exhibit a mixture of specular and diffuse reflection along with absorption and transmittance (refraction); examples are given in Materials for HCPV Optics . For most interfaces, the fraction of light increases with increasing angle of incidence until, in scenarios capable of TIR, the critical angle is surpassed.

The refractive index is also wavelength dependent, and although this variation can be negligible at certain solar energy wavelengths and for relevant materials, for high-concentration optics it can compromise the refractive optical design, thus limiting the concentration ratio (such as for Fresnel lenses) and affecting the reliability of the system by way of the optical efficiency, acceptance angle, and irradiance distribution.

Most solar concentrators will be encased for protection including a transparent cover material forming the input aperture of the collector system. There are two parallel interfaces for this as well as any other panes used (e.g., air/glass and glass/air) with reflection at each interface. Every transparent material exhibits some absorption due to the interaction of incident radiation with the molecular structure of the medium. Norton [21] discussed the effect of incidence angle on the transmittance of light and indexed sources of material data to replicate the theoretical absorbance/transmittance as well as strength and other properties important for solar collectors.

When using a refractive optic, care must be taken that TIR does not work against the design by reflecting light backwards instead of toward the receiver. This is negligible when the optic is in optical contact with the solar cell, but errors in the interface (mismatched slopes, grooves, cracks, bubbles) will allow for air ($n = 1$) and unwanted reflection. Antireflection coatings for solar cells are common, but information about the angle of incidence required is limited. The coating could decrease reflection for approximately normal incident rays but increase it for wide-angled rays. For final-stage refractive optics, which have a greater portion of output rays at wide angles, the overall energy incident on the solar cell would be decreased.

1.3 Historical Overview

1.3.1 HCPV Optical-Design Milestones and Current Trends

John Hadley introduced parabolic mirrors into practical astronomy in 1721 when he used one to build a reflecting telescope with little spherical aberration [22]. Before that, telescopes used spherical mirrors. The first reported use of an external flat reflector in a solar thermal concentrator was in 1911 by Shuman for a water-pumping system powered by a flat-plate reflector assembly [21]. Lighthouses also commonly used parabolic mirrors to collimate a point of light from a lantern into a beam before being replaced by more efficient Fresnel lenses in the Nineteenth century [23]. Augustin Jean Fresnel was the first to discover the use of Fresnel lenses in 1822 as glass collimators in lighthouses [24, 25]. Only when less costly materials such as poly(methylmethacrylate) (PMMA) were discovered were Fresnel lenses implemented as solar energy collectors in the 1950s. In the late 1970s, the first modern Fresnel lens CPV system was built at Sandia National Laboratories [26]. Interest in Fresnel lense solar concentrators increased in the second half of the twentieth century [4].

In the 1960s, Giovanni Francia was the first person to apply the Fresnel reflector concentrator concept for industrial thermal processes in Italy [27]. The compound parabolic concentrator (CPC) was the first 2D concentrator ever designed, also in the 1960s, but the theory was not explicitly explained until the 1970s when the generalized entendue was derived [2].

Regarding concentration measurements, since the first ultra-high flux measurements were performed at the University of Chicago in 1988, there has been very rapid progress including experimental investigation of laser pumping and materials processing experiments performed at the National Renewable Energy Laboratory High-Flux Solar Furnace and the Weizmann Institute Solar Tower [2].

Concentrating solar technologies have passed the testing and small-scale power-production phases and are now being commercialised [19]. A noticeable trend in large solar concentrator designs is the shift from continuos surfaces to segmented surfaces of optics, e.g., using many smaller flat or circular facets to make a large parabolic dish. Evidence shows that this is now one method to improve the performance of reflector concentrators as shown by Zanganeh et al. [28]. Solar dish concentrators based on ellipsoidal polyester membrane facets and V-groove reflectors have been showing improved irradiance distributions whilst still obtaining optical efficiencies of >80 % [28]. Nilsson et al. [11] proposed a stationary asymmetric parabolic solar concentrator with a microstructured reflector surface; three different microstructures were tested for their effect on irradiance distribution and optical efficiency. The highest optical efficiency reached 88 %, and all distributions decreased distribution peaks. For high concentration, an array of small concentrators per cell module is the safer design considering manufacturing, maintenance, damage, and replacement [9], and it is the same for systems with mulitple concentrators per cell.

Third-generation organic PVs have begun to be tested under concentrated sunlight as well. Organic PVs are a potentially low-cost, lightweight, and flexible alternative to inorganic PVs, but they have poor durability. Under concentration levels <10 suns, the short-circuit current increases with concentration in a linear fashion, whereas the open circuit voltage increases logarithmically [29]. At >10 suns, heating of the organic PV material causes a decrease in the open circuit voltage [29]. At present only low-concentration optics—such as light funnels, wedges, luminescent concentrators, and small reflective dishes—are being used with organic PVs.

2 Primary Optics

The majority of HCPV concentrators will be point focus and require two-axis tracking. They are well suited for large field installations in the 10–100-MW range [8] rather than smaller scale systems or for domestic use. High-concentration optics are only suited to sunny areas where direct sunlight is available due to their high dependency on normal incident light rays and specular reflectance rather than diffuse.

2.1 Fresnel Lens

The most developed refractive concentrator is the Fresnel lens, which is made up of a chain of prisms (see Fig. 3) where each prism contributes a section of the slope of the lens surface but without the material of the full body of a conventional singlet [4].

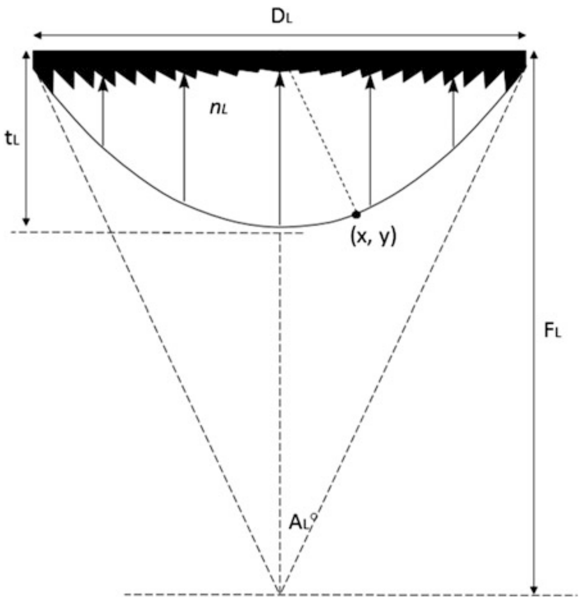


Fig. 3 The conversion from a conventional convex lens to a compact Fresnel lens by way of truncation. Dimensions and geometry of the lens are shown: diameter of the lens D_L; original thickness t_L; original focal length (which is now termed the "back focal length" of the Fresnel lens) F_L; refractive index of the lens n_L; and the maximum angle of concentration A_L

According to Fermat's principle that all rays have an equal path length, then the following equation can be obtained for a full-bodied aspheric convex lens [26]:

$$F_L + (n_L + 1)t_L = \sqrt{(F_L - y_L)^2 + x^2} + n_L y \tag{9}$$

By substituting $D_L/2$ for × and the thickness of the lens t_L for y, the following equation relates the focal length to the thickness [26]:

$$\frac{t_L}{D_L} = \frac{\sqrt{F_L^2/D_L^2 + 1/4} - F_L/D_L}{n_L - 1} \tag{10}$$

For a solid lens, only the angular orientations of the outer surfaces on which light is incident and transmitted are relevant to the focusing action. The thickness of the inner medium is not important and in fact absorbs more energy the longer the light travels in the medium. So by collapsing the convex lens down to minimise the thickness, the rays should approximately still focus in the same area but require less lens material to do so.

The centre of curvature of each ring in a Fresnel lens can be designed to recede along the axis according to its distance from the centre to eliminate spherical aberration. Fresnel reflection causes approximately 8 % loss within the Fresnel lens, and for easy mold removal any vertical lines shown in a Fresnel diagram are typically actually inclined at 2° [26].

In a Fresnel lens, the discretisation and the sharp edges of the prisms, which are absent in the convex, are a source of unwanted diffracted rays. Consequently, the Fresnel lens is a much poorer imaging lens than the original smooth convex lens; however, as stated previously, imaging of the source is not necessary in power collection. This small percentage of loss is greatly outweighed by the relative lightness and compactness of the Fresnel lens. The convex lens would not be used in a commercial HCPV system as a primary optic. In general, high-concentrating Fresnel lenses are actually also avoided commercially because in large structures mainly formed from glass, such lenses are still considered unwieldy, heavy, and expensive [9]. This gives more reason for modular designs with Fresnel lenses focusing toward very small solar cells ($100\ mm^2$) or all focusing to one PV receiver.

The *f*-number (relative aperture) of a Fresnel lens is the focal length over the diameter. Because the *f*-number is increased, the irradiance is decreased. They are typically point-focus circular-faced lenses, although line-focus Fresnel lenses have been designed, and they can be cut to square shapes to increase the packing factor. The maximum concentration ratio of a single Fresnel lens, which is limited by chromatic aberration, is approximately 1000× [30]. However, by combining a diverging polycarbonate (PC) lens and a converging PMMA lens, the concentration limit can be increased up to 8500× [31].

There are two types of Fresnel lens: imaging and nonimaging [12]. The nonimaging Fresnel lens has a lower manufacturing cost, but the performance is far from optimum due to the low acceptance angle and decreased geometrical optical efficiency [32]. However, nonimaging Fresnel lenses are considered less sensitive to chromatic aberration, especially when the design process considers multiple wavelengths such as in the case of the domed Fresnel lens [17]. In the case of imaging Fresnel lenses, the output image can be altered by aberrations due to inaccurate manufacturing of the prism tips and grooves [4]. However, acceptance angles close to the theoretical maximum and 100 % geometrical optical efficiencies are [32–34]. For both types, ray-tracing software can be used to improve the optical efficiency, acceptance angle, chromatic aberration, spot shape, and flux uniformity. For Fresnel lenses, there is a compromise to be made between module thickness and the above mentioned list of attributes, which increase as thickness decreases [23].

The irradiance distribution for Fresnel lenses, such as for many concentrator optics, is originally a Gaussian shape, which is difficult to match to a square solar cell. However, an asymmetrical curved Fresnel lens, which has very good uniform irradiance (ratio of maximum and minimum irradiance points <2), is possible [32]. There are significant manufacturing problems with this type of Fresnel lens due to the nonsymmetric design and problems in molding the curved lens [32]. A hybrid Fresnel-based concentrator with a significantly improved uniformity, compared with a traditional Fresnel lens, can be obtained by tailoring the order of the Fresnel prisms as shown in Fig. 4 (adapted from Zhuang and Yu [35]).

The use of an aspheric lens (Fresnel or not) to obtain high concentration by eliminating spherical aberration is widely known, and the profile can be calculated using Fermat's principle. When considering chromatic aberration, ray-tracing

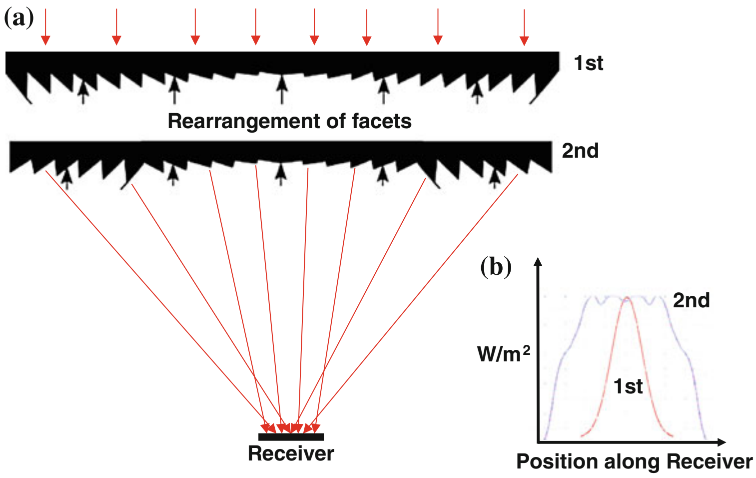


Fig. 4 **a** Diagrammatic representation of improved Fresnel-based concentrator and **b** irradiance distribution profile on the receiver [35]

methods or calculations involving two or more wavelengths are an effective method to decrease the dispersion of the focus beam. A dome-shaped nonimaging Fresnel lense can be made in such a way with improved optical efficiency and less transmission of infrared rays, which may or may not be beneficial to the PV material being used.

Fresnel lenses offer high optical efficiencies and low production costs, which explains their development as PV concentrators over the years.

2.2 *Parabolic Reflectors*

The point-focus parabolic dish and line-focus parabolic trough can be concave or convex (inverse) where the active side (that which is used to redirect the light) faces the source. The parabolic dish is a paraboloid of revolution, a surface obtained by revolving part of a parabola about its axis of symmetry. The parabola shown in Fig. 5 may be represented in cartesian coordinates by:

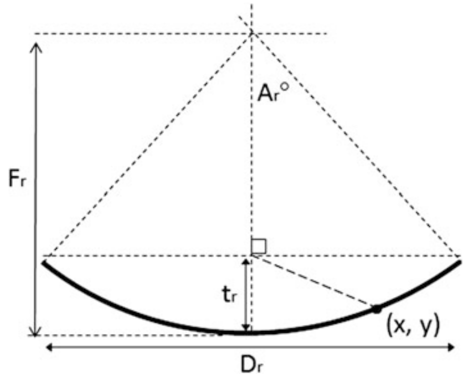
$$D_r^2 = 8\ F_r\ t_r \tag{11}$$

and:

$$4\ \tan(A_r/2) = \frac{2x}{F_r} \tag{12}$$

As shown in Fig. 1b, when two parabolas have coincident focal points and hence the same angle A, then the following equation relates the two:

Fig. 5 Dimensions and geometry of a parabolic curve reflector in two dimensions



$$\frac{x_1}{f_1} = \frac{x_2}{f_2} \tag{13}$$

Parabolic troughs are usually designed for low to medium concentration ratios with a half-acceptance angle two to three times the apparent angular width of the Sun's disk. The maximum concentration ratio of a parabolic trough concentrator, which can attain high optical efficiency and high acceptance angles without the aid of a secondary optic, is limited to $\sim 70\times$ [36]. Beyond this, the parabolic trough is suitable for concentrations up to 200 suns and although possible, it is rarely used for HCPV applications [3]. The use of a second concentrator is needed to bring the concentration value as close to the limit as possible. Therefore, the usual approach is to take advantage of the low aspect ratio values of focusing primary optics and use second-stage concentration at the receiver to increase the overall concentration value. Parabolic trough concentrators are the most proven and commercially tested solar thermal concentrator technologies, and the California Mojave Desert has nine large commercial-scale solar power plants in operation [19], but the parabolic dish is used for HCPV systems.

Large paraboloids are difficult to manufacture accurately, and sometimes smaller flat or conic mirror facets are arranged to approximate the paraboloid shape. The trough is inherently easier to manufacture and can be performed so by bending a flat reflective sheet [3].

A parabolic dish (point-focusing) solar collector is advantageous compared with other collector systems due to the absence of cosine losses and the increased concentration ratio compared with the line-focusing parabolic trough [37]. The 3D parabolic dish can be thought of as the most efficient high-concentration optic with the fewest restrictions, but maximizing their full potential is very expensive compared with the point-focus Fresnel lens [19]. Parabolic dishes have greater optical efficiencies than that of the linear Fresnel reflector or central receivers where cosine losses ensue.

As for their performance at high-concentration ratios, although parabolic reflectors on their own can reach high optical efficiencies or have relatively uniform irradiance distribution (by matching receiver size to beam radius), they cannot perform both unless other optical stages are used due to the gaussian shape of light from the Sun [38, 39].

Parabolic mirrors for dish power-generation systems are generally constructed from one large parabola per dish, although less expensive techniques, such as forming the dish from an array of small mirrors, are becoming more common [9].

2.3 Linear Fresnel Reflector and Heliostat Fields

Linear Fresnel reflectors (LFRs) implement flat mirrors in strips at increasing tilt positions at further distances from the receiver (usually positioned above the LFR). Most LFR systems are solar thermal, and research into receiver shapes and areas has been conducted. They have been classed as low-concentration optics in the past, but they can be used as medium concentrators. To reach greater concentrations, bent or parabolic mirrors are needed in place of the flat mirrors, and hence LFRs are sometimes not considered as high-concentration optics, but their parabolic or similarly curved counterparts would be. The central receiver set-up has the advantage of being a stationary fixed receiver, which is easy to structure and support, and it decreases the weight and strain on moving optics. This can be adoptable for any collector field-tower receiver set-up, and typical support tower heights are up to 10 × 15 m tall [9].

Abbas et al. [40] reviewed LFRs and described how the variation of the total power impinging onto the receiver and its flux map along the day has traditionally been identified as a major handicap for LFR technology. This problem is first due to the optical efficiency of the solar field, which varies more than in trough collectors [41], as well as the change on total radiation falling within the field, which is caused by the zenith angle.

The linear Fresnel reflector has the ability to “reshape” the mirror surface, which is a major advantage compared with the trough system. Solar movement across the sky can be compensated for by simple adjustment of the mirror elements rather than requiring movement and control of the reflector/receiver unit as a whole. This simplifies the support and tracking structure leading to fewer implementation costs [9].

Linear Fresnel reflector systems have relatively low initial cost, and because the reflector strips are ground-mounted, wind loads on the reflector strips are low.

Fields of heliostats are similarly used for thermal power towers and some smaller-scale PV central receivers have gained growing interest, but at present their use as HCPV optics is rare. Plans for space solar-concentrator optics, which would direct light toward solar fields on Earth, consist of a lightweight array of heliostat mirror satellites in a constellation in low Earth orbit (1000 km). Although this may seem far-etched, NASA is developing a solar sail due to be finished by 2015. The Earth-based solar fields, which would receive the extra 6 $kWh/m^2/day$, are already being constructed [8]. This idea involves taking advantage of the dawn-to-dusk sunsynchronous orbit adopted, i.e. a near-polar orbit of inclination angle 99° rotating at 1°/d, to remain consistently normal to the Sun's rays.

On the Earth's surface, each heliostat has a dual-axis tracking system, and the overall field usually takes on a circular or semicircular array [21].

3 Secondary and Final-Stage Optics

In high-concentration optics, secondary optics are necessary for high performance and high reliability. Due to the low optical tolerance of HCPVs, this is important even during prototype stages where manufacturing and alignment is perhaps not optimum. This is even more important for optical systems of multiple stages, such as the cassegrain, and as the concentration ratio is increased. As one can imagine, tertiary optics are common depending on the design of the optical system, and a wide range of shapes is used. Reflective secondary optics tend to have increased flux uniformity and colour-mixing effects, but dielectric secondariness using TIR can withstand more internal reflections without much loss [42]. Too many reflections in both optics results in severe light ray loss by way of Fresnel losses, not meeting TIR criteria, or in light being reflected back (opposite direction of receiver). The three main families of final stage optics are the dome-shaped lens, the compound parabolic concentrator (CPC), and the light funnels (light cones). Although all are capable of increasing the concentration ratio, irradiance distribution, and/or acceptance angle on the solar cell(s), the optimum receiver optic will depend on the design and constraints of the system.

Nonimaging secondary optics can improve the irradiance uniformity and eliminate shadowing better than imaging secondary optics for certain systems. The nonimaging secondary optic can be formed by rotating a segment of curve from a linear, quadratic, and even cubic order function [10].

3.1 The Revolved Conics

This section refers to the ellipsoid, paraboloid, hyperboloid, and even the sphere (the circle can be argued to be and not be a true conical shape) as revolved conics producing 3D point source optics. These are typically used as the second stage of reflection in the cassegrain set-up described earlier, and thus their size should be kept low to avoid shadowing effects on the primary. Although these secondary optics will share the same advantages and disadvantages as the larger primary versions, due to their smaller size they are easier to manufacture accurately. They will also undoubtedly introduce their own errors into the optical system, but these too are easier to minimise on a small scale than in the high-concentrating versions. The revolved conics are imaging optics, and so microscopic and macroscopic imperfections will increase the focusing point diameter and cause lower concentration.

As mentioned in the Introduction, high concentration is difficult to achieve with line-focusing optics, but the combination of two linear optics can produce an overall point focus capable of high-concentration ratios up to 2000 suns [3]. This is performed by the primary linear optic focusing in one plane along its length to create a line focus and then the secondary linear optic focusing that line to a point. In this set-up, the path of most rays within the optical system are longer than in the conventional point source counterpart, and so further beam spread is incurred as is increased shadowing from the oblong secondary optic, but accurate manufacturing is more economic.

A 2D profile of a dome lens can be designed that redirects all incoming rays from the first-stage (and possibly second-stage) optic toward the cell. The 3D lens is then rotated around the optical axis. The dome lens typically uses less material than a CPC and can be easier to manufacture [20]. The significant advantage of the dome-shaped lens is the uniform irradiance distribution it can provide on the cell [20]. A ball lens can also be used as a secondary optic, but this would perhaps still require a tertiary optic at the receiver. 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.

The paraboloid, ellipsoid, and hyperboloid mirrors are typically used as secondary reflectors wherein the latter is more tolerable to errors and hence can improve the acceptance angle of a system when replacing a secondary paraboloid. The ellipsoid, semisphere, and sometimes even flat mirrors are used in arrays to emulate a larger parabolic dish with simultaneously high optical efficiency and irradiance distribution.

Many novel secondary optics have been aimed at improving irradiance distribution on the PV receiver, but most of these require the input aperture to be fully illuminated, which—although possible in HCPVs—does then limit the acceptance angle.

3.2 The CPC and Its Variations

The 2D profile of the CPC can be described as having focal points of both parabola sides located at the intersection between the opposite parabola and the receiver. The compound parabolic concentrator is designed using the edge-ray principle and is considered an ideal concentrator in two dimensions. This means that no rays within the acceptance angle are lost, and hence it achieves maximum theoretical concentration. All rays entering at the extreme collecting angle are conserved on the output exit aperture with no loss of rays. The length is bound by the extreme rays at θ_i where both rays reach the receiver. The focal length can be given as [2]:

$$f = \frac{a'}{1 + \sin\theta_i} \tag{14}$$

where α' is half the exit aperture.

The overall length is [2]:

$$L = \frac{a(1 + \sin\theta_i \cos\theta_i)'}{\sin^2\theta_i} \tag{15}$$

And the entry aperture diameter in:

$$a = \frac{a'}{\sin\theta^i} \tag{16}$$

From Eqs. (16) and (1), the CPC matches the maximum theoretical concentration ratio. In the ideal 2D CPC design, the rays incident on the rim of the exit aperture are said to be at the boundaries of failure regions, which in 3D designs are realised for skew rays. A 3D CPC can be made from revolving the 2D profile (circular), by crossing two linear CPCs (square), or by more complex computation methods for specific geometries such as the rotationally asymmetrical compound parabolic concentrator [43].

In the 3D CPC (Fig. 6a, b), there is a 3-fold infinity of rays as opposed to the 2-fold infinity in the 2D design, and the rays outside the meridian sections can no longer be guaranteed accommodation in the same way as the 2D rays (because the light ray can now be skewed) and hence be reflected out of the CPC.

The linear dielectric-filled CPC can also be designed to account for the acceptance angle inside the dielectric due to refraction using:

$$\sin\theta_i\ (n - (2/n)) \quad \text{or} \quad \sin\theta_i'(1 - (2/n^2)) \tag{17}$$

From this equation, it is preferable to choose refractive materials with a refractive index greater than the square root of 2, but in the case of 3D, rays will still be lost. The dielectric-filled CPC takes advantage of TIR and increases the collecting angle for the same length as a reflective CPC. Thus, this gives the possibility of a higher acceptance angle or shortening of the CPC [2].

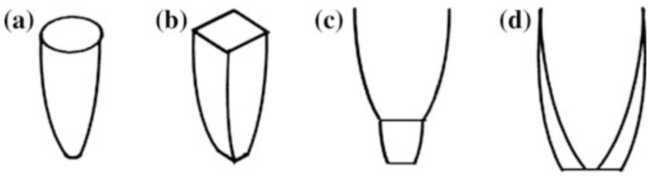


Fig. 6 Variations of CPC. **a** Revolved CPC. **b** Crossed CPC. **c** CCPC. **d** Lens-walled CPC

The CCPC (Fig. 6b) has been found to be an ideal concentrator for a half acceptance angle of 30° and outperforms the revolved CPC as a static solar concentrator at 3.6× concentration [44]. The square-apertured CCPC is also preferable due to its higher packing factor when arrayed side by side, and less PV material is wasted in manufacturing because of the efficiency of cutting square PV cells rather than circular ones. However, the CCPC, like the CPC, does not have a good output irradiance distribution for a flat receiver, and hot spots can reach 50× the energy of the incident rays [44]. The CCPC can be classed as a new type of secondary optic for HCPV systems, which requires further study.

In attempt to decrease the amount of material required in a CPC (the high length-to-width ratio) and hence decrease the weight and expense depending on the material used, the two-stage CPC [CCPC (see Fig. 6c)] is an option. The first stage is in the air with a regular reflective CPC; then, instead of a solar cell at the exit aperture, there is another transparent material filled CPC using TIR. Another method to decrease the length of the CPC is to use truncation, i.e., removing part of the entrance aperture end, which tends to a gradiant of 0. By doing so, there is little decrease in the concentration ratio with a sizeable decrease in the length. Truncation can increase the half acceptance angle of a CPC, but it also decreases the geometrical concentration ratio. The maximum concentration ratio can only be achieved by a full-height CPC without truncation [21]. Larger-opening angles can decrease wind-induced deviations, manufacturing tolerances, and sagging effects, whist through optimisation they can still yield high acceptance angles [36].

CPCs can absorb direct and diffuse solar radiation, and, as low concentration devices, their acceptance angle is much greater than that of high-concentration systems. Correspondingly, optical efficiency decreases slowly within the range of the acceptant angle the CPC is designed for, but it decreases rapidly beyond this range. The main disadvantage of the CPC is the very nonuniform irradiance distribution it outputs with a very high peak in the centre [20]. The lens-walled CPC (see Fig. 6d) is designed such that the the two parabolic curves of the 2D CPC profile are each rotated from the light-entry side to create a type of wedge shape with parabolic curves. The optical efficiency is lower than the original filled CPC or mirrored CPC, but the irradiance distribution is somewhat improved. The lens-walled CPC is also capable of higher acceptance angles [45]. One design of the lense-walled CPC reports ∼65 % optical efficiency at 0° incidence, which decreases slightly to ∼60 % at 20° from normal [45].

For an ideal CPC the exploitable part of the diffuse irradiance is 1/c but this contribution to a high concentrating system is negligible.

3.3 Light Funnels

Light funnels (light cones or homogenisers) all follow a funnel shape (Fig. 7) and are typically used in the same fashion as a funnel where their prime aim is to capture more stray light due to errors and redirect them toward the receiver. Light

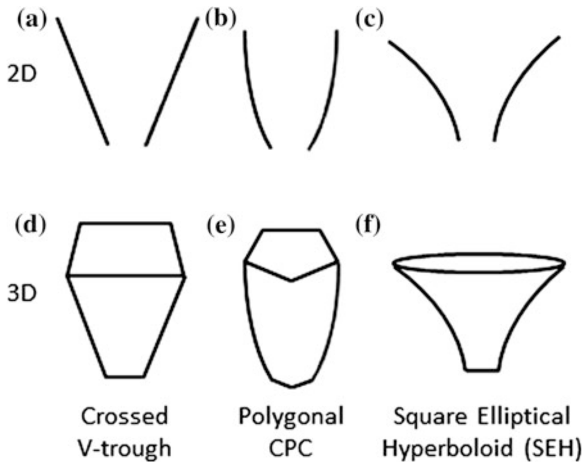


Fig. 7 Examples of 2D profiles and possible 3D transformations. **a** V-trough. **b** CPC. **c** Compound hyperbolic concentrator. **d** 3D square-apetured V-trough. **e** Polygonal apertured CPC. **f** Hyperboloid with an elliptical entry aperture and square-exit aperture

funnels can first be described by their 2D curves (Fig. 7a–c) where the side walls will be flat (V-trough), hyperbolic, or elliptical. However, the most popular cones are the CPC, as described previously, and simple V-shaped cones in order to save on manufacturing costs and decrease complexity. Further variations are possible when the 2D profile (V-shaped, CPC-shaped, or hyperbolic curved as shown in Fig. 7a–c) is translated into 3D where circular, square, or polygonal entry apertures can be realised (Fig. 7d–f). In this way we obtain the square-faced V-trough, the circular cone, the elliptical cone, and many more complex variations. Merged forms, including the circular-square cone, which has a circular entry merged with a square exit, are possible as well. Square solar cells are more common than circular, and hence square-exit faces are usually desired, but there are plenty of examples of circular cells with circular optics [42, 46].

At present, light funnels are all used in the same fashion in HCPVs which, as described, is to funnel light toward the receiver with the receiver being a solar cell, an array of solar cells, or possibly another type of low concentration optic that is attached to the solar cell(s) (specifically the two-stage CPC design and any variations would fit this description). In arrangements with an array of solar cells, the HCPV system will only work as efficiently as the lowest-performing cell. Hence, errors in irradiance distribution or tracking can severely limit the system's full potential. There is less risk of this happening with an accompanying optic or array of optics attached to the receiver.

The light cones are simple forms of nonimaging devices, some of which have been used for many years [2]. The advantage of these light cones is by far their simplicity yet effectiveness at increasing acceptance angle. They are not ideal optics; many of the light rays, even within a critical angle of incidence, can still be lost. In all of the designs there is a compromise between entry aperture width, which allows a greater acceptance of deviated rays, and slope or height of the walls. A smaller gradient in the walls results in smaller reflection angles, hence more reflections and rays not meeting TIR criteria or reflecting backward out of the system. Similarly, if the height is increased to maintain the wall slope whilst increasing aperture width, then the ray will travel longer in the light funnel and incur a greater number of reflections resulting in the same problems.

The equation:

$$2y = (\pi/2) - \theta_1 \quad (18)$$

can be used to determine the length of a cone for a given entry aperture diameter, but some rays within θ_i can still be reflected out of the cone. The 2D V-trough is far from ideal as depicted by earlier literature [2]. The identification rays that are reflected out of axisymmetric cone shaped concentrators can be performed according to the procedure outlined by Winston et al. [2] for the CPC. The optical efficiency of a cone for rays within the acceptance angle is approximately 80 % with smaller-angled cones performing closer to ideal concentrators. A V-trough concentrator will have very high acceptance angles when its geometrical concentration ratio is <2 [47]. The crossed V-trough (inverted pyramid) and similar square-shaped light funnels are the simplest but most effective method to couple a circular primary optic with a square cell as well as homogenizing the irradiance distribution on the cell.

The square elliptical hyperboloid (SEH), which is based on the ideal trumpet concentrator, has recently been developed with an elliptical-entry aperture connected to a square-exit aperture by way of hyperbolic curves (Fig. 7f) [48]. 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 %. The main use of this type of concentrator, however, is for building integrated PV applications, and its performance as a final-stage light funnel still has to be tested. The SEH designed for 4× concentration ratio has a greater optical efficiency of 68 % and may be more suited to HCPV optical systems.

One particular type of optic, which has no concentration effect and is purely for ensuring that rays travel toward the receiver, is the straight-forward light pipe or light rod. The light rays are focused onto the surface in the same way as in a light funnel, but the width of the entry aperture is not greater than that of the receiver. The light rod would be used in optical systems where it is beneficial to position the solar cell outside the optical system or not in the location of focused rays (cooling purposes). The light rod can transport the light rays to the cell and act as a homogeniser to distribute rays evenly. If we ignore this homogenising effect, which would improve the performance of the cell, then technically the acceptance angle would be the same as when the receiver was placed at the entry-aperture position of the light rod. For that reason, it cannot be called a light funnel or cone that directly improves the acceptance angle. Depending on the condition of the focusing light rays, it may only improve the irradiance distribution by a small factor and will somewhat decrease the optical efficiency due to absorption and if too many internal reflections are incurred. The light rod is hence the simplest method purely to reposition the cell.

4 Materials for HCPV Optics

A critical task in any concentrating optic design is identifying the best possible materials. Ideally a material would have high optical efficiencies (90–100 % reflection or transmittance), high thermal and ultraviolet (UV) tolerance, physical durability against environmental conditions, and overall economical to produce. In some systems using both a refractive element and a reflective element, both refractive and reflective issues must be addressed, but with careful design they may complement each other. For example, a secondary mirror optic may correct for primary lens aberrations as long as they are not severe. Generally, reflective materials are more cost-effective than refractive materials [10].

4.1 Refractive Optics

Glass can withstand high temperatures and is typically the best choice for high-quality accurate optics. Most plastic materials have less effective light-transmission properties compared with glass and tend to degrade with heat and UV exposure. Glass can be used over decades in some applications (regular maintenance, such as cleaning, is still required), whereas plastics typically last for only a few years [21]. The combination of strength, flexibility, and light weight, however, makes plastics more attractive with an overall aim to save money on capital and running costs (less-expensive solar tracker systems are required for lighter systems). Polymers—such as PMMA, which has a refractive index of 1.49 (very close to that of glass)—are often used in solar concentrators with good solar spectrum matching and resistances to ageing. PMMA remains thermally stable up to at least 80° [4] and is perhaps the most popular polymer used in CPVs. Polyethylene is used widely in other areas, such as a plastic film, but it has a short lifetime of only 1 year [21]. Polyamide, polystyrene, acrylics, and PC have been investigated (at least as covers for flat-plate collectors), but more research is required, especially regarding their durability. Durability is a topic that lacks data in many areas. Testing requires several years to pass, although some advanced weathering simulations are possible as is modelling. High levels of temperature, humidity, and solar radiation have, however, been proven to accelerate ageing with thermal effects proving most detrimental.

The properties of plastic films are dependent on the length of the polymer chain: Longer chains result in less brittle material. However, degradation due to heating, light exposure, oxidation, and mechanical breaking (scratches and repeated flexing) split these long polymer chains [21].

Fresnel lenses have traditionally been manufactured out of PMMA, which, due to the dispersion curve, makes shorter wavelengths converge faster than longer wavelengths and hence causes longitudinal chromatic aberration (LCA). Fresnel lenses may be manufactured by hot-embossing, casting, extruding, laminating, compression-moulding, or injection-moulding thermoplastic PMMA [49]. Optical or mirror-grade PMMA material may come from the automotive, lighting, or skylight industries. Applicable formulations of optical-grade poly(dimethylsiloxane) (PDMS) material are shared with the aerospace, electronics, and light-emitting diode industries. A heavier lens technology consists of acrylic or silicone facets patterned on a glass superstate as researched in the late 1970s [50, 51]. PMMA and PDMS can be adhered to a glass superstate and patterned as a Fresnel lens. PC is sometimes suggested as an alternative to PMMA due to its significantly greater resilience, which prevents mechanical fracture and fatigue. However, PC has a smaller spectral bandwidth, less optical transmittance, and lower resistance to scratches [52]. It suffers more from optical dispersion, chromatic aberration, and solar-induced photo oxidation [53–56].

PMMA has a transmittance of ~95 % and has a low glass-transition temperature meaning that high-temperature treatments, such as calcination, which is a preparation method of antireflective and antifogging coatings, cannot be used on PMMA material. Zhou et al. [57] successfully fabricated antifogging and antireflective coatings on Fresnel lenses by way of spin-assembling silica nanoparticles without any high-temperature posttreatments and reached a transmittance of 98.5 %. Super hydrophilic coatings (antifogging) can effectively prevent water condensation on transparent substrates, which can alter light concentration in CPV systems. Another way to achieve an antireflective property on PMMA (refractive index = 1.49) is to layer a single coating of refractive index 1.22. However, at present there are no bulk materials that possess such a low refractive index [57], but nanoporous coatings have voids leading to a lower refractive index and better antireflective properties [57].

As mentioned previously, the acceptance angle decreases with greater concentration ratios. To combat this trade-off between concentration ratio and half acceptance angle in CPCs, a large refractive index dielectric medium could be used to form the solid concentrator instead of the common mirror one. However, this increases the weight and amount of material required for manufacturing. The lens-walled CPC, which uses less material and thus decreases the weight, has a lower optical efficiency partly due to the low transmissivity of the lens material chosen for the lens-walled CPC and so could be improved with different materials.

Computer-controlled diamond turning machines, as well as other modern materials and molding techniques, have significantly improved the design and accuracy of refractive optics such as Fresnel lenses [24]. Similarly, computer-aided design and machining has improved the quality of reflective optics, but in both cases good-quality prototyping can be expensive when requiring smooth and accurate geometries.

4.2 Reflective Optics

Reflective concentrators do not suffer from selective wavelength absorption and dispersion associated with dielectric lenses. They use less material than any other equal concentration system because they are not filled with an optical material.

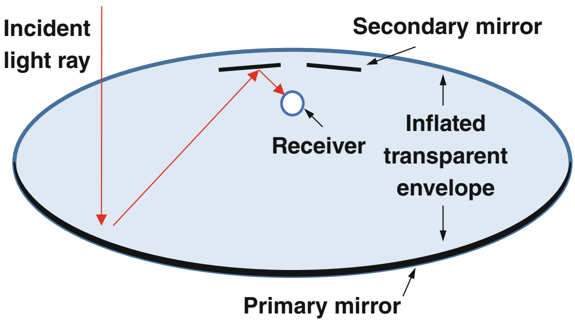


Fig. 8 Diagram of inflatable solar concentrator optics for solar thermal application. The primary mirror consisting of a silicone coated fiberglass fabric with an aluminum mirror layer [59]

They are, however, said to be more prone to manufacturing errors and are less tolerant to slope error than lenses.

In general, the optical efficiency of reflective concentrators is a coupled function of both the geometry and the mirror reflectivity. A common approximation for the effect of reflectivity on optical efficiency follows from the pioneering work of Rabl [58].

Polymer mirror films can be used as a low-cost option for reflective surfaces and have low weight and costs compared with a curved glass or polished aluminium mirror. They are, however, difficult to apply, especially to 3D shapes, and if not properly applied will not replicate the intended curve or line intended.

V-trough concentrators are one of the easiest-constructed of all low-concentrating systems: They can be fabricated from a single aluminium sheet. Bader et al. [59] attempted to lower the manufacturing costs of solar concentrators by investigating the use of pneumatic polymer mirrors. By applying slight pressure over an inflatable elastic enclosure, two opposing cylindrical curved surfaces were obtained. These encompassed a transparent foil on one side and a silicone coated fibreglass fabric with an aluminium mirror sheet on the other side as shown in Fig. 8.

Wind-induced vibrations were eliminated due to the use of a concrete structure, which is more rigid and stronger than conventional metallic frames. Self-cleaning scratch-resistant foils were applied easily, and the high-quality mirror foils were well protected from the environment. There is a high potential for a cost decrease due to the cheaper and lightweight materials, which can also be easily transported. The concrete structure would be built on site. The cylindrically shaped optics, which suffer from optical aberration, were corrected somewhat with the use of a tailor-made secondary specular reflector incorporated in tandem with the primary cylindrical mirror. However, the resulting prototype was only suitable for thermal receivers, but it shows the variance of materials possible and how they may be used to reach high solar concentrations.

Parabolic reflectors designed for high concentrations in particular can be costly to build on such a large scale. They require stronger structures and more expensive solar trackers due to their weight and high accuracy requirement. A silvered mirror using smooth glass produces a common mirror with reflectivity >85 %. The smooth glass is covered from the back and sealed with an oxidation layer. These types of mirrors are only applicable as flat reflectors. Curves—such as the parabolae, hyperbolae, ellipse, or circular—are extremely difficult and hence costly to manufacture with accuracy. Manufacturing processes used include precise grinding, milling, polishing, and a variety of coating methods for a mirror finish. Flab et al. have manufactured a mirror with a reflectivity >94 %, which is successfully being used in Colorado [19].

Jagoo et al. constructed a very low cost parabolic dish with basic tools using wood, cement, silicone paste, and fibreglass [19]. A chrome polymer reflector with an adhesive back was used for this application. It had the advantages of high weathering durability, and the system reflected 82 % of the incident sunlight. Fiberglass is cheap, impermeable, and easy to use and mould.

Alanod is a reflective thin film comprised entirely of aluminium that has a total reflectivity of 95 %. Samples coated with a polymeric chemical to protect the alumina layer can survive for a few years. ReflecTech mirror film is a polymer-based film for concentrating sunlight in solar energy arrays. The film has an overall reflectivity of 94 % and is immune to water and UV radiation.

5 Conclusion

High-concentration optics for PV applications require all types of optics including low-concentration and nonconcentration devices. As the geometric concentration ratio is increased, the acceptance angle is decreased and errors in alignment, manufacturing, reflectivity, and refraction are more noticeable. The use of smaller optics to replicate a high-concentrating optic is becoming more popular as a means to achieve high optical efficiency as well as high irradiance uniformity on the receiver. Receiver optics are essential to increase the acceptance angle, and an array of possible optics have been outlined herein. The Fresnel lens and parabolic dish maintain the most popular form of high-concentrating optic for PV applications. A variety of possible materials has been given for both reflective and refractive optics along with manufacturing methods. Depending on the constraints of a project, different concentrator types, geometries, materials, and manufacturing methods will be chosen as optimum, but tailoring a design to an application is always important, especially for high-concentration optics for PV applications. This chapter provided many options for concentrator design and manufacturing and explains the basic optical behaviour and materials used today.

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