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Review

Using Static Concentrator Technology to Achieve Global Energy Goal

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Abstract: Solar energy has demonstrated promising prospects in satisfying energy requirements, specifically through solar photovoltaic (PV) technology. Despite that, the cost of installation is deemed as the main hurdle to the widespread uptake of solar PV systems due to the use of expensive PV material in the module. At this point, we argue that a reduction in PV cost could be achieved through the usage of concentrator—which are commonly produced from polymers. A solar concentrator is a type of lens that is capable of increasing the collection of sun rays and focusing them onto a lesser PV area. The cost of the solar module could then be reduced on the assumption that the cost of introducing the solar concentrator in the solar module design is much lower than the cost of the removed PV material. Static concentrators, in particular, have great promise due to their ability to be integrated at any place of the building, usually on the building facade, windows and roof, due to their low geometrical concentration. This paper provides a historic context on the development of solar concentrators and showcases the latest technological development in static photovoltaic concentrators including non-imaging compound parabolic concentrator, V-trough, luminescent solar concentrator and quantum dot concentrator. We anticipated that the static low concentrating PV (LCPV) system could serve to enhance the penetration of PV technology in the long run to achieve the Sustainable Development Goal (SDG) 7—to open an avenue to affordable, reliable, sustainable, and modern energy for all by 2030.

Keywords: solar energy; solar photovoltaic; solar concentrator; energy

1. Introduction

Energy is essential for life. As stated in the Sustainable Development Knowledge Platform, 'energy is an essential factor for sustainable development and poverty eradication' [1]. Despite this fact, nearly 2.8 billion people around the globe lack access to modern energy services [1]. A recent report by the International Energy Agency (IEA) [2] indicated that the number of people without access to electricity has dropped below 1 billion for the first time in 2017, but predicts that around 700 million—most of which are residing in rural areas in sub-Saharan Africa and developing Asia—will still lack access to electricity in 2040. Another statistic shows that every year, close to 4.3 million people are dying prematurely mainly because of indoor pollution due to the use of unsustainable fuels for cooking and heating [1]. The World Bank states that having access to electricity has a great impact on the quality of life as it is essential for adequate health, education, entertainment, security, food production and more [3]. Finding alternative sources of energy to satisfy the global energy needs is therefore not just an environmental or economic case, but it is also a humanitarian one.

Achieving Sustainable Development Goal (SDG) 7 targets is a global responsibility and must be tackled as such through international collaborations rather than nationalistic solutions. It is frustrating to observe that from the first Conference of Parties (COP) to the last one held in Paris at the end of 2015, their outputs contain only non-binding references just to plead the concerns that are connected to renewable energy resources and energy efficiency. The problem regarding the access to energy services for sustainable development was not directly addressed. The Paris Agreement, for example, makes little reference, only in its preamble, about renewable energy as one of the factors that has been taken into account in coming out with the Agreement when it states: "acknowledging the need to promote universal access to sustainable energy in developing countries, in particular in Africa, through the enhanced deployment of renewable energy" [4]. This and other brief and small references to energy were agreed upon despite the fact that the energy sector: (i) contributed to 67% of all anthropogenic greenhouse gas emissions in 2013, and (ii) releases the CO_2 emissions which have reached higher levels over the last 100 years [5].

Access to affordable, reliable, sustainable and modern energy is integral to global development in the 21st century [6]. The four dimensions of SDG 7 are affordability, reliability, sustainability and modernity. These different dimensions are not mutually exclusive. They overlap, and in some cases even entail each other [6]. According to the UN, the targets are: (1) by 2030, considerably increase the portion of renewable energy in the universal energy mix; (2) by 2030, assure global access to inexpensive, modern, and reliable energy services; (3) by 2030, in order to cater more access to clean energy research and technology; increase the worldwide collaboration that includes energy efficiency, renewable energy, and cleaner and advanced fossil-fuel technology, and boosts financing in clean energy technology and energy infrastructure; (4) by 2030, in terms of energy efficiency twice the universal rate of improvement; and (5) by 2030, upgrade technology and increase infrastructure development in order to supply sustainable and modern energy services for everyone in developing nations, especially, small island developing states, the least developed nations, and land-locked developing nations, as per their corresponding plans of support [7].

To mobilise efforts to achieve sustainable energy and the newly adopted SDG 7, the UN Sustainable Energy for All (SE4ALL) global initiative had started and IRENA works as the initiative's Renewable Energy Hub in order to gather forces to attain sustainable energy and the recently chosen SDG 7 [8]. In this endeavor, IRENA has stated the Global Renewable Energy Roadmap (REmap 2030), which investigates gateways to increase the portion of renewable energy in the global energy mix [8].

The earth receives enough solar energy in 1 hour to satisfy the global energy needs for 1 year; making it an especially attractive solution to reduce energy consumption in buildings and minimise greenhouse gas emissions [9]. The two main ways to convert this abundance of energy into useful energy are solar photovoltaic (PV) and solar thermal technologies. The former utilises semiconductor materials such as silicon to convert the light energy into electricity while the latter collects and stores thermal energy for later use.

According to the IRENA, the era of solar energy has already begun and it hit much quicker than anyone foretold, as cumulative capacity reached 402 GW by the end 2017, which is more than 25 folds the capacity of only a decade ago [10]. In addition, it is leading the worldwide transformation through the ownership of energy. People are just about to realise the importance of this change. By now, the solar PV energy is the most extensively owned source of electricity in the world, in respect to the number of installations, and its usage is increasing [11].

Although the prices of PV modules are going down, partially due to an oversupply in the market; the overall PV system's installation cost in numerous nations is still deemed to be quite expensive. Based on the IEA- Photovoltaic Power Systems Programme (PVPS) analysis, the PV module contributed between 40% and 50% of the total cost of installation [12]. The IRENA [13] reported that numerous factors make differences of installation cost, which include: (i) the characteristics of the PV module (installation size, module type); (ii) the incentives employed in every country (policy, subsidies, tax exemption loan); (iii) the sectors (off-grid or on-grid, industrial or ground mounted, residential, commercial), and (iv) the countries' PV market (maturity, size).

To draw the consumers to place any solar PV system, the cost of installation plays an important role [14]. With an aim to obtain the goals addressed in the prior sections, it is important to drag the installation cost down even more to stimulate more installations. This will assist furthermore to expedite the benefit of the solar PV in providing the worldwide electricity requirement from the current 2.1% [12] to a much higher percentage. By decreasing the use of costly PV material that takes up to 73% [15] of the cost of the PV module can be one of the means to reduce the cost, i.e., 36.5% of the overall installation cost comes from the PV material. A number of researchers have recommended combining a solar concentrator in the PV module in order to obtain this cut in PV material without jeopardizing the PV module's output performance [16–18].

Concentrating PV (CPV), is one of the PV variations that has been explored with the aim of producing a low-cost highly efficient solar PV system, and is usually categorised on the basis of concentration ratio; high, medium and low concentration [19]. Technologies presented in high and medium concentration ratios can generate greater output, although their performance is dependent on solar tracking. Solar tracking in such concentrators introduces additional costs to the overall PV system, which is not desirable. Moreover, misalignment of the solar tracker can drastically reduce the overall system efficiency. The concentrators in the low concentration category, known as the low concentration PV (LCPV), either implement one axis solar tracking or are static and quasi-static (requiring seasonal adjustment) [19]. These static concentrators have high acceptance angle which not only eliminate solar tracking requirement, but are also able to concentrate diffuse and direct radiations making them more favorable for northern areas. Moreover, this high acceptance angle property would also allow the static concentrators to have a smoother response in cloudy conditions than high concentration PV (HCPV). However, the output of such concentrators is fairly low compared to high and medium concentrators. Additionally, the LCPV systems cannot use solar cells with higher efficiency and have to depend on silicon solar cells that are used in flat plate PV panels [20].

2. Target, Materials and Methods

This paper argues that international initiatives and collaborations are essential to ensure global access to energy and demonstrates how solar PV is already being deployed internationally at an accelerating pace to achieve the Sustainable Development Goal (SDG) 7—"to provide access to affordable, reliable, sustainable and modern energy for all by 2030" [7]. The development of solar concentrators is also demonstrated from simple and limited tools to a promising solution which has the potential of reducing the cost of solar energy by replacing expensive semiconductor material with cheaper reflective or refractive concentrators. Finally, the technological development of static LCPV particularly over the last decade is showcased to make a case that LCPV has the potential to make significant contributions towards achieving SDG 7 targets.

This paper is different from previously published review papers since it argues that the CPV system could be used to achieve the SDG 7 goal by 2030. This paper captured the history of concentrator and provided an up-to-date review of concentrator technology in the last eight years and its future prospect. Other published literature only capture certain element of the CPV technology, such as the review on specific type of concentrator, e.g., compound parabolic concentrator (CPC) designs [21], volume holographic concentrator designs [22], non-imaging concentrator designs [23], or on certain thematic theme such as the development of concentrator for portable PV system [24] and the LCA and environmental aspect of utilising concentrator technology [25].

Specifically for Section 4, the selection of material was chosen for papers published between January 2012 and February 2019. The selection of database includes Springerlink, Elsevier SCOPUS and IEEE Xplore. The key phrases used were solar, photovoltaic, solar concentrator, low concentration photovoltaic, sustainability, and sustainable development goal. Only full length peer-reviewed journal papers and conference proceedings were selected; while review papers, communications, theses and book reviews were excluded from this search. After careful consideration, 30 of the 'most appropriate' articles were selected, grouped in specific categories and discussed in Section 4 of this article.

3. Solar Concentrator: A Historic Overview

Despite generating strong interest over the last two decades, solar concentrators have existed for over a millennium and this overview showcases concentrators' development; from simple low power applications to MW scale solar plants. The concentrator operates by focusing the solar energy into a much smaller area ensuring that the performance from such CPV system matches the one produced from a traditional non-concentrating PV system. A solar concentrator is typically produced from a cheap plastic material, mirror or an alternative reflective material in the PV module design [16]. Cogenra [26] showed that the cost of fabrication of its parabolic mirrors was less than \$20.00/m^2, while Sarmah et al. [27] showed that their concentrators were fabricated using polyurethane at a cost of \$33.19/m^2. These were far cheaper than the cost of PV material which could range between \$77.00/m^2 and \$213.88/m^2 depending on the installation size. This calculation is carried out based on the estimations where the cost of PV material is approximately 36.5% of the overall installation cost [15,28]. The lower estimate comes from the installation in a typical solar power plant [29] and the higher estimate comes from the installation in a typical residential building [30]—assuming that the conversion efficiency of the panel is 15% [31].

A solar concentrator can be classified in many ways: according to its geometrical concentration gain, the requirement for electro-mechanic tracking for the system, the type and the material of the lens/reflector [32]. A summary of these classifications is presented in Figure 1.

The first usage of solar concentrators can be traced back to the 4th Century BC, where it was recorded that the ancient Romans and the Chinese used mirrors to focus the sun energy into a focal point which then started fires and torches for their religious rituals [33]. In the 19th century, Augustin Bernard Mouchot, a French mathematician carried out a number of experiments related to the capture of solar energy for cooking and steam engine applications [32]. In 1877, he was successful in utilising a parabolic concentrator from mirrors to create a solar oven after more than a decade of research [34,35]. He expanded his research to create and improve the solar powered steam engine and attracted funding from the French government [36]. However, his solar research came to an abrupt end when the government terminated his funding. It claimed that his research was not economical due to a drop in coal price, which was driven down by the free trade agreement with Britain and the improvement in transport efficiency [36].

After the first practical solar PV cell was created in 1954 [37], its high production cost of \$200/W prevented this technology from becoming the replacement for fossil fuel in generating power [38]. To overcome this cost issue, the research in solar concentrator started to resurface after nearly a century of being dormant. The Wisconsin Solar Energy Centre spearheaded the research in the 1960s—researching in parabolic dish concentrators. To improve the concentrator designs, the team tackled a number of issues including reducing the series resistance in the cell and maintaining the cell's temperature as low as possible [17]. In the mid-1960s, Eugene Ralph [39] proposed the implementation of a reflective conical concentrator which was able to increase the power by 2.6X when compared with a non-concentrating PV cell. He continued to develop other types of concentrators (such as the high-concentration heliostat fields) and envisioned that in the future, mega-watt sized CPV systems that utilised only a fraction of expensive PV material could be built at a cost of less than $1.00/W, making the CPV systems the dominant power source for terrestrial applications [17]. Despite these discoveries, the research in concentrators did not attract much attention until the oil crisis that happened in 1973 [17].

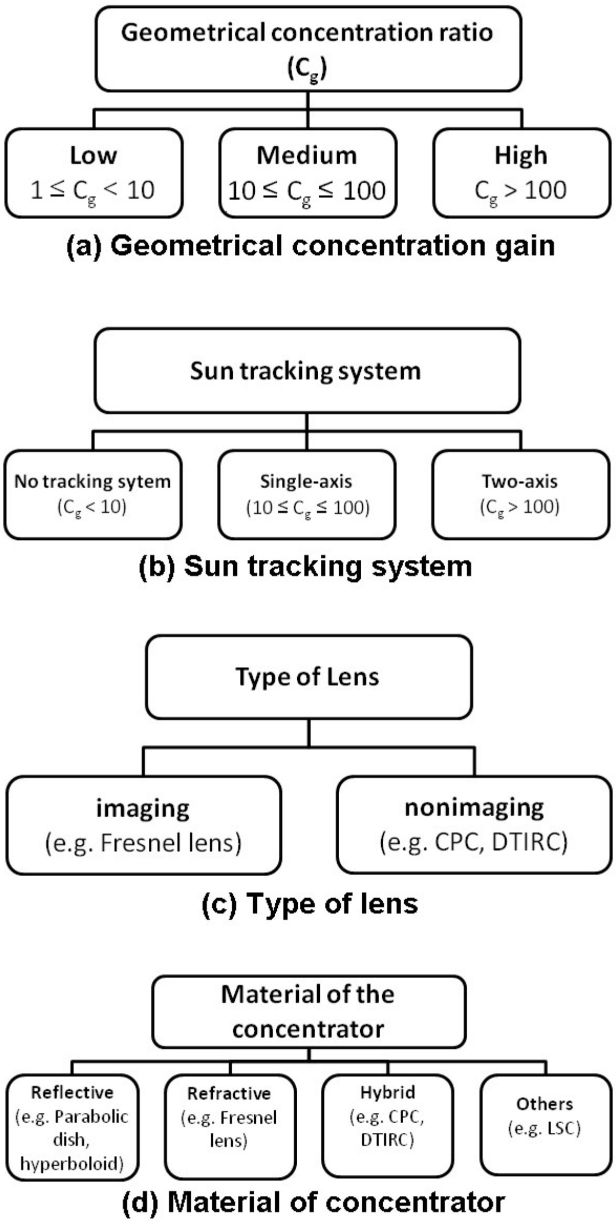


Figure 1. Classification of solar concentrators. Adapted from [18,32].

In the mid-1970s, the concentrator research gained substantial funding from the United States' government under the Department of Energy (DOE) with the aim of achieving a CPV system that cost around $2.00/W [17]. This ambitious project was led by the Sandia National Laboratories in Albuquerque, New Mexico and spanned from 1976 until 1993. It covered three major areas: the concentrator design, the solar cell and the overall CPV system [17]. Specifically in the concentrator design, various designs were investigated by different researchers including the parabolic dishes and troughs, linear and point focal Fresnel lenses and compound parabolic concentrators. Figure 2 shows the first successful CPV system developed by Sandia National Laboratories utilising acrylic Fresnel lenses.

Figure 2. First prototype from the Sandia National Laboratories created from an array of acrylic Fresnel lenses in 1977 [40].

In 1978, seventeen demonstration projects were implemented under the Photovoltaic Concentrator Applications Experiments with installed capacities ranging from 20 to 500 kW [17]. The efficiency of these projects varied according to the type of CPV system, with the lowest and highest efficiencies recorded at 5% and 12% respectively [17]. Interestingly, despite receiving massive funding from the DOE, no viable CPV system materialised until 1990 [17]—the projects only achieved a maximum efficiency of 10% and were considered not cost effective [32]. The DOE introduced a final programme called the Concentrator Initiative in 1990, focusing specifically on a variety of Fresnel lenses [17]. This initiative combined the expertise from eight research groups namely the Applied Solar Energy Corporation (ASEC), Spectrolab, Sunpower, Solarex, Entech, Solar Kinetics, Alpha Solarco and the SEA Corporation [17,32]. In spite of the 'excellent technical progress' [17] - peak electrical conversion efficiencies of between 19% and 25% were achieved - and potential for commercialisation [41], the programme was terminated by the DOE in 1993 [17].

Besides the USA, the concentrator research was also explored by other researchers in Europe particularly by the Polytechnic University of Madrid in Spain where they studied a bifacial cell coupled with a CPC extrusion [17]. The massive funding from the DOE, USA to search for a cost-effective CPV system further motivated many groups in Europe to venture into a similar line of research. One of the successful projects was called the EUCLIDES Project (European Concentration Light Intensity Development of Energy Sources). The research employed a reflective parabolic trough with a C_g of 32X and achieved an overall efficiency of 10.64% [42]. It was also demonstrated that for an on-grid solar power plant installation, a total cost of $3.30/W could be achieved provided the installation was at 10 MW or more [43]. The EUCLIDES project continued to install the second-generation system in Tenerife at a capacity of 480 kW in 1998 achieving an overall conversion efficiency of 9.84% [44] while the third generation was completed in 2007 with an overall electrical conversion efficiency of 10% [45].

From the late 1990s, the research on concentrators ventured into a new concept known as the 'two-stage concentration', which literally meant that two concentrators were employed in one CPV system. The aim was to use a more compact CPV system, with a much higher concentration while keeping the cost at minimum [46]. These combinations include: (i) a parabolic trough and a dielectric CPC studied by Brunotte et al. [47], (ii) a 'snail' and a 'helmet' concentrator by Benitez et al. [48], and (iii) a linear Fresnel lens and a CPC trough by Feuermann and Gordon [46].

As of now, the quest for a less costly but extremely efficient CPV system still prevails. It is thought-provoking that, in addition to concentrating on constructing the finest concentrator for a power plant, furthermore, the researchers began to pursue more to the use of concentrators in building integration applications, researching particularly on the low concentration concentrator. The blend of a low concentration photovoltaic (LCPV) structure to build integration is identified as building integrated concentrating photovoltaic (BICPV) system.

Market wise, the was a surge in terms of the CPV installations between 2012 and 2014, and by the end of 2015, it stood at 360 MW, with the majority of the installations were contributed by the high concentration systems [49]. The CPV consortium [50] has produced a website that detailed out the installation of CPV plants worldwide. The top five installation in terms of peak capacity is presented in the following Table 1. Note that, since this technology is considered quite 'young' [49], some companies decided not to share any information with regards to installation and deployment (e.g., possibly due to intellectual property of the concentrator design, assembly process etc.), which made it impossible to monitor the actual installed capacity worldwide.

Table 1. Top five concentrating photovoltaic (CPV) installations worldwide [50].

Project	Location	Capacity (MW)
Golmud 2	Golmud, China	79.83
Golmud 1	Golmud, China	57.96
Touwsrivier	Touwsrivier, South Africa	44.19
Alamosa Solar Project	Colorado, USA	35.28
Hami Phase II	Hami, China	5.88

In terms of cost, it is difficult to determine the data pertaining to its installation cost [24]. It has been predicted that the cost of a CPV system is able to compete with the traditional solar PV system. A recent report by the Fraunhofer ISE indicated that the installation price of a high concentration CPV system ranges between $1.47/W and $2.32/W [49]. In a separate analysis, Abu-Bakar [51] shows that their LCPV system could reduce the installation cost by 14.5%, when compared to a traditional non-concentrating system. By 2030, it is predicted that the cost of installation for a CPV systems could range between $0.74/W and $1.16/W [49]. This prediction corresponds to a levelised cost of electricity of between $0.047/kWh and $0.079/kWh [49], which is almost similar to the conventional PV system.

Several studies have been carried out to evaluate the life cycle analysis of a CPV system. Lamnatao et al. [52] studied an LCA for a linear CPV system. Their analysis indicated that PV cell and concentrator material contribute to 54.1% and 33.5% respectively in term of embodied energy requirement during manufacturing process. However, their CPV system is capable of producing much higher CO_2 savings in 20 years lifespan compared to a roof-top PV of 30-years lifespan, which could be between 0.1 and 2.7 t CO_2. Menoufi et al. [53] carried out an LCA of a BICPV installed in Spain. Their analysis indicated that if a PV system replaced their CPV system, it will increase the environmental impact by more than double, i.e., 2.35, suggesting that the CPV is more desirable for building integration. Meanwhile, Zawadzki et al. [54] indicated that their CPV system could have a lower embodied energy per square meter when compared with a conventional PV module, a reduction of 11.73%. Their system generate comparable electrical output throughout the system's life span when compared with a non-concentrating PV system.

Static LCPV systems are also showing promising results as they are being investigated for use as smart windows which transmits visible and infrared light to reduce artificial lighting costs whilst simultaneously harvesting ultraviolet light [55]. In Japan, applying static LCPV to vehicles is being studied as a potential solution to reduce energy consumption in the automotive industry [56].

4. Low Concentrating Photovoltaics: Technology Overview

As mentioned in Sections 1 and 3, CPV is usually categorised on the basis of concentration ratio; high, medium and low concentration [19]. Technologies presented in high and medium concentration ratios can generate greater output which relies greatly on solar tracking—with the additional cost of implementation. Static concentrators, which are commonly known as the LCPV, have superior properties of high acceptance angle, which can capture the sunlight at longer hours without the need of solar trackers, but are also able to concentrate diffuse and direct radiations making them more favorable for northern areas. However, the output of such concentrators is fairly low compared to high and medium concentrators. Additionally, this property also allow such systems to have a smoother response in cloudy conditions than the HCPV. However, the LCPV systems cannot use solar cells with higher efficiency and have to depend on silicon solar cells that are used in flat plate PV panels [20]. The development of the most promising static LCPV are reviewed to showcase their remarkable development, particularly over the last eight years and to make a case to their potential to help in achieving SDG 7 targets.

4.1. Compound Parabolic Concentrator

The concept behind a compound parabolic concentrator (CPC) is to concentrate the incoming rays on to the receiver (solar cell) through reflection or total internal reflection, where the latter is achieved by producing the concentrator from dielectric material [57,58]. Generally, as shown in Figure 3i, the CPC will be constructed through the intersection of two parabolas. The constructed CPC will have an entrance aperture (AB), the sides (i.e., parabolic segment) of the CPC where the reflection and TIR take place and the receiver or exit aperture where the solar cell will be placed. The half-acceptance angle (θ_a) of the CPC is the main parameter that eliminates the need for solar tracking. The half acceptance angle is the angle where 90% of the rays reaching the entrance of the concentrator exit the receiver (exit). In addition, the CPC is able to concentrate both the diffuse and direct radiations through wider acceptance angle [57,59]. On the other hand, as shown in Figure 3ii, various geometries of CPC's have been studied which consisted of 2-D and 3-D designs [60]. Although different geometries will achieve different acceptance angles, to get the maximum benefit from a designed CPC, a higher acceptance angle (or half acceptance angle) would be more desirable otherwise the context of static or stationary would not be attained.

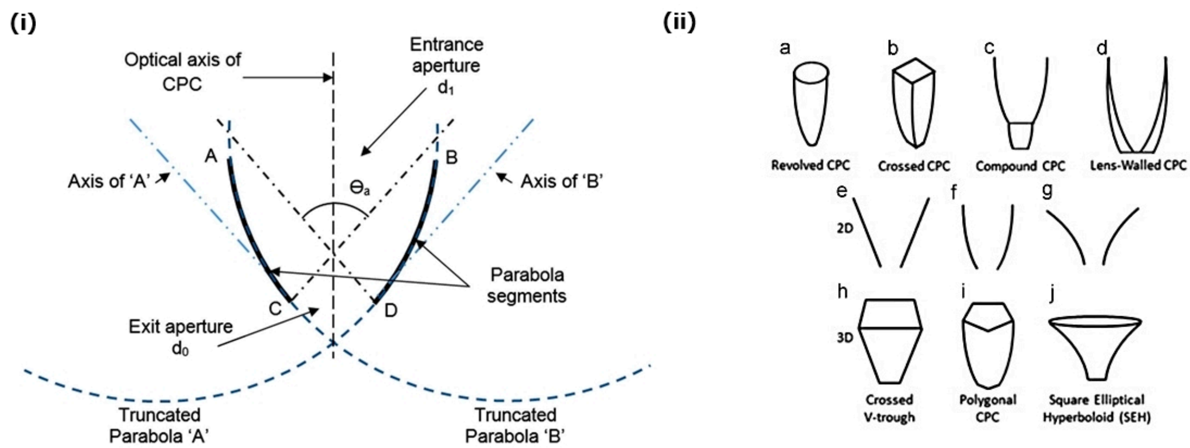


Figure 3. (**i**) A basic geometry of compound parabolic concentrator (CPC) [57], and (**ii**) Distinction of CPC: (a) Resolved (b) crossed (c) compound (d) Lens-walled (e) 2-D V-trough (f) 2-D (g) 2-D compound hyperbolic concentrator (h) 3-D Square V-trough (i) Polygonal (j) Square elliptical hyperbolic [60].

Abu-Bakar et al. [57], performed a study on a rotationally asymmetrical compound parabolic concentrator (RACPC), consisting of a plain entry and square receiver. The study showed similar dilemma in acceptance angle and optical efficiency.

Abu-Bakar et al. [57] argues that the refractive index is another factor that could alter the optical efficiency and the acceptance angle of a concentrator. This indicates that the material used for a concentrator could enhance its optical efficiency and acceptance angle. Although, such enhancement might be true for 3-D designs but for 2-D designs, increasing the refractive index does not have the similar effect on the optical efficiency as in 3-D designs. Su et al. [61] conducted a study on 4X lens-walled CPC which showed through simulation that the refractive index lowered the optical efficiency of the concentrator. The impact on optical efficiency was minor but the shape of the graph showed that the enhancement in optical efficiency was seen after the incident angles were greater than 14.5° (i.e., the nominal half acceptance angle for a mirror CPC).

Lens-Walled CPC can provide a better performance in terms of acceptance angle compared to a mirror CPC and thus have shown its ability to be used as a static concentrator in building integrated concentrated photovoltaic systems (BICPV). Su et al. [61] conducted an optical analysis through Radiance/Pmap on a 4X trough-type lens-walled CPC, which consisted of a lens attached to a mirror CPC as shown in Figure 4i. The study was performed to show the enhancement brought through the inclusion of a lens, which would not only provide a larger acceptance angle when compared to mirror CPC but is also lighter than a CPC that is constructed from a dielectric material. An additional study by Su et al. [62] was carried out to investigate the optical efficiency of a 2.5X lens-walled CPC, which should have higher optical efficiency than the 4X lens-walled CPC. Moreover, the study produced results related to annual solar energy collection for mirror, solid and lens-walled CPC. It claimed that the annual energy collection for the trough-type CPCs is dependent on the incident angles that changed from time to time. This change on angle from time to time affected the collection of direct and diffuse radiation which impacted the annual energy collection of the CPCs. Although the lens-walled CPC had a larger acceptance angle than both mirror and solid CPC due to the presence of multiple specular reflections, the optical efficiency of the lens-walled CPC was higher than the mirror and solid CPC. For such implications, a lens walled CPC with the air gap can be implemented instead as shown in Figure 4ii. An experimental study presented by Li et al. [63] showed that the air gap in lens-walled CPC reduced the optical losses and resulted in better efficiency than the original lens-walled CPC making the lens-walled with air gap CPC a better alternative for the original lens-walled CPC. Xuan et al. [64] studied about an asymmetric lens-walled CPC (ALCPC) with a geometrical concentration ratio of 2.4X. The ALCPC was tested using a solar simulator under standard test conditions (STC, 1000 W/m^2, 25 °C) and produced a short circuit current (I_{sc}) of 0.64 A and maximum power of (P_{max}) 273 mW compared to an I_{sc} of 0.64A and P_{max} of 163 mW for a bare cell. The achieved 1.74X geometrical concentration ratio is 72.5% of the 2.4X maximum theoretical value. Moreover, when comparing experimental results to ray tracing simulations generated by LightTools a maximum deviation of 19.9% was found, partially due to manufacturing errors, mismatch and series resistance losses. The proposed ALCPC design did however maintain a 90% optical efficiency at incident angles of 0° to 60° which shows good promise for potential use as a static concentrator for a building south wall integration.

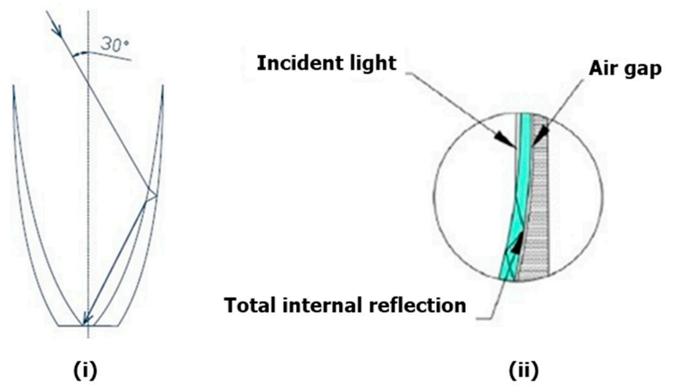


Figure 4. (**i**) Novel-lens walled CPC [62]. (**ii**) Lens-walled CPC with air gap [63].

Lu et al. [65] has designed an asymmetric compound parabolic concentrator with a geometric concentration ratio of 2.0 and experimentally characterized its properties. The system is designed with acceptance half angles of 0° and 55° making it suitable to operate year-round in European climate. The system was tested under solar intensities of 69 and 280 W/m^2 which resulted in power outputs that were 1.74 and 1.33 higher for concentrator system compared to a non-concentrating system. They then tested the integration of phase change material (PCM) system on the rear of the concentrator to control the heat elevation of the solar cells and improve the electrical efficiency. The PCM container was filled with RT27, which delayed the temperature rise and led to an improvement of 5% compared to a non-PCM concentrator when tested under solar radiation intensity of 180 W/m^2. The PCM addition was more effective at a higher illumination of 670 W/m^2 where it increased the electrical efficiency by 10%. This concept of heat management might prove to be an attractive alternative for building integrated solar system than photovoltaic thermal concentrator concepts such as that proposed by Meng et al. [66] due to relative ease of implementation. Nanofluids have been generating a lot of interest recently, as a potential coolant for concentrating systems and particularly photovoltaic/thermal hybrids. Sardarabadi et al. [67] investigated silica/water nanofluids and found that nanofluid suspension can significantly improve the performance of the energy and exergy of their photovoltaic/thermal system. However, they had some reservations regarding its economic feasibility. Yazdanifard et al. [68] has similarly found that increasing the concentration of nanofluids in laminar flow leads to improved energy and exergy. More significantly, they also found that using nanofluids in turbulent cooling to actually lead to reduced energy efficiency could indicate the unsuitability of nanofluids for use in turbulent cooling.

Usually, the 2-D CPC trough design is considered to be an ideal CPC concentrator although the 2-D designs exhibit low geometrical concentration ratio and collection of solar radiation. However, 3-D designs are able to have higher geometrical concentration ratios and can show the performance of an ideal concentrator. Sellami and Mallick [69] constructed a prototype of 3.6X 3-D cross compound parabolic concentrator (CCPC), which was initially designed through the intersection of 2-D CPC troughs. The designed CCPC had the same size of the entry aperture as the 2-D CPC, however, its geometrical concentration increased by the reduction in the solar cell area. Through optical analysis, the CCPC achieved similar optical efficiency as the 3-D CPC (having a circular entry and exit). By having a square shape at the exit and entry of the CCPC, the area for sunray collection was increased. Moreover, the 3-D CCPC was able to save around 47% solar cell material when compared to 2-D CPC. Efficiency losses can occur at the junction of the concentrator and the encapsulant which leads to a deteriorated power performance. An optical analysis performed by Baig et al. [70] showed that as the thickness of the encapsulant was increased from 0.1 mm to 3.0 mm, the optical efficiency of the concentrator was drastically reduced from 85.6% to 55.6%. Such losses through the encapsulant can be lowered by implementing a reflective film which would reflect the escaping rays on to the solar cell. Through this implementation, the drop in optical efficiency of a concentrator can be reduced, making it more efficient for BICPV.

CPC truncation is another area that is under research, although truncation will reduce the parameters such as the geometrical concentration of the concentrator which would affect the performance, the technique can be useful to provide low cooling loads in summer and low heating loads in winter. Sabry et al. [71] presented an analysis on low concentration facade integrated photovoltaic systems that generates electricity whilst simultaneously allowing transmission of solar radiation into the interior of the room. The study incorporated 9 segments (8 truncated and 1 un-truncated) of 3-D CPC, all made from a dielectric material (PMMA). Through truncation, the direct component of the radiation will be blocked while the diffuse component is allowed to pass through the dielectric CPC. The truncated CPCs showed lower geometric concentration as the area of the entrance aperture kept on decreasing while the receiver area was kept the same for all 9 segments. The maximum optical efficiency achieved for a complete CPC was about 96%, on the other hand, increasing the truncation percentage, leads to a drop in optical efficiency. That showed at the lower truncation percentages, more radiation is transmitted and not collected by the CPC. Moreover, studies [59,70,72] showed that for complete CPC, the optical efficiency at the positive angle is similar to the negative angle, however, the truncation showed deviation in the optical efficiency for positive and negative incident angles. The lower segments showed better performance on positive side rather than negative [71]. This implies that there were more reflections taking place in the positive angle and fewer reflections took place while more transmission was achieved from one side. Additionally, through simulation, an optimum truncation percentage was reached which was about 70%. The complete CPC showed higher electricity generation while a transmission radiation below 200 W/m^2. On the other hand, truncation lowered the electricity generation due to the fact lower reflections were taking place but the transmission radiation was much higher than the complete CPC. Such studies prove that truncation can be done in order to achieve the requirement of a building. Further analysis is required for truncation at different location which would provide the optimum truncation percentage for a particular building. Tian et al. [73] was similarly interested in the use of concentrators for building integration but rather than generating electrical energy through a solar cell they tested the feasibility of using an dielectric crossed compound parabolic concentrator (dCCPC) to reduce lighting and thermal loads in buildings. By using EnergyPlus building energy simulation software and Radiance/Days lighting analysis tool they investigated the performance of their dCCPC across 14 cities with latitudes ranging from 13° to 67°. The design was found to be particularly suitable for hot climate cities were energy savings can reach 13% due to reduce solar thermal load. However, the dCCPC was ill-suited for cities with prolonged winter such as Aberdeen where the annual energy consumption increased by 1–5% depending on location. They experimentally validated the accuracy of the transmitting simulation of their model by testing the dCCPC skylight panels in Hefei, China and found the deviation to be lower than 10% for virtually all the deviations.

Figure 5 and Table 2 summarise the CPC studies. Figure 5 shows that different dimensions, aspect ratios and different shape of entrance and exit aperture can alter the maximum optical efficiency (at an incidence angle of zero) and half acceptance angle.

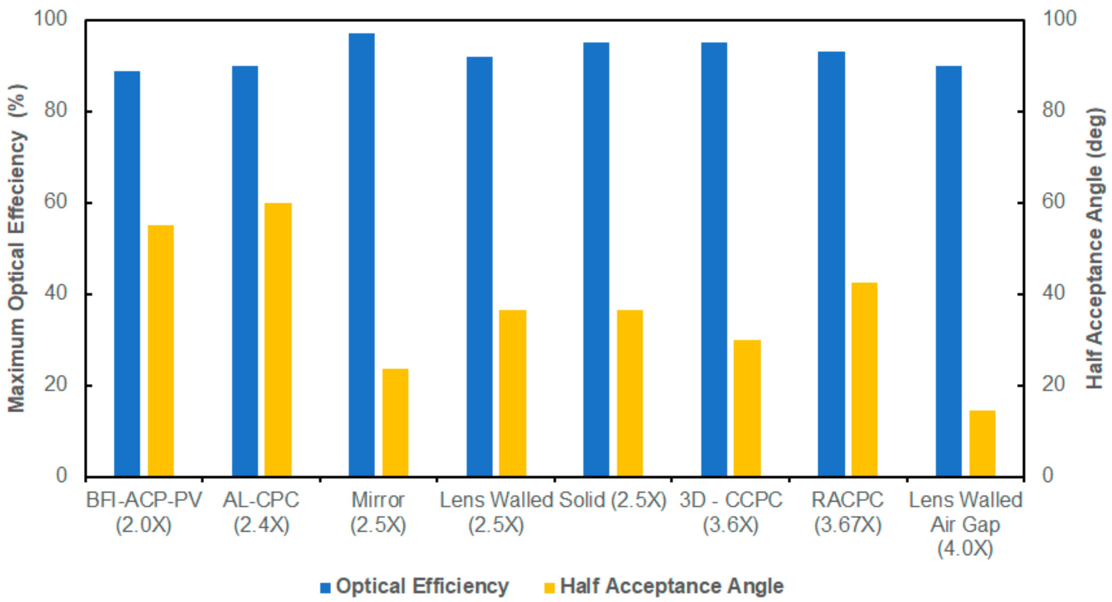


Figure 5. Various CPC designs are compared in terms of maximum optical efficiency and half acceptance angle.

Apart from acceptance angle and optical efficiency, irradiance distribution is another factor that needs to be taken into account when talking about the performance of CPC. Every single design of the concentrator will provide a pattern for the concentration distribution on the receiver (solar cell). Concentrators can also be compared on the basis of the amount of non-uniform irradiance distribution present on the receiver as well as performing indoor and outdoor experimental analysis to see the effects of hot spots on the performance of the solar cell which would impact the overall performance of the static system. Hotspots cannot be excluded completely from the static system mainly because of excluding the tracking system. However, different techniques can be placed to check the performance of the solar cell such as, air flow or mechanical system providing cold fluid to the receiver for removing the excess heat that would rather deteriorate the performance of the solar cell and the concentrating system.

Table 2. Summary related to various compound parabolic concentrator (CPC) designs.

Year	Author(s)	Type of CPC	Findings
2012	Su et al. [62]	2-D Lens walled CPC	Looking at the monthly accumulated solar energy collection, the lens-walled CPC was able to achieve 20 to 30% larger than mirror CPC.
2013	Sellami and Mallick [74]	3-D CCPC	The experimental results deviated from the simulation by 12%. During the experiment, the designed CCPC was able to concentrate the sunlight for 5 h with an optical efficiency of more than 80% providing an optical concentration of 2.88.
2014	Abu-Bakar et al. [57]	3-D RACPC	The optical concentration gain increases as the height of the concentrator was increased, however, it showed a negative effect on the acceptance angle. The predicted annual power output from the system was about 220 kWh per year showing that the system increased the electricity output by 3.25 times.
2014	Li et al. [63]	Lens walled with air Gap (2-D)	It was observed that the fill factor of the mirror CPC dropped more drastically than lens-walled CPC with air gap after the incident angles were greater than 14.5°. The flux distribution in both the lens-walled and lens-walled with air gap showed improvement.
2017	Xuan et al. [64]	ALCPC	An asymmetric lens-walled CPC with a geometrical concentration ratio of 2.4 was tested. Maximum power output and short circuit current were 1.74 and 1.67 times higher than a bare cell respectively.
2018	Lu et al. [65]	BFI-ACP-PV	A building façade integrated asymmetric parabolic photovoltaic concentrator with a geometric concentration ratio of 2.0 and wide acceptance half angles of 0° and 55°. Electrical conversion that is higher by 5% and 10% at solar irradiance of 280 W/m^2 and 670 W/m^2 respectively compared to a system without PCM (phase change material).
2019	Tian et al. [73]	dCCPC	A dielectric CCPC with an inner, outer half-acceptance angles and refractive index of 14.47°, 22.02° and 1.49 respectively was tested. Total energy savings in buildings reached up to 13%, 10% and 5% in hot, continental and cold climates respectively.

The impact of altering the height of the concentrator on the irradiance distribution was seen in the study presented by Abu-Bakar et al. [57] on a 3-D RACPC. Although, increasing the height increases the value of concentration distribution, the pattern of non-uniform irradiance was different than the above study. This could mainly be due to the shape of the concentrator that showed a similar irradiance shape on the four corners of the solar cell. However, changing the height affected the shape of the irradiance at the corners, increasing the height of the concentrator would enlarge the area, while a smaller concentrator would have a smaller area at the corners of the receiver. This would also indicate that smaller concentrator at the same incident angle would go through a few reflections while the taller concentrator would have more reflections on the same incident angle. The location of the hotspots will mainly be affected by the shape of the concentrator and in some cases due to the height. The height not only plays a part in the optical efficiency and acceptance angle, it also affects the irradiance distribution of a concentrator.

A further experimental study was conducted by Abu-Bakar et al. [75] on the performance related to RACPC due to the impact of the non-uniform irradiance distribution. On the part of the thermal analysis, the study concluded that the presence of non-uniform irradiance distribution and exposure to sun rays for a longer period of time would increase the temperature of the solar cell. By exposing the RACPC for 4.5 h, the temperature of the solar cell increased from the room temperature of 25 °C to 57 °C. This sharp increase in the cell temperature was seen for 2.75 h and then the temperature stabilised. The maximum power was reduced by 13.7%, a large fall was seen on the voltage side, from 0.51 V to 0.44 V and the fill factor was dropped from 80% to 77%. One of the causes for such would be the increase in the interatomic spacing which was a direct impact due to increase in the amplitude of the atomic vibrations (due to increase in temperature), which then decreased the potential of the electrons. This further justifies, that if compact concentrators (having larger acceptance angle) were used for 8 h, the impact of the rise in temperature would drastically reduce the system's efficiency. The only way is to implement a mechanical cooling system or introduce a hybrid/thermal system. Whereas, taller concentrators might not be needing such adjustments due to their lower acceptance angle. Non-uniform irradiance is also seen in 2-D designs of the CPC, which can impact the system performance. Hatwaambo et al. [76] presented a study related to the mitigation of these hotspots on a 2-D CPC. The study showed that, by implementing a reflector with rolling grooves which will be parallel to the plane of the receiver, can improve the scattering of the sun rays when they hit the sides of the concentrator. Through this scattering of rays can show a uniform distribution of irradiance and will eventually reduce the hotspot formation. It would be interesting to see if this idea is implemented on the 3-D design of CPC.

4.2. V-trough Solar Concentrator

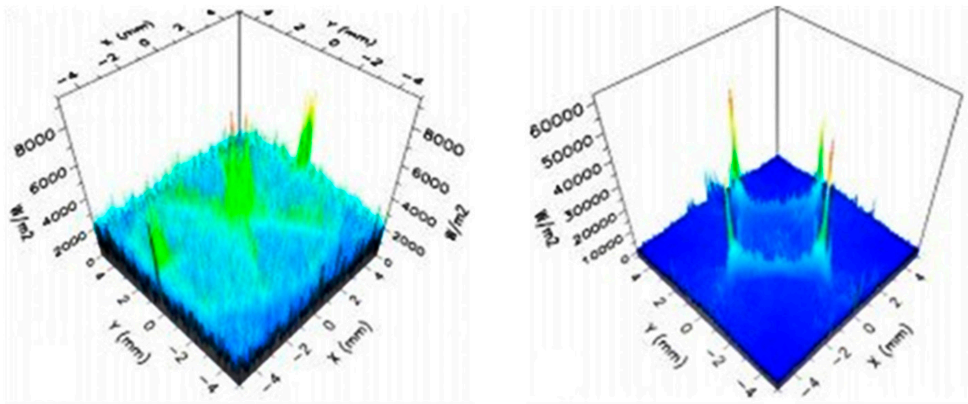
The concept of V-trough is similar to a compound parabolic concentrator. Through reflections, the 2-D V-trough is able to concentrate light onto the solar cell. Due to the geometry, the V-trough concentrator is not able to work for larger acceptance angle and therefore they can no longer be regarded as static concentrator unless tilt adjustments are made seasonally. Tang and Liu [77] showed that, with a geometric concentration of less than 2X, the V-trough will not require any tilt adjustments, however, a V-trough with a geometric concentration of more than two will be needing several tilt adjustments in order to generate maximum energy throughout the year.

The justification regarding the acceptance angle was given in a study conducted by Paul [78]. The study was conducted on two 2-D designs, CPC and V-trough, having the same dimensions and are prepared from a similar material. During the ray tracing analysis of 1000 rays being projected on the concentrator, it was seen that at incidence angle of 0°, for CPC, 52% of rays showed no reflection and 4% of rays showed 2 or more reflections, while for V-trough, 52% of rays showed no reflection while 0% showed 2 or more reflections. Once the incident angle was changed to 25°, for CPC, 28% of rays were not reflected and 0% of rays went through two or more reflections. On the other hand, for V-trough, the no reflection decreased to 10% while 40% of rays went through two or more reflections. This depicts that due to the presence of V-geometry, at larger incident angles, the reflection quantity was high compared to CPC. Therefore, this contributed to high reflection losses for V-trough, restricting it to be used for longer period of time. Although V-trough was not able to work for a larger acceptance angle, the irradiance distribution on the receiver was uniform compared to CPC. This determines that even though the V-trough concentrator was unable to be used for a larger period of time; it would, however, perform better than CPC due to exclusion of hotspots on the receiver.

Michael et al. [79] tested the performance of one-mirror and two mirror arrangements of V-trough concentrators and evaluated their performance throughout the year. The one-mirror arrangement which only uses one side of the typical V-shape had a fixed tilt of 13° chosen based on ray-tracing optimisation. The system which and uniform illumination for seven months but it had a relatively lower concentration ratio of 1.44X. Most of the solar gains compared to a non-concentrating system were obtained around 90–120 minutes around noon; making this set-up more suitable for applications where high energy demand is expected during noon such as air conditioning in hot climate countries. The two-mirror arrangement on the other hand which is a typical V-trough concentration had a higher concentration ratio of 1.91X lead to a higher overall power output but it only had uniform illumination during the month of June. This result would suggest that two-mirrored V-trough concentrators would see an increase power performance from seasonal tilt adjustment to provide a more consistent power performance. Alternatively, Michael et al. [79] observed that increasing the length of the reflector mirrors by 2.82 times the length of the PV module tends to also minimise the amount of non-uniform illumination on V-trough concentrators.

4.3. Elliptical Concentrators

Square elliptical concentrators are made up of an elliptical entry and a square exit aperture as shown in Figure 3ii(j). Sellami et al. [59] carried out a computational and experimental analysis on a 4X square elliptical hyperboloid (SEH) concentrator, consisting of an elliptical entry aperture and square exit. Performing optical analysis through a 3-D ray trace software, Opti-Works, a higher value of the acceptance angle is achieved using a compact (smaller) concentrator although, the optical efficiency was low which restricted the concentrator from generating higher power output. However, the compact nature would allow the concentrator to gather light rays for a longer period of time, whereas, a taller SEH, could generate a higher power output while working for shorter period of time. The choice of optimal SEH height should therefore be based on location and expected energy load profile of the building. Sellami et al. [59] also showed in their study that as the height of SEH increased, the irradiance distribution changed from uniform to non-uniform. Apart from that, a high value of concentration was seen for taller concentrators compared to compact ones. This would drastically impact the solar cell efficiency and the system performance. Compact SEH did not completely eliminate the non-uniform distribution of the irradiance, however, having a height ratio of one showed an acceptable uniform concentration distribution as shown in Figure 6. This implies that based on concentration distribution, an optimum height can be achieved.



(i) (ii)

Figure 6. Concentration distribution at the receiver for different height ratios (**i**) Height ratio of 1, and (**ii**) Height ratio of 3 [59].

Another study conducted by Saleh Ali et al. on a 3-D elliptical hyperboloid concentrator (EHC) [72] showed the same analysis regarding the height of the concentrator, and arrived at similar conclusions as Sellami et al. [59].

4.4. Luminescent Concentrating Systems

The concept behind luminescent solar concentrator (LSC) systems as shown in Figure 7, is to trap the incoming light in a dielectric matrix which will be either doped in, organic or inorganic dyes. These dye particles will absorb the part of the sunlight and emit isotopically and through total internal reflection, the rays will reach the solar cells [80,81]. The mechanism of TIR would occur only if the luminescence angle from the dye is greater than the critical angle [80].

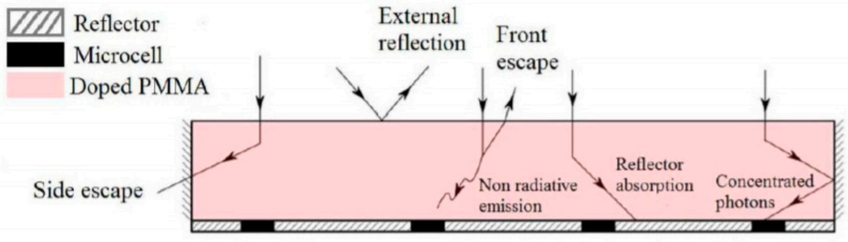


Figure 7. Principle for luminescent solar concentrator [81].

4.4.1. Luminescent Solar Concentrator

The concentration factor of a Luminescent solar concentrator can be increased by adding a photonic band stop (PBS). The PBS will stop the photons from escaping the doped matrix and reflect them back. This method seems to be more like the presence of a reflective film that was used in 3-D CCPC to stop the light escaping the concentrator. Here, the LSC does not opt for optical elements for generating power through solar cells and its performance can be based on the dyes and doped matrix.

Joudrier et al. [81] performed a study on a rectangular LSC with and without a PBS. The solar cells in this configuration were placed at the bottom of the LSC and the PBS was placed at the top of the concentrator. During the study, a polymer layer of PMMA was used. The dye quantum yield was kept as 100% and the back reflector was assumed having perfect reflection indicating some of the ideal parameters for LSC. The PBS will transmit and reflect the photons based on the bandgap and reflection spectrum. During the analysis, LSC with PBS was able to concentrate 40.1% of the light onto the solar cell, whereas LSC without PBS was able to only concentrate 16.1% onto the solar cell. This implies that the losses without PBS were significant as the photons were able to escape. Although the PBS increased the amount of light reaching the solar cell, it ended up increasing the external losses, which represent that PBS did not capture 55.4% of the photons. Wu et al. [82] proposed a 5X smart concentrating system that would be placed on the building facade and windows. The concentrator uses a hydroxypropyl cellulose (HPC) hydrogel polymer, which has a threshold switching temperature. This allows the concentrator to act according to the variation of the climate; to allow scattered rays into the interior of a room during summer to reduce heat gain and to allow high transmission of solar rays during winter to reduce the cooling load. The solar cells in this study were placed onto the ends of the concentrator. The advantage of such alignment can be seen as the optical efficiency tends to increase when the incident angle increases. Such case was not seen in CPC as discussed in Section 4.1. Reflectivity plays an important role in LSC. A higher reflectivity of the thermodynamic layer would constitute to a higher optical efficiency. Moreover, the optical efficiency decreases as the geometric concentration was increased, this was mainly due to the light escaping the top of the concentrator. PBS could have been applied for this concentrator to allow it to work more efficiently.

LSCs are able to generate electricity at the higher incidence angle, which means they can operate at an acceptance angle of 120°, although they have shown an inversely proportional relationship between power density and optical efficiency. The characteristics of the dyes and their concentration also impact the performance of the LSC. Kerrouche et al. [80] conducted an experimental and optical simulation on different dye colours and concentration. In this study, five fluorescent organic dyes were used along with different concentration values. Firstly, as the concentration of the dye increases so does the absorbance. This absorption, therefore, increases the power density of the LSC. This trend was similar for all the dyes that were used. Secondly, edge emission increased with dye concentration, however, at the highest value of the concentration, there was an increase in the presence of reabsorption losses which would tend to decrease the edge emission. Finally, the circular LSC showed greater power density than the square LSC which was mainly due to the shortest path length for the photons to reach the solar cells that were placed on the edges of the concentrator.

The key advantage of a static concentrator is to gather sun rays during the whole day without implementing solar tracking. This can only be achieved if the concentrator has a wider acceptance angle. In the study presented by Kerrouche et al. [80], while tilting the LSC, there was a reduction in the power density mainly because less light being incident on the front surface of the reflector and increase of reflectance losses. However, the optical efficiency of the concentrator increased due to an increase in absorption and decrease in reabsorption. The setup could have been changed by imposing PBS on the top of the surface of the LSC to reduce the frontal reflective losses as shown by Joudrier et al. [81]. Due to low optical efficiency, the LSC have not yet reached their maximum potential. According to Kerrouche et al. [80], ray tracing simulations do not take into account of the losses that occur in reality such as, the presence of imperfection on the top and bottom surface of LSC, imperfection related to edge polishing and presence of spectral differences of the solar simulator. Apart from that, the presence of the loss channels also contributes to the drop in the efficiency of LSC. Tummeltshammer et al. [83] concluded that non-unity quantum yield (related to the dyed property) and escape cone losses can further reduce the optical efficiency of the concentrator.

4.4.2. Quantum Dot Solar Concentrator

The concept related to this technology is similar to that of LSC. However, the research related to this area is new and has just shown its potential recent years. As discussed in Section 4.4.1, the properties of organic dyes place a halt on the efficiency of the LSC. Here, the quantum dot concentrator (QDC) implies using quantum dots (QDs) in place of organic dyes. These dots are less biodegradable and more stable than organic dyes, which increase their popularity to be used in LSC. In this case, the concentration related to QDs will be the parameter to determine the efficiency of the system, however, other losses as described in LSC system will take place as shown in Figure 8.

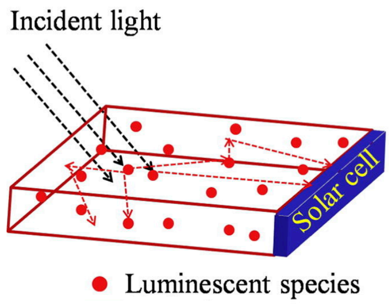


Figure 8. Mechanism of quantum dot solar concentrator [84].

In the study presented by Chandra et al. [84] related to a rectangular concentrator, it showed that the intensity of the absorption increases as the concentration of the QD is increased and the power output of the concentrator increases as the concentration is increased. However, Chandra et al. [84] claimed that the losses considered in the ray trace program were related to low fluorescence quantum yield, reflection losses on the front and back of the concentrator and the escape cone losses which were identified in the study related to LSC. Additionally, there were high scattering losses induced in a high concentration of QDs. Longer optical path length was seen during the study which implies the presence of reabsorption and scattering. Through this study, it is realised that optimum QD concentration is needed for the concentrator to work efficiently. This optimum value will also depend on the size of the concentrator as specified in Section 4.4. In addition, Gallagher et al. [85] specified that high quantum efficiency is observed in quantum dots at room temperature and due to the freedom of altering the dot diameter, the absorption threshold can be tuned.

Gallagher et al. [85] conducted a study on the performance of the concentrator related to the quantum yield and volume fraction. The study determined that the low performance of QDC is mainly related to the low value of the quantum yield for the quantum dots used. Moreover, in relation to quantum yield and concentration, samples that used low quantum yield and high concentration of QD showed a dramatic increase in the reabsorption losses, which directly impacted the power output of the system. In relation to the above study by Chandra et al. [84], it can be observed that the optimum concentration will be required for the concentrator to work efficiently.

5. Discussions

The primary driver for the solar revolution is dramatic cost reduction [11]. Solar PV renders around 2.1% of the world's electricity today [12] and this will grow to as much as 13% by 2030. Despite that, solar PV is still considered as expensive in many parts of the world. Although the production cost of photovoltaic solar cells have come a long way from $200/W in 1954 to as low as $0.71/W in 2017's China, this is not the case with all developing countries, where PV energy is sometimes still prohibitively expensive. This introduces the need for concentrators which aim to reduce the total cost of solar energy devices by replacing expensive solar cell material with reflective or refractive components. Static concentrators in particular show great promise due to their high acceptance angle which allows them to generate sufficient power without the need for a tracking system, thus reducing cost and maintenance requirements. The review covered different aspects of the various technologies included under the LCPV umbrella.

Looking back at the reflective systems, their integration is usually on the building facades, rooftops and windows. These systems are required to have high acceptance angle; however, this parameter is inversely proportional to the optical efficiency. The height factor in reflective systems, governs the optical efficiency, the geometric concentration and the irradiance distribution. Apart from that, irradiance distribution is the key issue related to the compound parabolic concentrator. Different techniques such as mechanical air flow or cold fluid flow can be applied to a 3-D CPC in order to reduce the rise in temperature of the solar cell which impacts the voltage and power output of the system. To reduce hotspot formation in a 2-D CPC, the implementation of rolling groves has to be applied to allow scattering of rays to take place. On the other hand, V-trough is not able to gather sun rays for a longer period of time, however, they do not show the presence of hotspots on the receiver. CPC truncation can provide an alternative for the reduction of cooling and heating loads in the building without implementing a photovoltaic thermal system which could be costly in BICPV. Generally, an optimum design will be required for reflective concentrators, which would not only depend on the location, but on specific requirements of the building users and the climate of that location.

Moving on to the luminescent systems, they can only be integrated on building facades or windows. In addition, due to high losses present because of the larger size of the concentrator, smaller geometries have to be applied. Most of their performance is governed by the placement of the solar cells either bottom mounted or side mounted, the concentration of doping, the properties of the organic and inorganic dyes and the value of quantum yield. These concentrators are more aesthetically pleasing than the reflective systems, which would make them more favorable to be implemented on tall building structures. In contrast to reflective systems, whose optical efficiency decreases as acceptance angle increases, here these concentrators work in an opposite way, the efficiency is the lowest when the sun rays are perpendicular to the surface and increases for larger incident angles. However, due to the presence of high amounts of losses through the escape cone, reflection on the surface, larger optical path, scattering, and reabsorption; the efficiency of luminescent concentrators is very low compared to the reflective concentrator. On the merit side, the luminescent concentrators show no signs of hot spots, whereas, in reflective systems, hotspots present a serious issue for the concentrator. Just like truncation allows CPC to act as a photovoltaic–thermal system, the use of the thermal polymer in luminescent systems can reduce heating load and cooling load in the interior of the building. It should be noted that static concentrators not only generate electricity but also provide some amount of transmission of radiation to heat the inner areas of the room. This makes them more favorable for the northern areas.

6. Conclusions

- Despite the SDG 7 goal to provide access to affordable energy for all by 2030, the IEA predicts that 700 million people will still lack access to electricity by 2030, significantly compromising their quality of life.
- Global initiatives such as the African Renewable Energy initiative (AREI) and the UN's Sustainable Energy for All initiative will play a great part in accelerating the adoption of solar energy, which is predicted to generate 13% of the world's electricity by 2030.
- Although the cost of solar panels reaching a low of $0.71/W in China, the technology is still considered prohibitively expensive in developing countries that lack the economies of scale.
- Solar concentrators can potentially reduce the cost of solar installations by 36.5% by replacing expensive PV material with cheaper reflective or refractive material. Static concentrators are particularly promising as they can operate without tracking thus reducing maintenance and cost demands.
- Compound parabolic concentrators offer high acceptance angle but suffer from irradiance distribution and increases in temperature. Nanofluids are gauging increasing interest as solution to reduce the gain within solar concentrators, but they are still not economically feasible and are not suitable for turbulent cooling.
- V-trough concentrators can operate without tilt adjustment given a concentration ratio below 2X but they suffer from non-uniform illumination most of the year
- Luminescent concentrators do not suffer from hot spots like CPC but they have significantly lower efficiency than the other reviewed concentrators because of the presence of losses due to escape cone, reflection on the surface, larger optical path, scattering, and reabsorption.
- This paper argues that static solar concentrators can help achieve the SDG 7 goal by 2030 by reducing the cost of solar, which make it economically and financially sustainable. The LCA studies also indicated that the CPV has much lower embodied energy requirement during manufacturing process and produces much lower CO2 emission throughout their life time when compared with the traditional PV system, making the system more desirable.
- However, many challenges such as the irradiance distribution in CPC, the non-uniform illumination in V-trough and low efficiencies of luminescent concentrators need to be overcome if concentrators are to truly offer a more cost-effective solution than standard PV panels. A comprehensive economic, social and technical overview of static solar concentrator and their potential to help achieved SDG 7 goals is provided here to support this viewpoint.

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