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Enhancing the efficiency of luminescent solar concentrators (LSCs)

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Abstract Recent developments in the endeavor to enhance the efficiency of luminescent solar concentrators (LSCs) are presented in this paper along with an analysis of LSC devices. In recent years, several experimental and numerical research works have been carried out to improve the performance of LSCs in different ways. LSCs date back to the 1970s and comprise an extremely interesting notion of solar cells for various reasons. First, LSCs are cost-competitive and function in diffuse light, and as such, it is not necessary to use expensive solar tracking devices. Second, luminescence facilitates the cells to gather only cold light, which results in higher PV efficiency. LSCs generally consist of transparent polymer sheets doped with luminescent species. The luminescent species absorb incident sunlight and emit it with high quantum efficiency, such that the emitted light is trapped in the sheet and travels to the edges where the solar cells can collect it.

1 Introduction

The objectives of enhancing renewable energy and reducing energy utilization and contamination are strongly based on solar technology, which is one of the most attractive means employed to develop conversion efficiency at lower cost [1, 2]. Achieving higher efficiency at lower cost is the key driver in innovative photovoltaic (PV) works and has been so for a long time. On the other hand, the efficiency of solar cells to date is not sufficiently proficient nor cost-competitive. Solar power is still five to ten times more expensive than power generated from fossil fuels [3, 4]. Different approaches are being pursued to reach lower PV costs. It is reported that the most effective way of using solar cells more efficiently is to use concentrators. Building solar cells with large surface areas capable of capturing abundant sunlight is not cost-competitive because lots of materials are used. Instead, it is more cost effective to collect and concentrate sunlight from a wide area to small and highly efficient cells [5–7]. Many of the highly efficient solar cells work even better under intense sunlight conditions than in non-concentrated sunlight. Luminescent solar concentrators (LSCs) offer an attractive approach of concentrating sunlight economically and without tracking and have been proposed as an alternative device for generating electricity from sunlight that may be well suited for use in urban settings [8, 9]. We will illustrate how this is achievable with the use of LSCs. LSCs generally consist of transparent polymer sheets covered with luminescent species. These luminescent species absorb incident sunlight and emit it with high quantum efficiency. The emitted light is thus trapped in the sheet and travels to the edges where it can be collected by the solar cells [10]. One of the greatest features of LSCs is their ability to be combined with components such as windows, doors, or facades to create

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more appealing structures [11–13]. Figure 1 shows four luminescent solar concentrators illuminated by ultraviolet light. The main purpose of LSCs is to cut down the usage of expensive solar cells in order to reduce the cost of PV electricity generation. Compared with traditional geometrical concentrators that commonly use tracking and cooling systems, LSCs can accept both direct and diffuse light without the expensive tracking system, while cooling systems are not required due to the long-wave, radiation can transmit the device [4, 5]. The first part of this paper provides a definition of luminescent materials, followed by a history of LSCs. In the next part, the working principles of LSCs are evaluated. Then, a characterization of the components in different configurations is discussed (LSC materials and shapes). In this research, the current efficiency and achievements of LSCs developed recently (2012–2016) are introduced.

2 Luminescence

Luminescence is the emission of light by a material, which is not caused by its temperature. There are many types of luminescence, e.g., chemiluminescence, electroluminescence, and photoluminescence. In these three types, luminescence is caused by energy freed by a chemical reaction, an electric potential and absorbed photons, respectively. Photoluminescence is luminescence with which a luminescent solar concentrator works, and it can be divided into two sub categories, i.e., fluorescence and phosphorescence. The difference between these two is mainly the decay time. Fluorescent light is emitted almost instantly after absorption, whereas phosphorescent light is radiated significantly longer after illumination. The reason is that phosphorescence is caused by spin-forbidden transitions, and fluorescence is caused by spin-allowed transitions [11–13].

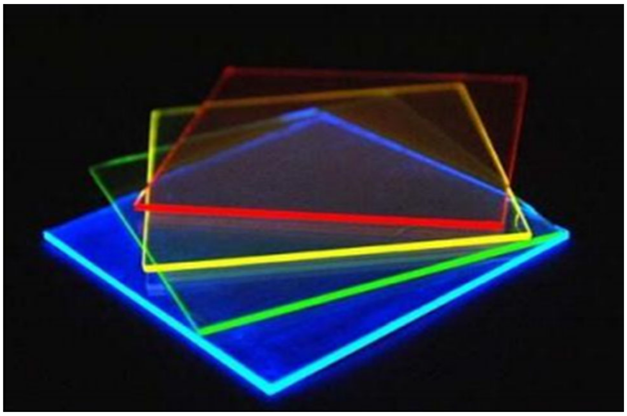

Fig. 1 Snapshot of four luminescent solar concentrators illuminated by ultraviolet light

3 Luminescent solar concentrators (LSCs): past, present, and future

Although the idea and invention of trapping fluorescence inside a transparent body by total internal reflection (TIR) have stemmed as early as 1949, the beginning of experimentation on LSCs dates back to the late 1970s [14]. At that time, the TIR effect of specific dyes was discussed in terms of implementing solar components with reduced PV surfaces in order to minimize technological costs [15–17]. Table 1 presents the history of LSCs since their discovery.

Lerner first had the idea of a device for collecting solar energy using a solution of laser dye between two glass sheets. He also published the first paper on LSCs in 1973 [28, 29]. LSC development was initially limited by the performance of the luminescent dyes available some decades ago. Nevertheless, efficiency of up to 4 % has been reported for a stack of two plates, one being coupled to a GaAs solar cell and the other to a Si solar cell [28–30]. The non-uniform light decreases the greatest current capable of streaming, lessening the proficiency by around 20 % [31]. The increasing realization of the lack of fossil-fuel availability is one of the main causes for the meaningful enhancements in LSCs within the last 10 years. Another reason is the various designs suggested by different architectural and building sectors for more freedom in their design choices [28, 29]. Nowadays, the needs of the architect can be fulfilled more flexibly with their ideas, such as different colors, shapes, transparencies, and weights [23, 32]. Rapp and Boling were the first to report on a luminescent collector consisting of a thin luminescent film deposited on an undoped substrate. They appear to have coined the phrase LSC, which will be used generically henceforth in this report of a broad range of luminescent collectors [13]. In 2004, Earp et al. reported of an LSC with a light transport half length of 1.2 m. Kennedy et al. presented an LSC based on quantum dots, overcoming the problem of photo-stability at the cost of lower luminescent quantum yield [13, 32]. Recently, LSCs have attracted much interest as an optical precursor device for PV cells [33–35]. Two different types of LSCs can be identified. The first is the single-plate concentrator, in which the luminescence centers are homogeneously spread throughout the plate. The second type is the thin-film LSC, which consists of an optically passive glass- or polymer-based substrate coated with one or more luminescent layers [36]. Today, LSCs represent a very promising solar technology, especially semitransparent LSCs that are suitable for building integration. These components can likely offer an effective way of producing renewable energy while preserving the transparency of the building envelope by using wide surfaces that are at the moment neglected, such as windows, skylights, shading devices, etc. [7, 37, 38].

Table 1 History of LSCs

Year		Cell type	References
1949–1970	Invention		[13, 15, 16]
1970–1980	First experiments and publication		[17–19]
1980–1990	Limitations of fluorescent organic dyes hindered further development	GaAs/ silicon	[13, 20, 21]
1990–2000	Application of new luminescent materials semiconductor quantum dots (QDs)	Silicon	[22, 23]
2000–2010	Discovering materials such as photonic layers, liquid crystals have also been utilized to reduce losses within the devices	Silicon	[15, 16, 24]
2010–2015	New material and developments in ray-trace, thermodynamic modeling software		[25–27]

4 Working principles of LSCs

The luminescent molecules can be organic fluorescent dyes, or inorganic phosphors or quantum dots. The absorbed light is re-emitted at longer wavelengths, and a fraction of the re-emitted light is trapped in the waveguide by total internal reflection and becomes concentrated along the plate edges. Small PV cells attached to the waveguide edges collect the emitted light and convert it to electricity [1, 28]. Figure 2 illustrates the incident sunlight on the front surface of the sheet being absorbed by a fluorophore molecule and fluorescence then being emitted by the fluorophore and transported to the edge via total internal reflection. The solar cells collect the fluorescence. Several loss mechanisms are present that reduce the amount of fluorescence reaching the solar cells [9, 21, 28].

One of the biggest challenges in LSC enhancement involves diminishing LSC losses. The loss mechanism is presented in Fig. 3 in detail. The overall optical efficiency of an LSC, η_{opt}, which is defined as the fraction of incident solar power that reaches the edges, can be expressed as the product of the efficiencies of the different processes within the LSC. The first loss is sunlight that is not absorbed by the dye molecules: This light is lost through the bottom surface. The second loss is light emitted by dye molecules at an angle that is refracted out of the waveguide instead of being reflected internally. The third loss entails absorbed photons that are not re-emitted by the dye molecules but are lost instead as heat and vibrations. The re-absorption of photons emitted by subsequent dye molecules via overlapping emission and absorption bands is the fourth loss. Waveguides can exhibit parasitic absorption, especially in the near-infrared spectrum, which is the fifth loss cited. Sixth, waveguide surface imperfections may cause photons in waveguide mode to leave the surface. Seventh, at the waveguide edge, the PV cell has a non-uniform spectral response, with a fraction of incident photons being lost due to the finite conversion efficiency. Waveguide bulk imperfections are responsible for the eighth loss—scattered wave-guided photons. In addition, a small part of the input light is reflected from the waveguide surface, entailing the ninth loss. Finally, loss is caused by dye molecule degradation, primarily due to UV absorption [39].

5 LSC sheets

Numerous materials and designs have been utilized in the development and improvement of LSC devices, for instance, a variety of host material sizes, thicknesses, and shapes. This paper presents a review of these properties.

5.1 Material

The primary difficulties challenging luminescent materials include: first, less absorption in cases of lower amounts of the utilized spectrum. Another problem that was discussed in the previous section is re-absorption. Emitted light re-

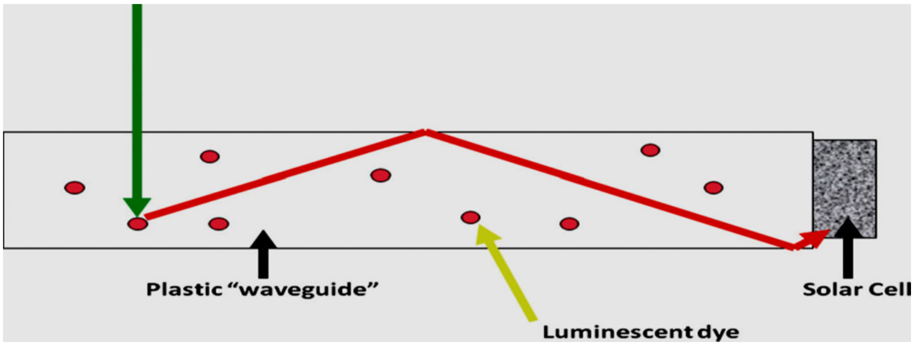

Fig. 2 Incoming sunlight is absorbed by a luminophore. The light is re-emitted at a longer wavelength, and a fraction becomes trapped by total internal reflection. A photovoltaic cells is attached to the edge [32]

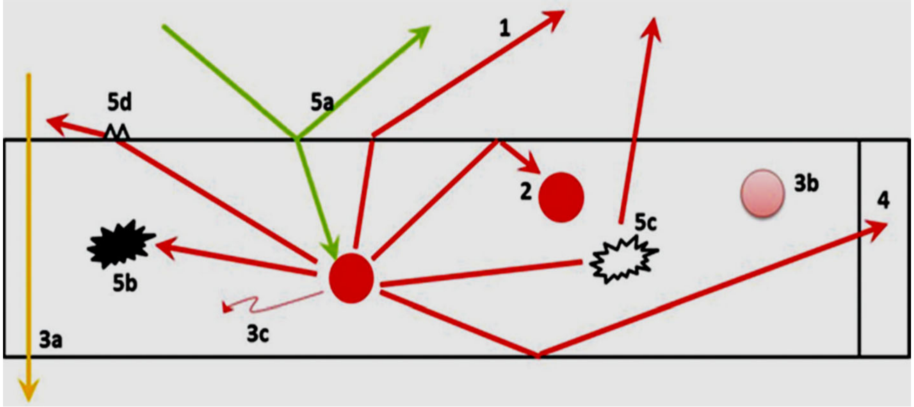

Fig. 3 Loss mechanisms in LSCs: input light not absorbed by the dye molecules, light emitted outside capture cone, quantum efficiency of the dye molecules <1, re-absorption of emitted light by another dye molecule, absorption of emitted light by the waveguide, surface scattering, solar cell losses, internal waveguide scattering, reflection from the e surface, limited dye stability [32]

absorption is followed by increasing escape-cone losses and reduced FQY. Stability is another important factor, which, for LSC plates, should take more than 10 years to make more cost-competitive than existing PV systems. The optical properties of fluorophores and their absorption depend on the material used. Polymer poly(methyl methacrylate) "PMMA" is the most well-known host material. The main advantages of PMMA are its low cost, high optical transparency, and the fact that it can be dissolved in the monomer prior to polymerization. It has great photostability with lifetime of up to 17 years [40]. Some researchers reported epoxy resins instead of PMMA, which display about 30 % lower absorption in the visible region than PMMA. This is an advantage for fluorophores due to their sensitivity to temperature. Epoxy resins have lower photostability compared to PMMA but unlike PMMA, they have stability at room temperature. Another element that can be used as a host material is glass owing to its inorganic material and high transparency at NIR wavelengths (>700 nm) unlike organic polymer, and in contrast to polymer glass, glass is not subject to photodegradation. However, glass has certain drawbacks such as in the process of preparation. Glass should be prepared from a melt at high temperatures (usually >600 °C), and consequently, the choice of fluorophores is restricted to rare-earth ions and other inorganic compounds that can resist the required temperatures. The two basic types of luminescent materials are organic and inorganic. The major inorganic luminescent materials are quantum dots (QDs) and rare-earth (RE)-based luminescent materials. Each type has certain benefits and drawbacks, making neither the ideal LSC candidate [41].

5.2 Shape

Considering the influence of shape on the uniformity of edge illumination, one of the most common choices of shape for LSC sheets is square due to the simplicity of manufacturing and covering. However, a square sheet produces a non-uniform intensity distribution along the sheet edge (and hence, along the solar cell). The power is 20–30 % greater at the center of the edge compared with the ends. The non-uniform radiance decreases the maximum current and is followed by about 20 % decrease in device performance. Shapes such as right-angle triangles with a reactor on the hypotenuse reportedly result in improved uniformity, while the best shape is a circular sheet [42–44]. In another research, it was indicated that the best shape is hexagonal, as it leads to using straight solar cells with good illumination uniformity. Despite the fact that the hexagonal shape is ideal for a generation module, research has been centered on square and rectangular modules because they are easier to build physically. Sheet thickness is commonly in the range of 0.2–0.5 cm, based on the fact that sheet material (glass, PMMA) is readily accessible in such thickness and can be shaped easily. A sheet with minimal thickness has no quality to support it over the width of the LSC. On the other hand, a thicker sheet will expand the weight and embodied energy of the LSC module. A thicker sheet can also yield higher proficiency, as the desired fluorophore concentration can be diminished, followed by reduced re-absorption losses. Nevertheless, thickness must be adjusted against the embodied energy expanded and material cost [25]. A novel configuration with the PV cells on the front face allows the cells to obtain both direct solar irradiation and wave-guided photons emitted from a dye embedded in an acrylic sheet, which is optically coupled to the PV cells. Many investigations have been done on waveguide thickness, window edge treatment, cell width, and cell placement [45]. The effect of different LSC designs on the photovoltaic performance of waveguide devices has also been analyzed. An enhancement factor of up to 5.7 in the maximum output power of FDSCs was realized through omnidirectional absorption enhancement over a large area [46–48].

6 LSC current efficiency achievements

6.1 Experimental work

According to reports in tropical countries such as Malaysia, photovoltaic systems are introduced as the most attractive renewable energy sources because of how they consistently obtain enormous measures of solar irradiation. However, Malaysia is surrounded by South China Sea and the Malacca Straits. The vapor from the ocean water with occasional winds is the reason for abundant mist passing over the country, henceforth creating the variety in direct and diffuse sunlight throughout the day. The effect of concentrators and reflectors for bifacial solar cells under the various direct and diffuse sunlight has not been studied thoroughly [14, 27]. As such, a couple of concentrators and reflectors have been arranged, constructed, and set up under particularly planed bifacial solar cells. The setup of each concentrator and reflector is according to the accompanying diffusing particles sprinkled over the plane mirror under the solar panel [4]. Some experimental works on static concentrator and reflector structures have been recognized in perspective of the pilot results. An assessment demonstrated the cost-competitive suitability of the proposed solar cells [49]. It was shown that dye concentration and LSC film thickness have a major effect on the optical response of LSC devices. The efficiency is found to decrease with increasing geometric gain, although saturation is observed for high geometric gains, suggesting that LSC devices perform best with very large LSC areas. The surface roughness of the back reflector appears to have a key role in improving LSC film efficiency because it induces reduced specular reflectivity and increased isotropic light scattering [50, 51]. Recently, a new thin film of dye-doped parylene was synthesized by a deposition method consisting of coarse vacuum co-sublimation of parylene C dimer and perylenediimide dye Lumogens F Red305 (LR). Another synthesis method was introduced by depositing LR-containing parylene film on glass and polymer waveguides [52–54]. Fluorescent polymeric coatings as thin-film LSCs have emerged as a fascinating application in the field of solar energy. Polymer-based thin-film LSCs depend on poly methyl methacrylate (PMMA) as the host matrix material. It has been reported that a load of 30 % w/w of ceria nanoparticles offers a realistic compromise in terms of UV protection and absorption in the visible range. The coated PMMA sheet demonstrated enhanced protection against UV degradation compared to bare substrate, although the adherence should be further improved for optimum performance [1, 38]. The reported efficiencies of luminescent solar concentrator devices are shown in Table 2. The addition of an offset Yell083-doped pattern to a Red305-patterned waveguide increased the total efficiency from 10.4 to 13.9 % [9]. It has been shown that LSCs coupled to silicon solar cells could achieve a combined theoretical efficiency limit of 26.8 % [55]. A new mechanism to conventional theory was proposed to illustrate the large enhancement in fluorescence efficiency [56]. The plasmonic thin-film luminescent solar concentrator (PTLSC) was proposed as a potential application of PMMA nanocomposite films doped with mixed coumarin dye stuffs and noble metal nanoparticles in solar energy conversion [31]. The two dyes used have been well studied for solar concentrator applications, and both demonstrate desirable stability, quantum yield, and complementary absorption spectra. The concentration-dependent Förster-type energy transfer in an LSC material containing two high quantum yield laser dyes in a PMMA matrix has been shown [57, 58]. However, the optical constants and photoluminescence spectra of fluorescent nanohybrid films showed an enhancement of the photon trapping efficiency and matrix stability with increased concentration of SiO_2 nanoparticles [59]. However, there are some limitations when using PMMA-based LSCs because they still suffer from degradation due to the limited photostability of the polymer. Researchers have reported a new cross-linked fluoropolymer-based system. It was shown that efficiency values comparable to those obtained with optimized PMMA-based thin-film LSC devices can be reached with the new cross-linked fluoropolymer-based LSC system. They also demonstrated that cross-linked fluorinated polymers represent a class of promising host matrix materials for achieving environmentally stable LSC devices [2, 60]. It was concluded that polysulfone is a good candidate for obtaining guest/host composites [61, 62].

Another problem with LSCs is their lifetimes, but it was found that in the long-term, the light exposure regime of some additives may lead to improvements in LSC device lifetime [65]. A study showed that the photodegradation mechanism of perylene-based thin-film organic LSCs facilitates the development of efficient stabilization strategies to lengthen organic LSC lifetime [66]. Highly efficient luminescent materials based on the europium complex Eu(tta)3(phen) (tta = 2-thenoyltrifluoracetonato, Phen = 1,10-phenantroline) incorporated into different polymer matrices (polyvinyl butyral, polysulfone and polyurethane) have been prepared. As a result of this interaction, the efficiency of the doped films enhanced dramatically (photoluminescence quantum yields in the range of 58–86 %) compared with the precursor complex. The luminescent Eu(tta)3(phen) complex hybrid polymer materials developed in the study could be applied

Table 2 Recent efficiencies of LSCs devices

Year	Luminophore	Cell type	η (%)	References
2013	Red305/Yell083	Dye	13.9	[9]
2014	Red 305/DCM	GaAs	–	[57]
2014	CdSe/CdS	Silicon	35	[63]
2015	Red 305/Yellow 083	Silicon	24.2	[8]
2015	Red 305	Silicon	26.8	[55]
2015	Red 305	Silicon	11	[50]
2015	Red 305, Yellow 170, Yellow 083, Orange 240 and Violet 570	Silicon	–	[64]

successfully in optical devices as polymer light-emitting diodes or active polymer optical fiber applications [67]. A series of luminescent materials were prepared by embedding the ternary europium complex Eu(tta)3(phen)(tta = 2-thenoyltrifluoroacetonato, phen = 1,10-phenanotroline) into different polymer matrices (polystyrene, poly(vinyl difluoride), poly(acrylonitryle), and poly(methyl methacrylate)) in order to investigate the effect of the polymer on the luminescent properties of the hybrid materials. The results may support the conclusion that while some polymers can interact with the complex, act as antennae, and transfer energy to the central Eu(III) ion, others may quench the luminescence of the complex [68]. The performance of LSC-PV elements with narrow PV cell strips that can be integrated in an outdoor lighting pole was evaluated. Silicon PV cells were attached to the back of both flat and cylindrically bent PMMA light guide sheets containing the dye Lumogen Red 305, and mirrors were attached to the non-covered light guide edges. Due to the reduced sensitivity to the angular dependence of incoming irradiance, it was expected that these bent LSC-PV elements would perform well on both sunny and cloudy days [7, 9, 69]. A new LSC phosphor, i.e., nanocrystalline $Cd_{1-x}Cu_xSe$, was introduced, which outperforms all other leading nanocrystals (NCs) by a significant margin in both small- and large-scale LSCs under full-spectrum conditions [70]. CdSe/CdS core/shell quantum dots (QDs) were optimized for LSC applications [71–73]. It was found that CdSe/CdS-seeded nanorods as tunable luminophores are suitable for luminescent concentration [74]. From the emission characteristic parameters of the 6A1 g (S) level, X shows that CaZnBP glasses may have potential applications as luminescent optical materials, visible lasers, and fluorescent display devices [75]. It is also suggested that type-II semiconductor hetero-nanocrystals may offer a solution to the self-absorption problem in LSCs [6, 76]. Upconversion is a promising technique for harvesting sub-bandgap photons in photovoltaic devices. Furthermore, energy transfer mechanisms were proposed for the reduced efficiency of higher concentrations and depletion of upconversion luminescence [77, 78]. Combining multiple organic dyes to form a fluorescence resonance energy transfer (FRET) network is a useful strategy for extending the spectral range of sunlight absorbed by an LSC. The photostability and performance of an efficient FRET LSC rest heavily upon the photostability and fluorescence quantum yield of the final dye [79, 80]. To investigate the effect of the luminescent emission of InGaP/InGaAs/Ge on different operating conditions of the tandem, a combination of electroluminescence (EL) and photoluminescence (PL) measurements was conducted. Luminescence was recognized at high temperatures, and it was found that significant radiative recombination is available at even higher temperatures. The significant amount of radiative recombination at the band-gap edges of the top junctions observed in the measurements is evidence that optical coupling may occur to the lower junctions [81]. The development and current status of luminescent solar concentrators were reviewed, and it was predicted that optimized LSCs could offer potentially lower cost per unit of power compared to conventional solar cells [25, 82]. It was also predicted that the device can deliver three times more luminescent power to an opposing GaAs photovoltaic cell, when the emission profile is conically directed than when it is isotropic or the non-imaging optic is absent. These results preset a significant general opportunity to improve LC performance for a variety of applications, including photovoltaics, photobioreactors, and scintillator-based radiation detection [83].

6.2 Modeling work

Several research works have reported results based on modeling (Table 3). According to these research works, there are two different methods of modeling LSCs. One method is a detailed balance model that is related to the radiative energy exchange between lattice points in the concentrator plate, and the other is a ray-tracing model, where each incident photon is followed, and its density measured [27, 36, 43, 84].

The promising innovation of LSCs for building integrated photovoltaics (BIPV) is reported. To enhance LSC proficiency, the expansion of a photonic band stop (PBS) was discovered. Simulations were analyzed in different systems, with and without PBS. The loss mechanism was

Table 3 Recent modeling works on LSCs

Year	Modeling	Purposes	References
2012	Monte Carlo ray tracing	To achieve high quantum yield	[27]
2013	Thermodynamic and ray-trace modeling	To improve the LSC efficiency	[25]
2013	Detailed balance model	To achieve high conversion efficiencies	[85]
2013	Detailed balance model	To derive the Shockley–Queisser limit	[86]
2014	Homemade ray-trace Monte Carlo	To improve the LSC efficiency	[26]
2014	Ray-trace modeling	To improve the LSC efficiency	[64]
2015	Ray-tracing modeling	To predict the expected electrical output	[42]
2015	Presents a new model	To describe the angular dependence of the photon flux exiting the LSC edge	[55]

predicted, and therefore, the expected improvement had an additional photonic component. At that point, LSC and PBS were determined and characterized [26, 87]. It was indicated that the luminescent solar concentrator under a solar simulator would allow the photovoltaic cells attached to the edge to operate at up to 10 °C less than cells experiencing direct solar exposure owing to the infrared light avoided. The researchers also demonstrated the importance of correct adhesion to avoid rupturing of the attached cell [88]. Overall, the validated experimental results provide confidence in the use of modeling for future, larger LSCs for BIPV [43, 64]. Two model systems were suggested for thin-film LSC systems. The first model had a transparent PMMA/SiO_2 nanohybrid layer coated on a coumarin-doped PMMA substrate. The second model was designed with an ordinary configuration, in which coumarin dye was dissolved in the PMMA/SiO_2 nanohybrid layer and then coated on a transparent PMMA substrate. The obtained results suggest the first model is a durable design for thin-film LSC applications, especially in hot regions [89, 90]. Another new model was proposed that reveals the main features of the angular distribution of light escaping an LSC edge. The benchmark between this model and experimental measurements provides an assessment of non-ideal losses and identifying which emission angles are affected most by these losses [55]. Each type of numerical LSC modeling has specific benefits and drawbacks. In device design, the ray-tracing model has led to more choices and a greater number of luminophores and other details, but it is quite demanding computationally. LSCs with high efficiency have been simulated using the detailed balance theory of a single-stage fluorescent collector with a high-efficiency luminophore and wavelength-selective surface reflectors. Such device demonstrated efficiency of up to 90 % that of a directly illuminated cell of equivalent size [91, 92]. The optical efficiency along the edge of a square LSC and the influence of the tilt angle have also been reported. Based on these results and colors achieved, a model of a stained glass window (as shown in Fig. 4) was constructed, and its performance throughout a solar day was simulated. Besides, the same modeling structure mentioned already exists in our old buildings, so this design can be useful for LSCs these days (Fig. 5).

Fig. 4 Stained glass window used for the modeling (47 cm × 58 cm × 0.3 cm); this window was commissioned for a Bristol house and was designed by artist Carol Arnold [64]

7 Nanocrystals for luminescent solar concentrators

The use of different exposed areas, back reflectors and/or mirrors on the edges as well as efficiency evaluation using different parameters makes the comparison of different LSC setups quite difficult. Moreover, LSCs are sometimes evaluated with parameters referring to other solar generating systems like photon-per-electron efficiency or fill factors, which are meaningless in this specific case since the LSC itself is not an energy-generating device but only achieves light concentration [93–95]. Recent advances in the synthesis of luminescent nanocrystals with high photoluminescence quantum yields, tunable solar absorption, and good photostability have stimulated interest in nanocrystals for LSC technologies [27, 96, 97]. The colloidal chemical method is one of the most attractive

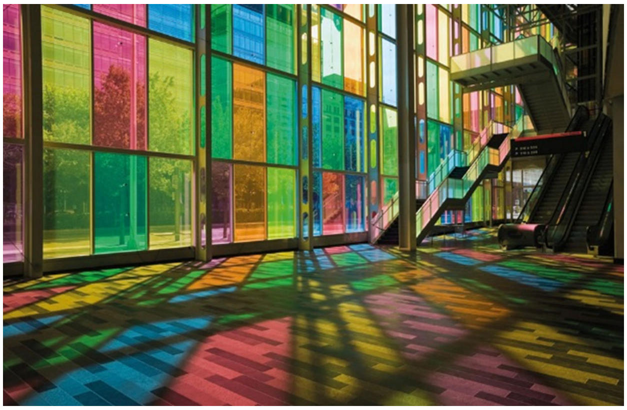

Fig. 5 Examples of design structure

methods for preparing luminescent nanocrystals for application in LSCs. Luminescent nanocrystals have many more benefits compared with organic chromophores, for instance, large absorption cross sections, tunable emission, near-unity emission efficiency, enhanced photostability, and the ability to be incorporated into organic or inorganic matrices via solution-based procedures [90, 98]. Currently, thin-film solar cells are the most interesting scheme in solar cell development and research. Therefore, various researchers are investigating new materials for use in solar energy conversion [99]. Doping impurities into nanocrystals enables the introduction and tuning of optical, electrical, and magnetic properties. Growing interest in the development of new types of doped colloidal nanocrystals is motivated by both fundamental science and potential applications. Successful nanocrystal doping requires an understanding of the doping process and the development of new doping strategies. There are two major classes of doped nanocrystals: transition-metal-doped chalcogenide semiconductor IIB–VI nanocrystals (e.g., CdSe, ZnSe, and ZnS) and lanthanide-doped wide-bandgap insulator nanocrystals (so far limited mainly to fluorides, phosphates, and oxides) [93, 100–102]. A largely unexplored class of nanocrystalline host materials is the alkaline earth sulfide IIA–VI NCs, e.g., CaS and SrS. As bulk materials, they are well-known hosts for a variety of luminescent dopant ions, including Mn^{2+}, Cu^{+}, Ce^{3+}, and Eu2 [93]. Researchers have reported improvement in the quantum efficiency of thin-film CdTe/CdS solar cells, predominantly in the ultraviolet regime. Similarly, a broad enhancement in the quantum efficiency of crystalline Si solar cells from the ultraviolet to the visible regime can be expected for an infrared-emitting LDSL based on PbS quantum dots. A photoluminescence quantum yield of 80 % or higher is required to achieve the maximum possible short-circuit current increase of 16 and 50 % for the CdTe/CdS and crystalline Si solar cells, respectively [103]. A new LSC phosphor, nanocrystalline $Cd_{1-x}Cu_xSe$ was introduced, which outperforms all other leading nanocrystals by a significant margin in both small- and large-scale LSCs under full-spectrum conditions. Several reports have proposed that nanocrystals can mitigate the re-absorption problem. One strategy for eliminating self-absorption involves the growth of nanocrystal heterostructures that integrate wider-gap semiconductors with small cores having a narrower bandgap [104, 105]. A new, cost-competitive, high-performance, and transparent luminescent solar concentrator based on “zero self-absorption” doped quantum dots was designed by researchers at the University of Washington and Western Washington University in the USA. This concentrator might even be ideal in applications like smart windows. Although researchers have been working on LSCs since the 1970s, LSC devices are still not efficient enough to be employed in real-world applications. Their main drawback is the so-called self-absorption. The zero self-absorption doped quantum dots may be one way of overcoming this long-standing fundamental problem. The doped quantum dots that have been discovered absorb high-energy UV light and re-emit it at lower energies. This energy is too low to be re-absorbed by other quantum dots within the concentrator, so the light can travel to the edges of the concentrator relatively unimpeded. In turn, this allows for larger, more highly concentrated, and efficient solar light collection. In proof-of-concept experiments, visibly transparent, ultraviolet-selective luminescent solar concentrators have been prepared using colloidal Mn2 + -doped ZnSe nanocrystals that show no luminescence re-absorption. In summary, colloidal-doped nanocrystals seem to be a promising new class of zero-re-absorption luminophores for LSC applications [93].

8 Conclusion and future research

A short overview of experimental works and numerical modeling was discussed and presented in this paper. The large number of methods and applications since 2012–2015 has led to the development of LSCs, especially in the field of thermodynamic and ray-tracing models, which can predict and describe the performance of LSCs. Moreover, new dyes and, more importantly, new quantum dots have been developed and included in polymer concentrators and nanocrystals. Security tests over more than 2 years have demonstrated that great competition exists for LSC utilization in terms of business. There are a great number of advancements that can and ought to be pursued on LSCs to render them a professional device for usage in the urban environment. Further research on LSC response to spatial disposition and solar radiation spectral composition will be required in the future. The Lumogen dye lifetime has an important role and is nominated as one of the major unknown factors in LSCs. Although there have been a few reports on the photodegradation rate of these dyes, there has been no endeavor to correlate real world with accelerated weathering. Therefore, prediction is one of the most essential factors to be addressed for LSCs in future works. Another essential factor is the actual efficiency of the total internal reaction (TIR). It is clear that after several decades of research, actual LSC performance levels remain far below par. It is primarily due to surface loss, the re-absorption of emitted photons by other luminophores, limited absorption, photovoltaic losses, and waveguide losses. TIR proficiency estimation would be considered more precise with LSC performance modeling and simulation. In addition, an especially attractive point to consider is the chance to use organic-based photovoltaics (OPVs). The biggest difficulty with OPVs is their powerlessness to utilize the UV range. Moreover, laboratory research on LSC technology should be aimed at optimizing the single parameters of luminescent nanocrystals, which affect overall LSC performance, such that luminescent nanocrystals can be optimized and implemented together in a functional and less expensive system. Finally, cost optimization studies should prove the economic viability of LSCs [39, 56].

References

1. M. Aklalouch, A. Calleja, X. Granados, S. Ricart, V. Boffa, F. Ricci, T. Puig, X. Obradors, Hybrid sol–gel layers containing CeO_2 nanoparticles as UV-protection of plastic lenses for concentrated photovoltaics. Sol. Energy Mater. Sol. Cells **120**(Part A), 175 (2014)
2. A.A. Al-Ghamdi, E.M. Mahrous, A.M. Al-Enizi, A. Azam, Preparation and characterization of pyrromethene-567 dye-doped polymer samples using gamma irradiation polymerization method (GIPM). J. Lumin. **157**, 310 (2015)
3. S. Chandra, J. Doran, S.J. McCormack, M. Kennedy, A.J. Chatten, Enhanced quantum dot emission for luminescent solar concentrators using plasmonic interaction. Sol. Energy Mater. Sol. Cells **98**, 385 (2012)
4. D. Chemisana, Building integrated concentrating photovoltaics: a review. Renew. Sustain. Energy Rev. **15**(1), 603 (2011)
5. B. Fisher, J. Biddle, Luminescent spectral splitting: efficient spatial division of solar spectrum at low concentration. Sol. Energy Mater. Sol. Cells **95**(7), 1741 (2011)
6. Z. Krumer, S.J. Pera, R.J.A. van Dijk-Moes, Y. Zhao, A.F.P. de Brouwer, E. Groeneveld, W.G.J.H.M. van Sark, R.E.I. Schropp, C. de Mello Donegá, Tackling self-absorption in luminescent solar concentrators with type-II colloidal quantum dots. Sol. Energy Mater. Sol. Cells **111**, 57 (2013)
7. N. Aste, L.C. Tagliabue, C. Del Pero, D. Testa, R. Fusco, Performance analysis of a large-area luminescent solar concentrator module. Renew. Energy **76**, 330 (2015)
8. Y. Zhang, S. Sun, R. Kang, J. Zhang, N. Zhang, W. Yan, W. Xie, J. Ding, J. Bao, C. Gao, Polymethylmethacrylate-based luminescent solar concentrators with bottom-mounted solar cells. Energy Convers. Manag. **95**, 187 (2015)
9. P.T.M. Albers, C.W.M. Bastiaansen, M.G. Debije, Dual waveguide patterned luminescent solar concentrators. Sol. Energy **95**, 216 (2013)
10. G.J.H.M. van Sark Wilfried, K.W.J. Barnham, L.H. Slooff, A.J. Chatten, A. Büchtemann, A. Meyer, S.J. McCormack, R. Koole, D.J. Farrell, R. Bose, E.E. Bende, A.R. Burgers, T. Budel, J. Quilitz, M. Kennedy, T. Meyer, C. De Mello Donegá, A. Meijerink, D. Vanmaekelbergh, Luminescent solar concentrators—a review of recent results. Opt. Soc. Am. **16**(26), 21773 (2008)
11. A.A. Earp, J.B. Franklin, G.B. Smith, Absorption tails and extinction in luminescent solar concentrators. Sol. Energy Mater. Sol. Cells **95**(4), 1157 (2011)
12. M.H. Keefe, K.D. Benkstein, J.T. Hupp, Luminescent sensor molecules based on coordinated metals: a review of recent developments. Coord. Chem. Rev. **205**, 201 (2000)
13. A.M. Hermann, Luminescent solar concentrators—a review. Sol. Energy **29**(4), 323 (1982)
14. N. Agnihotri, Computational studies of charge transfer in organic solar photovoltaic cells: a review. J. Photochem. Photobiol. C **18**, 18 (2014)
15. S.J. Gallagher, P.C. Eames, B. Norton, Quantum dot solar concentrator behaviour, predicted using a ray trace approach. J. Ambient Energy **25**(1), 47 (2004)
16. U. Rau, F. Einsele, G.C. Glaeser, Efficiency limits of photovoltaic fluorescent collectors. Appl. Phys. Lett. **87**(17), 171101 (2005)
17. J. Lambe, W.H. Weber, Luminescent greenhouse collector for solar radiation. Appl. Opt. **15**(10), 2299 (1976)
18. A. Greubel, W. Greube, Solar energy conversion with fluorescent concentrators. Appl. Phys. **14**, 123 (1977)
19. A. Goetzberger, Fluorescent solar energy collectors: operating conditions with diffuse light. Appl. Phys. **16**(4), 399 (1978)
20. V. Wittwer, A. Zastrow, Daylighting with fluorescent concentrators and highly reflective silver-coated plastic films: a new application for new materials, in *Optical Materials Technology* (1986)
21. V. Wittwer, W. Stahl, A. Goetzberger, Fluorescent planar concentrators. Sol. Energy Mater. **11**(3), 187 (1984)
22. K. Barnham, J.L. Marques, J. Hassard, P. O'Brien, Quantum-dot concentrator and thermodynamic model for the global redshift. Appl. Phys. **76**(9), 1197 (2000)
23. A.P. de Silva, T. Gunnlaugsson, T.E. Rice, Recent evolution of luminescent photoinduced electron transfer sensors. A review. Analyst **121**(12), 1759 (1996)
24. V. Sholin, J.D. Olson, S.A. Carter, Semiconducting polymers and quantum dots in luminescent solar concentrators for solar energy harvesting. J. Appl. Phys. **101**(12), 123114 (2007)
25. W.G.J.H.M. van Sark, Luminescent solar concentrators—a low cost photovoltaics alternative. Renew. Energy **49**, 207 (2013)
26. A.-L. Joudrier, F. Proise, R. Grapin, J.-L. Pelouard, J.-F. Guillemoles, Modeling and fabrication of luminescent solar concentrators towards photovoltaic devices. Energy Procedia **60**, 173 (2014)
27. J. Bomm, A. Büchtemann, A.J. Chatten, R. Bose, D.J. Farrell, N.L.A. Chan, Y. Xiao, L.H. Slooff, T. Meyer, A. Meyer, W.G.J.H.M. van Sark, R. Koole, Fabrication and full characterization of state-of-the-art quantum dot luminescent solar concentrators. Sol. Energy Mater. Sol. Cells **95**(8), 2087 (2011)
28. A. Greubel, W. Greube, Solar energy conversion with fluorescent collectors. Appl. Phys. **14**, 123 (1977)
29. V. Wittwer, W. Stahl, A. Goetzberger, Fluorescent planar concentrators. Sol. Energy Mater. **11**(3), 187 (1984)
30. T. Trupke, M. Green, P. Würfel, Improving solar cell efficiencies by down-conversion of high-energy photons. J. Appl. Phys. **92**(3), 1668 (2002)
31. S.M. El-Bashir, F.M. Barakat, M.S. AlSalhi, Metal-enhanced fluorescence of mixed coumarin dyes by silver and gold

nanoparticles: towards plasmonic thin-film luminescent solar concentrator. J. Lumin. **143**, 43 (2013)

32. M.G. Debije, P.P.C. Verbunt, Thirty years of luminescent solar concentrator research: solar energy for the built environment. Adv. Energy Mater. **2**(1), 12 (2012)
33. X. Wang, T. Wang, X. Tian, L. Wang, W. Wu, Y. Luo, Q. Zhang, Europium complex doped luminescent solar concentrators with extended absorption range from UV to visible region. Sol. Energy **85**(9), 2179 (2011)
34. T. Wang, J. Zhang, W. Ma, Y. Luo, L. Wang, Z. Hu, W. Wu, X. Wang, G. Zou, Q. Zhang, Luminescent solar concentrator employing rare earth complex with zero self-absorption loss. Sol. Energy **85**(11), 2571 (2011)
35. M.V. Kovalenko, L. Manna, A. Cabot, Z. Hens, D.V. Talapin, C.R. Kagan, V.I. Klimov, A.L. Rogach, P. Reiss, D.J. Milliron, Prospects of nanoscience with nanocrystals. ACS Nano **9**(2), 1012 (2015)
36. J.W.E. Wiegman, E. van der Kolk, Building integrated thin film luminescent solar concentrators: detailed efficiency characterization and light transport modelling. Sol. Energy Mater. Sol. Cells **103**, 41 (2012)
37. M. Rüdiger, S. Fischer, J. Frank, A. Ivaturi, B.S. Richards, K.W. Krämer, M. Hermle, J.C. Goldschmidt, Bifacial n-type silicon solar cells for upconversion applications. Sol. Energy Mater. Sol. Cells **128**, 57 (2014)
38. N. Aste, L.C. Tagliabue, P. Palladino, D. Testa, Integration of a luminescent solar concentrator: effects on daylight, correlated color temperature, illuminance level and color rendering index. Sol. Energy **114**, 174 (2015)
39. P.P.C. Verbunt, M.G. Debjie, Progress in luminescent solar concentrator research: solar energy for the built environment, in *World Renewable Energy* (2011)
40. E. Klampaftis, D. Ross, K.R. McIntosh, B.S. Richards, Enhancing the performance of solar cells via luminescent downshifting of the incident spectrum: a review. Sol. Energy Mater. Sol. Cells **93**(8), 1182 (2009)
41. N. Asim, K. Sopian, S. Ahmadi, K. Saeedfar, M. Alghoul, O. Saadatian, S.H. Zaidi, A review on the role of materials science in solar cells. Renew. Sustain. Energy Rev. **16**(8), 5834 (2012)
42. H. Baig, N. Sellami, T.K. Mallick, Performance modeling and testing of a building integrated concentrating photovoltaic (BICPV) system. Sol. Energy Mater. Sol. Cells **134**, 29 (2015)
43. L.Z. Broderick, B.R. Albert, B.S. Pearson, L.C. Kimerling, J. Michel, Design for energy: modeling of spectrum, temperature and device structure dependences of solar cell energy production. Sol. Energy Mater. Sol. Cells **136**, 48 (2015)
44. H. Baig, K.C. Heasman, T.K. Mallick, Non-uniform illumination in concentrating solar cells. Renew. Sustain. Energy Rev. **16**(8), 5890 (2012)
45. C. Corrado, S.W. Leow, M. Osborn, E. Chan, B. Balaban, S.A. Carter, Optimization of gain and energy conversion efficiency using front-facing photovoltaic cell luminescent solar concentrator design. Sol. Energy Mater. Sol. Cells **111**, 74 (2013)
46. M. Peng, X. Yu, X. Cai, Q. Yang, H. Hu, K. Yan, H. Wang, B. Dong, F. Zhu, D. Zou, Waveguide fiber dye-sensitized solar cells. Nano Energy **10**, 117 (2014)
47. O.Z. Sharaf, M.F. Orhan, Concentrated photovoltaic thermal (CPVT) solar collector systems: part I—fundamentals, design considerations and current technologies. Renew. Sustain. Energy Rev. **50**, 1500 (2015)
48. O.Z. Sharaf, M.F. Orhan, Concentrated photovoltaic thermal (CPVT) solar collector systems: part II—implemented systems, performance assessment, and future directions. Renew. Sustain. Energy Rev. **50**, 1566 (2014)
49. Y.S. Lim, C.K. Lo, S.Y. Kee, H.T. Ewe, A.R. Faidz, Design and evaluation of passive concentrator and reflector systems for bifacial solar panel on a highly cloudy region—a case study in Malaysia. Renew. Energy **63**, 415 (2014)
50. G. Griffini, M. Levi, S. Turri, Thin-film luminescent solar concentrators: a device study towards rational design. Renew. Energy **78**, 288 (2015)
51. J.J. Huang, Z.F. Zhong, M.Z. Rong, X. Zhou, X.D. Chen, M.Q. Zhang, An easy approach of preparing strongly luminescent carbon dots and their polymer based composites for enhancing solar cell efficiency. Carbon **70**, 190 (2014)
52. G. Maggioni, A. Campagnaro, S. Carturan, A. Quaranta, Dye-doped parylene-based thin film materials: application to luminescent solar concentrators. Sol. Energy Mater. Sol. Cells **108**, 27 (2013)
53. S. Mahamuda, K. Swapna, M. Venkateswarlu, A. Srinivasa Rao, S. Shakya, G. Vijaya Prakash, Spectral characterisation of Sm^{3+} ions doped Oxy-fluoroborate glasses for visible orange luminescent applications. J. Lumin. **154**, 410 (2014)
54. S. Mahlik, A. Lazarowska, M. Grinberg, J.P.R. Wells, M.F. Reid, Luminescence properties of MgF2:Yb2+ at high hydrostatic pressure. J. Lumin. **169**, 788 (2015)
55. T.S. Parel, C. Pistolas, L. Danos, T. Markvart, Modelling and experimental analysis of the angular distribution of the emitted light from the edge of luminescent solar concentrators. Opt. Mater. **42**, 532 (2015)
56. Y. Wu, S. Ren, X. Xu, L. Liu, H. Wang, J. Yu, Engineered fluorescence of quantum dots via plasmonic nanostructures. Sol. Energy Mater. Sol. Cells **126**, 113 (2014)
57. B. Balaban, S. Doshay, M. Osborn, Y. Rodriguez, S.A. Carter, The role of FRET in solar concentrator efficiency and color tunability. J. Lumin. **146**, 256 (2014)
58. N. Yeh, P. Yeh, Organic solar cells: their developments and potentials. Renew. Sustain. Energy Rev. **21**, 421 (2013)
59. S.M. El-Bashir, Photophysical properties of fluorescent PMMA/SiO_2 nanohybrids for solar energy applications. J. Lumin. **132**(7), 1786 (2012)
60. G. Griffini, M. Levi, S. Turri, Novel crosslinked host matrices based on fluorinated polymers for long-term durability in thin-film luminescent solar concentrators. Sol. Energy Mater. Sol. Cells **118**, 36 (2013)
61. L. Marin, A. Zabulica, I.-A. Moleavin, Luminescent guest–host composite films based on an azomethine dye in different matrix polymers. Opt. Mater. **38**, 290 (2014)
62. F.D. Martinez-Mancera, J.L. Hernandez-Lopez, Physical characterization and photoluminescence properties of thioglycolic acid-stabilized lead sulfide nanocrystals. Mater. Chem. Phys. **148**(3), 1045 (2014)
63. Y. Chen, Q. Tao, W. Fu, H. Yang, X. Zhou, Y. Zhang, S. Su, P. Wang, M. Li, Enhanced solar cell efficiency and stability using ZnS passivation layer for CdS quantum-dot sensitized actinomorphic hexagonal columnar ZnO. Electrochim. Acta **118**, 176 (2014)
64. A. Kerrouche, D.A. Hardy, D. Ross, B.S. Richards, Luminescent solar concentrators: from experimental validation of 3D ray-tracing simulations to coloured stained-glass windows for BIPV. Sol. Energy Mater. Sol. Cells **122**, 99 (2014)
65. G. Griffini, M. Levi, S. Turri, Novel high-durability luminescent solar concentrators based on fluoropolymer coatings. Prog. Org. Coat. **77**(2), 528 (2014)
66. G. Griffini, L. Brambilla, M. Levi, M. Del Zoppo, S. Turri, Photo-degradation of a perylene-based organic luminescent solar concentrator: molecular aspects and device implications. Sol. Energy Mater. Sol. Cells **111**, 41 (2013)
67. J. Garcia-Torres, P. Bosch-Jimenez, E. Torralba-Calleja, M. Kennedy, H. Ahmed, J. Doran, D. Gutierrez-Tauste, L. Bautista, M. Della Pirriera, Highly efficient luminescent materials: influence of the matrix on the photophysical properties of

Eu(III) complex/polymer hybrids. J. Photochem. Photobiol. A **283**, 8 (2014)

68. J. Garcia-Torres, P. Bosch-Jimenez, E. Torralba-Calleja, M. Kennedy, H. Ahmed, J. Doran, D. Gutierrez-Tauste, L. Bautista, M. Della Pirriera, Modulating the photoluminescence of europium-based emitting polymers: influence of the matrix on the photophysical properties. J. Photochem. Photobiol. A **275**, 103 (2014)
69. B. Vishwanathan, A.H.M.E. Reinders, D.K.G. de Boer, L. Desmet, A.J.M. Ras, F.H. Zahn, M.G. Debije, A comparison of performance of flat and bent photovoltaic luminescent solar concentrators. Sol. Energy **112**, 120 (2015)
70. L.R. Bradshaw, K. Knowles, S. McDowall, D.R. Gamelin, Nanocrystals for luminescent solar concentrators. Nano Lett. **15**(2), 1315 (2015)
71. I. Coropceanu, M.G. Bawendi, Core/shell quantum dot based luminescent solar concentrators with reduced reabsorption and enhanced efficiency. Nano Lett. **14**(7), 4097 (2014)
72. F. Bella, G. Griffini, M. Gerosa, S. Turri, R. Bongiovanni, Performance and stability improvements for dye-sensitized solar cells in the presence of luminescent coatings. J. Power Sources **283**, 195 (2015)
73. A. Boccolini, J. Marques-Hueso, D. Chen, Y. Wang, B.S. Richards, Physical performance limitations of luminescent down-conversion layers for photovoltaic applications. Sol. Energy Mater. Sol. Cells **122**, 8 (2014)
74. N.D. Bronstein, R.G. Nuzzo, L. Li, L. Xu, Y. Yao, V.E. Ferry, A.P. Alivisatos, R.G. Nuzzo, Luminescent solar concentration with semiconductor nanorods and transfer-printed micro-silicon solar cells. ASC Nano **8**(1), 44 (2014)
75. M.H. Wan, P.S. Wong, R. Hussin, H.O. Lintang, S. Endud, Structural and luminescence properties of Mn^{2+} ions doped calcium zinc borophosphate glasses. J. Alloys Compd. **595**, 39 (2014)
76. C. Lamnatou, D. Chemisana, Solar radiation manipulations and their role in greenhouse claddings: fluorescent solar concentrators, photoselective and other materials. Renew. Sustain. Energy Rev. **27**, 175 (2013)
77. S.K.W. MacDougall, A. Ivaturi, J. Marques-Hueso, K.W. Krämer, B.S. Richards, Broadband photoluminescent quantum yield optimisation of Er^{3+}-doped β-NaYF4 for upconversion in silicon solar cells. Sol. Energy Mater. Sol. Cells **128**, 18 (2014)
78. R.W. MacQueen, T.W. Schmidt, Molecular polarization switching for improved light coupling in luminescent solar concentrators. J. Phys. Chem. Lett. **4**(17), 2874 (2013)
79. A.M. Mooney, K.E. Warner, P.J. Fontecchio, Y.-Z. Zhang, B.P. Wittmershaus, Photodegradation in multiple-dye luminescent solar concentrators. J. Lumin. **143**, 469 (2013)
80. E. Moretti, A. Talon, L. Storaro, A. Le Donne, S. Binetti, A. Benedetti, S. Polizzi, Concentration quenching and photostability in Eu(dbm)3phen embedded in mesoporous silica nanoparticles. J. Lumin. **146**, 178 (2014)
81. V. Paraskeva, M. Norton, M. Hadjipanayi, M. Pravettoni, G.E. Georghiou, Luminescent emission of multi-junction InGaP/InGaAs/Ge PV cells under high intensity irradiation. Sol. Energy Mater. Sol. Cells **134**, 175 (2015)
82. G. Venkataiah, C.K. Jayasankar, K. VenkataKrishnaiah, P. Dharmaiah, N. Vijaya, Concentration dependent luminescence properties of Sm^{3+}-ions in tellurite–tungsten–zirconium glasses. Opt. Mater. **40**, 26 (2015)
83. Y. Shen, Y. Jia, X. Sheng, L. Shen, J.A. Rogers, N.C. Giebink, Nonimaging optical gain in luminescent concentration through photonic control of emission étendue. ACS Photonics **1**(8), 746 (2014)
84. B.C. Rowan, L.R. Wilson, B.S. Richards, Advanced material concepts for luminescent solar concentrators. IEEE J. Sel. Top. Quantum Electron. **14**(5), 1312 (2008)
85. E.D. Kosten, J.H. Atwater, J. Parsons, A. Polman, H.A. Atwater, Highly efficient GaAs solar cells by limiting light emission angle. Sci. Appl. **2**(45), 2047 (2013)
86. D.J. Farrell, M. Yoshida, Operating regimes for second generation luminescent solar concentrators. Prog. Photovolt. Res. Appl. **20**(1), 93 (2012)
87. M.D. Hughes, C. Maher, D.-A. Borca-Tasciuc, D. Polanco, D. Kaminski, Performance comparison of wedge-shaped and planar luminescent solar concentrators. Renew. Energy **52**, 266 (2013)
88. V.A. Rajkumar, C. Weijers, M.G. Debije, Distribution of absorbed heat in luminescent solar concentrator lightguides and effect on temperatures of mounted photovoltaic cells. Renew. Energy **80**, 308 (2015)
89. S.M. El-Bashir, O.A. AlHarbi, M.S. AlSalhi, Optimal design for extending the lifetime of thin film luminescent solar concentrators. Opt. Int. J. Light Electron Opt. **125**(18), 5268 (2014)
90. L.R. Bradshaw, K.E. Knowles, S. McDowall, D.R. Gamelin, Nanocrystals for luminescent solar concentrators. Nano Lett. **15**(2), 1315 (2015)
91. T. Markvart, Detailed balance method for ideal single-stage fluorescent collectors. J. Appl. Phys. **99**(2), 026101 (2006)
92. C. Lamnatou, J.D. Mondol, D. Chemisana, C. Maurer, Modelling and simulation of building-integrated solar thermal systems: behaviour of the system. Renew. Sustain. Energy Rev. **45**, 36 (2015)
93. C.S. Erickson, L.R. Bradshaw, S. McDowall, J.D. Gilbertson, D.R. Gamelin, D.L. Patrick, Zero-reabsorption doped-nanocrystal luminescent solar concentrators. ACS Nano **8**(4), 3461 (2014)
94. F. Meinardi, A. Colombo, K.A. Velizhanin, R. Simonutti, M. Lorenzon, L. Beverina, R. Viswanatha, V.I. Klimov, S. Brovelli, Large-area luminescent solar concentrators based on/Stokes-shift-engineered/'nanocrystals in a mass-polymerized PMMA matrix. Nat. Photonics **8**(5), 392 (2014)
95. Y.K. Liao, M. Brossard, D.H. Hsieh, T.N. Lin, M.D. Charlton, S.J. Cheng, C.H. Chen, J.L. Shen, L.T. Cheng, T.P. Hsieh, Highly efficient flexible hybrid nanocrystal-Cu (In, Ga) Se2 (CIGS) solar cells. Adv. Energy Mater. **5**(2), 80 (2015)
96. R. Inman, G. Shcherbatyuk, D. Medvedko, A. Gopinathan, S. Ghosh, Cylindrical luminescent solar concentrators with near-infrared quantum dots. Opt. Express **19**(24), 24308 (2011)
97. F. Purcell-Milton, Y.K. Gun'ko, Quantum dots for luminescent solar concentrators. J. Mater. Chem. **22**(33), 16687 (2012)
98. H. Lin, P. Xie, Y. Liu, X. Zhou, B. Li, Tuning luminescence and reducing reabsorption of CdSe quantum disks for luminescent solar concentrators. Nanotechnology **26**(33), 335401 (2015)
99. I. Rousseau, V. Wood, Nanophotonic luminescent solar concentrators. Appl. Phys. Lett. **103**(13), 131113 (2013)
100. F. Sgrignuoli, P. Ingenhoven, G. Pucker, V. Mihailetchi, E. Froner, Y. Jestin, E. Moser, G. Sànchez, L. Pavesi, Purcell effect and luminescent downshifting in silicon nanocrystals coated back-contact solar cells. Sol. Energy Mater. Sol. Cells **132**, 267 (2015)
101. R. Beaulac, P.I. Archer, J. van Rijssel, A. Meijerink, D.R. Gamelin, Exciton storage by Mn^{2+} in colloidal Mn^{2+}-doped CdSe quantum dots. Nano Lett. **8**(9), 2949 (2008)
102. M.S. Kang, A. Sahu, C.D. Frisbie, D.J. Norris, Influence of silver doping on electron transport in thin films of PbSe nanocrystals. Adv. Mater. **25**(5), 725 (2013)
103. S. Kalytchuk, S. Gupta, O. Zhovtiuk, A. Vaneski, S.V. Kershaw, H. Fu, Z. Fan, E.C. Kwok, C.-F. Wang, W.Y. Teoh, Semiconductor nanocrystals as luminescent down-shifting layers to

enhance the efficiency of thin-film CdTe/CdS and crystalline Si solar cells. J. Phys. Chem. C **118**(30), 16393 (2014)

104. Y. Zhao, F.T. Rabouw, T.V. Puffelen, C.A.V. Walree, D.R. Gamelin, C. de Mello Donegá, A. Meijerink, Lanthanide-doped CaS and SrS luminescent nanocrystals: a single-source precursor approach for doping. J. Am. Chem. Soc. **136**(47), 16533 (2014)
105. P.F. Smet, I. Moreels, Z. Hens, D. Poelman, Luminescence in sulfides: a rich history and a bright future. Materials **3**(4), 2834 (2010)