Renewable and Sustainable Energy Reviews 28 (2013) 654–663

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Spectral beam splitting for efficient conversion of solar energy—A review

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ARTICLE INFO

Article history:
Received 11 February 2013
Received in revised form
25 July 2013
Accepted 11 August 2013
Available online 4 September 2013

Keywords:
Solar energy
High efficiency
Spectral splitting
Hybrid
Photovoltaic

ABSTRACT

Spectral beam splitting is a promising method to achieve high efficiency solar energy conversion. Its potential applications include multi-junction PV receivers, hybrid collectors and even biomass production. Although spectral splitting receivers can achieve high theoretical conversion efficiencies, they have not yet evolved to the commercial level. In this paper, we provide a review on the recently published research in this field and discuss the drawbacks associated with practical applications. Suggestions are made which we believe will lead to improvements in optical efficiency (including geometrical limitations) and the fabrication costs of spectrally splitting solar receivers.

Contents

1. Introduction

Efficient energy harvesting from sunlight is considered to be a promising solution to the issues associated with burning fossil fuels. Burning hydrocarbons increases the concentration of greenhouse gases in the atmosphere resulting in adverse climate change. At the same time, depletion of such non-renewable resources in nature increases their prices.

The amount of worldwide energy consumption in 2011 was about 5.48×10^8 TJ [1] which means that the average total power consumption was about 17.4 TW. In comparison, the radiation on the Earth received from the Sun is about 162,000 TW [2]. This implies that harvesting even a tiny fraction of this solar radiation can meet both the current and future energy requirements of the world.

Two main mechanisms of capturing sunlight and delivering useful energy have been developed and commercialised so far: photothermal and photovoltaic. Photothermal collectors transform

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.08.026

the solar radiation into useful heat, while photovoltaic receivers (PV cells) are able to produce electricity directly from sunlight. The first reported practical conversion of solar radiation into power was carried out by Augustin Mouchot in 1878 [3]. He used a solar thermal collector including a conical reflector to run a heat engine. The first practical direct conversion of sunlight into electricity using photocells was carried out in the mid-1950s with a conversion efficiency of 6% [4]. Since then the collection and conversion mechanisms have evolved and conversion efficiencies have increased.

PV cells have now reached efficiencies as high as 43.5% [5] in laboratory measurements. However, such efficiency comes with a very high fabrication cost due to the need to manufacture multi-junction solar cells [6]. Commercially viable cells are mainly monocrystalline and multicrystalline silicon cells with module efficiencies ranging from 14 to 20%.

Utilising PV cells under concentrated solar radiation can reduce the cost of producing solar electricity [7] and also the embodied energy payback period [8] of the required devices. In this method, the majority of the PV cell area is replaced by solar concentrators such as lenses and mirrors, which are generally cheaper than PV cells. For example, the cost of a parabolic trough including the mirrors, tracking devices, and required structures costs about 295 ($/m^2$) [9], whereas a utility scale photovoltaic system made of polycrystalline silicon cells (with median efficiency of 14.5% and one axis tracking) costs about 638 ($/m^2$); 44% of the later is just due to the cost of the PV module [10] which is equal to about 280 ($/m^2$). Assuming the concentration ratio of the parabolic trough to be 10 times (which is easily achievable), just one-tenth of the same PV cell area is required to be installed as the receiver. This means that the cost of the cell–parabolic trough combination will be 323 ($/m^2$), which is almost half the price of the original system. The difference becomes more significant when high-efficiency, more expensive multi-junction cells are used as the receiver [11]. It should be noted that the cost benefit is practically achievable when the additional costs associated with using solar cells under concentrated radiation (such as the cost of cell cooling) is kept low.

An important issue associated with concentrating PV systems is that the efficiency of the cells is affected at high temperature [12]. Sufficiently high temperatures may also physically damage them. Various methods for cooling PV cells under concentrated illumination have been proposed [13] and these depend on the geometrical configuration as well. Such methods include passive (such as buoyancy induced flow) and active (such as fans, impinging water, and cooling channels) mechanisms for low and high ($>150\times$) concentration levels respectively.

In both cooling methods, the heat absorbed from the PV cells is either dissipated to the environment or delivered as additional useful energy in hybrid solar collectors [14–19]. These can be considered ‘post-absorption’ heat management solutions. Another solution for addressing the heating problem is by only exposing them to a selected spectral band in which the cells have better efficiencies. This ‘pre-absorption’ method removes the wavelengths of light that are not converted to electricity before they hit the cell, and requires spectral matching of the cells and the wavelength band.

Unlike thermal absorbers which capture the whole solar spectrum effectively, PV cells have a fixed, material dependent, spectral response. Photons with energies lower than the band gap pass through the semiconductor material and are generally absorbed (as heat) by the mounting at the back of the cell. Photons with energies higher than the band gap are absorbed by the semiconductor material; however, the excess energy is not used by conventional single-junction PV cells, and is generally dissipated as heat. Hence, wavelengths both higher and lower than the band gap incur conversion losses, resulting in increased cell temperature. The efficiency of a PV cell consisting of a single semiconductor material with band a gap of 1.1 eV under the full solar spectrum is theoretically limited to about 30% [20].

Three different mechanisms have been suggested in the literature to alleviate the spectral mismatch problem of solar cells and increase their efficiencies. The first one is using a thermophotovoltaic device [21,22] or a luminescent concentrator [23,24] to shift the wavelengths of the incoming radiation (by absorbing and reemitting the light) towards a wavelength range which can be better matched with the cells. The second method involves monolithically stacking different semiconductors with different band gaps to create a multi-junction solar cell [25]. The third method is spectrally separating sunlight into various wavelength bands using a spectral beam splitter and directing each band to the most efficient receiver (for example a solar cell with suitable band gap). Each method has its own benefits and drawbacks.

Geometric limitations of the absorber/emitter component, optical losses, and non-ideal properties of the emitter can affect the efficiency of a thermophotovoltaic device [26]. Luminescent concentrators suffer from degradation as well as optical and re-absorption losses [27] and hence they have low efficiencies. Practical multi-junction cells have achieved efficiencies as high as 43.5% [5] but they are still too expensive to be commercialised in the mainstream PV market. Lattice matching and a few more technical issues [28,29] need to be addressed in the design and fabrication process of multi-junction cells to make them competitive for terrestrial energy applications. It should be noted that multi-junction cells also take advantage of spectral separation. However, in the current text, spectral splitting refers to lateral spectral separation of light using optical filters.

The aim of this paper is to provide an up to date review of the research outcomes (published after 2003) in the field of spectral splitting and to evaluate prospects of utilising this method in solar receivers. We investigate spectrally splitting solar receivers from the system point of view, including the optical elements (such as concentrators and waveguides), net combined efficiency, and the type of splitting system used in the configuration. Furthermore, this article will review hybrid configurations which harvest useful thermal energy.

2. Spectral splitting methods

The concept of harvesting solar energy by splitting the solar spectrum and directing each band to the most efficient convertor was suggested for the first time by Jackson [30] in 1955; however the first experimental work was demonstrated by Moon et al. [31] in 1978. This method is still used extensively to address the spectral mismatch problem of solar cells.

A thorough review on the application of spectral beam splitting for efficient harvesting of solar energy has been presented by Imenes and Mills [32]. They reviewed an extensive range of research activities in this field published up to 2003. However, because of high conversion efficiencies and increased design flexibility achieved by spectral splitting, the field has advanced considerably since then. The later advantage is due to the possibility of using more versatile types of semiconductor materials compared to monolithic multi-junction cells that constrain the design due to considerations such as lattice matching between the adjacent semiconductors.

Various mechanisms for spectral splitting of sunlight have been proposed. For example, holographic concentrators [33,34] can split sunlight into several bands along with concentrating it. This mechanism has been shown to be advantageous in low concentration solar collectors [35]. The most well-known method is using

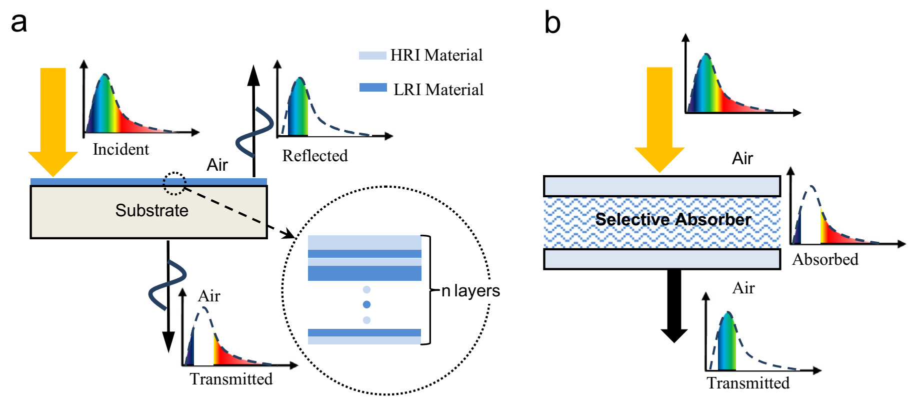

Fig. 1. Spectral splitting mechanisms. (a) Spectral splitting using a thin-film wave interference filter; HRI: High Refractive Index and LRI: Low Refractive Index. (b) Spectral splitting using a selective absorber (liquid or solid); the small graphs present the spectrum range available at each stage.

thin-film wave interference optical filters as shown in Fig. 1a. In such filters, a number of thin layers (in the range of a few nanometres to hundreds of nanometres thick) of non-absorbing dielectric materials with high refractive index contrast are deposited on a transparent substrate to achieve a certain set of optical properties (Fig. 1a). These filters can be designed to function as a band-stop, band pass, or an edge filter. A thorough theoretical background for designing such filters has been provided by Macleod [36].

Rugate filters are another class of wave interference filters that, unlike multilayer filters, consist of a continuously varying refractive index structure along their thickness. Because of their continuous nature, rugate filters offer higher mechanical strength and toughness, which gives them a high durability under thermal loading in comparison to discrete multilayer filters. A few attempts to introduce selective absorbing/transmitting filters (Fig. 1b) have been reported as well. A review on the physics of spectrally selective filtering methods has been presented by Peters et al. [37].

The cost of PV systems utilising spectral splitters is usually higher than the cost of standard PV systems. To be commercially viable this increase in cost should be offset by the efficiency gain. To achieve this, the optical efficiency of the beam splitter and the concentrating components should be high enough to minimise the optical losses caused by the higher complexity of the system [38,39]. Durability of such filters under high illumination in concentrating configurations is also a key issue to be addressed [40].

2.1. *Spectral splitting in PV receivers*

In this section, we review the design and performance of spectral splitting for PV receivers. Most, but not all, of such systems have been designed for concentrated radiation. These designs can be classified into two categories: proof of concept and integrated designs. At the proof of concept stage, concentrating devices are not "*optimally*" combined with the beam splitting zand/or receiver components. The main aim of such research is to evaluate the effect of spectral splitting on the efficiency of PV cells. Thus, this research feeds into and helps to improve the performance of the second category—integrated designs. The designs in the latter category are aimed at configurations with more manufacturability and/or less cost.

2.1.1. *Proof of concept designs*

The configuration of a typical concentrating spectral splitting PV system consists of a concentrating device such as a lens or a dish [41] combined with a spectral splitter close to the focal region of the concentrator. The splitter acts as a selective mirror to create two different focal points. The splitter may have a curved surface rather than a flat one to address the effects associated with non-collimated rays on the wave interference filters [37]. An advantage of using curved mirrors is shifting the focal point of the concentrating system to provide a suitable geometry for locating the receivers [42–46]; otherwise, the receivers could cause shadowing and thus optical losses.

In theory, dividing the spectrum into many bands and directing each band to a matched cell can achieve very high solar conversion efficiencies. In order to verify this, Zhao and Sheng divided the spectrum into three [47] (excluding the monolithically separation of light in the tandem cell) and five bands [48] as shown in Fig. 2b and Fig. 2d respectively using consecutive selective mirrors. Their systems achieved 38% and 35.6% efficiencies at 2.8 × concentration in three and five band systems, respectively. Presumably, the added complexity of increasing the number of sub-bands resulted in a lower total practical efficiency. Xiong et al. [49] suggested that to achieve high efficiencies through practical systems, the solar spectrum should not be divided into too many bands because the splitting losses will affect the total efficiency of the system. Spectral splitting losses include sloped transition from reflection to transmission, non-ideal cut-off wavelengths, and reflection losses of the mirrors. For example, the efficiency of the system shown in Fig. 2c can decrease by 3% if the transition range (the spectral range between highly transmissive to highly reflective regions) of the filter increases from 10 nm to 100 nm [49]. In addition to the splitting effects, different p–n junction arrangements in the systems similar to Fig. 2 can significantly change the total efficiency. For example, Morki et al. [50] used an arrangement similar to Fig. 2c with a Si/Ge dual junction cell and a GaAs single junction cell showing that different p–n arrangements of the cells can theoretically result in a 2.76% efficiency change.

Non-ideal cut-off can occur because of the effect of the light incident angle on the filter, the limited number of deposited layers, and manufacturing inaccuracies in filter fabrication process [40]. Fig. 2 shows that the incident angle on the spectral splitter in concentrating configurations can vary significantly. Hence, the geometrical configuration should be optimised to minimise or account for such incident angle variation.

Some researchers have attempted to combine light trapping with spectral beam splitting to decrease the reflection losses of the optical devices in spectrally splitting systems. For example, Mitchell et al. [51] proposed the configuration shown in Fig. 3a. In this system, the reflection losses can be minimised because any light reflected from the surface of a beam splitter or a cell will be captured by another one. Although the figure shows the configuration under non-concentrated sunlight, the receiver can be optimised to work under concentration as well.

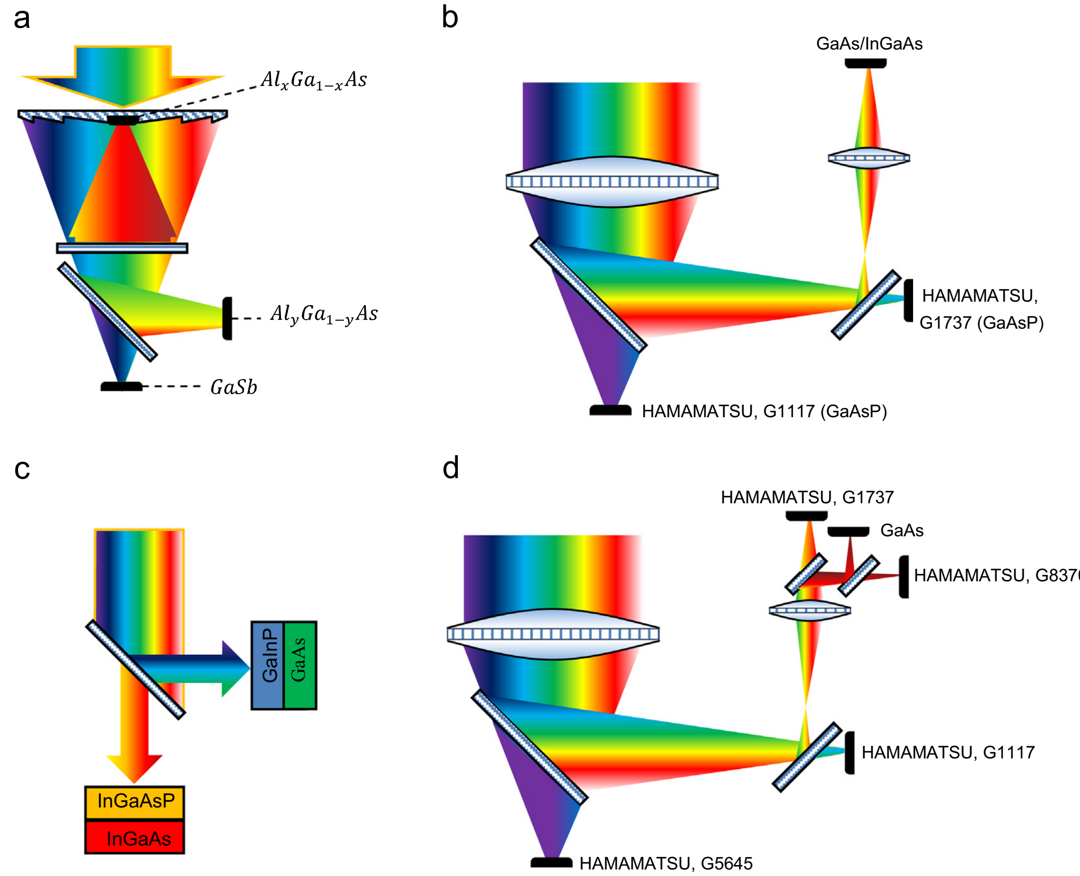

Fig. 2. Spectral splitting for PV conversion of sunlight. (a) A concentrating PV system enhanced by two dichroic mirrors dividing the spectrum into 3 bands; $0.3 \leq x \leq 0.35$ and $0 \leq y \leq 0$ [94]. (b) A concentrating PV system utilising two dichroic mirrors and one tandem cell dividing the spectrum into four bands [47]. (c) A non-concentrating PV receiver with one dichroic mirror that splits the sunlight into two bands which are monolithically separated again in the tandem cells resulting in conversion of light in four separate bands [49]. (d) A concentrating PV system utilising four dichroic mirrors dividing the spectrum into five bands [48].

Unlike the configuration presented in Fig. 3a, the design in Fig. 3b [52] is capable of collecting light from a large aperture area. Here, total internal reflection is used to trap the light inside the optical receiver and just one type of dichroic mirror is used to split the light between high and low band gap PV cells. When light hits the long pass filter, the long wavelength range of the spectrum is transmitted through the filter and absorbed by the low band gap cell. The short wavelength range is reflected to the high band gap cell. On the other hand when light hits the high band gap cell, the short wavelength range is absorbed by the cell and the longer range is transmitted through that and reflected by the highly reflective mirror at the back of the cell to the low band gap cell.

In order to take advantage of concentrated illumination in light trapping, Goetzberger et al. [53] suggested configurations as presented in Fig. 3c. The light is concentrated by the lenses and then sent through a tiny opening into the trap. The radiation inside the trap is transformed into diffuse light using randomising Lambertian (diffuse) reflectors. Each solar cell inside the trap is covered by a band pass mirror which transmits the optimised wavelength and reflects the rest of the spectrum. All other surfaces inside the trap are highly reflective.

A photonic structure with angular selectivity of not less than 0.27° (which is the angle subtended by the sun) can replace the top reflector and the concentrating lenses (Fig. 3d). In this case all radiation inside the cone with the above angle will enter the light trap and be reflected by the diffuse reflector. Since the acceptance angle of the photonic structure is very small, the major part of the reflected light will be trapped inside the structure resulting in concentration of sunlight without the need of lenses. However, this method does require two-axis tracking.

Another option to decrease the optical losses is to concentrate and split the light in a single stage using a single device. The advantage of this arrangement is that it decreases the number of interfaces and consequently the reflection losses. Such a device, shown in Fig. 4, can be made of a set of prisms implemented on a curved surface [54] (Fig. 4a) or dichroic concentrating mirrors (Fig. 4b) to produce spectral splitting and concentrating effects at the same time.

2.1.2. Integrated designs

Incorporating concentrators, waveguides, and various receivers in a practical compact system can be challenging. The external design should aim at reducing wind loads, increasing light acceptance, and providing satisfying aesthetics. Moving parts should be minimised as much as possible. A possible solution to address these challenges is using planar concentrators [55–58] or an array of small concentrating devices combined with spectral splitters [59–62] (Fig. 5).

In a compact configuration, eliminating the shadowing problems from components is essential in achieving high efficiency [63]. The arrangement shown in Fig. 5a could suffer from shadowing effects induced by the top cell and the splitter, while the arrangements shown in Figs. 5b and c addresses this problem.

A project to build a planar spectral splitting concentrated PV system with over 50% conversion efficiency was proposed by Barnett et al. [64,65] in 2006. The preliminary design of the system

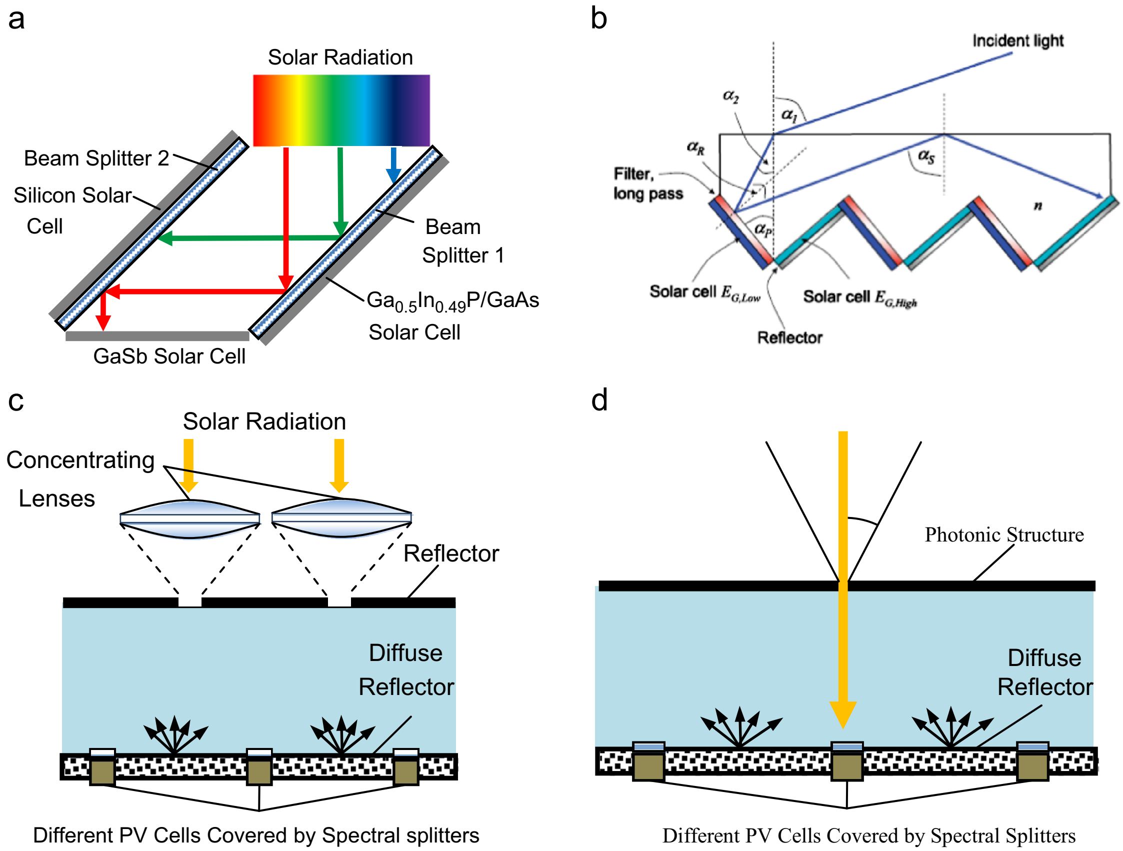

Fig. 3. Spectral splitting in light trapping PV receivers. (a) A light trap enhanced by two dichroic mirrors and three different solar cells in a 45° parallelepiped form [51]; beam splitter 1 and 2 transmit the wavelengths shorter than 850 nm and 1080 nm respectively and reflect the rest. (b) A light trapping receiver using total internal reflection; just one type of dichroic mirror is required for this configuration (shown by the red rectangle); long wavelengths passing through the high band gap cells are reflected by the simple mirror at the back of them [52]. (c) Spectral splitting for PV conversion using a set of concentrating lenses, a light trap, and small spectral mirrors [53]. (d) A light trapping receiver with a photonic structure with acceptance angle of θ replacing the concentrating lenses and the top reflector of the design in (c) [53]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

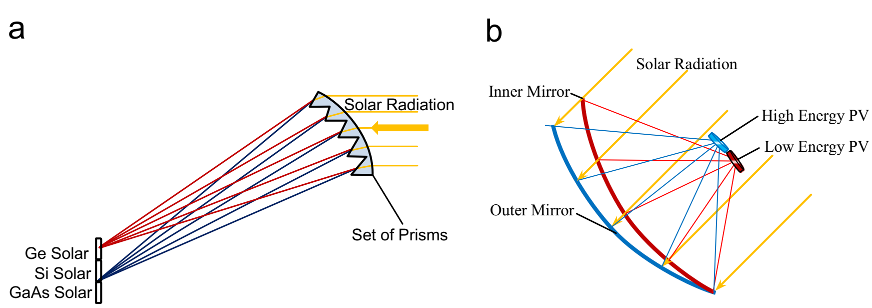

Fig. 4. Combining spectral separation and light concentration into a single stage. (a) A concentrating PV system with spectral separation using a set of prisms; 100 × and 17.5 × concentration levels for monochromatic and polychromatic (between 730 nm and 1000 nm) beams respectively were achieved [54]. (b) A concentrating PV system comprising a dish shaped 1 m^2 reflector made of two layers of faceted mirrors to create two focal points 20 cm off each other; Inner mirror reflects wavelengths above 650 nm and transmits below that; the outer mirror reflects all wavelengths [75].

is shown in Fig. 5c. The total efficiency of such configurations is equal to the product of the optical and cell modules efficiencies [66–69]. The system achieved a maximum total efficiency of 39.1% at 30 × concentration [70].

By changing the type of Si cells used in the system to UNSW's ZT-1-4E (PERL) Si cells, the efficiency of the cell (not the total efficiency) was shown [71] to be increased to 43.0 ± 1.9% because of better spectral match of the cells and higher conversion efficiency of the PERL cells. Moreover, options for improving the optical efficiency were proposed which would increase the total efficiency further. These options included using efficient anti-reflection (AR) coatings on the concentrating surfaces, optimising the dichroic mirror, decreasing the reflection losses from the dichroic mirror, and decreasing the reflections from different interfaces by immersing all components in silicone [72].

A significant portion of sunlight is missed in concentrating devices since they are not able to capture the diffuse component. A non-concentrating planar receiver as shown in Fig. 6a [73] can collect the global radiation.

A novel method to help capture diffuse radiation in concentrating systems is to use selective mirrors to concentrate the sunlight [74]. Such mirrors can be short-pass mirrors and since the diffuse component contains mainly the shorter wavelengths it can transmit through the mirror and be absorbed by a high band gap cell at the back of the mirror (Fig. 6b). The design proposed in this figure is an example of configurations that combine spectral

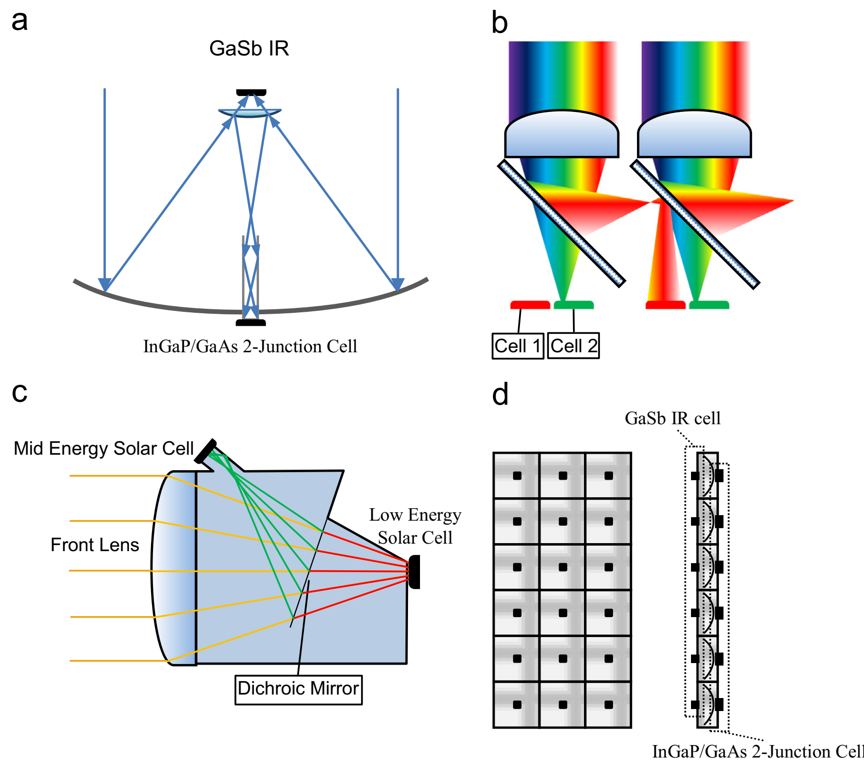

Fig. 5. Planar concentrating spectrally splitting PV systems. (a) A concentrating PV system using a Cassegrainian concentrator, dichroic hyperbolic mirror, and a light guide [95]. (b) A compact spectral splitting concentrating PV system consists of two types of cells which can be packed into larger compound planar collectors; each module consists of a concentrating lens which is integrated with a dichroic reflector [96]. (c) A concentrating PV configuration with less optical losses; the mirror has been located at an angle of 24° with respect to the optical axis of the front lens to address the shadowing problem of the Mid-E cells [72]; the whole optical component has been made of the same material to reduce optical discontinuities and alternatively Fresnel losses (d) a planar collector comprised of an array of the small modules mentioned in a. Modules similar to those mentioned in b and c can also be packed into the same array.

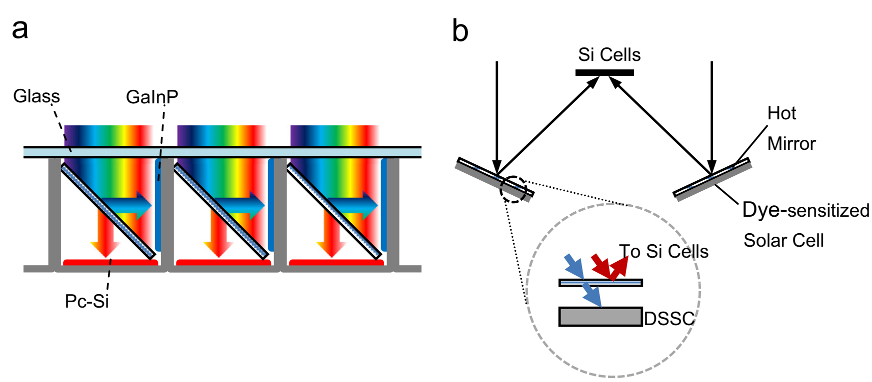

Fig. 6. Spectral splitting devices capable of capturing the global (diffuse and direct) radiation. (a) A non-concentrating PV receiver; the mirror was made of 48 layers of TiO_2 and SiO_2 with cut-off wavelength at 675 nm [73]. (b) The hot mirrors reflect the long band to Si cells and transmit the short one to DSSC (Dye-Sensitised solar cell) [74].

splitting and concentration of sunlight into a single stage [75] (however the diffuse component is not concentrated).

Table 1 summarises some of the important results of the outcomes of different papers. It should be mentioned that some papers have not reported any measured value for their designs and have relied on mainly theoretical predictions. Also not all papers presenting measured efficiencies have explained their measurement procedures in detail. Hence, some inaccuracy should be expected from some of these values. For research that has included optical losses in its reported efficiency, the total efficiency has been cited.

2.2. Spectral splitting in hybrid receivers

In concentrating PV applications, the cells require cooling (either actively or passively). One method that reduces the cooling requirement is to filter the spectrum so that only the wavelengths where the cell works most efficiently (and hence generates the least heat) are used. In this case, the aim is not to use the whole spectrum by PV cells, but to reduce undesirable heating. For example, Maghanga et al. [76] introduced a cut-off mirror made of a layer of TiO_2:Nb and a layer of Al_2O_3 deposited on a substrate of aluminium. This mirror reflects 75.6% and 28% of sunlight below and above 1100 nm (near the band gap of Si), respectively. The non-reflected radiation can be absorbed and delivered as useful heat. Segal et al. [77] investigated the feasibility of implementing spectral splitting in solar power towers to cogenerate electricity and heat through separate PV and thermal receivers (Fig. 7a).

A challenge associated with wave interference splitters in solar power towers is the effect of significant variation of angle of

Table 1
Summary of selected beam splitting devices in the literature; "Number of Bands" refers to the bands that are created by the spectral splitting filter. This may be different to the number of PV receivers because, for example, in some cases multi-junction PV cells are used to capture a band.

Reference	Type of radiation	Cell types	Number of bands (of the splitter)	Calculated efficiency	Measured efficiency	Aim of research
Mokri and Emziane [39]	Concentrated	AlGaAs/Si, InGaAsP/InGaAs	2	26.8%	Not-tested	Proof of concept
Mokri and Emziane [40]	Concentrated	Ge, AlGaAs	2	18.7%	Not-tested	Proof of concept
Mokri and Emziane[41,42]	Concentrated	GaAs/Ge, Si	2	25.71%	Not-tested	Proof of concept
Zhao and Sheng [45]	Concentrated	GaAsP1, GaAsP2, GaAs/InGaAs	3		38%	Proof of concept
Zhao and Sheng [46]	Concentrated	GaAsP(470 nm), GaAsP(600 nm), GaAsP(700 nm), GaAs, InGaAs	5	42.7%	35.6%	Proof of concept
Xiong et al. [47]	Non-Concentrated	GaInP/GaAs, InGaAsP/InGaAs	2	31.8%	29.2%	Proof of concept
Khvostikov et al. [38]	Concentrated	AlGaAs, GaAs, GaSb	3	49.4%	39.6%	
Fraas et al. [93]	Concentrated	GaInP/GaAs, GaSb IR	2	32.4%	32.9%	Integrated design
Barnett et al. [95]	Concentrated	GaInP/GaAs, Si, GaInAsP/GaInAs	2	Not provided	42.7% ± 2.5%	Integrated design
Barnett and Wang [68]	Concentrated	GaInP/GaAs, GaInAsP/GaInAs	2	Not provided	39.1%	Integrated design
Green and Ho-Baillie [69]	Concentrated	GaInP/GaAs, Si (PERL), GaInAsP/GaInAs	2	43%	Not-tested	Proof of concept
Wilcox et al. [96]	Concentrated		2	39%	38.5% ± 1.9%	Integrated design
Ruhle et al. [71]	Non-Concentrated	Pc-Si, GaInP	2	18.4%	Not-tested	Integrated design
Barber et al. [72]	Concentrated	Si, Dye-Sensitised Cells	2	20%	Not-tested	Integrated design
Vincenzi et al. [73]	Concentrated	Si, GaInP	2	29.5%	Not-tested	Integrated design
Mitchell et al. [49]	Non-Concentrated	GaInP/GaAs, Si, GaSb	3	Not provided	34.3%	Integrated design

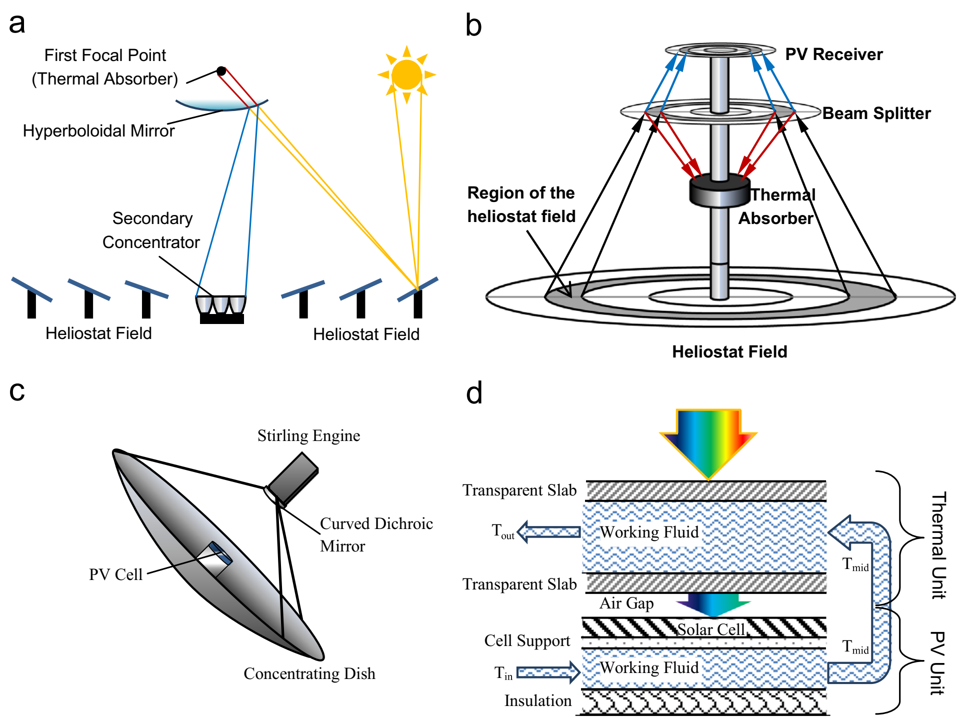

Fig. 7. Spectral splitting in hybrid receivers. (a) Spectral splitting in solar power towers using a hyperboloidal mirror with a radius of 23.8 m; 70% of the radiation can be captured effectively [77]. (b) Hybrid solar power tower enhanced by a flat dichroic mirror optimised for the effect of incident angle on the beam splitter [78]. (c) Hybrid collector consisting of a dish concentrator, PV cell, and a Stirling engine; the filter was made of 78 layers of TiO_2 and SiO_2 to provide a reflective window from 600 nm to 1050 nm; a combined efficiency of 28% at about 600 suns concentration level can be achieved [83]. (d) Schematic of a hybrid solar collector using a selective absorbing/transmitting fluid; T_{in} and T_{mid} are inlet and outlet temperatures of the solar cell cooling channel; T_{out} is the outlet temperature of the hybrid collector.

incidence on the receiver due to the large area of heliostats (Fig. 7b). A potential solution for addressing this problem is dividing the beam splitter into small segments and optimising each one according to the weighted mean angle of incidence [38,78,79].

Spectral splitting can also be implemented in parabolic troughs. For example, Jiang et al. [80,81] used Nb_2O_5 and SiO_2 to fabricate a spectral splitter to produce electricity through PV cells and a high quality thermal output with temperature in the range of 250–400 °C in a hybrid parabolic trough; however they have not reported the expected electrical output from the PV cells.

Similar to heliostats, dish concentrators can provide high concentration ratios but on smaller scales—up to 100s of kW. This makes them suitable for hybrid devices which are required to deliver high temperature output [82]. For example, Shou et al. [83] developed a spectrally splitting hybrid dish concentrating system which combines Si cells with a Stirling cycle to produce electricity (Fig. 7c). A major shortcoming of such hybrid systems is the slow response of the engine to transient conditions. This can be addressed by replacing the engine by a thermoelectric generator (TEG) [84]. However, current TEGs have very low efficiencies compared to other electric generators.

Ju et al. [85] developed a method based on a 1-D heat transfer model to include the influence of concentration ratio and PV cell temperature in hybrid PV-TEG systems. Since the spectral response of TEG devices is relatively constant across the solar spectrum, the cut-off wavelength of such hybrid systems is driven by the PV cell module only [86]. Implementing TEG devices in solar receivers will be competitive when the figure-of-merit of TEG devices can be increased to about three [87].

The last hybrid collector method presented here uses a selective transmission/absorption medium (Fig. 7d). In such systems, a filter (which can be a liquid or solid layer) which is transparent to wavelengths suitable for PV cells and highly absorbing in the rest of the spectrum is used to filter out the light. If a liquid is used, it can also act as the heat transfer fluid.

Chendo et al. [88] originally proposed the concept of selective absorption by heat transfer liquids for hybrid solar collectors in 1986. Recently, Jiafei et al. [89] and Otanicar et al. [90] presented a numerical one dimensional heat transfer and radiation model to optimise the optical properties (absorption characteristics) of a semitransparent heat transfer fluid suitable for a direct, selective absorbing hybrid solar collector.

A major shortcoming of such systems is the lack of available liquids with suitable optical properties. However, nanofluid-based heat transfer liquids which incorporate nanoparticles to achieve tuneable optical properties have shown potential in addressing this issue [91,92]. Such nanofluids can be produced at low nanoparticle volume fractions (e.g. much less than 0.1%), which indicates that it may be possible to design low cost nanofluid filters.

The possibility of employing spectral splitting in producing biofuel has been studied conceptually by Redwood et al. [93]. For this potential application, spectral splitting of sunlight can be implemented to overcome the problem of co-culturing different organisms which are sensitive to different wavelengths of sunlight. For example, spectral ranges suitable for green algae and purple bacteria are complementary. However, co-culturing these two organisms is not practical since photosynthesis by green algae captures CO_2 to produce oxygen, whereas photosynthesis by purple bacteria is inhibited by oxygen. A beam splitter can divide the spectrum and direct each band to the separate containers of these bioreactors to culture them in a more compact system.

3. Conclusion

We have presented a comprehensive review of recently published research outcomes in the field of spectral splitting for solar energy conversion. Many exciting proof of concept designs have been demonstrated in recent years which have considerably raised the bar for high energy conversion efficiencies (regardless of manufacturability and cost). At the same time, recent work has focused on introducing designs which show promise as commercial products. In the future we expect there will be many cases where the outcomes of these two groups can merge into successful commercial spectrally splitting solar collectors. We believe that is a likely outcome if the following issues can be techno-economically overcome and/or addressed:

- Concentrating devices such as dish and parabolic concentrators miss the diffuse component of global radiation. This incurs a significant loss which occurs especially in the short, high energy wavelengths.
- Non-ideal spectral splitting can cause some photons to be sent to the inappropriate receiver and reduce the total efficiency. The cost of fabricating quality splitters with tight optical tolerances should be balanced with the efficiency gain of the system.
- Dividing the spectrum into many bands can increase the splitting losses due to non-ideal behaviour of the filters.
- Concentrating spectral splitting systems create a distribution of incidence angles on the wave interference filter. This can result in deviated reflection/transmission characteristics.
- Reflection losses from the concentrating lenses could be minimised through efficient AR coatings.
- The number of transparent interfaces along optical paths should be minimised in order to keep the total Fresnel losses low. This can also be achieved by immersing the whole collector in a high refractive index, yet transparent, medium such as silicone.
- Short wavelength receivers are more sensitive to the daily and seasonal variation of spectrum. Hence the spectrum should be split in such a way that takes the time varying spectrum into account.
- Optimum integration of the concentrator, splitter, and receivers into an engineered package can result in a more compact, thinner receiver which could prove advantageous during manufacture and operation.
- Using direct selective absorption as a spectral splitting method in hybrid receivers could also help to avoid difficulties related to the manufacturing cost and operation. Initial research has identified some promising materials (solid and liquid) for this approach.

Author contributions

A.M. devised the study, gathered data, and prepared the manuscript and the figures; E.T. and R.T provided references, helped with organisation, reviewed, and edited the manuscript. G.R. supervised and led the research, evaluated the quality of the work, and carried out the final revision.

Acknowledgements

The authors would like to thank the University of RMIT and UNSW for hosting this research. The authors would like to thank the Australian Solar Institute and the Australian government for supporting this work and for providing a fellowship to A. Mojiri.

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