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Spectral beam splitting technology for increased conversion efficiency in solar concentrating systems: a review

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Abstract

Solar concentrating systems that employ one or more quantum receivers may realize improved energy utilization and higher electric conversion efficiency by incorporating spectral beam splitting technology. Such techniques were investigated in thermophotovoltaic conversion, introduced in the early 1960s, and in concentrating PV devices using cells of different band-gap materials, proposed as early as 1955. One major application was found in systems combining quantum and thermal receivers. This article presents a review of the various solar hybrid beam splitting systems proposed in the literature and the different spectrum splitting strategies employed.

Keywords: Solar concentration; Hybrid systems; Beam splitting; Conversion efficiency; Literature review

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1. Introduction

A hybrid solar energy conversion system refers in general to any combination of chemical, electrical, or thermal energy conversion processes which may increase the overall utilization of the incident broadband solar spectrum. One of the main types of solar concentrating hybrid systems discussed in the literature are those which combine photovoltaic (PV) and photothermal conversion, producing electricity in

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combination with useful thermal energy. The PV cell is still considered the most expensive component in a photovoltaic conversion system, but concentrating devices may offer cost benefits by reducing the amount of PV area required to convert a given amount of solar power.

Accompanied with increasing concentration levels is also a potential rise in PV cell temperature, which is an undesirable effect since this reduces cell efficiency. It is therefore necessary to provide cooling of the cells to maintain reasonable efficiencies. However, heat transferred away from the solar cells may be utilized for low temperature heating purposes. Another option is to use spectral beam splitting, directing only part of the solar spectrum onto the PV receiver. This substantially reduces the heat load on the cell and also opens up a possibility for placing additional solar converters in the part of the beam that is directed away from the PV cells, with a corresponding increase in system efficiency.

Increased conversion efficiency in a photovoltaic receiver system can be accomplished by (a) shifting the solar spectrum toward wavelengths more efficiently converted by the PV cell, as seen in thermophotovoltaic (TPV) and luminescent concentrators; (b) stacking PV cells of different band-gap material in series or parallel to absorb a larger part of the solar spectrum; and (c) splitting the solar spectrum to run photovoltaic and thermal processes in parallel, combining moderate to high-temperature thermal conversion with efficient PV conversion.

This paper will give an overview of the different spectral beam splitting strategies proposed in the literature and present the reader with a review of selected solar hybrid systems that have employed such strategies. A major part of these systems are purely theoretical, and in cases where it is not clear whether the presented results have been experimentally verified, it should be assumed that the values represent model predictions.

The block-diagram in Fig. 1 shows an outline of the development in solar concentrator beam splitting technology that will now be discussed. The beam splitting concept is introduced in Section 2, followed by more detailed discussions on TPV systems in Section 3, PV systems in Section 4, PV/thermal systems in Section 5, and a recently proposed thermally selective system in Section 6, with a general discussion and conclusion in Sections 7 and 8.

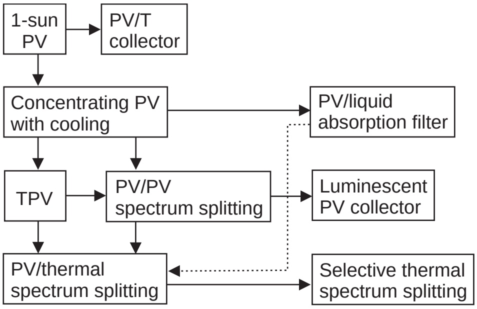

Fig. 1. An outline of the development of solar concentrating beam splitting systems.

2. The beam splitting concept

Photothermal processes tend to convert solar energy to heat with an efficiency that is relatively constant over the solar spectrum, depending only on the optical properties of the window and/or coating of the thermal receiver employed. Photovoltaic conversion, on the other hand, is highly wavelength-dependent and most efficient when converting photons of energies close to the PV cell band-gap energy. Photons below the band-gap energy pass through the active area of the cell without being absorbed, and are ultimately dissipated as heat in other parts of the cell. Photons of energy larger than the band-gap can only be partly utilized, and the remainder of their energy is also dissipated as heat.

Because of these factors, an optimal method of using solar cells is to direct onto them only the part of the solar spectrum for which high conversion efficiency can be achieved, and to recover the radiation outside this range by diverting it to a second receiver, i.e., thermal, chemical, or a different PV band-gap receiver. This is the underlying concept of PV/thermal solar hybrid systems, where the incident beam is split into PV and thermal spectral components as illustrated in Fig. 2.

Several filtering techniques for PV cells have been described in the literature; the main categories include all-dielectric and metal-dielectric multilayer filters [1–3], heat reflectors [4,5], refraction or prism spectrum splitting [6–8], holographic filters [9–11], fluorescent methods [12–14], and liquid absorption filters [3,15,16]. In PV-only systems, filtering techniques can be carried out using either the tandem-cell approach in which two or more solar cells of different semiconductor materials are mechanically or monolithically stacked in series and arranged in order of decreasing energy band-gap [17–19], or the spectrum splitting approach in which an optical filter separates the light into spectral components directed onto individual cells of different band-gap energies [20–22].

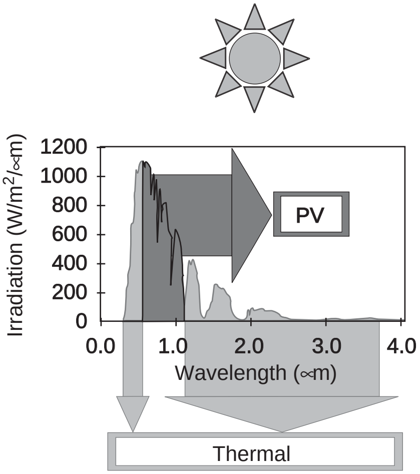

Fig. 2. Splitting the solar spectrum into components for PV and thermal energy conversion.

The PV cells can alternatively be bonded to the surface of a thermal solar collector in a so-called PV/T system, where one part of the spectrum is filtered out by the PV cells for electricity production and the residual is transmitted to a heat transfer fluid for thermal applications [23–25]. A similar method has been used for thermoelectric devices to extract waste heat by cooling and thus maintain a high temperature gradient across the device, which results in improved conversion efficiency [24,26]. The electric conversion efficiency for PV/T and thermoelectric receivers is constrained by the increase in temperature of the cooling medium, which is in direct thermal contact with the solar conversion device, and will not be further discussed here.

3. Thermophotovoltaic energy conversion

The first attempts to use spectral beam splitters as a means of increasing the efficiency of solar energy conversion may be traced back to the invention of the TPV converter in the early 1960s. In the TPV concept, a high-temperature energy source heats up a ‘‘black body’’ cavity, which re-emits radiation at a lower temperature. PV cells immersed in the cavity will absorb the emitted photons of higher energies and produce electricity. The longer wavelengths that cannot be utilized by the cells are reflected back to the radiator by a spectrally selective filter, allowing the energy to be recycled as heat.

The reason for adopting this two-step conversion process, as opposed to direct solar illumination of the cells, is the capability to control the spectral characteristics and the power level of the incident radiation. Due to its lower temperature, the spectrum of the radiator is shifted toward longer wavelengths with respect to the solar spectrum, thus avoiding losses at short wavelengths where the PV cells are not effective. However, efficient recycling of unused long wavelength radiation becomes a critical issue if high conversion efficiencies are to be achieved. Various semiconductor materials have been considered for TPV conversion; the most suitable materials appear to be those of low band-gap values which provide a better spectral match with the lower temperature thermal radiation sources contemplated for use in these systems.

Most of the early research was concerned with TPV systems where fossil fuels or radioisotopes provided the input energy, and the US Army played a significant role in advancing this technology due to a need for portable, low-noise power sources. But the energy crises that struck in the 1970s brought new requirements for fuel economy, and while fossil-fuel powered TPV development came to a virtual halt, solar TPV research was given a boost [27–30]. The reader is referred to Nelson [31] for a further reading on the historical development of TPV technology.

According to White et al. [32], the TPV converter was first presented by Pierre Aigrain during a lecture series as a visiting professor at the Massachusetts Institute of Technology, Massachusetts, in 1960/1961. Wedlock [33] demonstrated improvements in the TPV conversion efficiency by band-limiting the radiation incident on the PV cells to the region of maximum collection efficiency near the energy gap. He suggested a coaxial arrangement with a central radiator and photovoltaic cells placed along the outer walls, as shown in Fig. 3. A thin-film optical filter placed between the radiator and the PV cells allowed residual reflection to be utilized as heat.

A series of variations on the TPV concept followed, investigating the possibilities of using spectral selectivity to increase conversion efficiency. Werth [34] and Kittl and Guazzoni [35] suggested using a more advanced multilayer interference coating with germanium cells, whereas Bracewell and Swanson [36] and Swanson [29] investigated silicon cells with a silver plate heat reflector, placed at the back of the cells.

The solar TPV system proposed by Swanson is illustrated in Fig. 4. Concentrated sunlight from a primary parabolic mirror was incident on a secondary compound parabolic concentrator (CPC), which increased the solar flux to about 20,000 suns to allow cavity temperatures as high as 2000–2400 K. The PV converter, consisting of silicon p–i–n cells, received concentrated radiation at a level of 300–500 suns. The cells were kept below 70°C by active cooling and incorporated back-silvered surfaces for reflection of IR radiation back to the emitter.

Whereas system modelling had predicted TPV cell conversion efficiencies of up to 40–50% under these conditions, laboratory tests achieved a maximum of 26% for a radiator operating at 2300 K. The complete system was however not built, and the

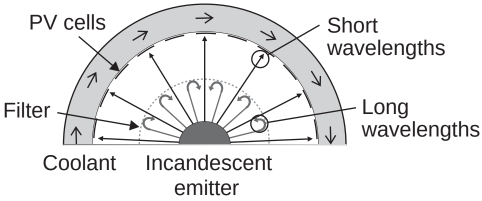

Fig. 3. Early coaxial TPV design with optical filtering [33].

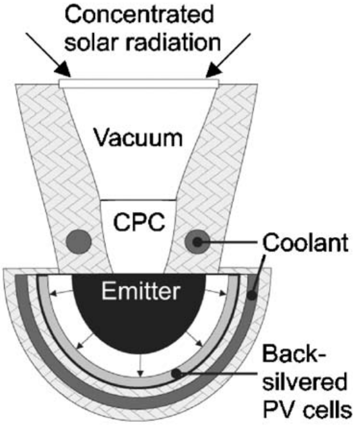

Fig. 4. A solar TPV design proposed by Swanson [29].

overall solar TPV conversion efficiency is thus not known. Swanson pointed out that although operation at such high temperatures allows a larger percentage of photons to fall within the useful PV range, stringent requirements are imposed upon the materials used and rapid oxidation may shorten TPV converter life markedly.

A different solar TPV configuration suggested by Horne [30] involved a Cassegrainian system in which a paraboloidal primary reflector and a hyperboloidal secondary reflector directed solar radiation in through a window of a black body cavity. As illustrated in Fig. 5, the cavity consisted of a paraboloidal ceiling which provided more uniform illumination of the emitted light and redirected the light towards PV cells attached to a flat wall at the back.

The requirements on mirror optics and alignment in a Cassegrainian system are in general quite stringent in order to have the focal point appear below the primary mirror, such as shown in Fig. 5. The system will suffer from increased Fresnel losses as the beam is reflected twice, then passed through a window to enter the high-temperature cavity. This particular design also requires an additional reflective surface within the cavity to redirect the emitted light, which adds to the optical losses, while uniformity may still be an issue as the emitter view factor of the center cells is different from that of the peripheral cells.

Oglesby and Crackel [37] proposed a spectral converter having much in common with the TPV configuration, but rather than tailoring the incident radiation for PV conversion, the idea was to shift the spectrum to UV frequencies within the range 105–400 nm and transport it through light guides for utilization in a chemical dissociation cell. The light would pass through a small window to a high-pass dielectric filter, before being collimated and coupled to the optical light guide.

There are several potential problems with this approach. A small window in the cavity wall would transmit only a fraction of the radiation field within the cavity, implying that very high temperatures and radiation densities are required if a substantial amount of radiation is to pass through to the light guide. The cavity walls would need to withstand high temperatures while providing high reflection of both UV and heat radiation. In practice it would be difficult to find suitable materials for the optical management system, i.e., lenses, dielectric filter materials, and fiber-optic guides, operating at high temperatures and being highly transparent in the UV. Special UV-grade synthetic fused silica is transparent only down to about 200 nm and available at a relative high cost. A major challenge is to collimate and couple

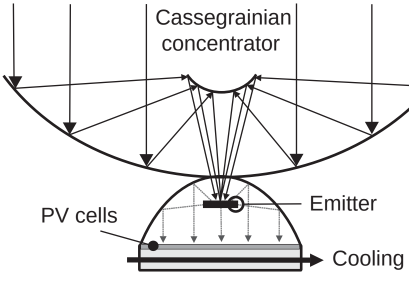

Fig. 5. Cassegrainian solar TPV system presented by Horne [30].

light efficiently into the light guide. The number of components connected in series would in practice limit the overall efficiency achieved by this system. It is questionable whether there would be any gain in cost or performance over a solar concentrator producing electricity for dissociation by more traditional means.

Other proposed TPV systems include the use of high-temperature thermal storage systems, for instance, Ref. [38–40]. Shown in Fig. 6 is a solar TPV system with thermal storage for terrestrial or space applications, proposed by Schmitt et al. [41]. Concentrated sunlight is trapped within a cavity receiver containing the thermal storage medium, with the emitter located at the rear end of the cavity. The aperture reflector is equipped with shutters to reduce spillage of concentrated light. Absorbed energy is conducted into the thermal storage material, and as its temperature increases, so does the emitter temperature with consequent emission of light.

During the warm-up time, shutters placed in front of the PV cells are closed. The shutters are coated with an IR filter that reflects thermal radiation back towards the emitter surface to be re-absorbed. When operation temperature is reached, one or more of the cell shutters are opened and in-band radiation is passed through to the PV cells for electricity generation. These shutters are also used to regulate the power generation according to the demand. When input solar radiation is declining, the aperture shutters close to prevent loss of energy from the receiver cavity while the power generation continues using the thermally stored energy. If necessary, alternative fuel sources are supplied when solar input is low.

The estimated peak power conversion efficiency of this system is 27–51%, but this may correspond to rather optimistic figures. A very similar TPV system with silicon storage had earlier been proposed by Chubb et al. [42] and Stone et al. [43], with calculated steady-state efficiencies in the range of 15–17% under ideal conditions, dumping the PV cooling waste heat to the atmosphere. The detailed design and implementation of these systems have not been further discussed by the authors. The primary concerns for space applications are reliability and lifetime in the space environment, compactness and low weight, and provision of steady power for the operation of equipment on a 24 h basis.

Optical bandpass filters suitable for placement between the TPV radiator and the PV cells were investigated by Bell [27] and Demichelis et al. [28,44]. Demichelis et al. looked specifically at all-dielectric and dielectric-metal-dielectric (DMD) broadband filters with a high visible and low infrared transmittance, for use with high temperature radiators and various cells. The thin film filters were optimized using layer thickness refinement methods and the DMD-filter was chosen in an optimum TPV configuration. However, considerable absorption losses at short wavelengths,

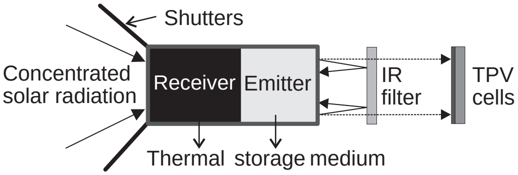

Fig. 6. Solar TPV system with thermal storage [41].

caused by the filter metal characteristics, imposed limitations on the efficiency of the design.

Demichelis et al. [45] and Höfler et al. [46] suggested applying a DMD-filter directly to the solar cell surface, eliminating the need for a separate optical filter and requiring a smaller number of layers to give a similar result. This approach has been pursued and successfully implemented with new semiconductor technology, as Fraas et al. [47] recently reported the application of simple dielectric filters deposited directly onto each PV cell at the wafer level before wafer dicing.

During the last decade, alternatives to the traditional dielectric multilayer filters and back-surface reflectors have been investigated [48,49]. These include plasma filters, which may be combined with multilayer dielectric edge filters to reflect photons in the range between the plasma wavelength and the band gap of the converter; and resonant filter arrays which appear to be highly suited to the filtering of IR light in TPV applications.

Horne et al. [48] have reported efforts of utilizing advances in the capabilities of e-beam and masked ion-beam lithography to make a high density array of antenna elements etched into or deposited onto a metal film, causing inductive or capacitive resonance, respectively. The filter performance can be adjusted to the response of a given PV cell via changes in antenna element length, density, and line width, and exhibits broadband, angular insensitive reflectance to out-of-band photons (e.g., 98–99% for a gold film). The performance of an antenna filter in combination with GaSb PV cells was measured to 13%. This value was expected to reach 20% with near-term improvements in fabrication technology. Although a promising result, the production costs may turn out to be excessively high due to the small antenna dimensions, which must be of the same order as the wavelength of the radiation.

In real TPV (and PV) systems there are also other issues than that of spectral filtering that may limit the performance. A challenge is the relatively large PV area illuminated with high flux, which results in high current densities accompanied by high parasitic power losses that are only worsened in low-band-gap devices. Ward et al. [50] have reported efforts to fabricate prototype GaAs-based monolithic interconnected modules (MIMs) with gold back-reflectors, suitable for TPV applications. The MIMs are comprised of a number of small PV devices, series-connected during the fabrication process to increase the voltage and limit the current generated under high-intensity illumination. An efficiency of 16.8% was measured for the prototype device, and future optimized MIMs are expected to exceed 20%.

Recent research has looked into alternative ways of creating highly selective emitters in TPV systems. There is evidence that three-dimensional photonic crystals may be used as selective emitters with substantially enhanced TPV energy conversion efficiency, see for instance Gee et al. [51] and Lin et al. [52]. Another interesting new concept is thermophotonics (TPX), shown schematically in Fig. 7, where a light-emitting diode powered by an externally applied voltage acts as an extremely selective emitter [53].

For each radiative recombination of an electron–hole pair, the luminescent diode in a TPX system emits a photon of more than the band-gap energy, even though the electron–hole pair has been injected into the diode at a bias voltage of only a fraction

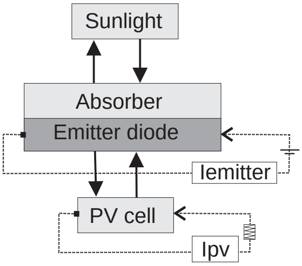

Fig. 7. The concept of thermophotonics [53].

of the band gap. The excess heat is provided as heat at the contacts, resulting in refrigerating action of the diode. Hence, if the diode and its contacts are thermally connected to a hot body, the luminescence of the diode provides a means for radiating heat from the hot body at "superthermal" power densities onto the PV cell. This comes at the cost of electrical energy used for biasing the emitting diode; however, for a sufficiently high external electro-luminescence quantum efficiency the increase of the power density is much larger than the electrical power consumption. If the emitter diode is short-circuited, it emits purely thermal radiation. In this case, TPX becomes equivalent to conventional TPV, with a selective emitter or a filter providing narrow-band radiation onto the PV cells, and TPX can therefore be regarded as a generalization of TPV.

Harder and Green [54] have shown that, for conversion of solar energy at realistic absorber geometries, TPX has substantially higher theoretical conversion efficiency than TPV. Furthermore, the suitable band-gap energies are greatly enhanced towards larger values over that of the TPV. An essential requirement, however, is a very high external electro-luminescent quantum efficiency, and such quantum efficiencies have not yet been achieved. For the practical realization of TPX there are also difficult technological challenges associated with the high-temperature regime and the stability of materials.

There has in the last few years been a renewal of interest in TPV-based generation of electricity, mainly due to the availability of new high performance cells based on the semiconductors from the III–V family. In particular, low-band-gap GaSb cells absorb radiation out to 1.8 ìm and are well suited for use with commercially available low NO_x SiC radiant tube burners that operate at up to 1250°C. Several small TPV prototype systems, primarily based on the combustion of hydrocarbon fuels, have been built for residential combined heat and power generation. TPV electric conversion efficiencies of about 2–3% are reported [55,56].

For cogeneration purposes, including the hot water and space heating thermal energy that may be extracted from the exhaust fumes and the PV cooling may give overall system efficiencies as high as 80–90% [57,58]. For TPV applications on a larger scale, Fraas et al. [59] suggest an inverted TPV cylindrical configuration suitable for insertion into large existing furnaces, such as those used in melting industrial operations or in apartment buildings. As shown in Fig. 8, the TPV tube is

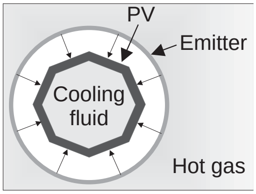

Fig. 8. Inverted TPV receiver [59].

heated on its outer surface, while water-cooled PV cells are placed on the inside, facing outward towards the emitter. Results of pilot experiments using GaSb cells and a furnace operating at 1150°C resulted in a TPV electrical conversion efficiency of about 11%.

Since the early days, numerous papers and reports have been published on TPV conversion systems, and a majority of these discuss fundamental limits and theoretical aspects of approaching the ideal conversion efficiency [60–63]. A bibliography on TPV papers published between 1960 and 1995 has been compiled by Broman [64], and the reader may consult Coutts [65] for a comprehensive review of state-of-the-art TPV systems. Although the idealized TPV converter is capable of very high efficiency, it is inevitable that a real system consisting of 4 or 5 separate components will suffer from severe thermodynamic losses.

There is also a tradeoff between power output and efficiency; as the bandwidth incident on the PV cell is narrowed, the cell efficiency approaches ideal but the power output falls toward zero. The predicted efficiencies for real TPV systems lie in the 5–15% range [65]. Whereas these systems cannot claim the conversion efficiency of their direct conversion counterparts, they still offer advantages for niche markets [66]. At present, most funding for TPV is aimed at military agencies where cost is not a pressing issue and features like fuel versatility, low weight, quiet operation, and high power density make TPV an attractive option.

4. Photovoltaic spectrum splitting systems

Very high conversion efficiencies can be achieved by directing different parts of the solar spectrum onto PV cells with matching energy absorption bands. In theory, efficiencies in the range of 85% are possible [67,68]. This may be realized either by stacking the cells on top of each other in an optical and electrical series connection, commonly called a cascade, tandem, or multijunction cell, or placed next to each other in a parallel connection. The tandem cell is illustrated in Fig. 9A. Sunlight is incident on the largest band-gap cell where short-wavelength photons excite electrons to a higher potential. Light not absorbed by the upper cell is transmitted to the second cell of a smaller band-gap value, where longer wavelengths will excite electrons to a potential somewhat lower than in the first cell. In theory, any number of different cells may be stacked on top of each other to fully utilize the incident solar spectrum.

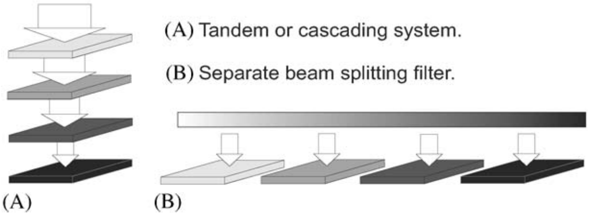

Fig. 9. Two schemes for PV spectrum splitting.

In monolithic tandem cells, tunnel junctions provide series connections which allow the voltages of the stacked cells to be added. Alternatively, a metal grid structure may be used to interconnect the cells for a high voltage output. A larger voltage and smaller current means smaller resistance losses at high concentrations. Another benefit of the tandem cell is that only a single load and power-conditioning circuit is required, and there is no need for separate optical filters. However, tandem systems face difficulties with current and lattice matching, as well as cooling issues since the top cell is normally cooled via the connection to the bottom heat-sinked cell.

Fig. 9B shows the alternative solution where the cells are placed in parallel; in this case, light is separated into spectral components by a beam splitting filter and is directed onto individual cells of corresponding band-gap energies. In this way, each cell can be separately designed and manufactured on unique, optimized substrates without concern for substrate transparency or lattice mismatch. There are no constraints on the currents flowing through each of the cells; hence, the spectrum splitting approach has a slightly higher theoretical efficiency than that of the cascading approach, assuming ideal beam splitting optics. The increase in efficiency is so small, though, that this may not be the determining factor [69].

Furthermore, there are several loss factors associated with the introduction of realistic dielectric beam splitting filters, e.g., sloped transition edges between reflective and transmissive regions which cause mixing of wavelengths at the different PV cells, Fresnel optical losses, angular sensitivity, and misalignment issues. Of the two spectrum splitting approaches mentioned, the tandem cell is by far the most commonly widespread technology today, mainly due to the cost-related advantages arising from mainstream semiconductor production techniques and from avoiding the cost of advanced discrete optical components.

The multi-layered solar cell approach was first mentioned by Jackson [70], who calculated the case of a 3-layer PV tandem cell capable of 69% energy utilization. However, at that time only one-sun illumination was considered and the added complexity could not be economically justified. The development of the multi-gap concept did not get much attention until the mid-1970s, when higher efficiencies and power densities were demonstrated in concentrating solar cell systems [18,19,69,71–73].

Experience gained from concentrator PV and TPV research stimulated the development of both cascading and spectrum splitting PV receivers, which effectively spanned the solar spectrum. Several studies followed on the optimization of multiple PV cell systems, their fundamental efficiency limits, and possible implementations, see for instance [20,67,74]. A review of the PV tandem cell development is beyond the scope of this paper. Instead, an overview is given of some of the systems that have proposed to use spectrum splitting techniques to operate separate PV receivers in parallel.

4.1. Transmissive and reflective filtering methods

Cape et al. [75] and Masden and Backus [21] studied a two-cell system in which the concentrated incident solar spectrum was split between GaAs and Si cells by a dielectric multilayer dichroic mirror. Predicted theoretical efficiencies were around the 30% mark, and a similar practical device reported by Vander Plas et al. [76] measured efficiencies of 27% at 113 suns concentration and 26% at 489 suns concentration, using Si and AlGaAs cells.

Moon et al. [77] considered the same system of Si and AlGaAs cells in combination with a computer-optimized dielectric multilayer filter, fabricated on a polished, fused silica substrate and mounted at 22° to the incident beam. The filter and cells were tested experimentally, giving a total efficiency of 28.5% at 165 suns and AM1.23 spectrum, which represented a marked improvement in performance compared to the single PV receiver systems. For an ideal filter this corresponded to 31% efficiency for the two cells combined. Allowing for losses in the concentrator optics and filter, the system efficiency was estimated to 25%.

The first demonstration of this spectrum splitting system at PV module level was presented by Borden et al. [78,79]. The modules were equipped with point-focusing, curved-groove, facet Fresnel lenses with transmittance of about 80% and a geometric concentration ratio of 477 suns. A dichroic mirror mounted below the lens would transmit light to the high-band-gap AlGaAs cell (~10% optical loss) and reflect light to the low-band-gap Si cell (~5% optical loss). Although the spectral performance of the dichroic mirror was lower than expected due to a fabrication error, the best module measured a solar-to-electric conversion efficiency of 20.5% at AM2 spectrum, not including the thermal recovery from the AlGaAs-cells operating at around 100°C.

If compared to the best GaAs and Si modules at the time, measured at 17% and 12% efficiency, respectively, the spectrum splitting module represented a 20% (GaAs) and 70% (Si) improvement. However, after lens transmission and beam splitting, the radiation arriving at each of the PV cells was reduced to an energy concentration ratio well below 200 suns. This was not sufficient for economic operation of the system. The two main factors that were found to contribute to excessive cost were the filter and the long focal length design, which had been chosen to minimize the effect of non-uniformities across the PV cells but also meant that more materials were needed and a tracking accuracy better than ±1° was required.

Spectrum splitting PV systems were also considered an attractive solution for power generation in space. Onffroy et al. [22] discussed a high-efficiency, concentrating multi-solar-cell system for orbital power generation, using several dichroic mirrors in series to divide the solar spectrum into the desired spectral bands. A two-stage optical concentration system consisting of a Cassegrainian and a CPC, both assumed to a have a reflection loss of 10%, was chosen to meet the design specifications of 1000 suns under AM0 spectrum for each of the PV cells. Ideal efficiencies were calculated for optimum band-gap materials, ranging from about 32% for 1 cell to 53% for 4 cell systems. Non-ideal efficiency calculations using realistic system design parameters were also performed; for the four potential solar cell materials Ge, Si, GaAs and GaP efficiencies up to about 33% were predicted.

Onffroy et al. concluded that the 4-cell system would not be cost-effective, since the assumed 10% transmission loss of each dichroic mirror reduced the overall potential increase in efficiency to a point where the associated system cost was too large. The most cost-effective configuration consisted of a single dichroic beam splitter with GaAs and Si solar cell arrays, generating 100 kW of power at an efficiency of about 28%, and a radiator which removed excess heat to keep both of the solar cell arrays at an operating temperature of 300 K. The main cost was found to be that of the primary mirror and the radiator, whereas the solar cells costs were almost negligible.

In a spectrum splitting configuration considered by Ellion [80], the solar cells were mounted in a non-coplanar arrangement so that the beam would be directed serially from one cell to the next by means of reflection from a silver surface at the back of the cell, each cell extracting energy from the incident light beam and ideally passing onto the next solar cell the portion of the beam not converted to electricity. A practical arrangement of four different band-gap cells was proposed, expected to obtain solar-to-electric conversion efficiencies of up to about 50%.

Fig. 10A illustrates a hollow triangular mounting structure with cells mounted on adjacent sides, the cells having their active interfaces lying at an angle to each other to avoid total internal reflection. The cells facing the sun are transparent to the portion of the light not utilized by the cells, whereas the remaining cells inside the cavity have back-silvered coatings to reflect non-absorbed light. Fig. 10B is in the shape of a parallelogram with at least one solar cell mounted on each side. The hollow core of the support structures allows heat to be radiated away from the solar cells or, alternatively, a coolant to be passed down the center of the structure.

Ellion has not specified whether the receiver is intended for a linear or point focus concentrator design, but the use of four different band-gap cells suggests that a point focus will be needed to justify the cost of materials. Apart from high tracking accuracy, high-quality optics would be required in order to produce an intense

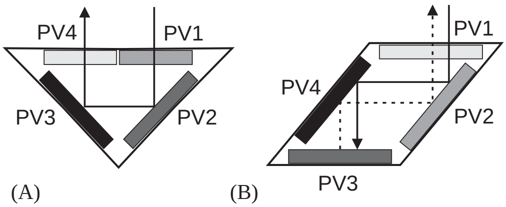

Fig. 10. PV cascade splitting in a non-coplanar configuration [80].

collimated beam that impinges normally onto the first, high-band-gap PV cell surface, which ensures that the solar rays follow the intended path within the receiver. Scattering and defocusing of the collimated light could become a problem if the PV surfaces are not smooth or the cells contain defects. The connection of metal leads and efficient cooling of the cells under high flux intensity, in particular of the selectively transparent front cells, represents a technical challenge that has not been further discussed by the author.

The alternative is a linear or low concentration system with long focal length, where the divergence of the beam stays small within the receiver and cooling will be less of an issue. The incident solar radiation would still have to be kept normal to the aperture or image enlargement and beam spillage would occur. It is unlikely that the latter would be a cost-effective system, although reducing the number of different band-gap cells within the receiver could be considered.

More recently Ortabasi et al. [81] presented a design for a photovoltaic cavity converter (PVCC) with the objective to achieve solar-to-electric conversion efficiencies of 50% for a four-cell spectrum splitting configuration. The PVCC was originally developed for space power generation [7] based on the idea of concealing the solar cells within a radiation-hardened cavity with a small aperture to protect the PV array against the space environment. The space power system employed a Cassegrainian design where the chromatic separation of the solar spectrum was achieved by a continuous gradient index lens covering the second stage hyperboloidal mirror. The lens selectively defocused and rejected the below band-gap energy photons to reduce the thermal load on the PV cells, while the above band-gap photons remained focused and entered the cavity receiver. In the terrestrial system however, a more advanced spectrum splitting procedure is performed using different dielectric filters attached to each of the PV cell surfaces [81]. The suggested system consists of a primary dish concentrator and secondary concentrating optics providing highly focused solar flux (~20,000 suns), and a PV-cavity receiver with internally reflecting walls. The solar radiation enters the cavity and is effectively trapped, as shown in Fig. 11. The surface of the interior cavity wall is coated with a dielectric material having a high average reflectance in the solar spectrum. After several bounces in the cavity the flux is evenly distributed, reaching equilibrium at about 500 suns. The solar cell array inside the cavity is actively cooled and consists of multiple single-junction PV cells with different, but complementary band gaps spanning almost the entire solar spectrum.

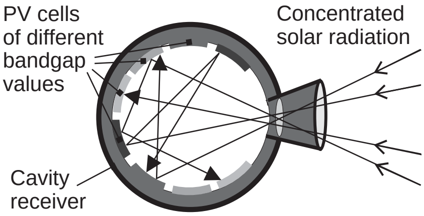

Fig. 11. Photovoltaic cavity converter [81].

Individual cells are covered with high-quality rugate filters, transmitting only the portion of the solar spectrum that matches the spectral response of the cell underneath and reflecting the rest. The high concentration of sunlight allows the use of complex filters and multiple PV materials, although there are still technical challenges that need resolving before a cost-effective product is available for the commercial market. The rugate filter is an interference coating based on a refractive index that varies continuously in the direction perpendicular to the film plane, and is well known as a high-quality, low loss filter for narrow-bandwidth applications.

The fabrication of broadband rugate filters, however, remains a challenge yet to be overcome. The production of four complementary, high-quality bandpass filters may, at least initially, be a costly affair. Furthermore, the photons bouncing around within the cavity will in general impinge on the PV cells at high incidence angles, which reduces the performance of the rugate filters. The (flat) PV cells must also be mounted in small modules in order not to substantially alter the spherical shape when inserted into the cavity walls.

4.2. Refractive and absorptive filtering methods

A prism will refract and disperse incident white light into a rainbow of colors. As illustrated in Fig. 12, a PV receiver assembly may use refractive elements to direct spectrally dispersed light onto PV cells of matching band-gap energies (Spring, [82]; Dettling, [83]). A collimated incident beam is required in order to prevent overlap of spectral bands on the different PV cell materials.

A practical prism arrangement may take the shape of a sawtooth Fresnel lens, as discussed in some recent studies where a line-focus of spectrally separated beams is incident on horizontally aligned sub-arrays of associated PV cells [8,84]. Penn [8] estimates achievable conversion efficiencies of 45–60% for such a line-focus concentrator system operating at 100–500 suns and incorporating 5–6 different single band-gap cells. This system achieves high concentration by combining a first lens or mirror, which provides a relatively high linear concentration along a first north-south aligned axis, with a second, orthogonal lens that tracks the daily motion of the sun along an east–west direction. The second lens splits the beam spectrally and may also perform a small degree of concentration to increase the overall effective concentration.

A one-axis pointing concentrator with seasonal adjustments of the other axis requires misalignment tolerant optics, and Penn suggests to use reflective surfaces

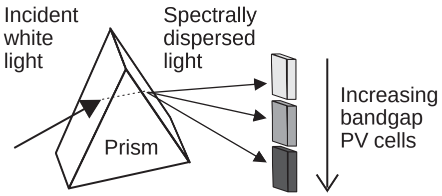

Fig. 12. Prism spectrum splitting.

disposed adjacent to the cells to maximize the intensity and uniformity of solar flux. The allowable pointing errors will nevertheless have to be kept to a minimum in order to maximize collection efficiency. The two-lens arrangement was chosen to provide high concentration at a reasonably low manufacture cost; however, because multiple cell sub-array lines are required instead of the single line in a system without a prism, the practical efficiency increase must be very high to offset the extra PV cost as this can be severe when using non-silicon cells in a line focus system. Further considerations include the assumption that each row of identical band-gap PV cells should be of a different height, and inefficiencies that may be caused by gaps between cells and shadowing by electrical contacts.

Absorption filters typically consist of a liquid contained within a transparent glass tube or channelled through thin glass plates. The liquid selectively absorbs the wavelengths not utilized by the PV cell and converts the energy to heat, which is transported away by the liquid filter itself. As long as the liquid is not in contact with the solar cell, reasonably high efficiencies may be attained since the maximum allowable temperature is not constrained by the operation of the PV cell [3,15,16,85].

For space applications, Powell [86] proposed a foldable parabolic trough reflector system with concentration of radiation onto a tubular thermal receiver containing a liquid absorption filter. The collected thermal energy would be used in a heat engine or for a heat load supply. The radiation not absorbed by the filter was transmitted through to a PV receiver, as shown in Fig. 13. The circulating liquid contained a scattering agent, e.g., small glass micro-spheres suspended in the fluid, to provide more uniform flux incident on the PV cell. This solution would however require some means of redirecting the scattered light onto the surface of the PV cell, and back-scattered light would be lost.

Sabry et al. [16] performed systems simulations to identify the ideal liquid absorption filter characteristics for operation with a Si concentrator cell. The optimum filter was found to have a transmission range of 450–920 nm, equivalent to 59% of the incident energy at AM1.5 spectrum. The ideal filter resulted in a 30% predicted increase in cell efficiency compared to an unfiltered cell under 7 suns concentration, accompanied by a potential thermal gain of up to 40% from the liquid absorption filter. The temperature of the thermal component was not discussed by the authors, and for a complete analysis it would be necessary to take into account the effects of thermal losses, pump power, filter reflection losses and non-ideal absorption.

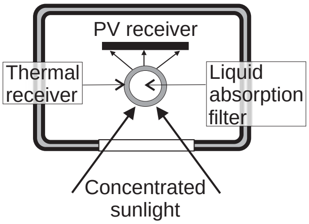

Fig. 13. PV cell receiver with liquid absorption filter [86].

Practical liquid absorption filters suitable for use in combination with PV cells have been studied by Osborn et al. [2] and Chendo et al. [3]. The materials were selected according to requirements of a satisfactory spectral response, solubility and stability within a range of temperatures, and environmental safety. The spectral response of more than 30 samples of optical liquid filters were tested across the solar spectrum between 300 and 1500 nm, either singly or combined, and the inorganic salts of cobalt, cupric, and nickel were found to have suitable spectral characteristics within the desired optical window.

Cobalt sulfate showed a nearly ideal optical response match to a Si cell, its thermal stability was verified in laboratory tests with temperatures ranging between 50°C and 200°C, and the filter did not lose its water of crystallization until 420°C. Also, a commercial high-temperature organic heat transfer oil, Brayco 888 HF, was measured and found to have sharp absorption edges at 600 and 1100 nm, suitable for light transmission to a Si cell in a PV/thermal system. The authors emphasized that many other commercially available heat transfer fluids remain to be characterized, and further studies of matching specific filters to specific quantum converters would be needed to establish cost-effectiveness on a case-by-base basis.

4.3. *Luminescent filtering methods*

Luminescent concentrators for solar cell applications were suggested in the mid-1970s, a concept which can be seen to follow on from the TPV and PV research aiming at enhancing the solar cell conversion efficiency by means of spectral control. A useful review of the physics and applications of fluorescent concentrators has been compiled by Zastrow [87]. These devices offer only low efficiency and low concentration of sunlight, but the cost of generating electricity may be reduced by concentrating both direct and diffuse radiation using inexpensive plastic sheets that require no tracking of the sun.

In principle, a fluorescent dye placed inside a planar transparent concentrator plate absorbs sunlight within a frequency range f_1 and emits light within a frequency range f_2 with close to 100% quantum efficiency. Most of the fluorescence light is trapped inside the concentrator due to total internal reflection and is guided to the edges of the plate, where it can be converted to heat or electricity by thermal absorbers or solar cells. Loss of light is prevented by applying a reflective coating on the edge faces not used for light collection. The light emitting edge area of the plate is much smaller than the light absorbing area, resulting in concentration of light.

About 75–80% of the fluorescence is typically trapped by total internal reflection in a plate of refractive index about 1.5 [14,87]. The luminescent concentrator may have the dye incorporated in the entire bulk of the plate, or a thin film incorporating the dye may be deposited in close contact with the transparent plate to reduce parasitic losses due to self-absorption and scattering from impurities. Luminescence intensity is typically directly proportional to concentration of the dye material, however, if the concentration is too high, light cannot pass through to cause excitation at larger depths.

For the monochromatic output of a single dye, a higher PV cell efficiency may be achieved but there is also a solar energy loss of incident photons not absorbed by the dye, so that no real gain is produced. Higher photon absorption may be achieved by doping the luminescent concentrator with several dyes or stacking differently colored concentrator plates on top of each other, allowing light to be converted with spectrally adapted solar cells.

The first suggestion to use fluorescent concentrators for the conversion of solar energy was made independently by [88] and Götzberger and Greubel [13]. For a single sheet luminescent concentrator, Weber and Lambe estimated an overall efficiency of about 10% using either a Neodymium-doped glass sheet with a Si cell receiver, or a soluble organic dye with a GaAs cell receiver. Götzberger and Greubel provided a more comprehensive background study of the concept, and introduced the idea of splitting the solar spectrum into separate wavelength bands by means of stacking collectors with different dye contents. The proposed system used collectors that were transparent to the non-absorbed part of the spectrum, and each plate was coupled to a solar cell of band-gap energy matching the emission band of the particular dye.

Stacking four collector plates with four different solar cells (Ge, Si, GaAs, and GaP) in series, the maximum conversion efficiency was estimated to be 32% under optimum conditions and AM1 spectrum [13]. Taking conditions under diffuse light into account, even more favorable results were obtained. For a composite spectrum of 60% diffuse and 40% direct radiation, corresponding to the yearly average radiation of central Europe, a theoretical conversion efficiency of about 38% was calculated [89]. The authors pointed out that these are theoretical values, unlikely to be reached in practice. With more realistic assumptions for the system losses and component efficiencies, the use of four different band-gap material PV cells would most likely not be a cost-effective option at the low concentrations implied.

A luminescent concentrator system such as described by Götzberger and Greubel [90] is illustrated in Fig. 14. The first concentrator plate receives the full solar spectrum and absorbs the shorter wavelength component, which is converted into fluorescent light of somewhat longer wavelength and passed onto a large band-gap PV cell mounted at the end of the plate. The non-absorbed light is passed through to a second concentrator plate, which converts a longer wavelength range into fluorescent light for a smaller band-gap PV cell. Using concentrators repeatedly arranged in series with adapted solar cells, the ideal overall conversion efficiency is increased. Radiation that passes through the concentrator plates without being absorbed may be collected by a thermal receiver and utilized as heat.

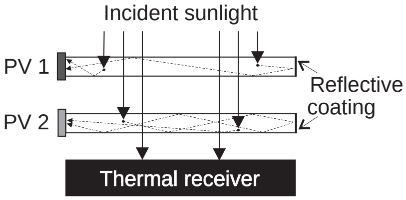

Fig. 14. Luminescent concentrator plates coupled to PV cells [90].

Reisfeld and Neuman [91] continued the work on this fluorescent concentrator, and disclosed a practical arrangement using three doped glass layers for CdS, GaAs, and Si cells that obtained an experimental solar-to-electric conversion efficiency of about 3.5–4.5%. This was considered a comparatively high efficiency for a non-tracking PV conversion system. Wittwer et al. [92] achieved a similar result when measuring the electrical efficiency of a stack of two fluorescent sheets coupled with Si and GaAs cells. The total efficiency reached a maximum of 4%, but as these cells were not optimized for the dye materials available at the time, conversion efficiencies of about 10% at an energy concentration factor of about 10 were predicted in an improved system.

There has not been a real breakthrough in PV energy conversion using luminescent concentrators. A number of energy loss mechanisms restrict the optical efficiencies to values far below the theoretical limits. Loss factors include reflected and transmitted light, non-ideal absorption quantum efficiency, Stokes shift (proportional to $f_1 - f_2$), overlapping absorption and emission bands, and scattering of light. Collisions and resonant energy transfer with other molecules will result in the loss of excitation energy as heat instead of as emitted light. An increase in temperature will affect the luminescence, as an increase in molecular motion causes more frequent molecular collisions and subsequent loss of energy. A major challenge is long-term photo-stability of the fluorescent dye, as most of the available dyes are subject to severe degradation, in particular in the UV region.

Nevertheless, research and development is continuing in this area and a range of luminescent concentrator designs have been suggested over the years. Amongst the alternative approaches proposed is the direct deposition of amorphous Si solar cells on the edge of the luminescent concentrator plate, or in similar fashion, the deposition of luminescent layers on the surface of the PV cell in an order of succession such that the light falling upon the outermost layer is transferred in cascade through the individual layers to the solar cell [12,93]. The problem here would be how to guide the light through to the PV cell without substantial losses, as light is absorbed and re-emitted randomly in all directions.

A recent suggestion to use quantum dots in replacement of the traditional dye materials holds promises of a revival of interest in the old concept, see for instance Barnham et al. [94] and Chatten et al. [95]. Quantum dots are nanometer-sized crystallite semiconductors which have advantages over dyes in that the absorption threshold and the red-shift between absorption and luminescence can be tuned by adjusting the size of the dots. Providing that the dots can be incorporated in suitable transparent media and retain their high quantum efficiency, minimization of re-absorption may give performances up to about 20% for a single luminescent concentrator.

4.4. *Holographic filtering methods*

In 1980, McGrew presented a new type of solar collector system which allowed simultaneous concentration and splitting of the incident spectrum by a single holographic optical element (HOE) [9,96]. The spectrally dispersed light was directed onto an array of PV cells of different semiconductor materials, arranged to make optimum use of the available sunlight. Light outside the optimum spectral range for PV conversion was reflected away from the cells, either to be disposed of or utilized as heat. McGrew suggested to manufacture the HOE as a surface relief hologram, created by recording the interference between two mutually coherent wavefronts to work in either transmissive or reflective mode, as illustrated in Fig. 15.

The holographic concept was already well known, but the development of new manufacturing techniques, such as those used in the volume phase and stacked holograms, made it a more attractive option for solar applications. In the volume phase hologram, a permanent pattern was recorded as variations in the refractive index of the material, providing the desired diffraction of light with little or no absorption of energy by the hologram itself. Reflective holograms effective over a wide spectral bandwidth were fabricated by adding several holograms, each with maximum reflectivity over a different spectral region, to provide high reflectivity over the entire spectral range. Some important theoretical considerations for the application of holographic filtering techniques were discussed by Kogelnik, Alferness and Case, and Welford and Winston [97–99].

The first attempts to use holographic techniques for solar energy applications involved stationary collectors performing so-called ‘‘passive tracking’’ with concentration of light onto suitable receivers at given angles of incidence. Bloss et al. [10] demonstrated the use of high-efficiency volume phase transmission holograms in which several holograms were superimposed at various recording angles in one photosensitive layer. The volume hologram was recorded in dichromated gelatin (DCG) plates and encapsulated to prevent degradation by exposure to the environment. An experimental setup employed a doubly exposed holographic plate focusing the incoming solar radiation on a high band gap and a low band-gap solar cell. Ignoring Fresnel reflection losses, monochromatic diffraction efficiencies of up to 97% was measured for this hologram.

Further improvements were reported by Jannson and Jannson [100], claiming DCG Bragg reflection holograms with diffraction efficiencies close to 99.7% and optical scattering/absorption losses below 0.2%. Over a 3-year period, the so-called US Department Of Energy Holoconcentrator Program had measured and documented the characteristics of more than a thousand holograms. These reflection holograms ranged from narrow-band (10–20 nm bandwidth) to broadband (up to 300 nm bandwidth), well suited for spectral splitting purposes in solar applications.

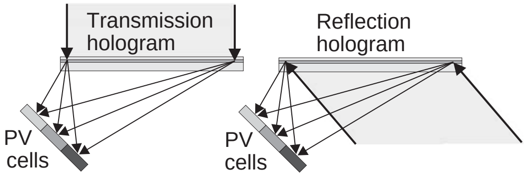

Fig. 15. Transmission and reflection holograms, splitting the sunlight into multiple bands for PV cells [9,96].

A unique foil technology was developed to produce compact multi-holograms in a sandwich structure which included more than 200 layers.

Polychroic spectrum splitting holographic concentrators with 85% optical efficiency were achieved using this foil technology, for a concentration ratio of 1000 within the visible and near-IR spectral region. Material stability was found to be sufficient for solar applications, with thermal stability up to 120°C, mechanical flexibility, and resistance against humidity, UV-radiation and chemical degradation, given the proper hologram encapsulation.

In Fig. 16, a polychroic mirror considered by Jannson and Jannson [100] is shown splitting the solar spectrum into three components with an ideal average optical efficiency of 96%. Using a red-enhanced Si cell together with GaAs and AlGaAs cells, the computed efficiency was 26.7% for this system. The assumptions made for this calculation were not clearly stated, but it seems clear that it would be difficult for a practical system to reach the reported efficiency. Potential problems mentioned by the authors include unwanted holographic gratings created by a non-ideal recording process, and aberrations in the optical system. Furthermore, the angular distribution of incident light and thermal effects under high concentration must be taken into account. Practical holographic filters operating at high broadband efficiency in real solar applications have not yet been demonstrated.

Although shown to provide high diffraction efficiencies, holographic filters may suffer from similar problems to those experienced by thin film dielectric mirrors (i.e., smooth spectral transition edges, Fresnel losses, angular sensitivity and alignment issues). Tholl and Stojanoff [101], investigating reflective broadband holograms for multiple PV receivers, reported problems with noise and undesired interference effects from the different holographic layers. Discussions on solar holographic concentrators working in either transmission or reflection mode were continued by Afyan et al. [102], Bainier et al. [103] and Stojanoff et al. [104].

An optimization technique for the design and manufacture of large aperture holographic lenses was developed by Stojanoff et al. [105,106] and Wagemann et al. [107]. The method involved a mosaic design consisting of individually optimized holographic segments assembled into a composite hologram. Although cross-coupling effects and aberrations were still present, experimental results confirmed that improved process control facilitated the manufacture of a large area ($\sim 1\,\mathrm{m}^2$)

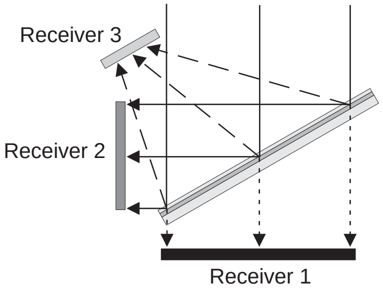

Fig. 16. Polychroic holographic mirror splitting the spectrum into three parts [100].

asymmetric transmission hologram with 90% diffraction efficiency and zero shift of the Bragg angle. Some of the fabricated HOEs exhibited apertures of up to 8 m^2. The fabrication method facilitated control of bandwidth between 15 and 400 nm, and control of operating wavelength between 300 and 1000 nm [106]. Fabrication methods of broadband holographic filters have also been discussed by Wreede et al. [108] and Riccobono and Ludman [109].

Fröhlich et al. [110] presented preliminary results from the fabrication and testing of a $50 \times 50\,cm^2$ PV concentrator composed of a stack of two holographic lens arrays, operating in the short and long wavelength spectral band for high and low band-gap PV receivers, respectively. Each lens array was composed of 7×7 single lenses focusing solar radiation at a geometric concentration ratio of 49 onto an array of $1 \times 1\,cm^2$ PV cells, arranged in a common plane as illustrated in Fig. 17. The two holographic lens arrays were arranged in succession and shifted in position with respect to each other to compensate for the shift in focal length experienced by the different spectral bands.

The holographic lens was successfully fabricated and laboratory experiments verified the efficient diffraction and focusing of the incident radiation onto the solar cells, provided a maximum illumination divergence of ±1 degree. No test results were reported for the full PV concentrator, but computer simulations performed for the AM1.5 spectrum at $1000\,W/m^2$ resulted in efficiencies of 9.63% for a GaAs cell array and 12.74% for a AlGaAs cell array, giving a total efficiency of 22.4%. A critical parameter for the efficient operation of this concentrator is a low divergence of illumination, which in practice implies a 2-axis tracking system to keep the incident rays normal to the surface of the concentrator. Although cost savings can be made in the production of the holographic concentrator, the tracking requirements and expenses associated with using non-silicon PV cells may prohibit the cost-effectiveness of the system at the relatively low concentration achieved.

Ludman et al. [11] proposed a PV solar collection system employing a lightweight, single-element, thick transmission hologram, aimed at both terrestrial and space applications. The output appeared as a thin concentrated line (~20×), focused perpendicular to the hologram and displaced to the side, as shown in Fig. 18A. Solar cells were placed along this line according to the wavelength range most efficiently converted to electric power by the cells. Infrared radiation was deflected away from the cells to reduce the heat load. The hologram was fabricated in DCG and sealed between two sheets of the substrate material for environmental protection.

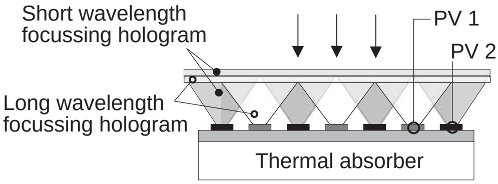

Fig. 17. Holographic lens for two-cell PV operation [110].

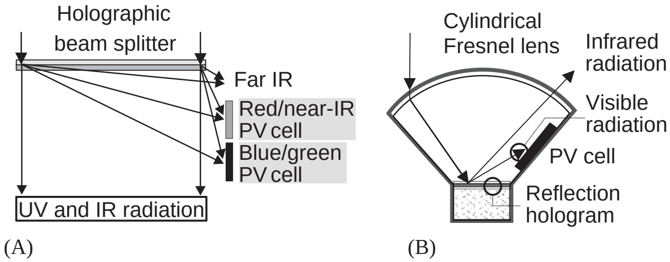

Fig. 18. Line-focussing holographic system for PV cell receivers [11,111].

Experimental evaluations revealed that essentially the whole visible spectrum could be diffracted with a single hologram about 2–3 μm thick. According to the authors, the advantage of using a single thick hologram, as opposed to a stack of holographic layers, is that cross-coupling effects and aberrations can be avoided. A single-axis tracking design suggested for terrestrial applications [111] is shown in Fig. 18B. Here, a reflection hologram is employed which diffracts away the unwanted infrared radiation, thereby reducing the cooling load. No experimental results have been provided, though, for the practical implementation and operation of the suggested systems.

Stojanoff et al. [106] discussed a hybrid holographic collector with Cassegrainian concentrating optics. In this design, the reflective hologram was pasted onto the surface of the hyperboloidal mirror, redirecting radiation onto a solar cell placed in the lower focus and transmitting radiation to a thermal evacuated tube absorber positioned in the upper focus of the hyperboloidal mirror. Holograms for use with different cells (GaInP, GaAs, AlGaAs, and Si) were analyzed, and simulations of the hybrid system predicted efficiencies of up to 19% electric from a GaAs PV cell receiver and 24% thermal at 120°C from an evacuated tube receiver, allowing a maximum angular tracking error of $\pm 1^\circ$.

The suggested Cassegrainian design would increase the concentration of energy incident on the PV cell, with a corresponding reduction in required PV area and hence cost for a given power output. The added cost of reflector materials as well as the effect of increased Fresnel losses would have to be weighted against the gain in PV power. The high tracking accuracy required may not be achieved in a one-axis linear system, in which case the filter performance will degrade with possible serious implications for the system economy.

Other applications of spectrum splitting holograms include glazing and daylighting. The standard window glazing may be replaced with a holographic window that diffracts the incident sunlight onto the ceiling, illuminating the back of the room [106,112]. A demonstration project utilizing light-directing holograms for both daylighting and PV power generation in buildings was discussed by Müller [113,114]. This technique has also been suggested used in greenhouses to direct light onto the plants from the sun-facing walls and roof, while allowing the other walls to be heavily insulated, thereby reducing heat loss. Bradbury et al. [115] refer to experimental results that show a 50% reduction in heating costs with a 10% reduction in yield.

Stojanoff et al. [106] proposed to use reflective holograms for shading purposes. The holograms were designed to transmit the low winter-sun (incidence angle 20–30 degrees) and block the radiation in summer (incidence angle 40–60 degrees). A prototype device was designed as venetian blinds having lamellae coated with a 2-layer holographic filter. The lamellae had to be positioned at 45 degrees relative to the window's normal, and the device was found to be rather cumbersome in use. A second prototype device was thus developed, consisting of only a single holographic layer that was integrated into the window pane. Promising results for the transmission characteristics of candidate holograms, tested in a solar simulator, were reported.

Rosenberg [116] suggested a combined holographic and light guide concentrator for use as a passive device in building windows or as a ground-mounted solar collector, with applications including electric power generation, thermal control, and daylighting. The concentrator consisted of a holographic filter attached to the surface of a highly transparent plate, where the filter would diffract the desired portions of sunlight into the plate. Total internal reflection would guide the light to one edge of the plate, where it was collected by PV cells or optical fibres. The holographic structure had to be angularly, spectrally, and spatially multiplexed in order to accept incoming light from a range of incidence angles and frequencies, and to prevent the various regions of the filter from undoing the holographic actions of previous regions.

The hologram was recorded for the intended solar orientation of the concentrator so that it could be mounted in a non-tracking configuration, collecting both direct and diffuse light. A dual-film holographic device was constructed where the first hologram collected energy in the visible part of the spectrum (400–700 nm) and the second hologram collected near-infrared energy (700–1100 nm). The measured peak diffraction efficiency was 65% and the electric conversion efficiency for the device was 6.1%. The concentrator collected solar energy from a 160 degree daily angular variation and a 45 degree seasonal variation in incidence angle.

The relatively low efficiency achieved demands low production costs in order to compete with other passive devices on the market. The low concentration limits the power output and the collector area must be correspondingly larger to produce any substantial contribution to the energy demand in a typical building. The author also suggested to use larger concentrator plates with several holographic structures and multiple focal regions to improve the performance of the device, however this would impose even more stringent requirements on the system to keep the optical losses and the overall production costs down.

5. Photovoltaic/thermal spectrum splitting systems

An important application of the beam splitting concept is found in systems where PV and thermal absorbers are allowed to operate in parallel, both converting solar energy into high-grade end-products. According to Osborn et al. [2], this approach was first proposed by Meinel and Osborn in 1976 [117]. Several years later, Haught [118] presented a thermodynamic analysis of quantum and thermal conversion, thereby establishing the fundamental relations governing the maximum efficiency of these processes.

Johnson [119] reviewed Haught's analysis for a blackbody solar spectrum incident on an ideal dichroic beam splitter, directing the low frequency part of the spectrum to a thermal receiver and the high frequency part to a quantum receiver. The results showed that for a "thermally coupled" system, in which the PV and thermal processes are connected in series, the PV conversion efficiency is limited by the broad wavelength range of the incident radiation and the thermal efficiency is constrained by the need to avoid overheating the PV cell. This reduces the achievable system efficiency considerably. For a "thermally decoupled" system, in which the PV and thermal components are connected in parallel, each process is allowed to operate at a different temperature and the spectral range directed to the PV absorber may be optimized for maximum performance. Hence, the decoupled system will have superior performance.

Hamdy et al. [120,121] and Osborn et al. [2] discussed the implementation of spectral selectivity in further detail, including system simulations using the TRNSYS software. They concluded that, when compared to a PV-only system, a spectrum splitting hybrid PV/thermal system would have an increased electric conversion efficiency due to the reduced heat load on the solar cells when subject to filtered radiation. The amount of electric energy produced by the PV/thermal system was found to be less than in the case of a PV-only system, but this decrease was compensated by the generation of thermal energy.

The spectrally selective filter was pinpointed as the critical component of the system and required a careful evaluation of associated optical losses in order to justify its usefulness. Of the different dichroic interference filters and liquid absorption filters investigated, the optical minus (bandstop) filter was found to have an optimum combination of design simplicity and optical performance. This result was also the conclusion of a comparison of all-dielectric and dielectric-metal-dielectric (DMD) bandpass and bandstop filters performed by DeSandre et al. [1], who included considerations of dispersion, absorption, and angle of incidence effects ($<30^\circ$) in their computations.

5.1. Linear receiver systems

Chendo et al. [3] and Hamdy and Osborn [122] performed theoretical evaluations of an east-west oriented parabolic trough PV/thermal system, operating at 50 suns concentration. The receiver consisted of a tubular absorber operating at 290°C and 50% thermal efficiency, and a passively cooled silicon PV cell operating at 13% electric conversion efficiency. An optical minus filter with negligible absorption was assumed for the beam splitter. The hybrid system was compared to a conventional silicon PV system operating under similar conditions with 12% net electric conversion efficiency.

In the hybrid system, the PV component reached a 26% efficiency with respect to the 38% of the solar spectrum it received from the beam splitter, and generating 83% of the power produced in a PV-only system operating under the full spectrum. The remaining 62% of the spectrum was collected as high-grade heat, giving an overall efficiency of 41% for the daily summer direct beam incident in Tucson, USA [3]. The successful implementation of the system would depend on the beam splitter being produced at a reasonable cost and optical efficiency, and that a suitable application for the thermal output could be found without large distribution losses.

Soule et al. [123,5] emphasized the concept of "total solar cogeneration", referring to the simultaneous generation of electricity, high-grade, and low-grade thermal energy with effective utilization of the full solar spectrum. The proposed system comprised a high-temperature evacuated tube thermal receiver and an actively cooled PV receiver, producing both electricity and low-temperature heat when held at slightly elevated operating temperature. Based on a Fermi-model developed for the optimization of heat mirror spectral profiles, computer-simulations were performed to determine the optimum output efficiencies for the PV, high-temperature (HT), and low-temperature (LT) components. Comparisons were made between systems producing heat output only, electric output only, or a combined heat and electric output.

As an example, a system consisting of a silicon PV receiver and a black-chrome coated evacuated tube receiver was optimised giving priority to the high-quality electric and HT energy output, while maximising the amount of electric output from the system. The resulting heat mirror profile diverted 55% of the incident energy to the PV receiver and 45% to the HT receiver. Assuming an operating temperature of 70°C for the PV cells and 400°C for the HT receiver, the projected conversion efficiencies were 14.3% for the PV receiver, 43.5% for the HT receiver, and 42.2% for the LT receiver, giving a high-grade energy sum of 57.8%. These figures do however not consider the optical and thermal losses that are unavoidable in any real system and may only be taken as ideal values. Furthermore, the experimental heat mirror films that were considered consisted of single-layer doped semiconductors suffering from a relatively large absorption.

An implementation of this system is shown in Fig. 19 [124], where a tracking linear Fresnel lens is focusing light through a cylindrical plano-concave lens and onto a linear PV array which is thermally anchored to a copper substrate containing cooling channels. A spectrally selective heat-mirror positioned between the plano-concave lens and the PV receiver splits part of the beam off to an evacuated tube receiver, placed out of the path of the incident rays. Reflective wing secondary concentrators are provided at the aperture of both the PV and evacuated tube receivers for improved light collection. The optical losses could be substantial in this design, hence attention should be given to whether the concentration achieved will be sufficient for the efficient operation of both PV and thermal receivers.

Various ways of implementing spectrum splitting in a compact receiver design have been suggested by Izumi [125]. Fig. 20A shows a transparent glass pipe enclosing the PV and thermal receivers, the upper half being of circular or elliptical

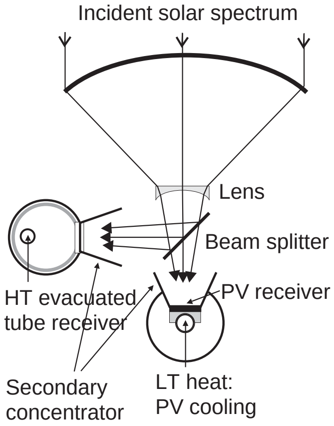

Fig. 19. Total solar co-generation system proposed by Soule [124].

cross section and the lower half of parabolic cross section. The lower half is coated with a thin aluminium layer to reflect long wavelengths onto a thermal receiver.

A one-axis tracking mechanism aligns the collector in such a way that solar energy is approximately normally incident on a parabolic cold mirror located in the centre of the glass pipe. The cold mirror reflects the short wavelength component onto a PV receiver mounted on a rectangular water-cooled aluminium tube. The long wavelength component is transmitted to the lower half of the receiver and redirected onto an evacuated tube receiver. The evacuated tube is painted black for increased absorption and contains a heat transfer medium of low boiling point, producing vapour which eventually rotates a turbine for electricity generation.

Fig. 20B shows an alternative design, in which a Fresnel lens is positioned in the upper opening of a cylindrical collector of quadrilateral cross-section. Solar radiation is concentrated onto a convex parabolic cold mirror positioned above the heat tube receiver, and is split into two components for PV and thermal conversion.

In Fig. 20C, double-faced PV cells are employed in a sun-tracking panel assembly. Fresnel lenses converge the long-wave solar radiation onto evacuated tubes containing a black heat-transfer medium. A reflective aluminium plate is placed below the tubes to improve light utilization. The upper half of each evacuated tube is shaped like an inverted V and is coated with a semi-transparent thin film coating for short-wave reflection. The short wavelengths are directed onto the rear surfaces of double-faced solar cells, positioned on each side of the Fresnel lenses. The solar cells also receive direct solar radiation on their front surfaces. The waste heat extracted from cooling of the PV cells is suggested utilized in greenhouses to promote plant growth or for domestic hot water purposes.

Although technically these receiver designs are feasible, the requirements to accuracy, optical quality, and material usage suggests that economic operation will be difficult. The relatively low concentration that is achieved may not be able to justify the production costs of glass tubes of a complex shape, PV cells with cooling

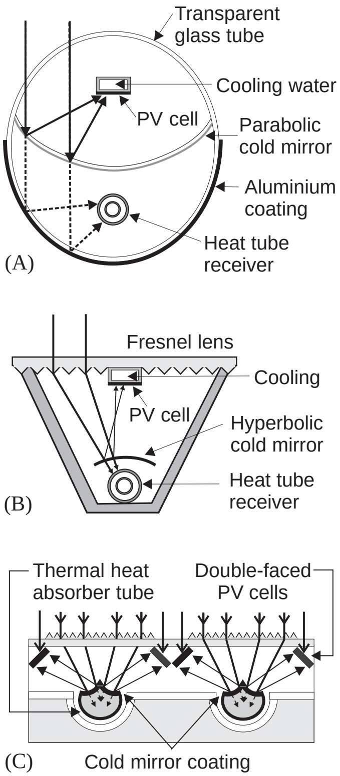

Fig. 20. PV/thermal collector designs proposed by Izumi [125].

arrangements, selective mirrors and heat tube receivers, or the efficient operation of both PV and thermal receivers simultaneously. The amount of electricity produced by the PV cell will be limited by the fact that, in a linear system, image size changes throughout the day and the collected light cannot be fully utilized.

The size of the transparent glass tube suggested in Fig. 20A would have to be of an unpractically large cross-section in order to collect and concentrate a reasonable amount of sunlight, whilst allowing enough room for the placement of heat pipes, cooled PV cells, and mirrors inside the tube. The Fresnel lenses in Figs. 20B and C would also face the challenge of sufficient light collection for the operation of both receivers at reasonable efficiencies. Optimized operation of the double-faced PV cells in Fig. 20C cannot be achieved, since the front side of the cell is exposed to the full spectrum, causing excessive heating and loss of efficiency.

5.2. *Dish receiver systems*

A curious dish receiver system has been proposed by Milton [126], combining a solar concentrator for generation of electricity with a microwave satellite receiver by means of holographic beam splitting techniques. A volume hologram containing a multiplicity of diffracting zone plates focuses and collimates selected wavelengths of light onto a PV and a thermal receiver while, at the same time, microwaves are transmitted unobstructed through to the microwave dish reflector. The operational axis of the apparatus is kept fixed at the required satellite view angle, and the volume hologram is recorded accordingly to focus sunlight onto the receivers at all times of the day.

As shown in Fig. 21, the short wavelengths (UV-visible) are redirected by the holographic filter so as to impinge along the optical axis of the dish, where they are absorbed by PV cells supported upon a heat absorbing substrate that also forms the reflective surface of the microwave receiver. The longer wavelengths (IR) are focused by the holographic filter to impinge on a thermal receiver located in the centre of the dish. The thermal receiver runs a Rankine cycle where the structural support of the parabolic dish forms the condenser. The dish structure is equipped with heat radiating fins, and heat is flowing into the fins from both cooling of the PV cells and from the Rankine cycle. The microwaves penetrate through the holographic filter and the PV cells to the dish reflector, which concentrates the microwaves onto a satellite receiver mounted in the focal region of the dish.

The viability of this system is dependent on the successful manufacture of a highly efficient and accurate holographic filter, recorded for a range of incidence angles and for a broadband spectrum. Filters of such quality have not yet been demonstrated, and it would be a challenge to ensure sufficient concentration for the operation of both PV and thermal receivers with the suggested passive tracking design.

Hybrid lighting is a new approach that integrates light from natural and electric sources and may offer benefits in commercial buildings where lighting represents the single largest user of electricity. Muhs [127,128], Fraas et al. [129] and Schlegel et al. [130] describe a system that collects and distributes the visible portion of sunlight using large-core optical fibres and combines it with electrically generated light in existing light fixtures, using intelligent control strategies to accommodate for night time or cloud cover lighting requirements. The light guides may be installed in a

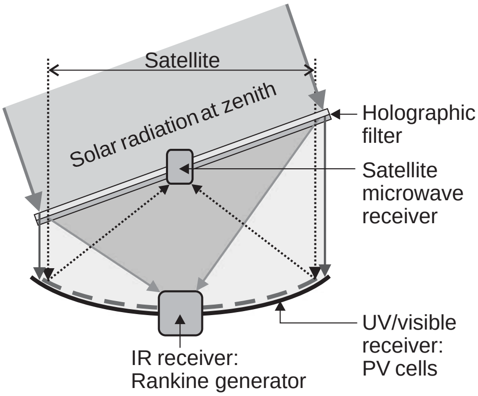

Fig. 21. A combined solar concentrator and satellite receiver [126].

manner analogous to a fire-extinguishing sprinkler system or an electrical conduit distribution system.

The light is collected by a two-axis tracking Cassegrainian concentrator mounted on the roof of the building. A cold mirror splits off the visible light, which is focused onto optical fibres for distribution into the building interior. Infrared radiation is transmitted to low bandgap GaSb cells for electricity production, as illustrated in Fig. 22. Fraas et al. [129] demonstrate that each Watt of visible sunlight may displace two Watts of electricity which otherwise would be used for fluorescent lighting and air conditioning. The high economic value of solar lighting results from the fact that there are more lumens per Watt in filtered sunlight than in fluorescent lighting. With the added value of the electricity produced by the GaSb cell array, the operating efficiency of the hybrid system will be in the range of 20–30% [127].

However, it will be difficult for the rather complex system of solar concentrators, optical fibre network, back-up power, and control mechanisms to compete with the rapid development of light-emitting diodes, which may offer a versatile, reliable and energy-efficient lighting system of low potential cost. An alternative usage of the visible part of the spectrum is for plant growth [131,132] by routing photosynthetically active radiation into a plant growth chamber, or utilization in a hybrid solar photobioreactor of the type used to mitigate CO_2 at power plants [133].

Several Cassegrainian cogeneration systems of the same basic design as shown in Fig. 22 have been suggested in the literature [129,133–135]. Common for these systems is the use of a reflective paraboloidal mirror producing a highly concentrated beam, and a Cassegrainian or Gregorian lens, positioned in front of or behind the focal point, respectively, that splits the beam by transmission and reflection of selected wavelength components.

In the system proposed by Lasich et al. [135], visible light is transmitted to a PV receiver placed in the focal region of the dish, while infrared energy is reflected into a light guide and redirected to a second thermal, chemical, or low-bandgap PV receiver. The system was successfully demonstrated in an experimental set-up comprising a 1.5 m diameter paraboloidal dish reflector, a 10-cell silicon PV module operating at 30°C, and a thermal receiver operating at 1100°C. The PV array

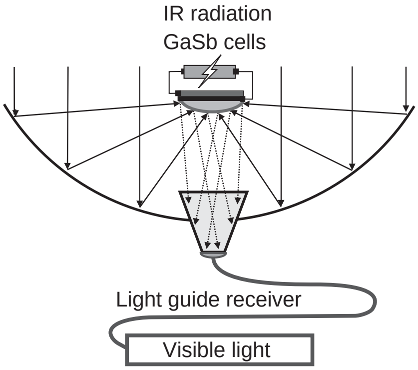

Fig. 22. Cassegrainian hybrid PV and lighting system [127–132].

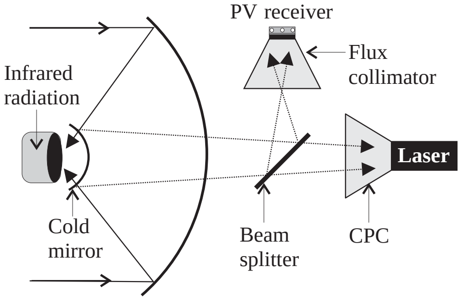

Fig. 23. Triple-foci beam splitting system for PV, laser, and thermal receiver operation [136].

produced 187 W at 282 suns, equivalent to a module efficiency of 18.4%, while the thermal receiver simultaneously produced 135 W of high-grade heat, equivalent to 13.4% efficiency, giving an overall cogeneration efficiency of 31.8%.

Yogev et al. [136] proposed a triple-foci Cassegrainian concentrator for satellite applications, as shown in Fig. 23. The incident spectrum is split into three parts by a Cassegrainian hyperboloidal mirror, coated with a long pass filter, and a dichroic beam splitter for the simultaneous operation of a solar pumped laser, a PV receiver, and a thermal receiver.

Whether a triple-foci system would be the most cost-effective way of providing the energy required for space applications, compared to a simpler single-focus or double-foci system, remains a question. It is clear that high quality of tracking and optics would be required to get a sufficiently high concentration of solar flux for the operation of three receivers. Using a beam splitter in series with a cold mirror adds another interface of optical losses, and cooling of all the components without cluttering the optical path may prove to be a difficult task. Still, if a compact, light-weight, reliable system can be designed, the costs associated with manufacture and assembly are allowed to be much larger than for a terrestrial system, due to the enormous expenses and risks involved when sending equipment into space.

5.3. Central receiver systems

Central receiver systems in general operate on a larger scale and comprise a field of sun-tracking heliostat mirrors that concentrate solar radiation onto a receiver mounted on top of a tower. An additional reflector may be mounted on the tower that redirects all, or parts, of the concentrated beam towards the ground, to allow the receiver and associated equipment to be installed close to the base plane. This so-called “beam-down” optics has been considered by Yogev et al. [137,138] and Segal et al. [139]. In the proposed system, a hyperboloidal reflector is mounted on the tower such that the upper focus is coinciding with the heliostat field aim point (~ 130 m above ground), and the lower focus is located at the entrance plane of a group of secondary concentrators (CPCs) mounted slightly above the ground level.

Yogev et al. [137] address the issue of how to avoid overheating of the tower reflector, and suggest to use a thin film dielectric multilayer filter with a negligible absorption coefficient, thus eliminating the need for cooling arrangements. The manufacture of a suitable high-quality filter with uniform properties across the relatively large, curved surface area of the hyperboloid mirror would be a huge task.

As a less expensive solution, Yogev and Epstein [138] also suggest to take advantage of the fact that glasses and metal coatings, of which the reflectors are usually made, have spectrally dependent reflection and absorption properties. The reflector materials may then be chosen in such a manner that most of the system losses will occur in the primary heliostat reflectors, absorbing a significant fraction of the solar radiation within the absorption range of the secondary tower reflector. Since the heliostat mirrors are only exposed to one-sun radiation they can easily withstand the excessive absorption. A larger portion of the incident spectrum intercepted by the heliostat field is then lost, however the loss may be justified by a reduction in cost of mirrors and cooling arrangements.

Segal et al. [139] have studied two different configurations for the integration of a selective mirror into the beam-down tower design. In the first case, the hyperboloid-shaped tower reflector itself is a dielectric bandpass filter that transmits a selected spectral band to a PV cell array, placed close to the aim point of the heliostat field. The reflected part of the spectrum is directed to a series of CPCs located at the focal zone near the ground. Results based on a theoretical analysis show that, from the total peak power that hits the heliostats, 20.5% arrives at the PV cells for conversion to electricity and about 50% is available for thermal conversion processes by the ground receivers, giving a total optical collection efficiency of about 70%. PV and thermal receiver electric conversion efficiencies, as well as power conditioning losses, must then be taken into consideration.

In the second case, the tower reflector is a regular mirror and the full solar spectrum is reflected down toward the ground level. Before reaching the lower focal plane, the spectrum is split and filtered by an additional paraboloidal selective mirror. This configuration is shown in Fig. 24. The beam splitter reflects one spectral band horizontally to a PV array, and transmits the remainder of the spectrum to the CPCs. From the total peak power that hits the heliostat field, 20.6% arrives at the PV cells and about 48% is available for thermal conversion processes, which indicates slightly larger optical losses for this configuration.

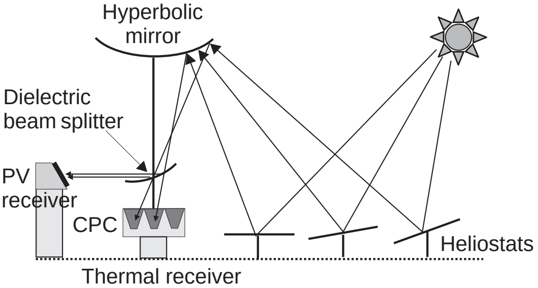

Fig. 24. Beam-down optics in a central receiver system [139].

An example based on the operation of commercial mono-crystalline concentrator Si cells, assumed to have an electric conversion efficiency of 60% within the spectral band 600-900 nm, and a 48% efficient combined cycle would provide an overall of about 36% electric. This is an optimistic figure, though, as such a high PV conversion efficiency cannot be achieved with current commercial c-Si concentrator cells, and power conditioning and distribution losses would also have to be taken into account for a central generation plant. Since the combined cycle plant is only working in daytime its lowered capacity factor will make the power block more expensive relative to fossil fuel plants by a factor of 3–5.

Possible applications of the collected radiation include solar pumped lasers, photochemical reactions, and heat storage. The authors also mention the possibility of adding supplementary reflectors for multistage beam splitting to increase the overall solar conversion efficiency of the power plant. The gain in efficiency would have to be carefully evaluated against the increase in cost and the optical losses associated with the introduction of additional reflectors.

Central receiver systems on a smaller scale may choose to have the receiver components installed directly on top of the tower to avoid the complexity of the beam-down optics. This is the proposed approach in the Multi Tower Solar Array (MTSA) system described by Mills and Schramek [140] and Mills [141]. The MTSA is a small- to medium-sized solar power tower system particularly aimed at distributed heat and power generation in urban areas. A special feature of the MTSA is a closely packed heliostat field, allowing high power densities where ground area is limited. The heliostat field concentrates solar radiation onto several receivers located on top of small ($\sim 10\,\mathrm{m}$) towers. Each tower receiver incorporates a spectrally selective filter that splits the beam into two components for PV and thermal electricity generation.

A range of receiver combinations has been assessed [142], and one receiver configuration likely to be implemented in an early MTSA prototype employs high-concentration silicon PV cells and a Brayton gas turbine thermal receiver. A volumetric receiver that accepts concentrated sunlight as input power for a Brayton turbine has been designed by Buck et al. (1999, 2001) [143,144]. The volumetric receiver efficiency is estimated to $(90 \pm 5)\%$, and the current peak efficiency for a $70\,\mathrm{kW_e}$ Ingersoll-Rand microturbine is 28% [145].

The turbine also provides thermal output at around 250 °C, suitable for medium-temperature applications like absorption air conditioning or process heat. Operation is on largely solar mode when the solar radiation is high, using gas as a back up power to maintain engine efficiency during night operation and in periods of low or unstable solar radiation. Since the thermal receiver generally is bulkier and heavier than a PV receiver, a bandpass filter design is preferred that allows the thermal component to be placed under the beam splitter and the PV component to be suspended above, as shown in Fig. 25. An all-dielectric multilayer filter is assumed, offering low absorption and flexible spectral characteristics.

For a commercial mono-crystalline concentrator Si cell operating at a temperature of 60°C and a concentration ratio of about 500 suns, optimization resulted in an approximate 40:60 percentage split of the incident AM1.5 direct solar spectrum

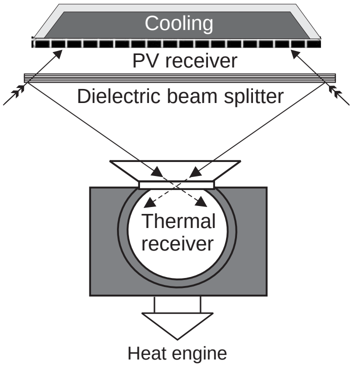

Fig. 25. Spectrum splitting for PV and thermal receivers in a multi tower receiver system [141].

between the PV and thermal receivers. The PV conversion efficiency within the optimized spectral band was 34%, compared to a nominal full spectrum efficiency of 21% at the given temperature and concentration. With an MTSA optical collection efficiency of 72% and including losses due to power conditioning and electrical wiring, the overall AC electric power conversion efficiency was found to be 20%. An additional 18% of medium-temperature thermal output was produced from the gas turbine, and 17% of low-temperature thermal output from cooling of the PV array. Assuming thermal network distribution losses of 10%, this gave an overall electric and thermal co-generation efficiency of 51% [142].

Since the MTSA offers power generation at retail cost, the system may compete with slightly higher efficiency central generation power plants. For the beam splitting approach to be an economical alternative, though, the thermal energy produced should be fully utilized. It may be necessary to consider options for the storage of thermal energy, in order to maximise the annual solar fraction.

5.4. PV/thermal systems for hydrogen production

Schell et al. [146] analysed a central receiver hybrid quantum/thermal system in which beam splitting techniques were employed to increase the efficiency of hydrogen production. Assuming an ideal beam splitting filter, the solar spectrum was separated into a thermal component for a Rankine-cycle/molten salt storage system generating electricity for electrolysis, and a quantum component for direct photo-electrochemical conversion of sunlight into hydrogen.

With a third of the beam split off to the quantum receiver and two thirds to the thermal Rankine-cycle, the spectrum splitting system was found to give only a marginal improvement in conversion efficiency compared to a traditional thermal-only power plant, and could not be economically justified. The poor performance was thought to be caused by large losses in the heliostat field and during the thermal-to-electric energy conversion step.

An improved PV/thermal hybrid system for hydrogen production has been discussed by Lasich [147]. The efficient conversion process is based on the fact that the electrical potential and energy necessary to produce hydrogen in an electrolysis cell decrease as the temperature increases. Hence, some of the energy required to operate the electrolysis cell can be provided in the form of thermal energy.

In the proposed design, a spectrally selective mirror of either Cassegrainian or Gregorian shape reflects long wavelength radiation to a thermal receiver and transmits short wavelength radiation to a PV receiver. One part of the collected thermal energy converts an inlet stream of water for the electrolysis cell into steam and heats it up to about 1000°C. The electrical energy produced, together with the remainder of the thermal energy, operates the electrolysis cell and decomposes the high temperature steam into hydrogen and oxygen. The hydrogen is then transferred from the electrolysis cell into a storage tank.

The system efficiency is further improved by extracting heat from the exhaust streams. The recovered energy has a relatively low temperature compared to the thermal energy generated by solar radiation, so it is used to preheat inlet water whereas the high temperature energy provides the balance of the heat component required to convert the feed water to steam at 1000 °C. In this way, the thermal energy used in the endothermic high-temperature process in the electrolysis cell is consumed at nearly 100% efficiency. The combined effect of solar-generated thermal and electrical energy results in high energy utilization, and the hybrid system performance is expected to exceed 50%. The hydrogen production efficiency would thus be larger than the efficiency of electricity production only, whilst simultaneously providing an energy storage medium.

To prove the concept, experimental work was performed on a 1.5 m diameter two-axis tracking paraboloidal dish and a GaAs concentrator PV cell receiver with output voltage matched to the operation of an electrolysis cell at 1000°C. During operation, a significant portion of the solar thermal energy was used directly in the electrolysis reaction, thereby reducing the required electrical input by almost a half. The recorded total system efficiency of the PV receiver, electrolysis cell, and optics was 22%.

According to Lasich, this is more than three times the best recorded figure for a working plant, thus proving it possible to produce hydrogen by high temperature electrolysis of water driven totally by solar radiation and at an improved efficiency. The proposed system requires high quality of the various optical components as well as accurate tracking strategies, and represents a large investment cost. There is still room for improvements in efficiency, and the small scale demonstration system would need further testing and development before being ready for hydrogen production on a larger scale.

6. Spectrum splitting for thermally selective receivers

Harrison [148] recently proposed to use the spectrum splitting approach for the operation of multiple thermal receivers in a cascading fashion. A working fluid is partially heated in a low temperature receiver, then passed on to a higher temperature receiver for further heat uptake. Each receiver has a spectrally selective coating which allows solar radiation of a certain shorter wavelength range to pass through and prevents longer wavelength thermal radiation from escaping, thereby reducing radiative losses.

Any number of receivers may be used, heating the working fluid in steps. The receivers are shaped as light-trapping cones to increase the absorption of light, whereas the apparatus housing is designed to pick up stray radiation. The working fluid is pre-heated by cooling of the filters and housing before it enters the low-temperature receiver.

One of the proposed designs is shown in Fig. 26A. Concentrated radiation is collimated and directed towards a prism, which splits the beam into two spectral components for a set of thermal receivers located at the opposite end of the apparatus' entrance. The thermal receivers may operate a single high-temperature

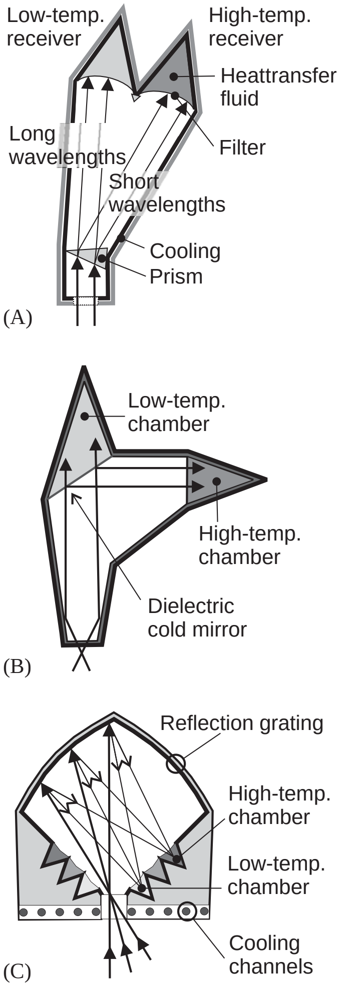

Fig. 26. Beam splitting for thermal receivers [148].

application or, alternatively, several applications at different temperatures. According to the author, working fluid temperatures of about 1300°C may be achieved for a high and low temperature receiver at 1700°C (edge filter cut-off at 800 nm) and 700°C (edge filter cut-off at 2500 nm), respectively.

The need for a beam collimator may be avoided by placing prisms of increasing refractive strength in the path of the converging solar radiation, tilted so as to provide overlapping foci at the different thermal receivers. The small portion of converging sunlight intercepted by each prism will be approximately parallel, allowing the dispersion of light onto separate receivers.

In a different design shown in Fig. 26B, a collimated beam impinges directly onto a cold mirror placed in front of the low temperature receiver, at 45 degrees to the incident beam. IR radiation is transmitted through the cold mirror, whereas visible and UV radiation is reflected and passed through a hot mirror placed in front of the high temperature receiver. Yet another design, shown in Fig. 26C, employs a cooled reflection grating on the inside of a spherical receiver housing, splitting the incident converging beam onto a series of receivers according to wavelength. As before, the receivers progressively heat the working fluid to a higher temperature. The front surface of the housing surrounding the aperture entrance has a black absorbing coating and a grooved surface to provide multiple reflections and improved light trapping for preheating of the cooling fluid.

The purpose of the various receiver designs is to lower the radiation losses at all insolation levels, assuming a constant working fluid temperature. The high grade heat produced would be transferred to a heat engine for electricity production, or could alternatively be used at the receiver for phase change or chemical reactions. No experimental data has been supplied to substantiate the assumptions made, and it is not clear what sort of heat transfer fluid could be used.

In addition to high requirements on the solar collection optics and tracking system, the optical alignment of the receiver and its internal components would have to be extremely accurate to produce the desired beam separation effect. Keeping the outlet temperature constant may be difficult as the solar irradiation and spectral contents change throughout the day. Heat mirror selectivity in general becomes poor at high temperature, and material degradation may become an issue at a filter temperature assumed to reach 400°C.

It is questionable whether the complexity of the suggested designs would permit a gain in efficiency compared to a more traditional black cavity receiver. Thermal losses at high concentration are relatively small in a single receiver point focus concentrator (~5–10%) so the added optical reflection losses from the proposed combination of prisms and heat mirrors may result in little or no overall gain in performance, combined with a significant rise in receiver cost.

7. Discussion

One of the main types of filtering methods investigated for the various spectral beam splitting systems is the dielectric or metal-dielectric multilayer filter.

Broadband filters that incorporate metal layers are a simple and very efficient way of reflecting heat radiation, but suffer from severe absorption losses. The alternative is to use a more complex structure, employing a large number of dielectric layers, where the absorption can be kept at a minimum but the production cost will be high.

If the filter can be deposited directly on top of the PV cell, savings in material usage and production time could offer economical benefits but this option requires careful attention to material mismatch with possible cracking or flaking due to thin film stress, and to the influence of temperature and flux gradients across the device. Plasma and antenna filters have shown benefits like broadband, wide-angle reflection of out-of-band photons, however the production cost is high and the reflection edge is set by the resonance wavelength or antenna dimensions, unless combined with a multilayer filter.

The selective emitter is of particular interest in TPV applications and is often used in conjunction with a heat reflecting filter, due to the non-ideal nature of suitable emitter materials. New theories on photonic bandgaps and TPX conversion give prospects to the development of more efficient selective emitters that could increase the practical efficiency achieved in TPV systems, however this is still far ahead in the future.

A liquid absorption filter has the advantage of serving multiple purposes simultaneously, both filtering the light and acting as a transport and storage medium of thermal energy. The main obstacle for making this a cost-effective strategy is related to the lack of non-degradable liquids with suitable absorption spectra for the simultaneous operation of PV receivers.

Luminescent and holographic passive concentrators have advantages over geometric concentrators in that solar tracking is unnecessary and that both direct and diffuse radiation can be collected. The low concentration and efficiency achieved by these passively tracking devices do however demand very low production costs in order to compete with other solar energy conversion devices on the market.

Luminescent solar concentrators provide a homogenization of flux which is advantageous for PV cells, and shift the spectrum toward optimum conversion efficiency of the cell. Although this does not gain anything with regards to solar conversion efficiency, it avoids excessive heating of the PV cell. Other advantages of the luminescent concentrator include good heat dissipation of non-utilized energy by the large area of the collector plate, which is in contact with air, and the area to be covered by the solar cell is small, hence reducing cost.

The development of luminescent concentrators has been constrained by the stringent requirements on the luminescent dyes, i.e., high quantum efficiency, suitable absorption and emission spectra, and long-term stability under illumination. In particular, UV light can cause certain molecules to break down and destroy their luminescence capability. The fabrication cost of a luminescent concentrator is low, but so is the achievable concentration and efficiency. Although research and development on luminescent solar concentrators is advancing, these devices are still not ready for the commercial market. If practical quantum dot solutions can be found, improved efficiency and stability may offer more cost-competitive products in future.

Holographic devices may also be used in actively tracking systems, and are in theory very desirable filters due to the high degree of spectral and spatial control of radiation that can be achieved. Light may be collimated, spectrally split or focused according to a given set of specifications, and, within practical limits, concentration and spectrum splitting can be achieved simultaneously by a single optical element. In practice, holographic filters suffer limitations similar to that of thin film multilayer filters, such as non-ideal spectral characteristics and angular sensitivity. Manufacture of large-area filters with uniform properties is challenging, and effects arising from cross coupling and optical aberrations must be considered.

Both passive, low concentration and active, high concentration holographic devices have been proposed and demonstrated on laboratory scale. There is no field experience, however, on the usage of these systems under broadband solar illumination. The successful operation of point focus holographic systems is dependent on very precise tracking control, as misalignment will alter the spectral performance of the filter and may affect system performance substantially. Holographic concentrators are currently only at the prototype stage, where the spectral bandwidth of the concentration and filtering action is limiting solar performance.

Common for all TPV systems is that the process involves a series of optical and energy conversion components that limit practical efficiency by introducing losses, and the cost-effective production of electricity has proven to be a difficult task. The TPV systems that seem to have a future on the market are smaller, stand-alone or portable units that run on common fossil fuels, and possibly the utilization of existing furnaces for an inverted coaxial TPV design, if lifetime of components under high temperature conditions is found to be satisfactory. The use of solar radiation as the energy source for terrestrial TPV systems has not taken off. The economy of such systems is not competitive with fossil fuelled systems that can be implemented at a lower initial investment and also use a more compact and reliable design, operating independently of weather conditions.

A solar TPV system with storage medium may have applications in space, where cost considerations are of less importance. However, solar TPV may have to compete with other concentrating PV systems, such as spectrum splitting systems with high potential efficiency using multiple bandgap PV cells. The main issue in this case is the high required tracking and alignment accuracy, which is necessary for the spectrum splitting system to operate optimally, as well as high quality of optical components.

In a historical perspective, space missions have employed high-efficiency multi-junction concentrator cells with great success and, although some work has been done on spectrum splitting systems, little practical experience with such systems is available. It may nevertheless be of interest to follow up on spectrum splitting systems of potentially higher practical efficiency than multijunction cells, since there are limits to the number of PV cells that in practice may be stacked on top of each other, and due to electrical, cooling and material constraints.

Several experimental investigations have been successfully conducted on PV spectrum splitting systems for terrestrial applications, but the results are still far

Table 1
An overview of the different spectrum splitting solar concentrating systems proposed in the literature

System	Optics	Efficiency	Technical issues	Ref.
Solar TPV	Point focus	Demonstrated, solar: —. Demonstrated, fossil: 2–3% [55–56] (residential), 11% [59] (industry). Predicted: 5–15% [65], space applications with storage: 15–17% [42–43], 27–51% [41]	Many components in series, optical losses, non-ideal filter/emitter, material degradation at high temperature, cooling of PV, parasitic (ohmic) losses.	Solar: 27–30, 41–43 General:27–66
PV splitting by reflection/transmission	Point focus	Demonstrated, filter + 2 cells: 26% (133 ×)—27% (489 ×) [76], 28.5% (165 ×) [77]. Demonstrated, concentrator + filter + 2 cells: 20.5% (477 ×) [78–79]. Predicted, 4 cell system: 33% (1000 ×) [22], 50% (500 ×) [81], 50% [80].	High cost, expensive PV cells and filters, non-ideal beam splitter, optical losses, cooling of PV, power conditioning.	21–22, 75–81
PV splitting by refraction	Linear focus	Demonstrated: —. Predicted, 5–6 cells: 45–60% (100–500 ×) [8].	Image size changes for horizontal axis systems, spillage and non-uniformity, low concentration, pointing errors, beam collimation required, expensive PV cells.	8, 82–84, 148
PV splitting by absorption	Linear or point focus	Demonstrated: —.	Liquid filter degradation, non-ideal spectral matching with PV, scattering and optical losses.	2–3, 15–16, 85–86
PV splitting by luminescence	Passive	Demonstrated: 4% (2 cells) [92], 3.5–4.5% (3 cells) [91]. Predicted: 10% (1 cell) [88], 10% (2 cells) [92], 32–38% (4 cells) [13, 89].	Degradation of dye materials, low solar broadband efficiency, low optical efficiency of concentrator, temperature sensitivity, PV cost.	12–13, 87–95
PV splitting by holography	Passive, linear or point focus	Demonstrated: 6% (passive, 1 cell) [116]. Predicted: 19% (1 cell, linear focus) + 24% thermal at 120 °C [106], 22% (2 cells, point focus) [110], 27% (3 cells, point focus) [100].	Manufacture of large filters is difficult, optical losses, low solar broadband efficiency, temperature and humidity restrictions, high tracking accuracy and low beam divergence required.	9–11, 96, 100–116, 126

PV/thermal linear receiver	Linear focus	Demonstrated: —. Predicted: 10% (1 cell) + 31% thermal at 290°C [122].	Non-uniform illumination and spillage loss on PV, low concentration, non-ideal beam splitter and optical losses, beam splitter cost, heat utilization, thermal loss.	3, 5, 122–125
PV/thermal dish receiver	Point focus	Demonstrated: 18.4% (PV module) + 13.4% thermal at 1100°C, 22% (H_2 production) [147]. Predicted: 20–30% (1 cell + indoor lighting) [127], 50% (H_2 production) [147].	High cost, expensive materials, high optical quality and tracking accuracy required, non-ideal beam splitter, optical loss with multiple concentrators/receivers, cooling of PV, light guide collection and distribution loss.	126–136, 147
PV/thermal central receiver	Point focus	Demonstrated: —. Predicted, central generation: 36% (PV + Combined cycle) [139]. Predicted, distributed generation: 20% (PV + heat engine, AC power) + 18% thermal at 250°C [142].	High cost, expensive materials, high requirements to tracking, non-ideal beam splitter, optical loss with multiple concentrators/receivers, thermal loss, non-homogeneous flux on PV. Lack of storage causes increased power block cost for combined cycle component and reduces combined heat and power efficiency.	137–142, 146
Thermal selective	Linear or point focus	Demonstrated: —.	Complex, high cost, manufacture is difficult, high quality optics and accurate alignment required, low concentration, non-ideal filters, optical losses. Improved performance over single receiver not guaranteed.	148

away from demonstrating the predicted efficiencies of up to 50%. There is also a lack of practical systems to demonstrate the feasibility of this technology. Experience, leading to more efficient solutions, and a larger production volume is needed to bring the cost down. Although this is true for all concentrating PV systems, spectrum splitting systems may find it hard to compete with tandem or multijunction cells since large research efforts have recently been put in to demonstrate "a third of the sun" electric conversion efficiency for such devices.

Demonstrated high efficiency and simplicity give the tandem cell approach a benefit on the market, since the spectrum splitting systems have added requirements to optics and cannot refer to the same history of long-term operation. Small- and medium-scale terrestrial systems are currently tending towards compact Fresnel lens systems with single PV receivers, however, as the cost of such PV systems is still too high to compete with fossil fuelled power generation, increasing the concentration and scale of operation could give spectrum splitting systems the benefit on the market.

In general, co-generation of electricity and heat enables a very high overall conversion efficiency that in many cases may be used to argue for a spectrum splitting system approach. It is however important that the heat produced is fully utilised, otherwise the system quickly loses its advantage over single receiver systems. Alternative strategies for what action to take if the heat load is low or not present should be considered, for instance, a storage facility may be the most cost-effective investment in the long run. It should also be taken into account that heat and power produced at the site of consumption will replace retail electricity cost, which gives distributed power generation an advantage over central distribution systems. For grid-connected systems, excess electricity production may be fed back into the grid, which maximises the annual solar fraction of the system and reduces the pay-back time of the power block.

The implementation of horizontal linear systems is challenging because the image size changes throughout the day and systems using lenses lose their focus with non-meridianal rays. Some linear low ratio concentration systems (less than about 20 suns) with lenses can be used with a polar or seasonally tilted North-South tracking axis, but these then become close to being two axis tracking collectors structurally and the PV cell cost, especially given that one must use expensive non-silicon cells for part of the split spectrum, becomes very significant at such low concentrations.

For the most part, high cost PV cells require high concentration and a two-axis tracking system using lenses or mirrors is implied to provide concentrations above approximately 60 suns. Lens systems for PV receivers may require a long focal length to minimise problems with non-homogeneity, but the drawback is larger sensitivity to tracking error. This may be of concern in a spectrum splitting system where the multiple components makes it desirable to allow as much room for alignment and tracking error as possible.

The various systems discussed in this paper have been summarized in Table 1. The systems are grouped according to the spectrum splitting method and receiver design employed, and the table gives information on the optical concentration, efficiency, and possible technical issues concerning the given design. A passive system is assumed to be non-tracking, whereas a linear focus refers to the moderate concentration (less than approximately 60 suns) achieved with one-axis tracking, and a point focus refers to the high concentration (above 60 suns) that is achieved in two axis tracking systems. As the concentration ratio increases, the requirements to optical quality, tracking and alignment accuracy become more stringent and the associated system costs will also increase. The listed efficiencies should be used with care, as the assumptions made by the various authors are vastly different, in particular the treatment of optical, thermal, and electrical losses that will be present in a real system.

8. Conclusions

A review of solar beam splitting systems has been presented, showing the great variety of techniques and implementations that have been proposed over the years. Spectrum splitting filters were first employed in TPV systems with the purpose of reducing the heat load on the PV cells. This was accompanied by spectrum shifting techniques to provide better spectral matching between the radiation source and the peak efficiency of the PV cell.

An alternative approach was suggested in PV systems, using solar cells of different band-gap materials to increase the conversion efficiency of multiple-cell receivers. Although proposed as early as 1955, this idea did not receive much attention until the mid-1970s when experience from concentrator PV and TPV research stimulated the development of cascading and spectrum splitting PV devices, effectively spanning the solar spectrum. A range of solar concentrator systems arose, in which various luminescent, holographic, and optical beam splitting techniques were employed.

One major application was found in systems combining quantum and thermal receivers. Studies performed during the 1970/1980s showed that physical decoupling of the PV and thermal receivers had a significant potential for improved conversion efficiency. During the next decade or so, several investigations elaborated on the advantages and possible applications of PV/thermal spectrum splitting.

There has recently been a renewed interest in beam splitting technology within several disciplines of solar energy conversion systems. The predicted efficiencies of these systems are promising, however, the losses associated with the spectrum splitting optics in a real system cannot be neglected. Experimental results and cost-performance evaluations will determine whether the added costs of the beam splitting approach can be economically justified.

Apart from cost considerations, other issues such as the large flexibility in receiver design and the energy output produced may be used to argue for the spectrum splitting approach. For instance, in a PV/thermal system the amount of electricity, medium-temperature, and low-temperature energy produced can be tailored to suit the particular end-user demand for typical applications like indoor lighting, air conditioning and hot water.

Common for all spectrum splitting techniques is the fact that, as the spectral range is narrowed down, the efficiency of the quantum conversion process is increased but the power output goes to zero. This is an issue also in concentrating systems, since the added cost of the concentrating optics must be justified by an increase in power generation. Introducing a larger number of quantum converters that are able to extract different parts of the solar spectrum may give high power output at an overall high conversion efficiency, but as the number of receivers is increased the cost of the system becomes excessively high.

Furthermore, the addition of multiple optical components and receivers introduce optical and thermal losses that in practice prevent the unlimited use of filters and concentrators. Hence, optimization analysis becomes an important tool in order to determine the optimum configuration of any beam splitting solar hybrid system.

Any direct comparison of the performance of the various beam splitting systems presented in this paper is a difficult, if not impossible, task. The reason for this is that, in most cases, only selected results are presented and the assumptions made during the analysis are not clearly stated. Some authors present only predicted or ideal performances, others include experimental results which may not relate to the complete system. But most importantly, the economic performance of the different systems will largely depend on practical engineering issues and real year round—not theoretical peak—performance, and each system should be evaluated according to needs of a specific target market, whether that market be central generation, end use combined heat and power, or space applications.

Many references show theoretically that the overall system efficiency will increase in a beam splitting system, but there is not much literature available on real, on-sun systems giving evidence to these predictions. However, the current revival of interest in solar beam splitting technology holds promises of renewed efforts in bringing the concept away from the drawing board and into real applications.

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