Building-Integration of High-Concentration Photovoltaic Systems

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Abstract The chapter addresses building-integration (BI) issues from the basic concepts to the most specific concerns related to high-concentration photovoltaic (HCPV) systems. The reader is introduced to the topic by learning the main aspects of the true BI of PV systems. Although CPVs were developed to generate electricity at a decreased price compared with nonconcentrating systems, their BI can provide additional advantages related to a range of building energy needs and functions. Characteristic case studies of building-integrated concentrating systems are presented and discussed to show how different types of optical arrangements are designed to be architecturally integrated. BI HCPV systems require two-axis tracking arrangements, which poses a range of challenges in addition to those general for low-concentration or nonconcentrating BI solar systems. Two examples of truly BI HCPV, from the very few that can be found at present, are presented.

1 Introduction to Building-Integration of Solar Energy Systems

Energy use in buildings represents 40 % of the total primary energy used in the European Union. The Energy Performance of Buildings Directive (EPBD) requires member states to set minimum energy performance requirements for buildings taking into account the positive contribution of renewable energy sources [1]. Therefore, developing building-integrated renewable energy technologies that offer effective energy alternatives is vital.

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Solar energy systems (SES) can be integrated onto roofs, facades, and other building elements offering several advantages such as the following:

- They do not require additional land use and can be used in highly built-up areas.
- They can produce electrical/thermal energy to cover part or all of the building's needs.
- They can decrease the building's energy needs by providing thermal insulation, natural daylight, and shading.
- They supply energy at the point of use, thus decreasing infrastructure costs.
- They replace conventional building materials and components, thus enhancing investment payback periods.
- They can improve aesthetic appearance.

In particular, building-integrated PVs (BIPV) offer the extra advantage of producing power at peak demand times, thus decreasing the utilitiy's peak grid loads.

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By superimposing a SES on a building structure, it is possible to achieve architectural integration and provide good aesthetic appearance. However, a SES is considered to be truly BI when it becomes a component that provides integrity and functionality to the building. Being part of the building structure it means that when dismounted, it will affect or will require the replacement of the adjacent building component(s). A dismounted BI SES must be replaced partly or totally by a conventional/appropriate building component to preserve the integrity of the building. Therefore, in addition to generating energy (heat, electricity, etc.), a BI SES must provide a combination of the following:

- mechanical rigidity and structural integrity;
- weather impact protection from rain, snow, wind and hail;
- life expectancy from the various materials involved (at least equal to the life of the building);
- fire protection;
- noise protection; and
- environmental benefit/influence (LCA, embodied energy, emissions).

It is essential for the wider acceptance of BI SES that apart from good energy performance and cost-effectiveness, they provide flexibility on a wide range of characteristics that affect the building aesthetics and the wider public acceptance. These include employed material and surface textures, colour of the solar absorber, shape and size of the units, and methods for interconnection and thermal/electrical storage options. Toward this end, solar concentrating systems have several advantages compared with non-concentrating ones. Nevertheless, at present, the use of concentrating technologies is limited, and most of the existing installations are stand-alone devices of considerable size (e.g., solar power towers, parabolic-trough concentrators, parabolic-dish concentrators, and large Fresnel concentrators with two-axis tracking).

The use of concentrating systems for BI requires development of reliable systems from the manufacturers. An important issue is the tracker mechanism, which must be simple to decrease the complexity and the cost of the system. When comparing such a system with a flat-panel PV device built for the same application, the additional cost of the tracker and its maintenance must be compensated for by the advantages provided by the use of the concentrating technology. In contrast, flat-panel systems can be used to replace structural elements of a building, which in most cases is not possible with concentrating technologies [2].

The way of integration of SES and the perception from people of how well-integrated is the system is a complex issue to define because there are many factors (cultural, economical, political, etc.) to consider. For instance, in a certain location where a solar concentrating collector is superimposed onto a façade, it could be considered an aesthetically pleasing system because the tracking movements provide a more dynamic image to the building. However in another location of the same façade, integration could be considered totally anaesthetic and incorrect. Reijenga [3] established a classification of the BIPV systems that has an inherent subjectivity. Five categories were defined based on the increasing extent of architectural integration:

1. applied invisibly,
2. adds to the design,
3. adds to the architectural image,
4. determines the architectural image, and
5. leads to new architectural concepts.

Now that the concept of BI of solar systems has been introduced, the next sections deals with the particular restrictions and requirements that an HC BIPV system should fulfill.

2 Characteristics of a Well-Integrated Solar System

The characteristics that a solar system should cover to be successfully building-integrated should be in balance between architectural and engineering issues. In other words, a good balance between aesthetics and engineering should be created.

Regarding the above-mentioned balance, Munari Probst and Roecker [4] performed a survey on how architects and engineers perceive integration quality. The study focused on building-integrated solar thermal systems, but the results can be effectively be applied to any solar device. This research was part of the Task 41: Solar Energy and Architecture from the Solar Heating and Cooling program (SHC) of the International Energy Agency (IEA). From the collected survey data, the authors defined the following criteria:

1. The multifunctionality of the solar energy system allows the architect to define a more effective project because fewer elements must be considered, e.g., when the solar device is also a construction element (facade cladding, roof covering, etc.).
2. The position as well as the dimensions of the collector field should be evaluated by considering the building as a whole. This implies taking into consideration energy production goals and formal integration needs (colour, size, shape, etc.). In some of the cases, the use of dummy elements (non-active) may help to achieve more coherence between the solar system and the rest of the building.
3. The choice of colours and materials for the system should match with colours and materials characterising building and context. The initial choice of technology is fundamental because it imposes the material of the external-visible-system layer (glass, metal, plastic, etc). In the frame of the chosen technology, material treatments (surface colour, texture) offered by the various available products can be considered.
4. Module size and shape should be chosen by taking into consideration building and facade/roof composition dimensions and characteristics (or vice versa). The proposed module jointing types should also be considered while choosing the product (different jointing types differently underline the modular grid of the system in relation to the building).

The criteria stated from the collected survey data were used by Munari Probst and Roecker [4] to define a design methodology. Figure 1 depicts the sequence of steps involved in the collector design. As indicated previously, the guidelines consider solar thermal collectors and, within them, concentrating hydraulic systems; however the design methodology for obtaining a well-integrated collector can be applied either for thermal or PV systems. Sometimes, the integration requirements are difficult to achieve as the currently available collectors on the market have been developed with insufficient awareness of BI aspects [5]. In the case of BI high-concentration photovoltaic (HCPV) systems, most of the collectors do not consider BI issues, and very few examples can be found. In Sect. 6, two representative cases will be described.

Almost in parallel to the work performed by IEA SHS Task 41 regarding PV systems, Task 7 of the IEA on the Photovoltaic Power Systems program evaluated the aesthetic quality of building-integrated PV systems. As a result, a set of requirements of a well-integrated PV system were defined [6]:

- natural integration;
- architecturally pleasing design;
- good composition of colours and materials;
- dimensions that fit the gridula, harmony, and composition;
- conformity to the context of the building; and
- well-engineered and innovative design.

As indicated for the case of BI solar thermal systems, these requirements can be used for any solar-collector type. In addition to the requirements listed, BI HCPV should overcome successfully a series of constraints caused by tracking requirement, extra weight, etc. These aspects are further discussed in Sect. 4.

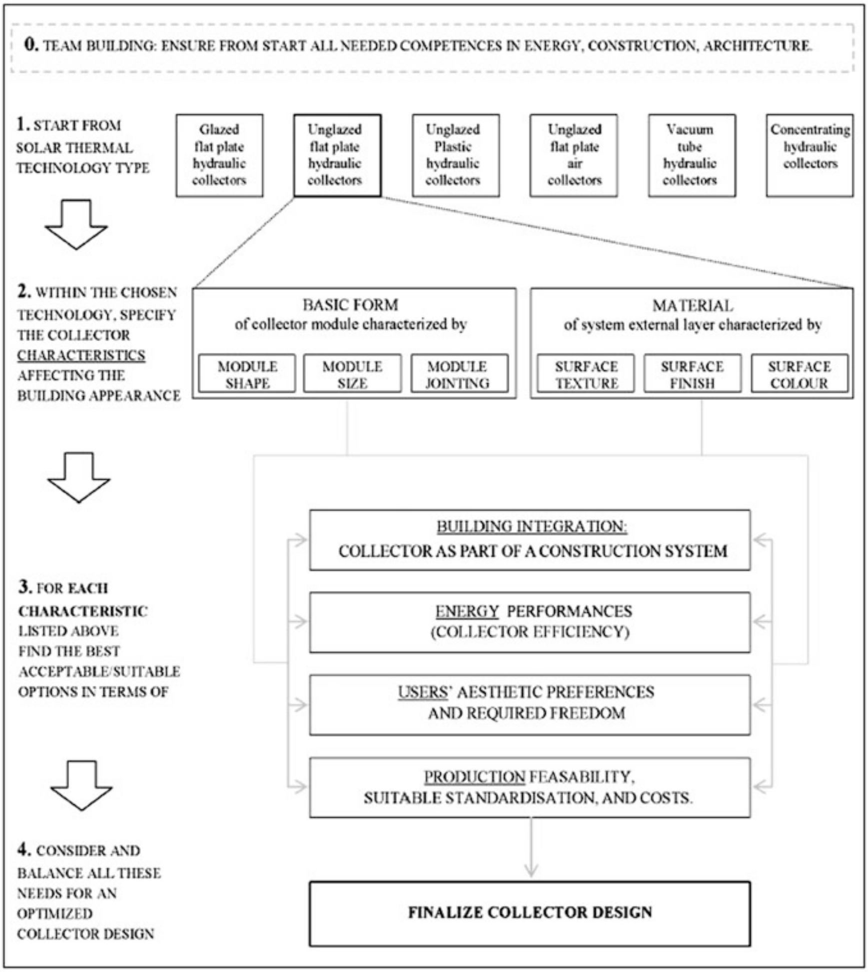


Fig. 1 Design methodology for a BI solar collector [4]

3 Representative Case Studies of Building-Integrated Concentrating Photovoltaic Systems

3.1 The Concentrating Photovoltaic Evacuated Glazing (CoPEG)

The incorporation of PV cells onto conventional gazing restricts daylight transmission, thus increasing the requirement for artificial lighting in the building. Recent concepts have attempted to improve transparency by removing sections of the PV material; however, this decreases the electrical-generating capacity of the system and offers no lighting control for the building's interior. Dielectric concentrating covers for PV façade BI enable increased electricity generation per unit area of PV material compared with conventional PV panels [7, 8]. In addition lighting control can be achieved by tailoring the dielectric concentrating lens design to allow daylight to enter the building for prespecified range of incidence angles of solar radiation. Evacuated glazing systems have significant potential in decreasing heat loss from buildings [9]. Laboratory evacuated glazing prototypes have shown that U-values as low as 0.6 Wm-2K-1 can be achieved [10].

The innovative CPV evacuated glazing (CoPEG) concept developed by the Centre of Sustainable Technologies at the University of Ulster [11] integrates evacuated glazing technology with transparent concentrating PV lens into a single multifunctional facade element. Integrated onto a building façade, CoPEG provides significant thermal insulation with enhanced optical daylight control whilst incorporating a concentrating PV lens to generate electricity.

The CoPEG concept can form part of the building envelope providing the following:

- high thermal insulation for the building decreasing heating and cooling requirements;
- low-cost and carbon-free electricity generation from the Sun; and
- control of daylight penetration into the building.

The concept technology consists of an evacuated glazing panel where one pane of glass is shaped into a series of linear concentrating lenses. A patented low-temperature sealing technique that uses indium [12] has been utilised to create an effective and consistent seal around the edges of the evacuated space formed by the flat and the concentrating glass panes. PV cells are placed at the focus of the concentrating lens. The vacuum between the outside glass pane and the PV concentrating lens pane minimises convective and conductive heat transfer, thus providing high thermal insulation to the building. The solar radiation is transmitted through the outer glass pane and concentrated onto the PV cells to generate electricity. The concentrating PV lenses are designed to allow a certain fraction of the beam incident solar radiation to reach the building interior at times when natural lighting is needed (Fig. 2). The lenses can also be designed to produce a seasonal effect with more direct sunlight allowed into the building in the winter months and less in the summer. In cooling-dominated climates, CoPEG can significantly decrease solar heat gain to the building by concentrating all incident sunlight onto the PV cells. At the same time, the generated electricity can be utilised to supplement air-conditioning cooling power requirements.

The technology is currently undergoing proof-of-concept to advance it to Technology Readiness Level (TRL) 4. The linear concentrating lenses are of prismatic shape and offer a geometrical concentration ratio of 2.7×. They are cut onto a 500 mm × 500 mm × 15 mm (length × width × thickness) opti-white glass pane using especially designed computer numerical control cutting tools. Multicrystalline PV cells, 14 mm-wide, are bonded onto the focal (absorber) area of the prismatic lens. To produce a building-integrated component with superior aesthetics, green

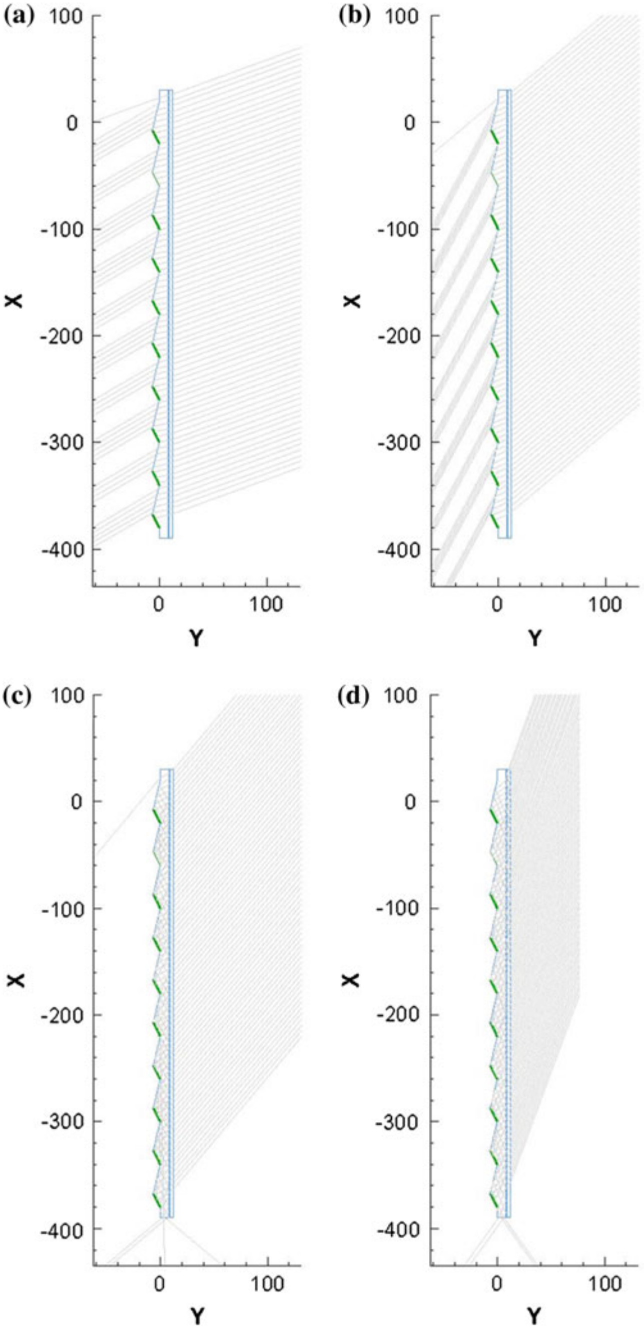


Fig. 2 Series of ray traces demonstrating the interaction between the linear concentrating lens of the CoPEG concept and direct sunlight incident at different angles (measured from the perpendicular to the outer glass pane): (**a**) 20°, (**b**) 40°, (**c**) 50°, and (**d**) 70°

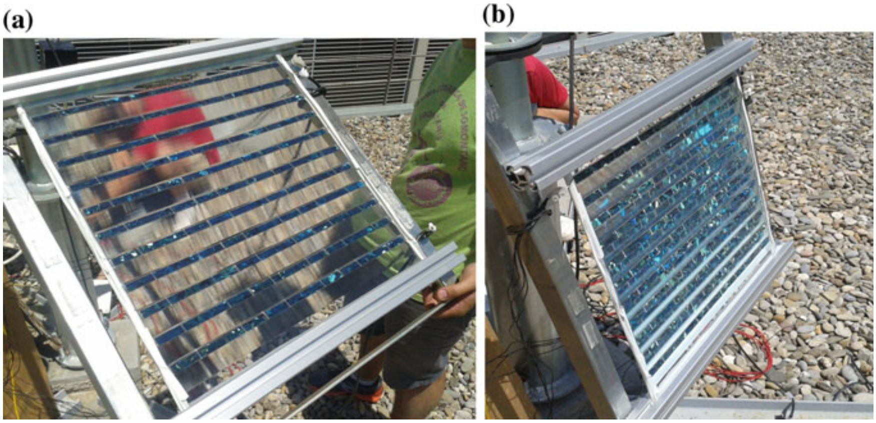


Fig. 3 The effect of the angle of incidence on the amount of beam solar radiation that reaches the PV cells concentrating PV glass pane: (**a**) at low incidence angles the PV cells receive only the solar radiation which is directly incident onto their surface. The remaining radiation penetrates behind the glass mane, (**b**) at high incidence angles the larger part of beam solar radiation is reaching the PV cells either directly or after total internal reflection at the prismatic surface

coloured cells are used. The effect that the incidence angle of solar radiation has on the amount of sunlight reaching the PV cells can be observed in Fig. 2. At low incidence angles, the PV cells receive the fraction of beam solar radiation that is directly incident on them (Fig. 3a). The remaining beam radiation penetrates behind the glass. At high incidence angles, most of the beam radiation reaches the PV cells either directly or after been totally internally reflected at the prismatic surfaces. This is indicated by the overall green colour of the prototype in Fig. 3b.

3.2 Hybrid Solar Wall Element

A hybrid solar wall element—which combines active and passive heating, PV electricity, and control of daylight penetration into the building—was developed by Fieber et al. [13]. The solar wall element uses a PV/Thermal (PV/T) hybrid absorber with tracking insulated reflectors integrated into a window (Fig. 4). The tracking reflectors offer an effective concentration ratio of 2.45, and they also act as sun-shades and added internal insulation for the window.

The hybrid absorber is fixed in an angle of 20° from the horizontal and made of 2 mm-thick aluminium sheet. PV cells are laminated on its upper side, and pipes are attached to the bottom for circulation of water. To maximise the fraction of solar radiation that reaches the PV/T absorber, highly transparent glass with an antireflective coating is used for the window.

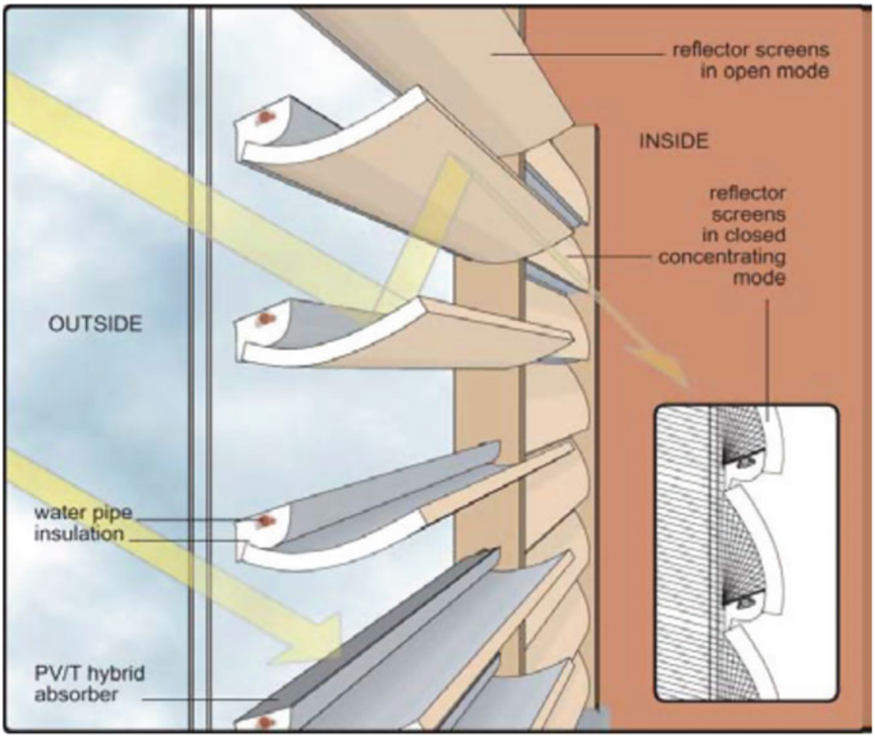


Fig. 4 The hybrid solar wall element [13]

The tracking reflectors can be set to achieve a range of combinations of solar radiation concentrated onto the PV/T absorbers and light penetrating the building interior. With the reflectors fully closed, all of the incident solar radiation is concentrated onto the absorbers, thus maximising electricity or heat generation and minimising solar gains for the building. In passive solar house designs that use large south-facing windows, this feature of the solar wall element-combined with the insulated reflectors—can minimise risks of overheating during daytime or thermal losses during night time. With the reflectors fully opened, all incident solar radiation penetrates the building to provide maximum natural lighting and solar gains.

The system is a visible element in the exterior of the building, particularly in the interior, and its performance is directly connected to the user's behaviour due to the wide range of different operating modes of the reflectors.

A 1 m^2 prototype of the system was fabricated and experimentally evaluated regarding its Sun shading and U-value properties and its photovoltaic and active thermal output [14]. For a double-glazed antireflectively coated window, the U-value was found to range between 1.2 (with reflectors fully closed) and 2.8 W/m^2 K (with reflectors fully open). The estimated annual energy gain was estimated to be 609 kWh/m^2, of which approximately 10 % was expected to be delivered as electricity-generated PV absorber elements (assuming that the reflectors are fully closed at all times). However, because providing natural daylight to the building interior is a more efficient strategy than using PV-generated electricity to power artificial lighting, it was suggested that the reflectors should not be closed at incident solar radiation levels <300 W/m^2.

A simulation program calibrated using actual data from installed prototypes in Lund, Southern Sweden, and a family house at Solgarden, Central Sweden, predicted that the hybrid solar wall element annually can produce approximately 35 % more electric energy per unit of employed PV area compared with a vertically installed flat PV module [15]. In comparison, a wall-integrated low-concentration PV system optimised purely for electricity production at similar latitudes (approximately 60°) was predicted to generate 120 kWh/m^2 of PV area, 72 % greater than that generated by a flat PV module [16].

Hybrid solar wall technology is not fully integrated onto the building façade because it is simply installed (superimposed) behind a window in the building's interior. It does offer the advantage of decreasing the total price of the construction compared with a conventional solar PV/T collector because it utilizes the frame and the window's double glazing for cover. It also offers improved thermal insulation to the building by using insulated reflectors. However, because it is an active system that requires tracking of the reflectors to operate effectively, it incurs operating and maintenance costs. The reflector and PV/T absorber assembly, even when the reflectors are fully opened, will impair the view of the building occupants toward the outside and prevent penetration of the sunlight into the building.

3.3 The Fresnel Lens PV/T Collector

The ability of linear Fresnel lenses to separate the beam from the diffuse solar radiation makes them useful for illumination control in the building interior space. Fresnel lenses are advantageous because they can combine within them both the concentrating element and the optically transparent window. In addition, nonimaging Fresnel lenses are much less demanding in tracking requirements than the image-forming ones. This feature is very interesting for BI as it simplifies the control needs, the weight, and the complexity. Based on these characteristics, the Applied Solar Energy group, at the University of Lleida, designed a solar concentrator that consists of a stationary wide-angle optical concentrator, which, for Sun position in the sky, transmits the incident solar radiation into a small moving focal area, which in turn is tracked by the absorber. The absorber is a hybrid PV/T collector that controls the cells from overheating to maximize electrical yield and simultaneously generates low-temperature thermal energy for domestic hot-water use [17].

The system combines a linear Fresnel lens (5×) with a secondary CPC reflector (2×). This option was selected to maximize the concentration ratio and to obtain optimum illumination for the PV cells (mainly homogeneity in the focal area). The secondary concentrator increases the acceptance angle of the lens and at the same time mitigates the non-uniformity caused by the Fresnel unit, thus obtaining a more uniform profile on the cell. The optical performance of the system was found to be consistent throughout the year. Figure 5 shows the concentration ratio as a function of the relative angles in the direction perpendicular to the focal plane (θ) and in the direction of the focal plane (ψ). The lens was placed at the latitude plane, and the angle variation was θ (−25°, 25°) and ψ (−70°, 70°) [18].

The system allows a range of different BI options because the lens is static, and the acrylic material of it [with the adequate ultraviolet (UV) treatment] is waterproof, light, easy to fix, etc. Therefore, it can be installed as an external element, e.g., in windows, and can be used for either the façade or roof closing element. Figure 6a illustrates the view of the concentrating system from the indoors and the effect of the sunlight that reaches the building interior. Clear shading is observed, which is caused by the large percentage of the incident irradiance that is

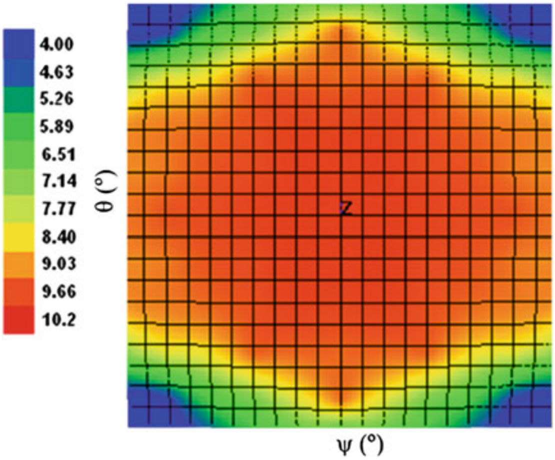


Fig. 5 Dependence of concentration ratio on angles of incidence

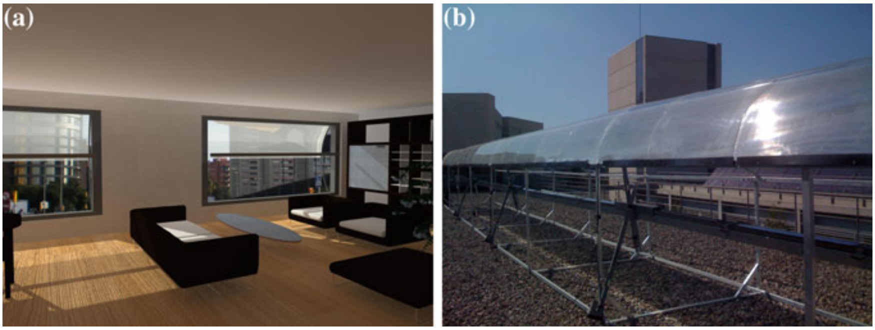


Fig. 6 **a** Architectural design of the Fresnel PVT collector. **b** Prototype system built using a structure of metallic profiles that supports the Fresnel lenses and the PV/T absorber

concentrated onto the PV/T absorber where the diffuse fraction enters the interior space. The lens was placed with its longitudinal axis horizontal and the PV/T absorber just outside the window. Figure 6b shows the prototype that was built using a structure of metallic profiles. The structure was designed to support the module and the lens in the same position as they would be in a real building-integrated installation.

3.4 Photovoltaic Facades of Decreased Costs Incorporating Devices with Optically Concentrating Elements (PRIDE)

Dielectric nonimaging concentrating covers for PV-integrated building facades make use of total internal reflection of sunlight to redirect the incident solar radiation onto PV cells placed at the absorber of dielectric nonimaging concentrators. They were designed as a replacement for the glass panes covering conventional PV modules while offering higher electrical outputs per unit of PV material employed. An asymmetric CPC was specifically designed for use in for building façade BIPV (Fig. 7a). The asymmetric design was shown to be more suitable compared with symmetric concentrators. It offered (after truncation) a geometrical concentration ratio of 2.46 with a 1.39 aperture width-to-depth ratio [7]. Refraction of the incident solar radiation at its aperture allowed it to collect beam solar radiation incident at any angle between 0° and 66.4° from the perpendicular to its aperture. A 5.3 mm deep concentrator was predicted to achieve optical efficiencies of up to 91 % when made from opti-white glass. A three-dimensional optical analysis predicted that the asymmetric CPC maintained optical efficiencies of >40 % (Fig. 7b) even for

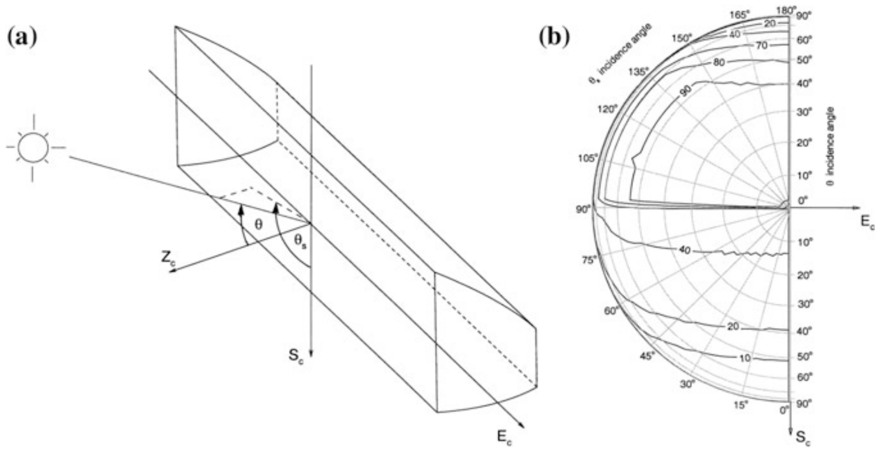


Fig. 7 The dielectric asymmetric CPC designed for use in façade-integrated PV covers (**a**) and its predicted optical efficiency (%) in the three dimensions (**b**)

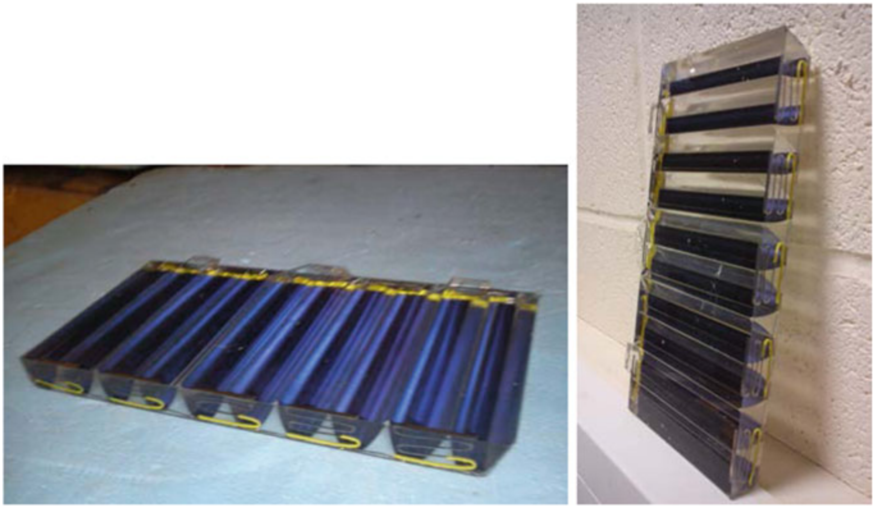


Fig. 8 Prototype concentrating PV covers made by casting acrylic material into a mould. The covers use 9 mm-wide PV cells at the absorber of asymmetric CPCs specifically designed for building-integration

incidence angles outside of its two-dimensional angular acceptance range. Compared with a nondielectric concentrating system, it offered increased acceptance of solar radiation for incidence angles both inside and outside its meridian.

The asymmetric CPC design was used in prototype covers of PV facades incorporating devices with optically concentrating elements that were fabricated using casting into moulds (Fig. 8). The prototype covers were compared with similar nonconcentrating systems under controlled simulated conditions and showed excellent power output. An injection moulding method was used to fabricate covers out of clear acrylic material using 6 mm-wide cells at the absorber of the dielectric asymmetric CPCs [8]. The method allowed large-scale manufacturing with improved durability and decreased weight and cost of the covers. The fabricated covers were optically characterised and evaluated outdoors compared with similar non-concentrating panels. The measured power ratios between the two systems showed a 2× power concentration (Fig. 9). The decrease in relation to the geometric concentration ratio of 2.45 was due to optical losses. The maximum solar to electrical conversion efficiency achieved for concentrating covers was 10.2 %. The power output from a 950 × 1000-mm cover measured at standard test conditions was 78 W.

The quality of the finish of the acrylic surfaces of the asymmetric CPCs was the main factor affecting the optical performance of the prototype concentrating covers. The employed asymmetric CPC design provides the optimum optical performance for building façade integration (with wide acceptance angle, high optical efficiency, concentration ratio of 2.46 and 1.4 with aperture width-to-depth ratio). However, the complexity of its geometry makes it difficult to fabricate accurately and

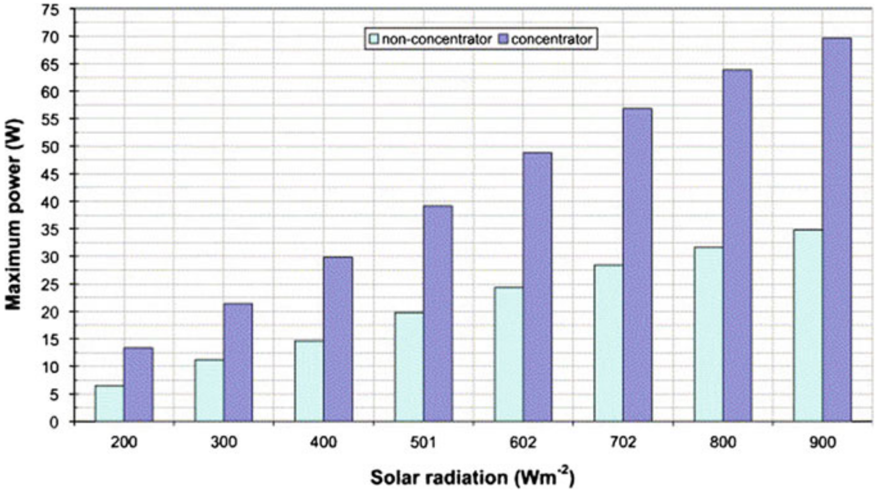


Fig. 9 Comparison of power outputs at different solar intensities for the prototype concentrating PV and a similar non-concentrating panel using the same area of PV material [8]

inexpensively. Although small concentrator depths mean shorter paths for the sunlight inside the concentrator body before reaching the PV cell and in turn greater optical efficiencies, achieving good fabrication quality becomes more challenging at small scales (such as when using 3 mm-wide PV cells). Baig et al. [19] modelled and experimentally evaluated a building-integrated CPV system based on symmetric elliptical hyperboloid dielectric elements. The geometric concentration ratio of the system was 6×. A power ratio of 3.7 was determined at normal incidence and an average ratio of 2.1 was determined over the entire incidence angle range. Fabrication defects, spectral transmission, and temperature losses were identified as the main loss mechanisms for decreased performance. However, the effect of the high nonuniformity of the solar flux incident on the cell surface was found to be negligible.

The concentrating PV covers were developed as a method of decreasing the unit price of electricity by using less PV material to achieve the same electricity output compared with conventional PV. Decreases in the price of PV cells over the last 10 years meant that the costs of fabricating the dielectric concentrators became greater compared with the costs saving from using less PV material. Any façade-integrated BIPV technology is exposed to lower levels of solar radiation compared with roof-mounted systems. This results in decreased electricity outputs and longer investment payback periods. To achieve cost-effectiveness, façade-integrated BIPV should provide other functions or advantages than just generating solar electricity. Ease of integration, good thermal insulation, natural daylighting, solar gain control and aesthetics must be part of the competitive offering package of the technology.

4 High-Concentration Systems: Critical Aspects

Compared with BI PV and BI CPV, BI HCPV offers the opportunity of achieving greater overall electrical conversion efficiencies by using HC solar cells, which achieve conversion efficiencies >40 %. In this way, significant amounts of power can be generated by the limited space available on building facades, roofs, and other elements. Furthermore, the cost-effectiveness of the system can be improved when the high-temperature waste heat generated by the large concentration fluxes (400×) incident on the PV absorber is used for other applications such as cooling and power generation [20].

By the two-axis tracking of the Sun, BI HCPV systems ensure that incident solar radiation is received within a very narrow angular range, which maximises acceptance and in turn power generation. Moreover, the tracking system can allow a more versatile use of a BI HCPV system. Connected to the appropriate control systems, the tracking mechanism can be used to control or allow daylight penetration into the building in response to changing ambient conditions and building occupant needs. During night time, the tracking mechanism can arrange the position of the concentrating system elements in such a way that improves the insulation properties of the building skin and decreases heat loss.

HCPV systems require a highly collimated light on their aperture, which is then focused on a very narrow area where the PV cell is located (point focus). It is possible to use this method in reverse and employ it for lighting purposes [21].

In HC systems, a distinguishing aspect compared with other PV technologies (e.g., flat-plate PV modules without concentration or PV of low concentration) is the requirement for two-axis tracking that can achieve the desired power densities. Due to this characteristic and the magnitude of the concentrated radiative flux itself, a number of critical factors, related with BI, arise:

1. The requirement for additional structural and mechanical elements to fix or attach the tracking system itself. Thus, the structural load of HC systems integrated into a building is always greater than that of a conventional solar system.
2. The space occupied (as part of the building) increases due to the moving parts of the tracking system and the PV generator. Therefore, in these devices it is necessary to consider the swept volume required to track the solar height and azimuth. The density of the elements on the surface where the system is installed is decreased by having gaps between them for tracking movements. In turn, the volume of the layer, understood as a constructive system, is also increased because of solar-tracking trajectories. The best method, which allows for low swept volume, is to install modules with the smallest possible size (one optical element–one PV cell). This means that more mechanical pieces will be used to fix each of the individual concentrating units, but the volume occupied is lower and the possibilities for BI improved (Fig. 10).
3. As a result of the previous requirement, moving parts mean that the interconnections of all of the installations involved (electrical circuits, hydraulic circuits, control circuits) should be prepared for these movements. This is a bigger

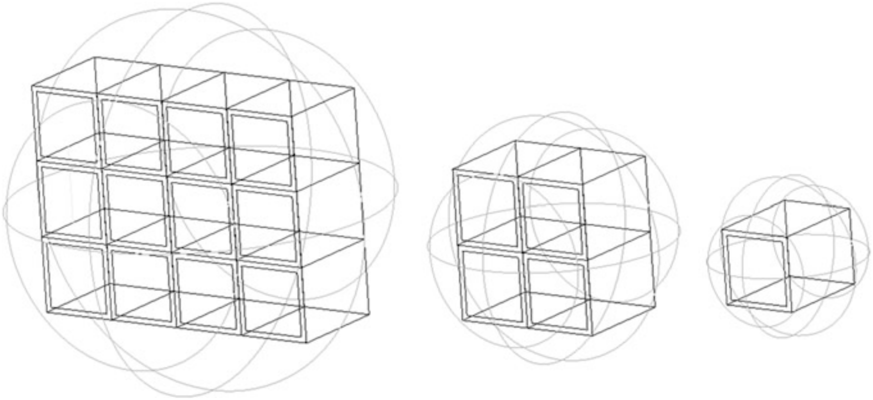


Fig. 10 Swept volume as a function of the elements forming the concentrating module

challenge in the case of PV concentrators equipped with active cooling, whereby an additional flexibility for pipe connections is required. It is worth mentioning that the majority of HC systems are equipped with passive heat sinks that work successfully due to the small size of the PV cell and its isolated placement in the module. These two factors allow using evacuation devices with high-dissipation active area with respect to the cell surface to be cooled.

4. In addition to generating electrical power, the system has an electrical consumption for the tracking system; thus, the net output is decreased. Moreover, this consumption implies the use of an additional electrical circuit to feed the tracking system and its corresponding control.
5. The solar tracking for HC systems is demanding with angular tolerances of approximately ≤0.2°. Because small deviations could cause several problems in addition to the consequent loss of production, the control must be precise and proper maintenance is required.
6. A large amount of the incident concentrated energy, between 60 and 70 %, is not converted into electricity and is lost as waste heat. Thus, hot spots with temperatures ranging from 50 to 100 °C should be managed by appropriate heat sinks and should be the air flow to which the waste heat is transferred.

Considering what has been presented in the previous sections, the majority of HCPV systems are not designed to be architecturally integrated. The most feasible option is to incorporate them on flat roofs where they are not visible from the street level. However, these configurations fall outside the “building integrated system” concept because they are instead superimposed on the building structure.

In addition to the requirements inherent to HC, these systems must comply with the general principles of a solar system well-integrated into the building. In this direction, the HCPV that are more suitable for integration in buildings are made by refractive optical systems, and their main components are Fresnel lenses. Refractive systems have a highly desirable property, which is their transparency; this enables them to be part of façades or roofs while allowing natural lighting to interior spaces. The direct fraction of the solar irradiance is concentrated onto a high-efficiency solar cell, and the diffuse fraction provides natural lighting inside the building. Depending on the arrangement of the concentrator elements, a portion of the solar irradiance passes directly through the interspaces of the modules needed to perform the two-axis tracking. The light-guiding devices, which combine refraction and total internal reflection, also have the property of transparency. The Light-Guide Solar Optics Sun Simba, commercialised by Morgan Solar, is a leading exponent of this typology [22]. This system operates with a geometric concentration of 500× and III-V cells of 5 mm^2. It is highly compact (similar to a conventional PV module) because the PV cell and the concentrator form a single element. In addition, the waste heat-removal system is minimized as the concentrator removes the infrared (IR) from the incident spectrum [23].

Parabolic-dish concentrators have the same constraints derived from two-axis tracking and volume occupied as the refractive systems using Fresnel lenses. However, being reflective systems, natural lighting of interior spaces is achieved only through the gaps between the array elements. Improving the compactness of the system, cassegrain-type concentrators combine several optical systems achieving a similar thickness as a conventional module but with a concentration of approximately 500× [24–26]. It is possible to allow lighting into the building by using spectral-selective reflectors that permit part of the incident irradiance to enter and other bandwidths to be concentrated onto the cell [27–29]. This is more suitable for PV technologies, such as the silicon or GaAs PV cells, that utilise narrow spectral bandwidths and a spectral response at a distinct maximum zone. A possible configuration is to use a reflector that only concentrates irradiance from a zone around the spectral response peak (i.e., approximately 900 nm in the case of silicon cells) while it is transparent in the rest of the visible region. However, in the case of multijunction cells where spectral response ranges from the UV to the near-IR region with very high external quantum efficiency, the benefits depend on other factors rather than the efficiency. Nevertheless, a band-pass filter configuration could be designed to satisfy the specific application.

5 Examples of BI HCPV Systems

5.1 Integrated Concentrating Solar Facade (ICSF) System

A BI HCPV system that fulfils the criteria for a well-integrated system in buildings is the integrated concentrating solar facade by researchers at the Rensselaer Polytechnic Institute [Center for Architecture Science and Ecology (CASE)] and the Harvard University [30]. The technical challenges addressed by the researches, in addition to developing a low-cost system, are as follows:

- to maximise the direct beam irradiance gain for producing electricity;
- to use the maximum amount of incident diffuse irradiance to provide natural daylight;
- to minimise maintenance issues;
- to capture and utilise the waste heat produced by the PV; and
- to be aesthetically pleasant and prevent glare effects for the building's occupants.

The solution adopted to meet all of the desired characteristics is a Fresnel lens optical system that concentrates the direct irradiance (approximately 600×) towards a III-V high-efficiency cell. The structure supporting the lens and the PV cell is completely transparent (made from either borosilicate glass or acrylic), and it constitutes the concentration module. The modules are suspended between parallel hanging fins that rotate to track the solar azimuth. On the front of the modules, thin vertical cables, which are practically invisible, are attached on the aperture area of the concentrator. The cables hold the module and track the solar altitude (Fig. 11).

To use the incident energy that is not converted into electricity, the system includes an active cooling system comprising a heat exchanger placed at the back of the PV cell and a hydraulic circuit located inside the vertical tube that connects the apexes of the modules. The connector of the hydraulic circuit with the cooler is flexible to absorb solar tracking movements. Because the hydraulic system is decoupled from the structural fins that track the solar azimuth, the connector between the heat exchanger and the distribution circuits must absorb only the limited movements required for tracking the solar altitude.

Fig. 11 Concentrating Fresnel lens module with detail of the individual concentranting element. *Courtesy* of CASE

The system minimizes the load impact on the building by using lightweight materials and by providing additional functions to the structural elements such as tracking element or hydraulic circuit housing. The fasteners are designed to be vertical, thereby bending deformation because all loads act in the main direction of the element is avoided. This fact enables the use of smaller section profiles. Thermal expansion of components is considered carefully to minimize stresses and maintain tracking within optical tolerances. By contrast, the fins performing the azimuth tracking are subjected to torques that may be important; therefore, it is necessary to take into account the distance from where the torque is applied (transmission system) and the different elements that rotate as well as the materials and the section of the twisting profiles. The ladder construction of the module axle and fin assembly is designed to delocalize the stresses from these torques.

In terms of swept volume, the researchers considered including an array of individual elements so that the occupied volume is minimized. These elements are housed between two glass panes in a curtain wall.

The system functions are illustrated in Fig. 12. Depending on the temperature of the heat-removal fluid and the available technology for utilising it, a wide range of combinations are possible that also produce, apart from the PV electricity, heat for different uses: space cooling, dehumidification, service hot water, desalination and wastewater treatment, power generation, heating, etc.

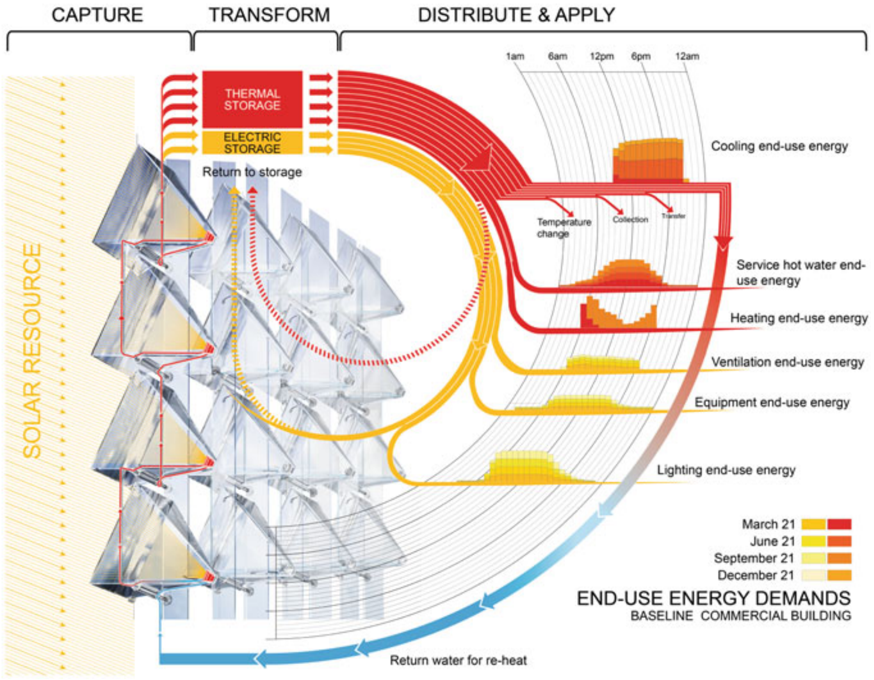


Fig. 12 Schematic of the applications of high-quality thermal energy collected through an envelope-integrated solar-harvesting system. *Courtesy* of CASE

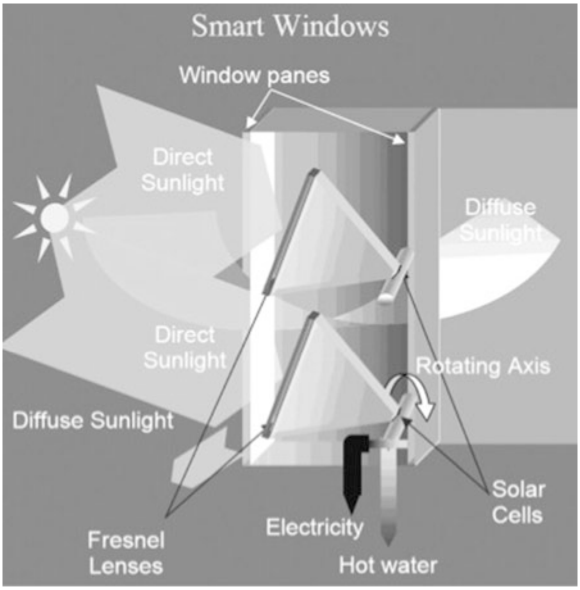


Fig. 13 Schematic of the concentrating system [31]

The proposed device has been tested in the SyracuseCoE Centre of Excellence and the SOM-NY Headquarters and is commercialised by HeliOptix.

The hybrid device ensures that the cell does not overheat; it works in optimum conditions and increases the overall efficiency of the system by producing thermal energy. However, even with a dissipater, a warm zone is produced behind the cells. Heat flux is transferred mainly by convention to the air located in the cavity between the two glass panes. This effect has been numerically investigated by Sabry et al. [31] in a very similar BI HCPV system. This system has the major support axis positioned horizontally so that the rotation achieves the solar altitude tracking. In this case, the loads of the structure are more demanding due to the bending deformation in addition to the torque (Fig. 13).

5.2 Spherical Solar Concentrator

The second example of a BI HCPV system, designed by the company Rawlemon, is based on acrylic spheres. The diameter of the spheres ranges between 50 and 1800 mm. Systems with smaller spheres are made from solid acrylic material and called MicroTrack 324. Larger spheres are made from a spherical acrylic shell with the internal cavity filled with water. The larger diameter systems are a hybrid receiver, using the water for cooling, and can reach a combined efficiency of approximately 57 %.

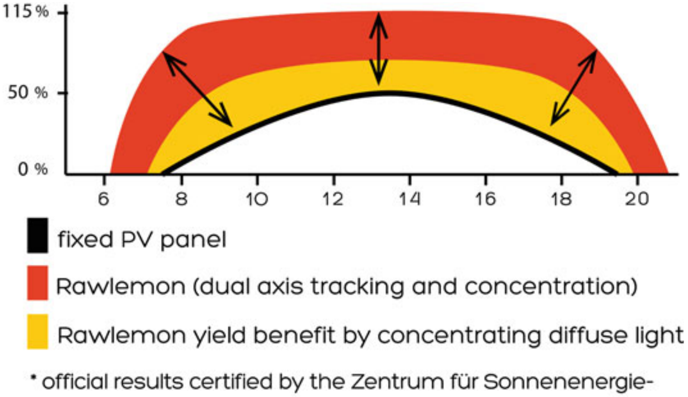
All of the systems are designed with a geometric concentration ratio of 100×. The smallest device (50-mm diameter) incorporates a single 5 × 5 mm^2

Fig. 14 Photograph of the receptor formed by a matrix of cells. *Courtesy* of Rawlemon

Fig. 15 Solar spherical concentrator. *Courtesy* of Rawlemon

concentration cell. The rest of the systems present an array of concentration cells with variable surface, depending on the sphere diameter, to achieve 100× concentration. Figure 14 shows a photograph of the matrix of PV cells for one of the large-size spheres.

The design is fully adapted for architectural integration with the concentrating element (array of spheres) manufactured as a single panel. Two-axis tracking is used on the PV element to track the focal point of the sunlight after being concentrated by the spheres as shown in Fig. 15. The PV cell is the element that moves to track the focus. The system is fully modular and does not need additional elements to support its operation. As defined in the technical specifications, it is the first concentrating solar module that allows complete integration. The designer



* official results certified by the Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg

Fig. 16 Comparative performance between a Rawlemon system and a conventional PV panel. *Courtesy* of Rawlemon

claims that it can utilise 15 % of the diffuse irradiance with a transparency of 99 % [32]. However, due to the increased lengths of paths the sunlight travels inside the sphere before reaching the PV absorber, it suffers large optical losses. In addition to generating electricity, or electricity and heat, the system also provides an alternative function for night lighting by placing a series of light-emmitting diodes in the focal points of the spheres.

The system has been experimentally analyzed by the Centre for Solar Energy and Hydrogen Research Baden-Württemberg showing that it can deliver up to 70 % surplus yield compared with a conventional PV panel also placed vertically (Fig. 16).

6 Conclusions

Building-integrated solar energy technologies such as PV systems can play an important role in covering part of the building energy needs and helping achieve the challenging targets such as EPBD. BIPV generates energy in situ where the consumption of it takes place. This does not require a distribution grid from the centralised power-generation unit; therefore, losses from supply side to the demand side are minimised.

Truly building-integrating systems are multifunctional offering extra benefits than just producing energy. They can work as structural elements of the building, such as windows or facades; they can provide and/or control the natural lighting to the interior spaces; they can improve the aesthetics of the building; and they enhance the insulation properties of the building's skin. In contrast, some BI configurations, where the system is superimposed onto the building structure, achieve less electrical yield compared with a PV system placed at the optimum tilt angle for a specific location.

Concentration of the direct sunlight decreases the amount of solar cell material required and makes the system more cost-effective. Solar concentrators may also help in increasing the amount of incident energy by means of increasing the acceptance of direct incident solar radiation for the full collection period and because they use more efficient cells, which can double the system's performance compare with using conventional cells such as silicon-based technologies.

Most documented building-integrated concentrating systems are of low concentration ratios. When the concentration ratio is low, the system can be static, which facilitates the integration into the building. Few high-concentrating PV collectors are designed to be architecturally integrated. HC systems need two-axis tracking to operate, which means that parts of or the whole system moves. This imposes extra requirements to consider when designing such collectors. Nevertheless, if the BI issues are considered from the beginning of the design and given the same priority as those issues related with the efficiency, suitable devices and good performance can be obtained.

Two HC building-integrated PV systems have been described. Both systems operate with cell efficiencies >30 % and increase the energy performance considerably compared with a similarly integrated standard PV system. From an aesthetic and architectural point of view, the concentrating devices are integrated in a way that improves the image of the building and enhances its public acceptance.

Further research should be performed into developing solutions for truly building-integrated HCPV systems that can offer high cost-effectiveness while enhancing building aesthetics and comfort for its occupants.

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