# Photovoltaic Concentrators – Fundamentals, Applications, Market & Prospective

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## 1. Introduction

The main obstacles for the photovoltaic energy to be competitive with standard energy sources are 3: the low efficiency, intended as low density of energy production for occupied area, the high cost of the constituting materials and the variability of the production which is correlated to the meteorological conditions.
While for the last point the solutions are related to technologies external to the PV, touching issues of grid management and distribution of solar plants, the first two issues are the aims of the PV research. One way investigated to improve the efficiency and reducing the costs is the concentrated photovoltaic (CPV); the light concentration allows higher efficiency for the cells' PV conversion and permits to replace large part of photoactive materials with cheaper components concentrating the light. Unfortunately, besides these advantages some limitations are present for the CPV too; the most evident are the necessity for the panel to be mounted on a sun tracker and the capacity to convert only the direct component of the sunlight; moreover, the reliability of the CPV systems has not yet been proofed in field for long time as for the standard PV, since this technology has achieved an industrial dimension only in the last years.
The photovoltaic concentrators spread on a large space of different possible configurations; there are concentrators with concentration factor from 2 to over 1000, there are CPV assemblies using silicon solar cells as well as using III-V semiconductors solar cells; there are CPV systems with one axis tracker as well as two axis tracker, and with different requirements on the pointing precision. All these different configurations have been developed from the first pioneer works in the '70s till the current commercial products, to find the best solutions for cost competitive solar energy.
The CPV industry is very different from that of other PVs; indeed, a CPV module or assembly is made of many components requiring high precision of mounting. So, the CPV sector appears like an hybrid between the microelectronic and the automotive industries. This possibility to derive large part of the automation necessary for medium-high volume of production from other well consolidated industrial field is an important advantage for the first assessment of CPV and an useful reference for the cost analysis of large productions.

## 2. Optics for concentrators

The optics for the Sun concentrators have been mostly developed during the last 30 years; the non-imaging optics, a branch of geometrical optics, has given a great contribution to the

evolution of the shapes for solar light concentrators. For this application there isn't the concern to reconstruct images avoiding distortions, but the aim is to maximize the transfer of light flux from the first intercepting area of the concentrator, to the photovoltaic receiver.
In this application, the light can be represented with sunrays, so the geometric optics is suitable to describe the optical properties of the concentrators.
Some optical parameters cover a substantial role in photovoltaic concentrators; the parameter are both geometrical, related to the ideal design of the parts, and physical, related to manufacturing issues and material choice.
The main geometrical parameters are:

- Concentration factor
- Acceptance angle

The main physical factors to consider in the optics for concentrators are:

- Light transmittance
- Light reflectance
- Light absorbance
- Dispersion
- YI (Yellowing Index)
- BRDF (Bidirectional Reflectance Distribution Function)
- BTDF (Bidirectional Transmission Distribution Function)

The BRDF is the Bidirectional Reflectance Distribution Function defined as the scattered radiance per unit incident irradiance; mathematically it's expressed as in Eq. (9).

$$BRDF(\theta_i,\varphi_i,\theta_S,\varphi_S)=\frac{dL_S(\theta_S,\varphi_S)}{dE_i(\theta_i,\varphi_i)} \tag{9}$$

Where $\theta_i$, $\varphi_i$ represent the angles of incidence for the incoming radiation, in spherical coordinates, while $\theta_s$, $\varphi_s$ are the angles indicating the scattering directions. $L_s$ is the scattered radiance, while $E_i$ is the incident irradiance. This optical property can become significant after the aging of the materials/surfaces, introducing unwanted light scattering at the reflector surfaces. The BTDF accounts for a detailed description of the scattering of the light through a transparent mean; usually, the parameter employed to describe the scattering of the light in transparent materials is the haze. The haze, defined as the ratio of the scattered light to the total light that get through a transparency, normally expressed as a percent, does not provide indication of the distribution of the light scattered (ASTM D 1003-97, 1997). Sometimes, this scattered light is not completely lost for CPV, but, however, the haze of a material is usually enough to estimate the optical performances useful for concentrators.
All these properties affect the optical efficiency of the solar concentrator, where the optical efficiency is usually defined as in (1):

$$\eta_{opt}=\frac{Irradiance\ @\ receiver\ surface}{Irradiance\ @\ entrance\ surface} \tag{1}$$

The aim of the optics designer is to maximize the optical efficiency, the concentration factor and the acceptance angle of the concentrator; moreover, for the photovoltaic application can be very important to consider other optical characteristics, like the spatial distribution of the irradiation onto the receiver surface and the light incidence angles distribution onto the

solar cells. Indeed, the PV devices usually work better with an even irradiation and with low incidence angles of the incident rays.
The geometrical concentration factor, defined as in (2), is a mere ratio of surfaces, which can growth indefinitely; however, to maintain an high efficiency, i.e. a maximal transfer of the incident energy flux of light, the concentration factor is constrained by the maximal light divergence of the incident rays.

$$C_{geom} = \frac{Entrance\ \ Area}{Receiver\ Area} \tag{2}$$

This constrain, obviously consistent with the second law of thermodynamic considering the Sun as heating body and the receiver (Smestad et al., 1990), is the sine brightness equation for ideal geometrical flux transfer; in its general form, with the receiver immersed in a material with refractive index $n$, this law is like in (3) for a 3D concentrator with axial symmetry. The $\theta_{in}$ represents the maximal incident angle for the incoming radiation respect to the normal direction at the entrance surface allowing for a maximal ray collection, while $\theta_{out}$ is the maximal angle for the rays at the receiver.

$$C_{max} = \frac{n^2 sin^2 \theta_{out}}{sin^2 \theta_{in}} \tag{3}$$

In fig.1 a schematic representation of a generic concentrator is sketched.

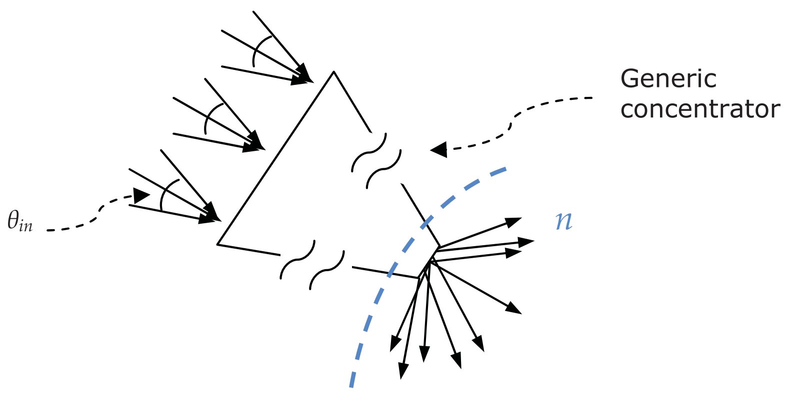



Fig. 1. Generic concentrator: the rays achieving the entrance with a maximal incident angle $\theta_{in}$ are collected to the exit aperture immersed in a means of refractive index $n$

Considering the maximal concentration achievable, the output angle is with $\theta_{out}$ = *90°*, so the theoretical max concentration becomes (4). For a solar concentrator with the receiver in air, i.e. with $\theta_{in}$=*0.27°* and $n$=*1*, this value is 46000; this and even higher values using $n$>1 have been experimental obtained (Gleckman et al, 1989). The sunlight divergence, due to the non negligible dimension of the Sun, is determined by the Sun radius and the Sun-Earth distance.

$$C_{max} = \frac{n^2}{sin^2\theta_{in}} \tag{4}$$

For a linear concentrator the sine brightness equation is as (6), for an $\theta_{out}= 90°$; the demonstration is straightforward. Considering a radiance $L$, an ideal concentrator must conserve the flux ($\Phi_{in}= \Phi_{out}$) given by the radiance integrated onto the entry surface. For a linear concentrator, this flux becomes as in (5) and the concentration factor becomes (6). For a solar concentrator in air, it becomes about 200.

$$\Phi = \Phi_{in} = LA_{in}\int_0^{\theta_{in}} \cos(\theta)d\theta = \Phi_{out} = LA_{out}n\int_0^{\theta_{out}} \cos(\theta)d\theta \tag{5}$$

$$C_{max} = \frac{A_{in}}{A_{out}} = \frac{n}{sin(\theta_{in})} \tag{6}$$

In the CPV field, the acceptance angle is defined as the angle of incidence for the rays at which the optical efficiency of the concentrator achieves the 90% of its maximal value.
The two geometrical properties (optical efficiency and acceptance angle) of a light concentrator with defined concentration level are well represented with a graphic like in fig. (2), where the optical efficiency is plotted vs the incidence angle. The rectangular shaped dashed line with a side at the limit angle is the graph corresponding at an ideal concentrator; it collects at the exit surface all the rays with angle lower than the $\Theta_{max}$ defined by the theoretical limit. The other lines represent 2 possible characteristics of non-ideal concentrators; their acceptance angle can be determined in correspondence of the 90% of the optical efficiency.

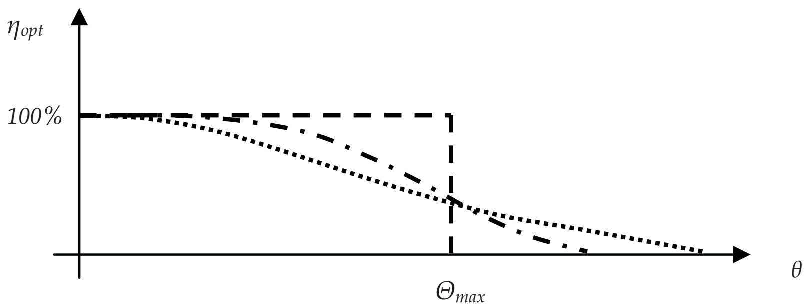



Fig. 2. Optical efficiency vs incident angle for solar concentrators: the rectangular shaped dotted line represents the characteristics of an ideal concentrator, while the others are for non ideal concentrating geometries

In the real applications, the concentrators have surfaces different from the geometrical ideals; this because the geometrical shapes allowing for the theoretically best results are limited and usually with complex structures or requiring special materials. These conditions are constrains for the cost competitiveness of the concentrators, so a trade-off between performances and cost must be achieved.
As previously indicated, the theoretically maximal concentration of an optical system is limited; an optical invariant, called Lagrange invariant or étendue, accounts for this relation

between concentration and angle of divergence consistently with the thermodynamic limits. It describes the integral of the area and the angular extends over which is set a radiation transfer, as in (7).

$$étendue = n^2 \iint \cos(\theta) dA d\Omega \tag{7}$$

Using this optical invariant is possible to derive (4,6) (Winston et al., 2005). Considering a bundle of rays, the étendue can be represented univocally as a volume in a phase space characterized by the cosine directions of the rays and their positions in the real space; a geometric concentrator works as an operator with the function to modify this volume; in this transformation the étendue must be conserved.

### 2.1 Design methods

The design of solar concentrators has different drivers respect to imaging optical elements. Indeed, the design goal here is to maximize the flux density, i.e. the irradiance, at the receiver. Different methods can be implemented to achieve this result (Winston et al., 2005); one of the most commons is the edge ray method. This is based on the assumption that the edge rays in the phase space, i.e. with higher incidence angle at the entrance boundaries of the concentrator, correspond at the extreme rays, in term of positions as well as angles, at the receiver too; the rays between the edge rays are collected to the receiver as well, supposing smoothing and optical active surfaces in continuous media for the concentrator. The first example of non-imaging concentrator obtained with this technique is the compound parabolic concentrator (CPC), as shown in fig. (3); a bundle of parallel rays with an angle respect to the CPC's axis of symmetry (which is the max angle of divergence for the collected rays), is focused onto a point at the exit area by the reflection on a parabolic surface; this point is on the edge of the exit of the concentrator. All the rays entering with lower angle of incidence are collected at the exit surface. This kind of concentrator allows for the maximal theoretical level of concentration for a linear collector, and it's almost ideal for the 3D case, with a surface obtained by revolution.

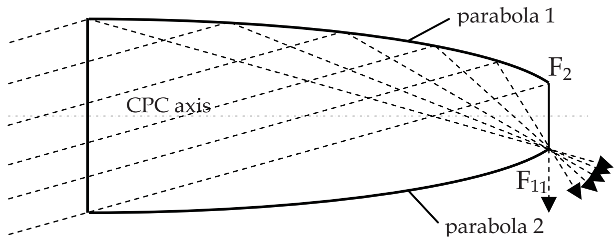



Fig. 3. Scheme of the edge ray method applied to a compound parabolic concentrator (CPC); the dotted arrows represents the incoming rays

Other methods have been developed since the 70's till today (flow line method, Tailored Edge Ray, Poisson bracket method, Simultaneous Multiple Surface, Point-source Differential Equation method) both analytical as well as numerical.
The design of solar concentrators must take into account many different aspects other than the geometrical optical efficiency and concentration levels; indeed, the physical optical properties former reported have to be considered, in order to achieve an effective high

optical efficiency. Moreover, the concentrators should be as much compact as possible, deliver a suitable irradiance distribution at the receiver, allowing for cheap assembling and good thermal management of the system components. All these variables have enlarged the space of possible configurations for CPV optics and there is indeed a wide spectrum of real applications. Currently, most of them are based on Fresnel lenses for the primary optics; the Fresnel lenses are particular kind of lenses for which the dielectric transparent volume material is reduced at the minimum, as shown in fig.(4a), in order to reduce the mass, so the weight, as well as the light absorbance. Other solutions use the reflection of the light instead of the refraction to concentrate the light; the classical parabolic reflectors are used as well as more complex configuration in the form of cassegrain designs, as in fig. (4c); this optical design based on two reflections has the aim to achieve a compact structure, with the light focus behind the primary concentrator. The cassegrain structure is normally employed in telescopes, for the magnification of the far field objects, and, in its basic design for imaging optics, use a parabolic mirror reflecting toward a hyperbolic mirrored surface.

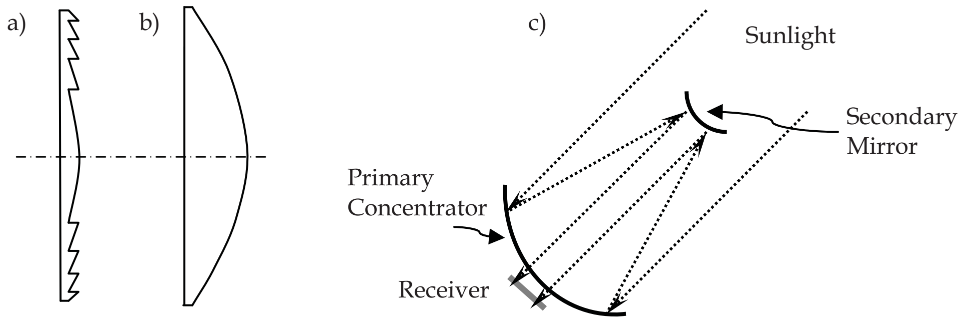



Fig. 4. Classical designs for photovoltaic concentrators: a) Fresnel lenses equivalent to the standard lens of b); c) schematic drawn of a cassegrain optics

The CPV optical systems are often composed of a primary concentrator with a secondary optical element (SOE); these secondary elements are usually joint to the photovoltaic cells and are employed to improve the concentration factor and the angular acceptance. Moreover, they are often used to increase the light uniformity on the receiver through multiple reflections with kaleidoscopic effect (Ries et al, 1997; Chen et al, 1963); in this latter case, to allow for good optical efficiency, the reflections must be associated to negligible losses. An optical phenomena used to achieve this result is the total internal reflection (TIR) effect; this is obtainable through the channeling of the light into transparent dielectric means shaped to allow the striking of the rays on their surfaces only with an angle lower than the limit angle $\Theta_c$ (8); this angle is a direct consequence of the Snell law, when the SOE is made of a material with dielectric index $n_1$, placed in a mean of dielectric index $n_2$. It works like a light pipe.

$$\Theta_c = Arcsin(\tfrac{n_2}{n_1}) \tag{8}$$

The shape of the secondary optics is directly related to the primary concentrator, because it works on the already deflected bundle of rays. So, a number of different designs for these components can be found. However, the most popular can be classified in few groups, like domed shapes, CPCs, truncated pyramids or cones (Victoria et al., 2009). Other original configurations can be found, depending on the requirements of every CPV manufacturer.

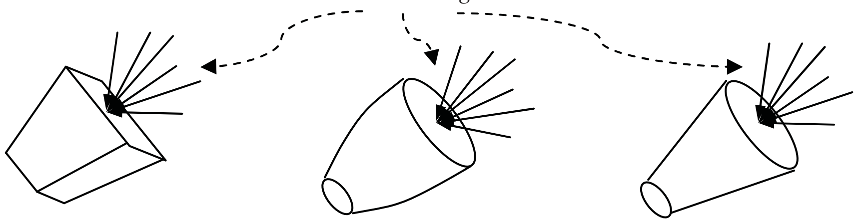



Fig. 5. Examples of geometries for simple secondary concentrators

Currently, powerful modern raytrace-based analysis tools for optics design are available; the majority of these software employ the Monte-Carlo method to solve the coupled integral differential equations used to calculate the illuminance distribution in 3D models (Dutton & Shao, 2010).
These software tools often allow for the accounting of physical parameters too, delivering very realistic estimations for optical performances.


Fig. 6. Cassegrain type optics for solar concentration arranged in modules by Solfocus Inc. (www.solfocus.com)

### 2.2 Other concepts

In order to maximize the conversion efficiency of the solar cells and of the complete concentrating system, some CPV designs act onto the spectral properties of the light together with the geometrical ones. Each photovoltaic materials has the best photovoltaic performances for wavelengths with energy slightly higher than the semiconductor bandgap. A splitting of the incoming light or the wavelength shifts are tricks used in dichroic and luminescent concentrators to try to increase the PV conversion efficiency.

#### 2.2.1 Dichroic concentrators

The idea to split the sun spectrum in light beams and to drive theem toward different cells of selected material is not new. As well as the idea of concentrating the light, it can be realized in a number of different configurations; the constrains for its implementations are mainly related to the costs of these assemblies, considering that additional complexities are introduced; indeed, to split the solar spectrum, two physical ways are possible: dispersion through a transparent prism or reflection/transmission through dichroic filter working for light interference. The light is concentrated too, in order to reduce the costs of the cells dedicated to defined wavelengths. In these configurations the theoretical efficiency can achieve its maximal level, because each cell produces power in the best conditions of irradiation, without constrains of series electrical connections as happen for multijunction monolithic structures. Multi-cells arrays with a record efficiency of 43% have been fabricated (Green & Ho-Baillie, 2010) to demonstrate the feasibility of this approach.

### 2.2.2 Luminescent concentrators

The aforementioned solutions and methods to concentrate the light are not the only developed for photovoltaic applications. One important limitation of these designs is the necessity to use tracking structure to follow the sun. This constrain must not be considered always a limitation; indeed, especially for utility scale installations, tracking structure are used for standard flat plate modules too, in order to improve the energy harvesting, being always on the plane perpendicular to the sunrays. However, the possibility to use static photovoltaic concentrator able to capture also the diffuse radiation has been developed, using a different optical approach, not just the geometrical optics, but involving also some physical properties of particular material like the luminescence; these concentrators, named luminescent concentrators, are usually made of a flat plate of transparent material, with solar cells connected to the sides of the plate; inside the transparent material, luminescent particles like organic dyes or quantum dots are dispersed, absorbing part of the light spectrum and re-emitting light with shifted wavelengths, matching the spectral response of the cells. The re-emitted light is than guided toward the solar cells through the transparent mean, using the total internal reflection at the surface. The limiting point of this technology is the low efficiency achieved due to the losses in the different physical processes involved; it is currently in the order of 6-7% for record prototypes; moreover, the usual concentration for this kind of modules is in the order of 10-40 and the overall size of each luminescent concentrator, to avoid significant losses for light absorption from the transparent material, must be limited.
In fig.(7) a sketch describing the basic concept of these concentrator is reported.

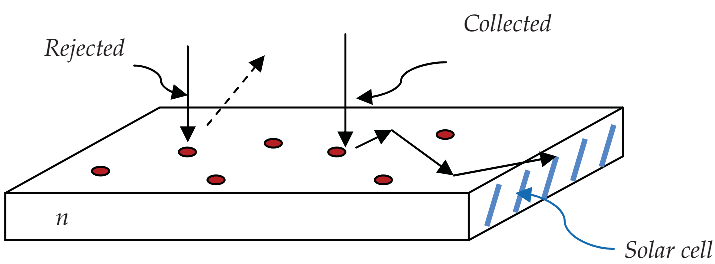



Fig. 7. Simplified drawn of a luminescent solar concentrator

## 3. Solar cells

The solar cells used in CPV are made with many different technologies, depending on the kind of used concentrator. In general, for low and medium concentration level, up to about

300 Suns, cells made of Silicon are still used; for higher concentrations, cells based on III-V semiconductors are usually employed; these latter cells allow for efficiency in the order of 40% and find their natural application under high concentration. Due to the high cost of the base materials and processes, these ultra-high efficiency cells found application for space satellites and for terrestrial concentrators. Thin film solar cells, in particularly made of CIS-CIGS, have given interesting results under concentration too (Ward et al, 2009), but, till now, no significant applications have been developed out of the laboratory scale.

The light concentration, through the increasing of the concentration of the minority carriers, improves the efficiency of the solar cells logarithmically. The produced current is linearly proportional to the irradiation level; because of the generated power is given by the product between the current and the voltage and the voltage increases logarithmically with the concentration level as in (9), the power increases in the mentioned super-linear way. In (9) $C$ is the concentration level, while $J_{ph\_1sun}$ is the photo-generated current under one standard sun level of irradiation.

$$V_{oc} = \frac{AkT}{q}\ln\left(\frac{CJ_{ph_{1Sun}}}{J_0}+1\right) \tag{9}$$

Where $J_0$ is the dark current of the diode and $A$ is the ideality factor of the device.

An additional advantage for CPV cells is the performances reduction with the temperature, which is lower under concentrated light respect to the same effect under one Sun of irradiation, for the same kind of cell. This is true in general, for all semiconductor; in addition, III-V cells, often used in CPV, have a lower temperature coefficient than standard crystalline silicon solar cells. For example, the interdigited back contact silicon solar cells have a voltage temperature coefficient of about -1.78 mV/°C under one sun and of about -1.37 mV/°C at 250 suns (Yoon, 1994), while for GaAs from –2.4 mV/°C under one sun, to -1.12 mV/°C at 250 suns (Siefer, 2005). The dependence of the temperature coefficient with the concentration appears, in first approximation, with a logarithmic behaviour, as in (10); considering the $V_{oc}$ as the voltage associated to the energy gap between the quasi-Fermi energy levels of the illuminated cell, as from fig.(8), this value is given by (11), where $C$ is the concentration level, while $B$ is a parameter dependent on various physical characteristics of the material.

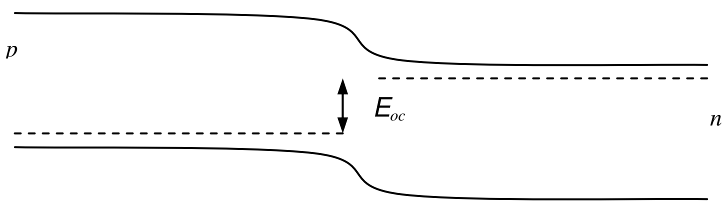



Fig. 8. Schematic band diagram of an illuminated p-n junction of a cell in open circuit conditions

$$V_{oc} \cong \frac{E_g - kT\ln(\frac{1}{CB})}{q} \tag{10}$$

So, the temperature coefficient becomes:

$$\frac{dV_{oc}}{dT} \cong -\frac{k\ln(\frac{1}{CB})}{q} \tag{11}$$

One of the main differences in the technology fabrication between concentrator solar cells and standard solar cell is the requirement for the CPV cells, producing high current density, to have low series resistance.
A simplified formula describing the I-V characteristics of a solar cell taking into account the resistance effect is eq.(12); two electrical resistances can be considered: a series resistance, $R_s$, and a parallel resistance, $R_{shunt}$. In a simple one dimensional model they are represented using the solar cell equivalent electrical circuit of fig.(9). It's a rough electrical schematization of the SC, because of the resistances are lumped; a more precise equivalent circuit should require distributed parameters in 3-D (Galiana et al., 2005).

$$J = J_{ph} - J_0 exp\left(\frac{q(V + JR_s)}{AkT}\right) - \frac{V + JR_s}{R_{shunt}} \tag{12}$$

Where $J_0$ is the dark current of the diode and $J_{ph}$ represents the photo-generated current.

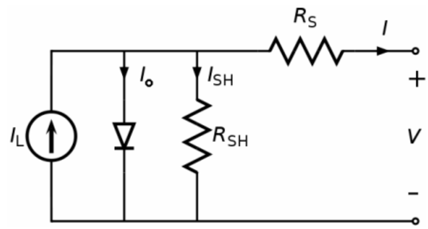



Fig. 9. Simplified 1D equivalent electric circuit of a solar cell

The simplified electrical equivalent circuit of fig.(9) is enough to explain the importance of attaining $R_s$ as low as possible, especially in the case of concentrator solar cells. Indeed, the higher the current, the higher the voltage drop across the series resistance; in this way, the diode senses a voltage higher than that one on the external load, so its exponential behaviour reduces the current in the external circuit when the voltage on the diode is closed to its threshold voltage. The discrepancy between the voltage on the diode and the voltage on the external load gives a shortage in the current delivered from the cell in the region of the I-V characteristic with higher V.

### 3.1 Silicon solar cells

High efficiency silicon solar cells have been manufactured since the 80's (Green, 1987). These cells were manufactured in labs with microelectronic technology steps and with ultrapure crystals, in order to allow for the maximal performances; efficiency in the order of 27% have been achieved for back contact solar cells under around 100x and in the order of 25% under around 250x for cells produced by Amonix Inc. (Yoon et al., 1994). However, the fabrication processes required for these cells is expensive, and the ultimate device cost is comparable to that for multijunction solar cells on III-V semiconductors. Mainly for this reason the back contact technology is no longer used for CPV under the mentioned value of concentration; Sunpower Corp. commercialized this kind of solar cells until the beginning of 2000$^{th}$ but moved forward and transferred the technology on low cost processes for one Sun module production. The silicon cells are currently used in CPV systems with concentration up to around 100 Suns; the technology used in this range of concentration must not differ so much from that of standard solar cells, in order to allow for an economical convenience of the CPV solutions. One established technology is the laser grooved buried contact (LGBC), in which the metallic contacts of the frontal grid are buried into the bulk of the wafer, as in fig.(10); the high aspect ratio of the fingers allows for low resistance of the contacts, while the large area of metal-semiconductor interface permits to strongly reduce the electrical resistance at the interface of the Shottky energy barrier, keeping a low shadowing of the photo-active material.

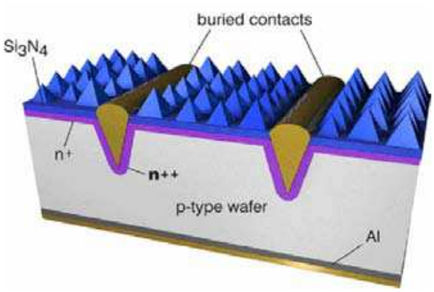


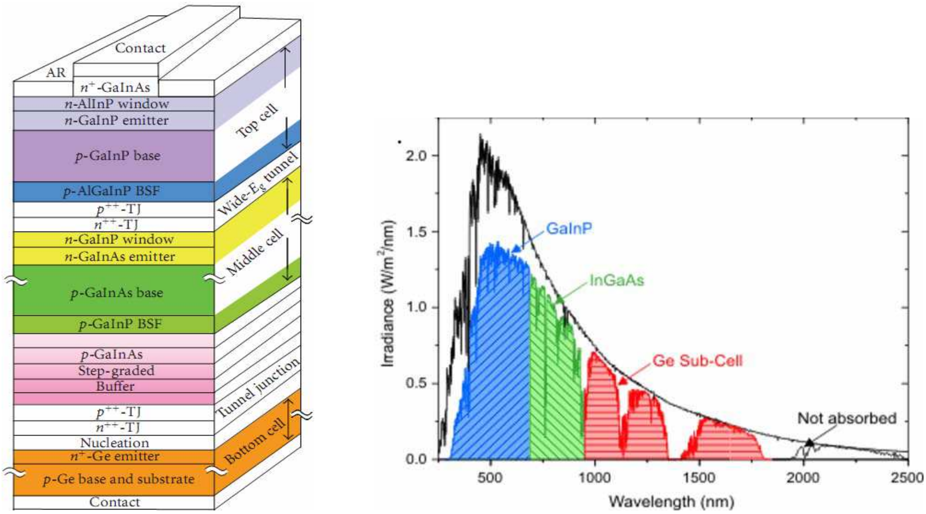

Fig. 10. Cross section of the LGBC silicon solar cell (Cole et al., 2009)

This LGBC concept is employed for the Saturn cells commercialized by BP Solar in flat plate PV modules (Bruton et al., 1994). For concentrated light BP Solar produced cells with this technology for the Euclides concentrators (40x) (Sala et al., 1998); at the Narec PV technology centre, these cells are manufactured and developed for different concentrating solutions, with efficiency approaching the 20% (Cole et al., 2009).
Standard solar cells obtained with screen printing technology and designed for one sun application strongly reduce their efficiency even at 2-3 suns because of ohmic losses due to series resistance; however, some improvements can be achieved through slight design modifications, varying doping concentrations, electroplating parameters, line pitches and other fabrication steps.

### 3.2 Solar cells of III-V materials

The highest conversion efficiency for solar cells has been obtained with the multijunctions approach. Through epitaxial growth the deposition of crystalline layers of compound semiconductors is possible whenever specific requirements on the lattice parameter are satisfied (Yamaguchi, 2002). Many layers of different semiconductors are stacked in order to create a structure where the first layers appear transparent at the light absorbed by the semiconductors at their bottom. This is obtained decreasing the band gaps of the compound semiconductors, from the frontal surface to the rear. The Germanium is often used as substrate material, both for its lattice parameter as well as for its band gap adapt for the bottom cell function. Unfortunately, some semiconductor compounds with suitable band gaps haven't a lattice matching with the other materials useful for the stack; however, cells growth with lattice matched (LM) technique have achieved the 40% of efficiency under concentration. To further improve the performances of the cells, the metamorphic (MM) approach has been developed (King et al., 2007), delivering record cells efficiency higher than 41% under concentration; with this technique, consisting in the introduction of step-

graded buffer layers allowing for stress/strain relief to avoid the formation of dislocations in the layers growth, the flexibility in band gap selection is greatly improved, providing freedom from the constrain of same crystal lattice constant for all the stacked material in the monolithic structure as for LM. In fig.(11) a semplified MM multijunction cell structure from (King et al., 2007) and the distribution of irradiance absorbed for photovoltaic conversion by the three active materials are reported. To electrically connect the integrated sub-cells of different materials, tunnel junctions are formed.
These complex structures represent 3 solar cells series connected. So, the active element producing the lower current limits the current generation. The current produced by each layer depends on the light spectrum too, so spectral variations, as happen with different weathering conditions, can affect the performances of the cells (Muller, 2010).




a) b)

Fig. 11. Triple-junctions solar cells; a) stacks of layers of different semiconductor compounds from (King et al., 2007); b) absorbed portions of the solar spectrum (AM1.5) for the three photo-active semiconductors

Theoretically, a cell with 4 junctions can achieve an efficiency of 58% under an AM1.5 spectrum; with a combination of real and known materials, a terrestrial concentration cell with efficiency of 47% is possible. Until now, however, the most performing cells are 3-J solar cells; at the end, for energy production installations, a trade off between costs and performances in field must be carried out. Because of the detrimental effect of the spectral changes becomes more influent increasing the number of monolithically stacked junction, the convenience to use, in the future, 4-J solar cells instead of 3-junctions solar cells for in Sun installation must be demonstrated.
The cost of these devices is decreasing, but it is still in the order of 4€/cm². To evaluate the cost contribution of the cells on the global system, let's suppose a collected area of the concentrator of 400 cm² and of a cell of 1cm² (physical area of the cell, usually higher than the irradiated zone, because of, at least, the area for the pads for contact leads is necessary); with a nominal irradiation level of 850W/m² and a module efficiency of 25% the cell

generates 8.5W, so the €/$W_p$ contribution of the cell on the overall CPV system cost is of 4/8.5 = 0.47 €/W. It's a significant voice of cost, but it can be reduced increasing the concentration level and with the specific cost reduction of the devices obtained with their volume production, as well as with their efficiency improvement.

New products based on III-V semiconductors are doing their first steps into the CPV market, moving from labs to pilot production lines. The approach of the strain balanced quantum well solar cells (SB-QWSC) (Barnham et al., 2002), appears of great technical interest for the efficiency improvement of multi-junctions solar cells as well as for the possibility to tail the cells on particular optical designs acting on the spectral properties of the light, like as dichroic concentrators (Martinelli et al., 2005).

In order to reduces the cost of these cells high research efforts have been invested, following different routes. From the manufacturing point of view, molecular organic chemical vapour deposition (MOCVD) equipments, industrially used for the epitaxial growth of the compound layers have been developed for high productivity. On the other side, different ways to reduce the cell cost replacing the Germanium or GaAs substrate with cheaper Silicon wafers (Archer et al., 2008) or using peeling-off techniques (Bauhuis, 2010) in order to use the same substrate for different growth have been investigated.

### 3.3 Solar cells assemblies

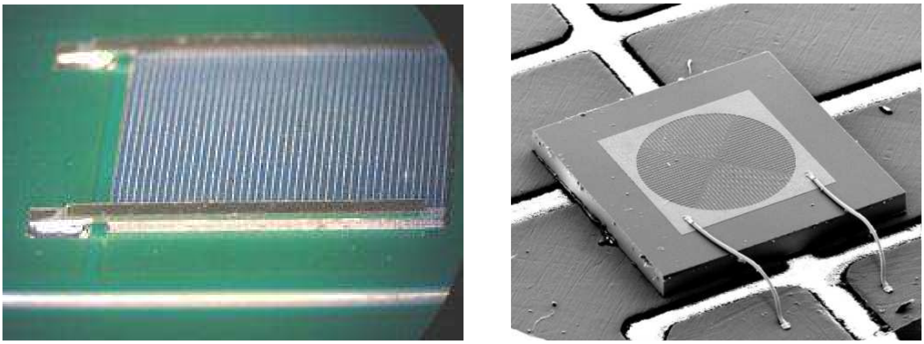
In general, the cells for concentration are assembled on supporting substrates, treated similarly to bare dies in electronic technology. So, the process is completely different to that for standard PV assembling, but can take advantages by the huge progresses, standardizations and experiences collected during the last decades by the electronic devices industry.

Depending on the cells nature (materials, sizes and manufacturing technologies) and on the operative working conditions, different mounting technologies are used. Generally, the surface mounting technologies (SMT) directly derived from power electronics are applied. Even in this particular subset of components there's plenty of different solutions. A good assembling is fundamental for the performances of the systems; thermal properties, reliability and optical matching are strongly dependent on the assembling solutions. Generally, thermal substrates are used, in order to drain out the high heat flux generated by the concentrated beam on the small cells; as every PV devices, the cells for concentration decrease their performances, as previously described, with the temperature. A substrate able to efficiently drain the heat out from the cells and spreads it onto a large area for heat exchange with the external air or with other cooling means is required. For this purpose, ceramic materials like alumina ($Al_2O_3$) or aluminium nitride (AlN) are often use, as in hybrid electronics, when the thermal flux are very high, because of their properties of thermal conductivity; when the thermal budget is lower, cheaper material can be employed as, for example, insulated metal substrate (IMS), i.e. an electronic support fabricated laminating an insulator between a massive mechanical substrate of aluminium and a foil of copper used as electrically conductive layer. Depending on the material and thickness adopted for the insulator layer, the circuit will have consequent thermal properties as well as dielectric capabilities. These insulating materials have usually a thermal conductivity in the range of 0.8 – 3 W/mK. In table (1) a summary of thermal conductivity of useful materials employed in CPV receivers assembling is reported.

The cells are electrically connected at the circuitry on the substrate; the rear contacts are attached using electrically conductive adhesives or soldering, while the frontal contact is connected with soldered ribbons or bonded wires; in fig.(12) two different solutions using soldered leads and wire bonding, with chip on board technology (CoB), are shown.

| **Material** | **Thermal conductivity** |
|---|---|
| | **W/mK** |
| | |
| Aluminium | 204 |
| Copper | 390 |
| Tin | 67 |
| Silicon | 150 |
| Germanium | 60 |
| Alumina | 25 |
| Aluminium Nitride | 160 |
| Silicones | 0.1 – 0.2 |
| Electrically conductive adhesives | 4 – 5 |
| Thermal conductive adhesives | 1 - 4 |

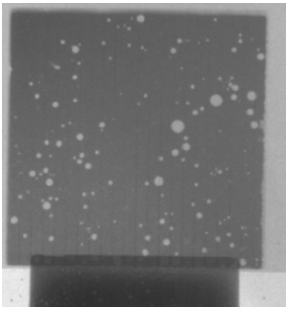
Table 1. Thermal conductivity of materials usually considered for the assembly of CPV receivers

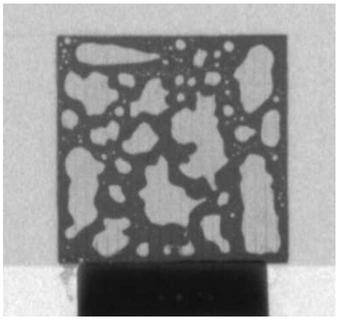


a) b)

Fig. 12. CPV solar cells assembled on substrates: a) soldered silicon solar cell (Courtesy of CPower Srl); b) solar cell of 1mm$^2$ assembled with chip on board technology (Courtesy of CRP – Centro Ricerche Plast-ottica)

Because of the technology used is derived from the electronic industry, the reliability issue related to the assembling with these approaches have been evaluated for long time; the CPV receivers in working condition can suffer different stresses respect to many electronic applications; however, many standards are already defined to verify the level of quality of the assembling processes and some possible defects leading to probable reliability problems can be identified even prior to carry out accelerated aging tests. In fig.(13a) a X-ray picture of a solar cell soldered onto a substrate using a correct surface mounting technology is shown, while in fig.(13b) a cell with an excess of voids in the soldering of the rear cell's surface is sketched. The voids can produce cracking and failures during thermal cycling, as known in electronic technology. (Yunus et al., 2003).





a) b)

Fig. 13. X-ray image of soldered solar cells – a) acceptable soldering with <5% of voids area; b) unacceptable soldering, with high fraction of voids under the cell

Bypass diodes are often mounted on the same substrate of the cells; for multijunctions solar cells these component assumes great importance due to the high sensitivity to reverse bias of these cells, protecting the devices against destructive reverse loads. Currently, each individual cell has its own bypass diode, which can be an integral diode or an external, more standard, Si-diode. Basically, the integral concept consists in separating small area of the multijunction cell via mesa etching, and using the p-n junctions of the cell as protective diode.

Secondary optics, wherever used, are components of the receiver. These components require a high level of precision for their assembling in the module; indeed, the higher is the concentration level to ménage, the higher is the precision of positioning, in order to avoid magnified losses; these secondary optics usually have to work under beams already highly concentrated. In high concentration photovoltaic modules, positioning errors higher than 100 microns can produce not negligible power losses (Diaz et al. 2005); however, this level of precision is usually achieved by high speed pick & place equipments for SMT in electronics, which are employed for the receivers assembly (Jaus et al., 2009).

## 4. Systems

The CPV system is composed of many parts which must cooperate efficiently; generally, the modules or assemblies must follow the Sun in its apparent motion, to ensure the collection of the direct irradiation from the cells, through the optics. The possibility of the concentrators to catch only the direct portion of the sunlight, with an additional circumsolar light dependent on the acceptance angle of the optics, is an important limitation for the CPV respect to standard photovoltaics. Diversely, the necessity to follow the Sun is not generally a limitation; indeed tracking installations are already in fields for standard, flat plate modules too. The tracking of the Sun gives a significant improvement in the energy collection, because of it allows for a constant maximal intercepted area of the modules for the sunrays. This fact permits to improve the energy production of 30-40% respect to fixed installations of same peak power, with this percentage depending on the latitudes of the installation. So, for an economical point of view, the additional costs introduced by the Sun-tracker have to be balanced by the gain in the energy production; this is the straightforward evaluation in the case of standard modules; for CPV the trackers are fundamental parts of the systems, so, it's an integral element and must be considered as an essential component as well as the inverters or the modules.

For these reasons, high efforts in the designing and production of cheap and reliable trackers are fundamental for the CPV establishment.

As previously described, CPVs, depending on the technology employed for the modules and cells, can use single axis trackers and two-axis trackers. While for the HCPV the 2-axis tracker is compulsory, the low concentration systems can be found, depending on the technology, on 1-axis or 2-axis trackers. In fig.(14) a 2-axis system mounting 25x concentrating modules with high angular acceptance is shown; in this case, the high optical acceptance permits to use standard trackers generally used for flat plate modules (Antonini et al., 2009a).

The most common kind of CPV systems are constituted with panels of many modules. These CPV modules are treated similarly to standard flat plate modules on a tracking structure; in the CPV panels, the rigidity of the structures and the precision of mounting on the frames are more critical than for standard modules, as well as the pointing precision in the Sun tracking. These modules are made of many cell-optics units, electrically connected internally into a closed, water proofed box. Each cell-optics unit play the role of a single cell in a standard flat plate module.

Fig. 14. CPV tracking system in Sun; installation of Rondine™ CPV modules on standard sun-tracker for flat plate modules in Sicily (South Italy). (Courtesy of CPower Srl – www.cpower.it)

An alternative approach uses a large concentrating optics collecting the light onto a dense array of cells. The most classic designs consist of big reflective dishes with paraboloid or similarly curved shapes and dense arrays positioned in the focuses of the concentrators or at the end of a secondary optical elements (Stefancich et al., 2007). In fig. (15) a dense array of silicon solar cells is shown. The main advantage of this approach is that there is a high technology core of small area, which can be assembled with standard equipments for electronics, while in the CPV modules the cells are distributed on all the module surface with consequent high area to be considered for the CPV receivers. However, the dense arrays have some important limitations too; first, an even light irradiation is required on the series connected string of cells. This is because the less illuminated limits the current of all the string. Second, it is necessary to reduce at the minimum the spaces between the cells and to reduces the bus-bars and interconnections areas; indeed, all these zones give optical losses for the photovoltaic concentrator. These two points are not in common with CPV modules, because the light irradiance on the optics-cell units is equal for all, and the connectors and bus bars of the cells are usually kept out of the illuminated region, using for these purposes the large area between the cells in the module receiver.

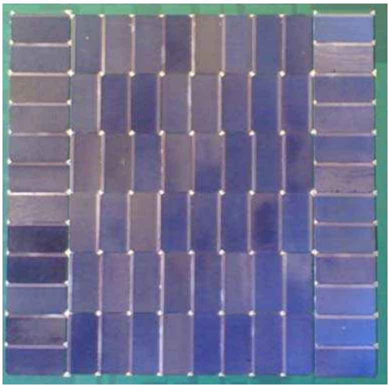


Fig. 15. 30cm x 30cm dense array of silicon solar cells (Courtesy of CPower srl)

The CPV systems have the advantage of a lower energy payback time (EPBT) respect to standard c-Si modules. The EPBT, an indicator for the energetic sustainability of a system, is the time a system for energy production needs to generated the input energy required during its whole life-cycle. The shorter EPBT for CPVs is because the material used for the concentrators are usually produced with low energy consumption. The high level of purification required for the silicon to achieve the electrical properties essential for the photovoltaic use needs a high energy utilization. To understand the order of magnitude, to produce about 100W of silicon for standard photovoltaic cells with efficiency of about 15%, about 300 kWh are necessary; considering an average annual production of 1400 kWh/kWp, more than 2 years are required to pay back the energy for the solar grade silicon alone. Adding to this energy consumption needed for the silicon purification the other fabrication steps to get a compete standard PV modules, the EPBT usually reported for the modules is in the order of 3-4 years (Stoppato, 2008). The CPVs technologies have only a small fraction of very purified materials, being mainly composed of plastics, glass and metallic frames. This fact leads to shorter energy payback time, in the order of 1 year (Peharz & Dimroth, 2005).

The localization for CPV installation is strongly dependent on the weather conditions; diversely than for standard flat plate modules, the fundamental irradiation data is not just the global irradiation, but it is the direct normal irradiation (DNI), i.e. the component of light collected by the concentrators. The humidity, the clouds, the dust and the pollution scatter the light coming from the Sun deflecting the rays; usually, the best conditions for CPV are in dry and highly sunny climates. The higher DNI/GNI ratios are typical of desert areas or elevated terrains. The evaluation of this parameter is fundamental, and the knowledge of the global irradiation is not sufficient to estimate the energy production of a CPV system; indeed, the yearly average DNI/GNI ratio can vary from 50% to 80% (NREL, 1994). Reliable solar maps for direct irradiance are not yet available for everywhere as for the GNI.

Sometimes, even the DNI is not enough to evaluate the energy production of a system; indeed, the light impinging the cells in a concentrator systems is not necessary the same read from the pyroheliometer, i.e. the instrument used to measure the direct irradiation; this instrument, basically a sensor of irradiation with a tube limiting the angle of incidence for the incoming rays, usually has a view angle of ±2.5° and a limit angle of about ±4°. Depending on the optical solution adopted for the photovoltaic concentrator, the acceptance angle of a CPV system can be higher or lower respect to the pyroheliometer, so the light seen by the cells can be higher or lower respect to the reference instrument. The effect of the soiling on the modules is similar to the scattering effect due to the atmospheric conditions; indeed, the particles deflect the sun rays and can contribute to significant losses. Generally, the higher the acceptance angle of the optics, the lower is the effect of the soiling on the performances; for low concentrator systems with high acceptance angle the losses seem to be comparable with that of standard modules (Antonini et al., 2009b).

The peak power for the CPV modules and assemblies is usually defined under a DNI of 850 W/m$^2$. Although the conditions for the performances testing of CPVs are not yet defined in international standards, the main producers and research institutions recently refer to the 850 W/m$^2$ of DNI and module temperature of 25°C; performances tests with the cell's temperature of 60°C are often found too (Hakenjos et al., 2007). The temperature is a more thorny issue for testing respect to the irradiation, because of the temperature in field are usually significantly higher than in lab. The outdoor characterizations are fundamental to evaluate the performances losses due to the heating up of the cells.

The irradiance condition of 850 W/m$^2$ of DNI has been selected because of a DNI/GNI ratio in the order of 85% is frequently observed in many locations around the world when the GNI is of 1000 W/m$^2$, i.e. the standard irradiance condition for the test of flat plate modules.

The energy productivity of a CPV installation can be evaluated, similarly than standard installations for flat plate modules, using the energy yield ($Y_f$) and the Performance Ratio (PR) (Marion et al., 2005). The energy yield represents the energy production for installed peak power of a system; it is measured in kWh/kWp and strongly depends on the location because of it doesn't take care of the incident radiation. It's the first parameter for the comparison of different installations in the same site. Diversely, the Performance Ratio (PR), dimensionless and defined as in (14), normalizes the energy production to the incident irradiation, delivering a useful parameter for the comparison of installation under different irradiation conditions; it quantifies the losses due to temperature, AC/DC conversion, soiling, down-times, failures and mismatching.

$$Y_f = \frac{generated\ Energy}{Peak\ Power\ installed\ (DC)} \tag{13}$$

$$Y_r = \frac{incident\ radiative\ energy}{Reference\ Irradiance} \tag{13}$$

$$PR = \frac{Y_f}{Y_r} \tag{14}$$

The PR can be read as the equivalent time the system has delivered it's nominal peak power ($Y_f$) respect to the time of equivalent nominal irradiance conditions on the panel.
The Reference Irradiance (the irradiance for the DC peak power estimation) for CPVs is 850 W/m$^2$ of DNI, instead of 1000 W/m$^2$ of GNI as for the standard modules. This difference must be taken into account during the comparison of the CPV with other different PV technologies.

## 5. Market & prospective

Large installations of CPV are not yet common. Until the end of 2009, about 21MW of CPV systems have been reported as set on Sun (Kurtz, 2009; Extance & Marquez, 2010); large part of them (13 MW) are from one HCPV technology of modules based on Fresnel lenses concentrator developed by Amonix Inc. in the last twenty years; the fraction of operational systems with low concentration level (LCPV) is less then 1MW, mainly of Entech Solar products installed in the 90's. Although at the end of 2009 around 70 vendors of photovoltaic concentrator systems have been found (EPRI, 2009), the CPV is a small niche of the photovoltaic market; indeed, at the end of 2009 already 7 GWp of PV modules have been installed and grid connected around the world. The market of CPV is mainly oriented toward solar farms and large installations, because of the necessity to use Sun-trackers. For this kind of large installations, big investments are required; this is one of the first hurdles for the CPV entry into the market. Indeed, to gather large investments for solar energy production, the demonstration of high reliability and durability of the systems is a fundamental issues, which need time and systems in Sun. Moreover, the high competiveness of the other PV technologies and their levels in industrialization and economies of scale is another high obstacle to face for any new PV product, which must have a price lower than the established technologies.
With the aim to demonstrate the reliability and durability of different CPV technologies the ISFOC project has been set in Spain, for the testing in field of some MWp of photovoltaic concentrator systems. In this experimental solar plant hundreds of kWp of different CPV technologies are continuously monitored and the performances are evaluated.
An important step forward for the commercial feasibility of CPV has been done with the publication of the international standard for the design qualification and type approval for CPV modules and assemblies (IEC62108, 2007). The tests defined in this IEC standard are mainly oriented to demonstrate the durability and reliability of the CPV modules. This recently published text, milestone for the CPV deployment, presents some tests more severe than for standard flat plate modules and takes longer time to be concluded (approximately one year).

Fig. 16. Installation of CPV systems of Amonix Inc. in Nevada (USA) (www.amonix.com)

Some pioneers companies, the US based Amonix Inc. and the Australian Solar Systems, have set in Sun large installations since the '90s. However, because of the huge difference between any CPV solution, each technology must proof its reliability independently.

Based also on the durability and reliability of the systems, the Levelized Cost of Energy (LCOE) is a parameter expressed in cents/kWh frequently used to evaluate the economical convenience of a PV solution; this parameter takes into account not just the energy production, but the cost complexities associated with the entire lifetime of a solar plant, from financing through to end of life (Short et al., 2005). The LCOE takes into account installation and commissioning costs, operations and maintenance (O&M), degradation and lifetime, and the output. It calculates the average value of the total energy produced, revalued at the time of calculation based on forward assessments of inflation and costs of financing. Starting considering this parameter, some CPV companies have claimed to can achieve the lowest LCOE in the market, in the order of 10 dollar cents/kWh for the next years ( Nishikawa & Horne, 2008).

An important advantage of the CPV approach is the reduced necessity of capital investments (scalability). Both the thin film industry as well as the Silicon standard module production require high capital investments. By reducing the amount of semiconductor material, the initial investment is also reduced. Although no CPV companies have yet demonstrated it, the relative easiness of scale-up of CPV is logical and could be a significant advantage in a rapidly growing market. Some companies have already declared production capacities of many tens of MWp per year in 2009, with large announced growth for the 2010 (Extance & Marquez, 2010).

Because of any CPV systems is composed of many parts, the economical advantage improves with the cost reduction of any components; it can be achieved with the economy of scale consequence of the rising of the number of installed systems. In order to achieve affordable product prices, some CPV companies are moving toward a sort of vertical integration on the value chain, being often producer of trackers, inverters, components, taking care of the field installations and even approaching the processes for the cells manufacturing. In this path CPV companies are rapidly following the way of the largest standard PV groups; indeed, in standard flat plate industry, some companies specialized in the module production, cells manufacturing, tracking fabrication and system integration are still working without integration. But for the largest groups this process is in progress, from the row material purification up to the final installation, in order to achieve the lowest costs.

Aside the CPV module and system producers, there are many companies working in the development of the components required for the installations; in particular, many companies are focused on the production of solar cells for concentration, on the production of specialized optics and for the fabrication of dedicated trackers (Extance & Marquez, 2010).

The CPV is an emerging technology in the photovoltaic sector. The cost of installed kWp is continuously decreasing to try to compete with standard c-Si modules and thin films. The wide range of solutions will lead to the accomplishment of some leaders and to the disappearing of other companies or technical solutions; because of the large amount of investments required for the establishment of a competitive technology, some of these inventions could not found a commercial deployment for financial reasons rather than technological imperfections.

The future of the CPV technologies will be probably defined in the next few years, with the direct comparison of the energy production of the first large solar farms of different photovoltaic technologies in different sites around the world.

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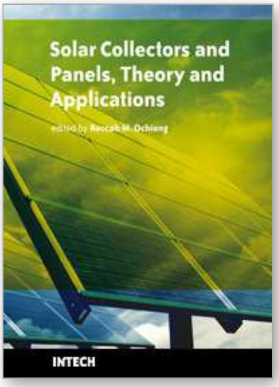


**Solar Collectors and Panels, Theory and Applications**
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This book provides a quick read for experts, researchers as well as novices in the field of solar collectors and panels research, technology, applications, theory and trends in research. It covers the use of solar panels applications in detail, ranging from lighting to use in solar vehicles.



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