1 Past Experiences and New Challenges of PV Concentrators

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1.1 Introduction

The general idea of a photovoltaic (PV) concentrator is to use optics to focus sunlight on a small receiving solar cell (Fig. 1.1); thus, the cell area in the focus of the concentrator can be reduced by the concentration ratio. At the same time the light intensity on the cell is increased by the same ratio. In other words, cell surface is replaced by lens or mirror surface in PV concentrators and the efficiency and price of both determine the optimum configuration.

Medium- and high-concentration systems require accurate tracking to maintain the focus of the light on the solar cells as the sun moves throughout the day. This adds extra costs and complexity to the system and also increases the maintenance burden during operation. For systems with small solar cells, or using low concentration, passive cooling (interchange of heat with the surrounding air) is feasible.

After 30 years of concentrator development and practically no industrial or commercial activities, the photovoltaic concentration market seems ready to take off and grow rapidly because of feed-in tariff laws approved in several sunny countries and the availability of a sufficient amount of very efficient, up to almost 40%, III-V multijunction cells.

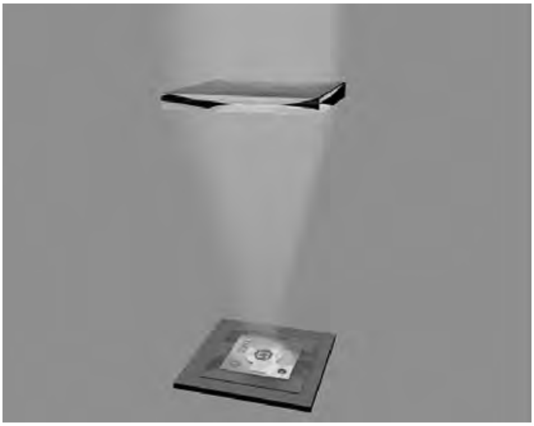

Fig. 1.1. The principle of PV concentration, using Fresnel lens optics. (Courtesy of FhG/ISE, Freiburg, Germany)

Fig. 1.2. The SANDIA-II array, the first modern PV concentrator made at Sandia National Laboratories, Albuquerque, New Mexico, in 1977. It consist of 5-cm-diameter Si cells operating on two axes under cast acrylic Fresnel lenses at 32 suns, with passive cooling

The lack of official qualification regulations may restrict the commercialization of unproven technologies until manufacturers define the minimum requirements before contracting and installing new power plants. Great strides are being made in this direction.

In this chapter a brief summary of the history of photovoltaic concentration is combined with an overview of the present and future of this technology, including an outline of the present situation as well as comments on the material availability and manufacturing challenges if photovoltaic concentration has to supply a significant portion of the world's electricity.

1.2 Past Experience

The development of PV concentrator technology started effectively in 1976 at National Sandia Laboratories with the construction of 1 kW peak array, later called Sandia I and Sandia II (Fig. 1.3) [1]. This early work identified and tried to solve the majority of the problems linked to concentration systems and gave satisfactory answers to many of them.

Fresnel lenses, two-axis tracking, concentrator silicon cells at 40× and analogue closed-loop tracking control systems were the characteristics of this pioneering prototype. Several reproductions, in some cases accompanied by component improvements, were soon made in France, Italy and Spain, with prototypes ranging from 500 W to 1 kW (Fig. 1.4) [2–4].

A pre-industrial, but not yet commercial, action was carried out in 1981 by Martin Marietta with version III of Sandia Technology, who installed

Fig. 1.3. The 1-kWp Ramon Areces Array was developed at 'Universidad Politécnica de Madrid', Spain, in 1980. It followed the Sandia Labs concept, but all components were locally made. Curiously, the Fresnel lenses were made of a thin film of silicone stuck on glass, an idea that has recently been taken up again and might be of interest in the future

Fig. 1.4. The 350-kWp SOLERAS project power plant was the world's first and largest concentration plant. It was built and deployed in Saudi Arabia, using the evolution of Sandia Labs (technology by Martin Marietta)

a 350-kWp demonstration plant in Saudi Arabia, called SOLERAS (Figs. 1.5, 1.6) [5]. Although there was no market pressure, Nasby and co-workers at Sandia Labs developed 20% efficient Si concentrator cells in 1980 [6] which allowed the expectations of both cost reduction of concentrators and conventional PV modules to be increased. Six years later, the man responsible for the SOLERAS project wrote the following:

This PVPS has been operating very well in the hot desert environment since its inception, however the net permanent power is degraded by 20% due to ceramic substrates solder joint delamination problem by the daily thermal cycling and fatigue, short circuit problems, and water penetration/condensation inside the modules. The temperature of the cells was found to be excessively higher than the original designed value, and the heat sink assembly was not enough to cool down the cells.

Fig. 1.5. Martin Marietta PV concentrator assembly line built for the SOLERAS project

Fig. 1.6. Checking the bifacial cells of a 4.5× fully static concentrator prototype before filling the module with transparent dielectric (Madrid 1986)

These are practically the same words that have been used to explain the results of more recent concentrator photovoltaic (CPV) demonstrations; Despite these problems, the Soleras plant continued in operation for 18 years.

So clear was the understanding that efficiency was a key factor in this technology that Swanson et al., after the experiences of R.J. Schwartz, developed the point contact (PC) solar cells – the best Si cell ever made – to be used at a high concentration level ($> 150\times$) [7].

Although there were several concentration cells developed in the world, with efficiencies ranging from 19.6% at the UPM to 27% by Swanson et al., the production capacity was poor and concentrator cells were difficult to find for 25 years. The rare investors that were interested in the PV concentration 'miracle' were discouraged when they discovered that concentration cells were not available, or that the cost ratio with flat-module cells was larger than the concentrator gain.

An alternative to the idea of high concentration that requires specialized cells and tracking was the concept of static concentration based on concentrators developed for Cerenkov radiation by Winston and Hinterberger [8] which was improved with the bifacial cell (Fig. 1.7) [9]. Once the bifacial cell came into in production in Isofotón – a spin-off of the UPM in 1981 – several prototypes were developed by these two partners (Fig. 1.8). This was a product with none of the supposed drawbacks associated with concentrator: it was static, modular like a flat panel, 12-V nominal and able to collect and concentrate (to a large extent) diffuse radiation. But the commercialization never started in reality, perhaps because the introduction of a new product was uncertain and expensive; The investment required to make this product was really small, but the margin of cost reduction was probably not sufficient to justify the effort.

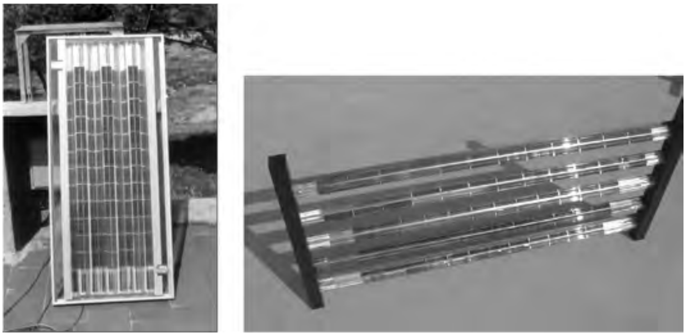

Fig. 1.7. Isofotón and the UPM developed several static concentrators with bifacial cells. The good technical performance was not followed up by their industrialization. *Left*: 1988; *right*: 1998. (From [10])

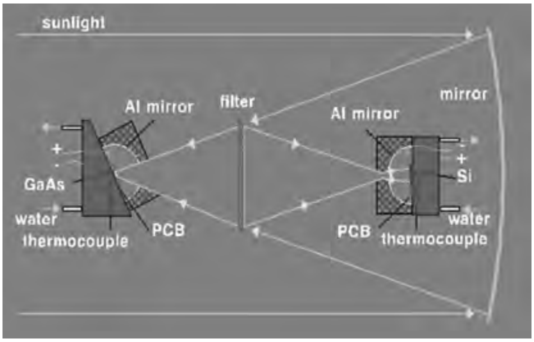

Fig. 1.8. The PV-EYE device combined light spectrum splitting and gap matching (AsGa and Si concentrator cells) with angular confining cavities which redirected cell surface reflected light to the cell again. A European record of 29.6% was achieved with this arrangement in 1990

Neither the ideas of spectrum splitting from 1980 at Varian, nor the realization with an European efficiency record (29.7%) from PV-EYE, using with two cells (AsGa and Si) inside angular confining cavities [11] at levels near 800× in 1991 [12], resulted in any attempt to industrialize concentrators (Fig. 1.9).

In the 1990s the most significant industrialization action was carried out by Entech who installed several hundreds of kilowatts using 20× curved Fresnel lenses (Fig. 1.10) [13].

With flat-panel cells whose price tended to decrease continuously due to mass production, one industrialization opportunity was linked to the Laser Grooved Buried Contact (LGBG) Cell [14] technology, an industrial approach

Fig. 1.9. A two-axis tracking 100-kW ENTECH power plant in Texas. System efficiency of up to 14% was demonstrated with this technology at 20 suns: curved Fresnel lenses showed optical efficiency of over 85%. Different cells were used to make the receivers

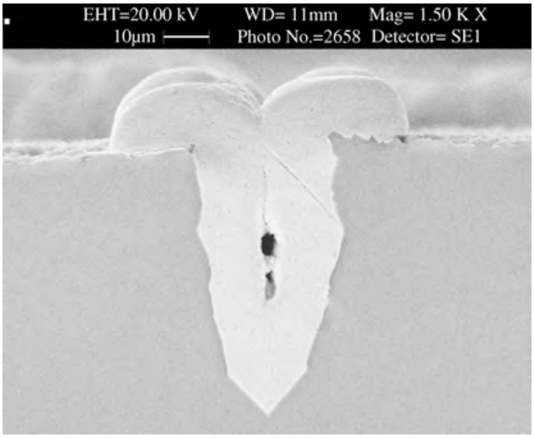

Fig. 1.10. Metal finger cross section of the BP Solar SATURN cell. The low grid resistance was key operating these cells in concentration very efficiently, despite their being made on the same production line as the 1-sun SATURN cell

following the outstanding progress of the University of New South Wales on crystalline silicon cells.

Concentrator LGBG cells (also called SATURN after the name of the industrialization project by BP Solar) shows near-uniform voltage in its metal grid (Fig. 1.11) and low recombination surface which allows it to reach 18.5% efficiency at 30× and up to 20% in small cells ($1\,\mathrm{cm}^2$) at 100× [15].

These cells were very convenient for use in concentrator systems because their 1-sun version is probably more expensive than the conventional cells from the competitors per watt peak but used as $125 \times 125 - \mathrm{mm}^2$ concentrator cells, and designed for 30×, they could be sold at 10 − 12 € each, which would be very attractive to the manufacturer (BP Solar).

An opportunity for this technology opened up in 1995 with the EUCLIDES prototype developed by IES/UPM and BP Solar which was installed in Madrid. It proved up to 14% power efficiency and 10% yearly energy conversion ratio at a lower cost than the flat-plate power plant at that time [16].

Following the Madrid prototype, a planed 480-kWp EUCLIDES demonstration plant was built in Tenerife under the joint effort of BP Solar, the Instituto de Tecnología y Energías Renovables (ITER) on Tenerife and the IES/UPM (Fig. 1.12). Several problems associated with receiver manufacturing and some overestimation of the concentrator benefits pushed BP Solar to abandon the project instead of solving its manufacturing defects. During the merge with Amoco (and its subsidiary Solarex) concentrator plans were practically abandoned, although they continue to manufacture short series of concentrator SATURN cells for R&D projects [17]. These cells were also occasionally used by Entech in their lineal concentrators.

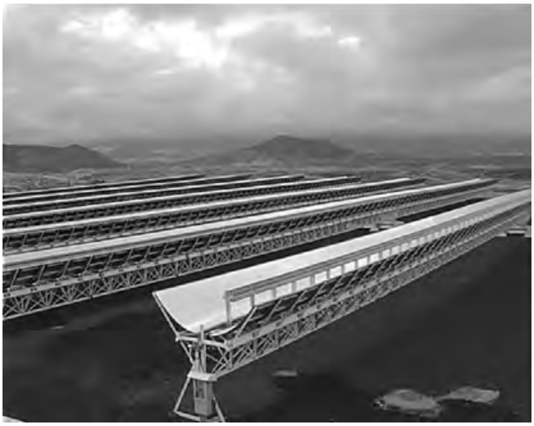

Fig. 1.11. The EUCLIDES demonstration power plant in Tenerife (1998) subsidized by the EU to industrialize the Madrid Prototype (1995). The mirrors were shaped aluminium plates covered with silvered acrylic film which cast $3.2\,\mathrm{W/cm}^2$ on receivers including SATURN cells. The partners were ITER, BP Solar and UPM

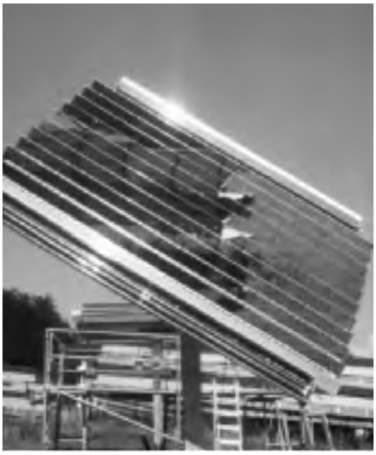

Fig. 1.12. ZSW (Stuttgart) developed very low concentration systems (2 and 10×) with the ARCHIMEDES concept, which includes one-axis passive-tracking hydraulic drivers. The picture shows a one-axis tracking 2× concentrator

The substantial European Commission investment in the EUCLIDES concentrator technology created a wave of activity in this field, many centred on the use of SATURN cells, such as ZSW with the ARCHIMEDES system (Fig. 1.13), but also others adopting the spacecraft Si cells technology (ASE; LETI, DEMOCRITOS and still others based on PC cells (Ferrara University).

The silicon PC solar cells, sized about 1 cm^2, have given rise to a set of concentrators of which the most successful version is the one by Amonix [18] leading to a product that is technically ready, probably, with the cell and receiver manufacture well tested and reliable (Fig. 1.14).

The PC cells are much more expensive than ordinary cells but, unlike ordinary solar cells, which, because the base resistance cannot operate above

Fig. 1.13. Two-axes tracking arrays from AMONIX, installed at Arizona Public Service, Scottsdale. They use 27% efficient BPC solar cells operating at 250× under point focusing laminated Fresnel lenses: the nominal array power is 25 kW. This technology was licensed to GUASCOR-FOTON (Spain) in 2005 and is currently being commercialized

Fig. 1.14. Field of PV parabolic dishes manufactured by Solar Systems in White Clifts, NSW (Australia). Each dish focuses the light on a compact actively cooled receiver, whose surface is a parquet of BPC cells. Each disk is rated 25 kWp nominal

about 100 suns, they can operate at much higher concentrations, in the range of 300 suns, because they are not traversed from up to down by any current [19].

The large parabolic dishes from the Australian company Solar Systems (Fig. 1.15) have been also equipped with these Si-PC cells in their focus area to produce about 25 kW per dish. The newest trends, however, are associated with III-V multijunction solar cells, which have achieved incredibly high efficiencies [20], approaching 40%, and the concentrators associated with them. Spectrolab and Emcore in the United States, and RWE in Germany, are cell producers and willing to sell these cells to system manufacturers. Sharp, the biggest Si cells manufacturers, is also a cell producer, but it is also planning to manufacture concentrator systems.

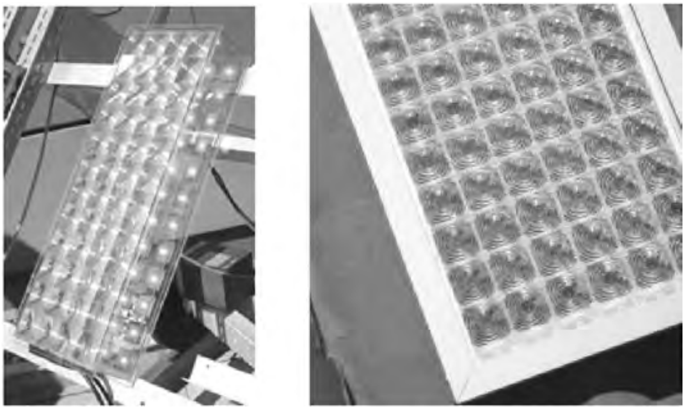

Fig. 1.15. CONCENTRIX (*left*) and ISOFOTON (*right*) have developed compact concentrator systems using 2- and 1-mm-diameter multijunction micro-cells operating at about 400 and 1000×, respectively

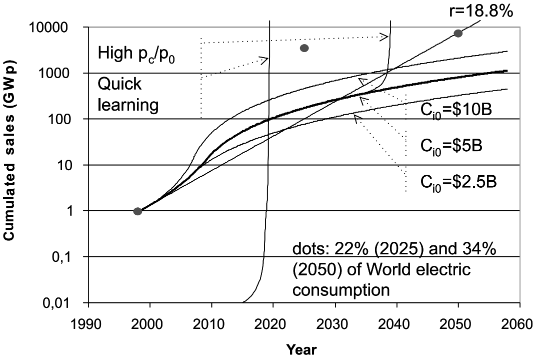

Fig. 1.16. Accumulated PV installations for different capital availability. Labels C_{i0} = \$ 10 B, 5 B and 2.5 B represent 0.1, 0.05 and 0.025% of the GDP of the industrialized countries. The cureve labelled *High* p_c/p_0 represents the case in which the competition with the prevailing electricity is produced for module prices of \$ 0.7/Wp (in the rest of the cases it is \$ 0.35/Wp). The case for high learning has a learning factor of 0.68 (for the rest of the cases the learning factor is 0.8253)

Research centres, such as the IES/UPM, the Fraunhofer Institute for Solar Energy (FhG/ISE) and the Ioffe Institute, are deeply involved in this new type of concentrator development. Isofotón, in cooperation with IES/UMP, is certainly the oldest company working in this new concept concentrator [21]. Other new venture-capital fed small companies spun-off from research groups are starting to work including Concentrix, a spin-off of FhG/ISE (Fig. 1.16) [22].

1.3 An Interpretation of the Past

When, after the first oil shock, the1974 Cherry Hill Conference in the United States took place, it appeared reasonable that a quick path to the mass production of solar electricity, taking into account that the available solar cells were too expensive, was to use concentrators. Accordingly the first industrializing trials and analyses, such as those of Martin Marietta in Saudi Arabia, were directed towards this end. However, the urgent problem posed by the oil shocks was solved before a cost-effective solar converter was in place; therefore, the interest waned and, for more than a decade, PV specialists were forced to find their own way. This path was ploughed along the land of sustainability.

The urgency of this motivation, however, is very different. It requires a large degree of intergenerational solidarity, and this is a feeling only recently added to our moral stock; thus, for many years it was assumed that the non-professional PV market would only fullfil developing-country applications, or the houses of individuals or institutions that wanted to contribute to sustainability goals through their involvements but even more so, by their example. Commercial effort was therefore made in these directions. Architectural integration to make the clean, but expensive, new PV technology attractive was necessary and, taking into account that the short-term forecasts for concentrators concluded that it did not reduce costs sufficiently to make it competitive with conventional electricity, all applications remained of a modest size and were not deemed appropriate to be satisfied by concentrators.

Under these circumstances, dedicated high-efficiency concentrator cells ceased to be manufactured or, if they were, it was in such small amounts that the indirect costs meant a cell price that offset the cost reduction per cell area reduction, with the few exceptions already described.

The CPV does not currently have a single line of their own in the PV market breakdown by technology. Despite this apparent failure, however, the more-or-less intermittent maintenance of R&D lines has permitted CPV to remain a subject at an academic level (e.g. concentrators are regularly researched in the doctorate program of the IES/UPM) and to create a small, but effective, group of specialists ready for the next step, which we described later. Among them, the group at the IES/UPM was the first to publish a book on this topic in English in 1989 [23]. In the same year scientists at the Ioffe Institute published another book on CPV in Russian that was translated into English in 1997 [24]. The latter book was oriented more towards heterostructure solar cells, whereas the former concentrated more on the non-imaging optics.

1.4 The Need for CPV

In 2001 one of us published [25] a forecasting model of the markets and prices for PV technology in the first half of this century. The model has been especially accurate in the short-term forecasting (from 1998 onwards). The model couples the learning curve, that characterizes the reduction of costs every time the cumulated production is doubled, with the elasticity of demand - which is the logarithmic derivative of the market with respect to the price, changed of sign. The results are detailed in Fig. 1.16. Vertical asymptotes tells us that the cost of PV electricity equals that of the prevailing electricity, but the vertical growth is an artefact of the model that is not intended for this situation (it assumes infinite potential demand); however, the asymptotes show when this competitive situation is reached. This model tells us that, while present PV technology will lead to very large markets, its penetration will not be enough to contribute substantially to sustainability. The reason is the slow PV learning curve. On the other hand, the same model predicts that if the learning curve is faster, like the one for semiconductor memories, in few years from the entrance into the market, prices in competition with the prevailing electricity could be reached.

What prevents the learning curve from being faster? In our opinion, it is the fact that the efficiency of the present solar cells is bound by theoretical fundamental reasons (essentially Shockley and Queiser [26]) to a value of 40% [27]. This makes any practical increase of efficiency very difficult and therefore reduces the learning speed. The fundamental theoretical reasons are based on the fact that a solar cell is a two-level device that only converts effectively the photons with energy close to the energy separation of these levels (the band gap). The photons with less energy are totally lost and for those of higher energy the energy separation between levels (the band gap) is an upper limit of the energy at which the electrons are delivered. The limit derived from the two-level nature of solar cells is referred to as the SQ limit.

Multijunction cells escape this limitation. In fact, their limiting efficiency is about 86% [27] under the same conditions that resulted in a 40% limitation for the cells made of a single semiconductor; thus, multijunction cells, or in general, some kind of solar converters not bound by the SQ limit, may, in principle, increase the efficiency much more than the single semiconductor cells. This should lead to a faster learning curve and, if they are able to reach the market, they may reduce prices faster than present solar cells and thus accelerate the penetration of solar electricity. One problem lies in the gaining of the small portion of market that would allow self-learning through experience and therefore trigger a faster learning curve.

Not only are MJ solar cells in this situation, but also a number of concepts have been developed that may fulfil these requirements. They are often called third-generation [28] or new-generation [29] solar cells. The FULLSPECTRUM Integrated project [30], with 19 R&D centres involved, has been launched by the European Union in order to fund R&D in innovative concepts (including multijunction solar cells) able to develop under this faster learning curve.

A common feature of these novel cells is their high cost. In fact, MJ solar cells developed for space applications have very different requirements. But MJ solar cells and many other sophisticated concepts may be adapted to terrestrial uses assuming that they are used in concentrators. In this way, concentrators are necessary to make use of the new opportunities that are offered by the latest developments in the science and the technology of solar cells. The consequence is that concentrators must be developed, and a bigger institutional effort should be devoted to this endeavour.

1.5 New Challenges in CPV

The present situation seems to replicate the one existing when the concentrators started in the mid-1970s, but now there are some important differences:

1. The non-concentrator option in MJ solar cells is only devoted to space. No large amounts of cells are expected for this market, and therefore

the reduction in price through the learning curve will not suffocate the development of terrestrial concentrator options.

2. Very high concentrations are needed to make these cells cost-effective, but unlike silicon cells, the concentration of which can hardly go above 300 suns, MJ solar cells can probably operate very efficiency at about 1000 suns. The optics and the tracking are also challenging subjects, but as we see later, all of them seem to have a solution.

Efficiency is an important aspect of the new scenario. It will decrease the very important BOS costs. The concentration factor is also important at least at the start, because it will avoid the cell cost from becoming a barrier to cost reduction. This requires new approaches to the cell itself, the optics, the automated module assembly and tracking development. Of these aspects, the development of the cell is the one to which more attention has been devoted. By 2004 the race towards 40% efficient MJ solar cells was already in progress. The leading results in the United States [31] and Japan, which have reached the world's top efficiencies, but also in Europe, show the way to others. University groups, research institutes and companies mostly in Spain [32], Russia and Germany soon envisaged a business model based on tiny MJ solar cells operating in integrated concentrators operating at over 400×.

Attempts to operate at higher concentrations were undertaken in 2001 at IES/UPM with GaAs single-junction solar cells with an efficiency of 26.2% at 1000× [32]. Later at FhG/ISE, 3 J solar cells of 35.2% at 700× were achieved [33]. This is possible because the MJ cells, usually of III-V materials are very thin, because they are made with direct-gap semiconductors. The substrate is inactive, and therefore it can be made with very low resistivity without compromising lifetime. Nevertheless, these high concentrations are only possible if the cells are very small, about 1 mm^2, so that the extraction of the current becomes easy. Again, such a small size is not possible in silicon because of its high diffusion length, which makes the cells very sensitive to perimeter recombination.

Cell efficiency for CPV has to be high for several reasons. Firstly, concentrators only collect direct radiation. Secondly, the concentrator itself has a less-than-one efficiency. If we assume that the direct normal radiation/global normal radiation ratio is 80%, as it corresponds to a good climate, and we assume that the optic efficiency is 80%, then we can conclude that only 64% of total available light is cast on the concentrator cell. Assuming that conventional modules are 15% efficient, we must conclude that the minimum efficiency allowed in concentrator cells is 23.4% in order to equal the energy production of flat module arrays with same collector area; thus, the efficiency of concentrator cells must be at least 24% (under standard test conditions) in order to be cost competitive with flat panels. Although it can be argued that a reduction in the cell area could be a factor in cost reduction, this is uncertain (concentrator cells are more expensive), and the commercial success for lower efficiency will be problematic. If this argument is true, only PC silicon cells, such as those used by Amonix in the United States, Guascor Photon in Spain and Solar Systems in Australia, have only a marginal chance of leading to a cost-competitive product. On the other hand, most MJ solar cell-based products, if operating at sufficiently high concentration, may be cost-effective with respect to a flat-module PV.

Concerning the optics, there are fundamental limitations that reduce the angular acceptance with the level of concentration [34]. The angular acceptance is the angle at which the rays entering the optics reach the cell. It must at least cover the apparent sun's semi-diameter of 0.26°, but it is good if it is larger because this will allow the requirements for manufacturing and tracking to be eased. Non-imaging optics attempt to enlarge this angle as much as possible, and this discipline has developed since 1978 (when Winston et al. published their first book on the topic [35]). In this development the IES/UPM staff has participated in a leading way [36]. An important topic for concentrators with a large angular acceptance is achieving a homogeneous illumination on the cell at the same time.

It has been said that high-concentration cells, operating at or near 1000 suns, must be small, in part, for the reasons stated (to reduce ohmic losses), and in part, to facilitate the spreading of the heat produced by the energy cast by the sun and not converted into electricity. In this way the cells are very much of the size of an LED, and novel concentrators may benefit very much from the development in LED manufacture [31]. (It is noteworthy that the heat dissipation in power LED's is higher that the one of a solar cells at 1000×.)

Finally, the remaining challenge is associated with the tracking. The tracking structure constitutes an important part of the CPV cost, and in the past it has been treated as a trivial part of the CPV system. Things have recently changed, and the Spanish company Inspira has made a significant effort in this direction, as explained elsewhere in this book.

The challenge is not associated with the lack of reliability, as is often said without any data to support it. In Spain several tens of MW in the so-called solar farms have been installed, and this market continues to grow fast, so it has to be assumed that the customers are satisfied. But the tracking structures for flat modules are designed to withstand gravity and wind stresses safely, whereas in concentration they are designed to flex, that is, the structure must not, under the operational designed conditions, have a flexure higher than that permitted by the optics and the tracking mechanisms, including the control electronics.

The safe design of the tracking structure must consider the high winds recommended under the local building codes, but the occurrence of these winds is very uneven. Operation of the trackers must be assured only for the winds usually present in the area by putting the tracker in a stowing position when they are exceeded [38].

Concerning the control electronics, in the past it was based on closed-loop solutions in which a sensing device assured a good alignment of the sun with the sensor. The aiming of the sensor with the modules was left to a purely mechanical procedure, completed in some cases with a unclearly defined output-based trial an error. Modern trackers tend to be built using control based on ephemeris calculations with an error model of the mechanical structure along the lines first developed by Penzias and presently followed routinely (T-Point tracking) in astronomical instruments [39]. Accurate measurements (to 1000th of a degree) of the tracking aiming error have been carried out [40] and for the moment an accuracy of less than 0.1° for 98% of the operation time has been reported, but it has also been reported that the use of less accurate error models brings the tracking error to more than 0.3°.

For the final design of the tracker the flexure of the modules has to be adjusted [41] in such way that the angular acceptance of the modules correlated with the sun's semi-diameter (between 0.3 and 0.7° in existing modules) must allow for the loss resulting from the tracking mechanism and its control (0.1° in good control systems) and for the flexure. This leaves to the

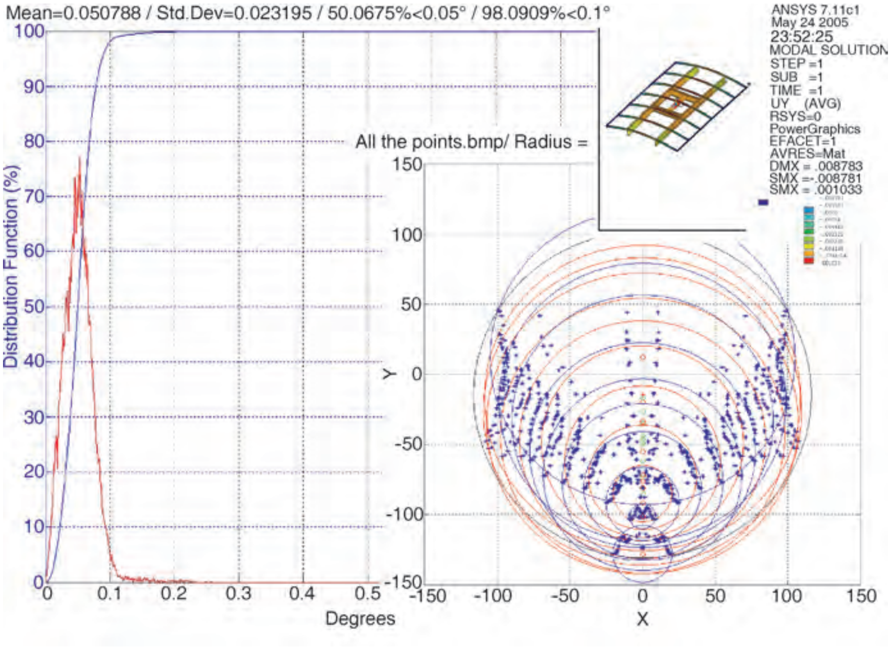

Fig. 1.17. *Left*: Distribution function of the misaiming angle. *Right*: Pointing vectors and minimum encircling circles (MEC) at different elevations with maximum service wind speed windward and leeward to the module's active surface. Tracking accuracy has to be higher than the MEC at any elevation

flexure an angle that is larger $(0.2 - 0.6^\circ)$ when the optics are more tolerant; however, more tolerant optics sometimes means less efficient and maybe more expensive ones, and all these factors must be taken into account in the optimal design of CPV systems. We are presently at the very beginning of understanding all these systemic approaches and, in reality, no system has thus far been designed following all of these principles.

There is very little experience of inverter operation with concentrators. On the one hand, they operate mostly at high power level, which is positive, but on the other hand, the variations in direct light intensity on cells as the result of clouds, limited acceptance angle, wind loads inducing tracking inaccuracies, etc., are fast and require the DC/DC maximum power point tracking to be fast as well. Several protections against inverter instabilities can make the control system too slow, wasting too much energy. Alternatively, the high efficiency of the inverter at low irradiance levels is not an advantage in CPV applications because the power level is usually high.

The PV concentrator modules will be asked to pass similar accelerated tests as flat modules, mainly because they are the closest references, but the variability of concentrator design options demand more complex regulatory documents and it is risky to extrapolate, without enough validated experience, the tests and valuation of results. Although this reserve exists between the manufacturers and regulation makers, it is generally accepted that tests on the following are required to demonstrate minimum module performance characteristics: (a) electrical insulation test, wet and dry; (b) thermal cycling plus damp heat test; (c) hail-impact test; (d) humidity freeze, water spray tests; (e) By-pass diode thermal, hot-spot test; and (f) off-axis damage tests.

1.6 Other Challenges Specific to Mass Production

In this section we depict the material availability and manufacturing potential for extending present technologies to a mass-production scenario. (We caution the reader that it is very likely that many new discoveries and inventions will appear that will make this analysis obsolete, but we still think the exercise has some value.)

The penetration of PV to supply about 20% of the world's electricity by 2025 should be about 100 GW per year. A production rate of 100 GW/year – 40% efficient (module efficiency) – will stress the steel market by approximately 2% and the glass market by about 10%, but should the lenses be made, like today, on a thick PMMA substrate, it would need 1.5 times the total current world production of acrylic. If we take into account that acrylic comes from oil, the perspectives are not too good for this material; thus, alternatives should be taken into account. Thin-film polymer on glass is already being used by some manufacturers. This might reduce the reliance on the oil product by more than one order of magnitude.

The 100-GW annual production rate will require an area of cells equivalent to 100 MW at 1 sun if the cells are to operate at 1000× under the concentrator optics. For multijunction cells based on germanium substrates 25 million wafers of 100 cm^2 are required. which is equivalent to 3.75 times the present annual production of electronic-grade germanium. Extraction from coal ash ensures total resources equal to 130 times the current yearly availability [42, 43]; however, if a migration of MJ solar cells to the abundant silicon substrates is successful, the stress on this material would be negligible.

The production of gallium metal is about 210 metric tons per year. With the previous hypothesis and assuming an active layer of about 10 μm, it is possible to produce about 1000 GW per year so that this material does not appear to be a drastic limitation to the PV growth.

Another challenge to high-level concentrator technology is given by the number of wafers and cells to be managed. The MJ solar cells are grown in a Metalorganic Chemical Vapor Epitaxy reactor. Assuming that a reactor can accommodate 12 wafers of the said size (presently they are somewhat smaller), and that including maintenance they may have 7 runs per day, 815 reactors will be necessary to grow the multilayer in the aforementioned 25 million wafers.

Regarding assembly, if we assume that cells are 1 mm^2 for the 1000× level, then the number of cells to be processed and interconnected is about 250 billion (250×10^9 per year. Current equipment used for the electronic chip market is limited to about three chips per second, which comes to (taking four cells per second to include tome for maintenance) 1982 the number of bonding machines to be built for cell assembly. Other manufacturing equipment will indeed be necessary for other tasks, but this paragraph, like the preceding one, aims at giving an order of magnitude of equipment that will be necessary for the manufacture of the cells and the concentrator modules.

We now consider the trackers. Assuming trackers of 50 m^2 (20 kW at 40% efficiency), the number of trackers required would be around 5 million per year.

All the preceding figures may be compared with those of the automobile industry. This industry manufactures more than 60 million cars per year and each car has 30 – 60 thousand parts; therefore, this industry is handling in the range of 1800 – 3600 billion (3600×10^9) parts per year. A concentrator PV module of 0.1 kW (with 250 cells) will probably not have more than 1500 parts in total; thus, we are talking about 1500 billion parts to be assembled; The PV industry, therefore, if based on concentrators for mass production, will be of a size not very different to the present size of the automobile industry.

1.7 Present Opportunities

The biggest opportunity probably comes from the rising awareness that CPV is necessary. One cannot witness the advances in MJ solar cells for space programs and remain unaltered. The immediate conclusion is that the only way of adapting these advances to the much bigger, terrestrial market is through the use of CPV. A number of programs (FULLSPCTRUM, DARPA, etc.) are also supporting the development of novel concepts based on sophisticated cells that will certainly have to be based on CPV.

A prominent example of this new interest is the presentation that Takashi Tomita, Corporate Director and Group General Manager of the Solar Systems Group of the Sharp Corporation – the biggest silicon solar cells producer in the World – presented at the special invited session organized on 8 May 2006 in the framework of the WCPEC-4 (the PV world conference) to deal with the transition to a world market. His talk was entitled 'Blazing A New Path to the Future' [44] and concluded:

I have explained in the above the current situations of photovoltaic industries and concentrator photovoltaic system towards next generation phase, not only silicon-based technology but also other technologies development including III-V compound cells is essential.

And then continued: *Concentrator type photovoltaic system will make a key role especially in the areas where direct sun irradiation is abundant. Technological breakthrough to overcome some of obstacles in dissemination of concentrator type photovoltaic system until now is getting ready and further electricity generation cost reduction by concentrator photovoltaic system is expected.*

This is not the only company, however, that has declared their interest in CPV. Other companies are probably more ready to enter the market. Among them, Isofotón, one of the top ten cell producers in the world (and a spin-off from the IES/UPM), which has a long standing R&D activity in this sector (in cooperation with IES/UPM) with the latest generation of optics and MJ cells, has made numerous declarations on their commitment to concentrators. For example, the magazine 'Energías Renovables', issued on the Internet on 22 July 2006, had an article entitled 'ISOFOTON to produce 5 MW of concentration cells for 2007'.

Newcomers are also entering the field. Jackie Jones wrote in Renewable Energy World (Internet issue of 2 September 2005):

The Guascor Group is investing in new manufacturing plant for CPV for the Spanish market, following an arrangement made with Amonix earlier this year (2005). Guascor Fotón is constructing a factory near Bilbao, Spain, to assemble the systems, apparently using solar cell assemblies shipped from Amonix's California plant. It is understood that Guascor plans to manufacture and install 10 MW *of CPV in Spain during 2006, and the capacity of the factory is expected to expand the following year.*

The expectations have not yet been totally fulfilled, but they say that they have already sold 1 MW, although nothing has yet been delivered. Assembly work is proceeding in their factory in Bilbao. To our knowledge, this is thus far the largest commercial activity in the world in CPV.

As a new venture-capital operation of Good Energies (who succeeded in launching Q-cells) and as a spin-off from the Fraunhofer Institute for Solar Energy (FhG/ISE), the company Concentrix, has been established. In a press release of 27 February 2006 they declared:
Concentrix will begin operating its first production line in midyear 2006 to manufacture concentrator modules. The company has already begun delivering demonstration plants to strategic partners. Commercial availability of concentrator photovoltaic power plants is scheduled for early 2007.

Furthermore, The Energy Blog published the on 19 February 2006 states:
SolFocus Inc., a spinoff from H2Go in 2004, and Xerox's Palo Alto Research Center (PARC) on 16 February announced a research collaboration to develop solar Concentrator PV (CPV) systems. The broad agreement is to jointly develop CPV systems that can deliver low-cost, reliable solar energy... Up to 2 MW *(megawatts) of the Gen 1 design will be installed in 2006-2007 at pilot sites in California, Hawaii, and Shanghai, China.*

According to these press releases, it looks like that 2007 will be the year in which PV concentration will unambiguously enter the market. Even if things go more slowly, there are enough participants who believe that this time concentrators will actually come into their own.

Despite that the American, German and Japanese markets that will not be absent, a good opportunity for CPV commercialization launching is linked to the feed-in tariffs in force in Spain, and more recently established in Italy, the two sunniest countries in the EU. Feed-in tariff opened the way to the 'power plant grid-connected market': the one dreamt of by concentrator makers over the past two decades.

Silicon feedstock shortage, consequence of fast market growth, is also giving an unexpected opportunity to concentrators to enter the market at prices similar to flat-plate power plants. In particular, the Spanish investors are anxious to install PV to profit from the good conditions brought in by the feed-in tariff and are disappointed by the lack of silicon cells on the market. They would be, in principle, most willing to accept concentrators.

Their enthusiasm decreases, however, when they learn that there is currently hardly any field experience in this technology. To amend this situation, a new initiative has been launched in Spain following plans developed by the IES/UPM. Below we reproduce some excerpts from the official presentation of this plan, which was presented on 8 March 2006:
Photovoltaic concentration technology has been the subject of investigation in Spain since 1976 and the country has attained an outstanding and well-regarded position for this work. For example, it was in Spain where the first monograph on the subject, published in Bristol in 1989, was authored and where, in Tenerife in 1998, the one of biggest photovoltaic concentration plants in the World was deployed. Nonetheless, this technology is not yet being manufactured. But we believe that the level achieved by prototypes is already ripe enough as to make its industrialisation imminent. The above-

mentioned Centre aims at being the global catalyst for this industrialisation.

In Spain we have climatic conditions well suited for concentration – that is to say, considerable direct radiation – that, combined with the economic conditions offered through Plan for the Promotion of Renewable Energies, is attracting a general interest to install such systems. Spanish companies are among the most advanced in the industrial development of this technology.

But the continuing lack of commercial applications means that approved norms suitable for photovoltaic concentration do not exist yet, nor have sufficient experiments been carried out on the precise prediction of the production of such systems, nor is it known for certain the costs of their installation and maintenance, etc.

The Centre will cover these aspects. In various places in Castilla La Mancha, plants of photovoltaic concentration with a total of 2.7 MW *using three or four concentration technologies that are now in development, in Spain and elsewhere in the World, will be set up. There is no precedent for such an operation.*

These plants will allow the selected companies to be able to move from the current state of prototypes-in-development to the manufacturing pilot line and to know the problems and costs of installation in the field, all of which is necessary for the commercial deployment of these technologies.

It is hoped that these actions will contribute to the achievement that photovoltaic solar energy begins a new path that should bring down prices sufficiently within the medium term to allow a massive penetration of solar energy.

The international call for tenders has already been issued and the deadline for bidding is 8 September 2006.If the call is satisfactorily resolved, we are sure that the reader will have more news on this.

1.8 Conclusion

During the 1970s photovoltaic concentrators looked like a promising solution to the stresses caused by the oil shock of 1973. The realization that the cost will not be as low as felt necessary in the short term aborted its deployment and held back the normal development of this technology for more than 30 years. Things clearly seem to have changed drastically. This is a special moment for PVC technology, because many positive factors have come together to promote the launching of industrial and commercial activity. Concentrator solar cell efficiency has almost reached 40%. Several companies are already entering the market and others have announced their forthcoming presence. Companies such as Sharp, which produces 25% of the world's solar cells (mostly silicon), strongly base their strategy on the new super-high-efficiency concentrators.

More than 1 MW has been already sold (but not yet delivered) in Spain. Other companies have already announced their products on the market.

These pioneering industrial and commercial activities must be helped as much as possible in order to avoid any significant problem at the beginning. A good guarantee for technical success is to qualify the system components before their deployment and to test the field performance of new products as soon as possible.

The new Spanish Institute of CPV Systems of Puertollano (Castilla La Mancha) will help in this process, guiding the companies and customers as much as possible to reach reasonable agreements that allow both, business to be carried out and their products to be improved as quickly as possible.

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