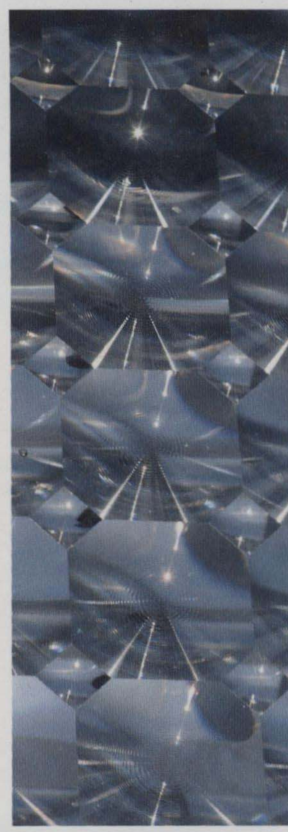

HANDBOOK OF CONCENTRATOR PHOTOVOLTAIC TECHNOLOGY

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Preface

This volume is the first handbook fully focused on Concentrator Photovoltaic Technology. Essentially, this handbook gathers, in one place, a comprehensive review of all scientific background around Concentrator Photovoltaics (CPV) as well as detailed descriptions of the technology and engineering developed to design, build and manufacture CPV systems and plants. In particular, this book essentially focuses on the current workhorse of the CPV industry: point focus designs based on refractive optics and III-V multijunction solar cells working at concentration levels from some hundreds to over a thousand suns.

In this Preface, we discuss why we believe this handbook is a timely and pertinent endeavor by reviewing the general situation of PV, the key advantages that CPV offers and the history of CPV to conclude with its present status and future prospects.

A Vision of Photovoltaics within the World's Energy Perspective

The Earth receives annually around $1.5 \cdot 10^9$ TWh of solar energy. This overwhelming figure constitutes by far the most abundant energy resource available for mankind heretofore. If adequately harnessed, only a miniscule fraction of this energy would suffice to supply the world's total primary energy demand, which in 2013 was about $1.6 \cdot 10^5$ TWh (i.e. the solar resource on earth is about 10 000 times the energy needs of mankind). The primary energy is processed by the energetic system into different types of readily usable energy forms, among which electricity is considered the key technology for the next decades. Accordingly, the direct generation of electricity from solar radiation (i.e., the production of the preferred consumable form of energy from the richest resource) is a topic of the highest relevance and is the essence of photovoltaics (PV). From the discovery of the photovoltaic effect in 1839 – by French physicist Alexandre-Edmond Becquerel – to the first successful application of photovoltaic panels to power the *Vanguard I* satellite launched in 1958, more than a century went by. Since those pioneering works, many steps forward have been made and the PV industry has evolved from the modest watt-ranged applications of the early days to the giant GW-ranged systems planned today. As a matter of fact, the evolution of photovoltaics over the first decades of the 21st century has been remarkable among all energy technologies. As Figure 1 shows, PV installations have been growing tremendously and by the end of 2015, it is expected to have left behind the non-negligible mark of 200 GW_p global cumulative installed capacity.

Another sign of ripeness of PV is the size and globalization of the market. As indicated by Figure 2, to reach the cumulated capacities described Figure 1 the photovoltaic industry has

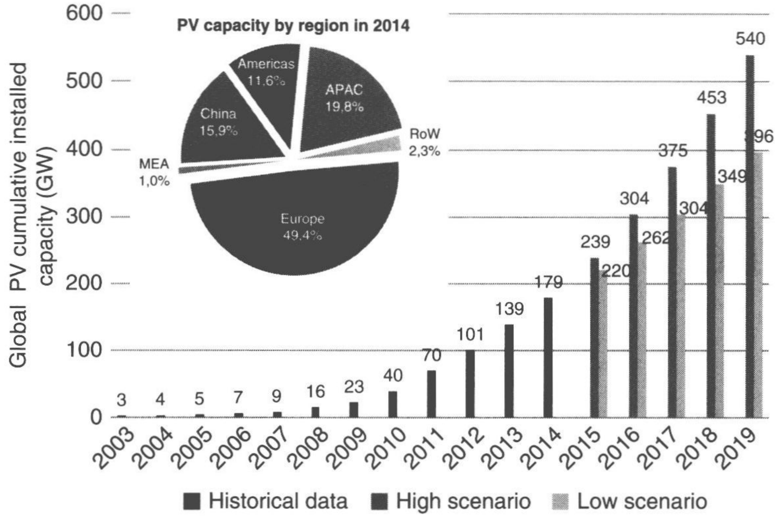

Figure 1 Global PV cumulative installed capacity forecast until 2019.[1] The forecast considers an optimistic (high growth) and a pessimistic (low growth) scenario. The pie chart shows how this capacity is distributed by region as of 2014 (The legend for the pie chart is as follows RoW: Rest of the World; MEA: Middle East and Africa; APAC: Asia Pacific)

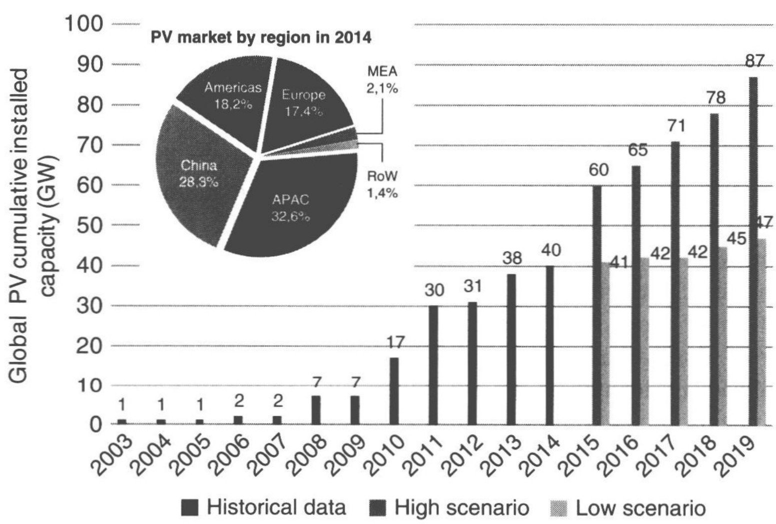

Figure 2 Evolution of yearly global PV installations until 2019.[1] The forecast considers an optimistic (high growth) and a pessimistic (low growth) scenario. The pie chart shows where these installations were made in 2014. (The legend for the pie chart is as follows RoW: Rest of the World; MEA: Middle East and Africa; APAC: Asia Pacific)

[1] *Global Market Outlook for Solar Power 2015–2019*, Solar Power Europe, formerly known as EPIA (2015).

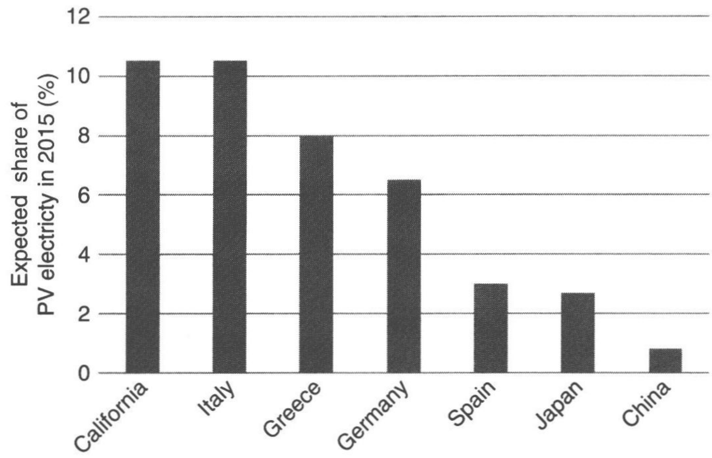

Figure 3 Expected percentage of the electricity demand in 2015 to be produced with photovoltaic power plants in different regions of the world.[2]

maintained almost unprecedented growth rates (annual growth rate of ~44% in installed power from 2003 to 2013). In addition, such growth is no longer concentrated in Europe (as shown in the pie chart included as an inset in Figure 2), but the PV market has become a truly global reality in recent years.

A side effect of the global dimension of the market is the significant penetration that PV is gaining in electricity markets in different regions of the world. Figure 3 shows the expected percentage of the electricity demand in 2015 that will be produced with photovoltaic power plants in different countries or regions. In brief, this figure demonstrates that the expertise to integrate significant fractions of PV electricity in the distribution networks is flourishing in parallel with installations.

In essence, photovoltaics today is a consolidated industry, growing fast worldwide, and gaining relevance in significant electricity markets. All these facts make clear that photovoltaic technology has demonstrated the maturity to become a major source of power for the world. That robust and continuous growth is expected to continue in the decades ahead in order to turn photovoltaics into one of the key players in the pool of technologies involved in generating electricity for the 21st century. The big question for photovoltaic solar energy as of today is not if it will expand, but by how much.

What is CPV? The Role and Advantages of CPV

CPV is one of the PV technologies. Therefore, CPV converts light directly into electricity in the same way that PV does. The difference of CPV regarding PV stands in the addition of an optical system that focuses direct sunlight collected on a large optics area onto a small solar cell. The optics area to the solar cell area ratio is called geometrical concentration or simply concentration level whose dimensionless units are typically referred to as 'suns or ×'.

[2] *Snapshot of Global PV 1992–2014*, International Energy Agency - Photovoltaic Power Systems Programme (2015).

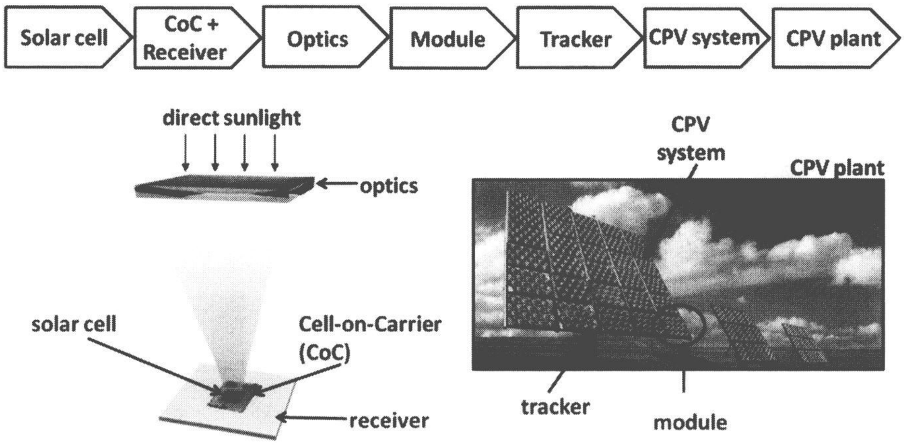

Figure 4 Components and systems of a CPV plant

The CPV approach allows the use of the most efficient cells (although expensive) since the small size of the cell consumes much less semiconductor material. Therefore, CPV replaces costly semiconductor solar cells with cheaper optics. For example, the production of 1 watt of electricity by means of a 40% multijunction solar cell operating at 1000 suns requires 2666 less semiconductor area than if a 15% silicon solar cell without concentration was used for the same purpose. Using much smaller cells promises for lower costs, but CPV systems are more complex than conventional PV systems. The key is if the overcost derived from the complexity of CPV is low enough to be counterbalanced by the savings in semiconductor cell area and the increase in efficiency. In that case, CPV would compete with conventional PV.

Figure 4 shows the different components of a CPV plant. Solar cells used in high concentration CPV systems are typically multijunction solar cells made up of III-V semiconductors. Cells have to be mounted on a carrier (Cell-on-Carrier: CoC) that usually includes a bypass diode. In many designs, CoC is mounted onto a heatsink in order to properly dissipate and remove heat. The optics consists typically of a primary optical element that collects direct sunlight, and may have a secondary element that receives the light from the primary. The assembly of a heatsink, a CoC and a secondary optics (if any) is typically referred to as a *receiver*. By means of the integration of several receivers and primary optics, CPV modules are built. Modules are placed on a sun-tracker structure which allows modules to be pointed towards the sun at all times. The tracker structure together with the modules constitutes the CPV system. Finally, several CPV systems together with inverters, transformers, wiring, etc. form a CPV plant which is able to inject AC electricity to the grid.

Differences in the architectures of PV and CPV plants result in different pros and cons for each technology. Nowadays, silicon-based PV dominates the solar market. When at the end of the 1990s, CPV promised system costs about €3/W_p, PV cost laid at about €6/W_p. Clearly, CPV has accomplished its cost forecast but PV has experienced an unexpected huge price drop. Therefore, if CPV wants to challenge PVs hegemony, it needs to beat PV cost. Nowadays, CPV starts to be cheaper (in terms of LCOE, i.e, Levelized Cost of Energy) than PV in some very hot locations with high direct normal irradiation. However this low cost of CPV electricity has to be widespread by using its advantages summarized in Table 1.

Table 1 Main differences between CPV and PV

Property	*CPV*	*PV*
Used sunlight	Direct	Global (direct and diffuse)
Suitable locations	High direct normal irradiation (usually no coastal regions located within 15°–45° of both N and S latitude)	Almost every location within latitude range from 60°N to 60°S
System efficiency	Current values of 30% with much more room for gains. More than two times energy yield per equivalent installation area	Limited to about 15%
Operation temperature	Good performance till 70–90°C	Good performance till 30–50°C
System cost (as of 2014)	$\sim$€2/W_p	$\sim$€1/W_p
LCOE (as of 2014)	€c8–20/kWh with room for €c2–3/kWh	€c10–20/kWh with room for €c5–10/kWh
Modularity and scalability	High	Very high
Reliability	Very high (based on a experience of about six years of operation in the field together with accelerated ageing tests suggesting more than 30 years of operation)	Very high (based on a history of about 30 years operation in the field)

Finally, it has to be highlighted than CPV is completely different than CSP (Concentrated Solar Power) which uses heat from the system to generate electricity in a traditional steam engine power plant environment.

History of CPV. Lessons from the Past, Present Status and Expected Future

The use of optical elements to concentrate sunlight, and thus reach higher energy densities, has been known and used by mankind since ancient times. Lighting fires, optical communications or signaling or even setting fire to enemy warships – a legendary feat attributed to Archimedes of Syracuse in the 3rd century BC – are some examples of ancient uses of concentrated sunlight recorded in history books. However, it is not our goal in this preface to present a detailed historical background of such uses of concentrated sunlight; not even of CPV. There are excellent reviews on this topic[3] so here we will focus on some key milestones that –in our opinion– have shaped our short life as a modern electric power industry.

It was the oil crisis in 1973 which spurred the interest on renewable energies in oil-addicted western countries. Solar electricity in general and photovoltaics in particular was a key part of this new wave of interest. Accordingly, it was in the middle 1970s when ambitious development programs were put into practice to develop terrestrial uses of photovoltaics (PV had been

[3] See for example, Chapter 1 of *Concentrator Photovoltaics* (eds A. Luque and V. Andreev), Springer Series in Optical Sciences (2007).

used in space to power artificial satellites since 1958). In this context, research on CPV begun as concentration was seen as a natural way to increase the modest efficiency solar cells in those early days.

The first notable effort in the history of CPV technology was the research conducted at Sandia National Laboratories, Albuquerque, New Mexico during the late 1970s. The team at Sandia designed a CPV system operating at 32–40×, based on acrylic Fresnel lenses and silicon solar cells with passive cooling and two-axis tracking. The third generation of this technology (namely SANDIA III) was pilot-produced by Martin Marietta Co. and a power plant of 350 kW_p was installed in the desert of Saudi Arabia by the end of 1981. This plant, namely, the SOLERAS project, operated for more than 18 years in the harsh conditions of the Arabian Desert and was for several years the largest PV installation in the world.

From this seminal milestone to the multi-megawatt CPV plants being deployed today many technological and scientific achievements have occurred over the last 35 years covering the whole value chain of CPV technology.

For example, in the field of solar cells, the early silicon based designs were soon refined into more advanced cell architectures (point contact solar cells) in the mid-1980s. A great leap forward was provided by the move to multijunction solar cells using III-V semiconductors. In 1995, a two terminal monolithic dual junction GaInP/GaAs solar cell was the first solar cell that surpassed the 30% efficiency barrier. By the end of the decade, the addition of a third Ge junction raised the efficiency to over 32%; this design was further optimized and by 2006 the 40% barrier was broken. As of today, we have four-junction solar cells fabricated using wafer bonding techniques with efficiencies in excess of 46%, and with several other architectures (inverted metamorphic, upright metamorphic, dilute nitride lattice-matched, etc.) laying siege to the milestone of 50%.

In the field of optics, a superficial look might give the impression that no such impressive advances have been made since the acrylic Fresnel lenses used in the SOLERAS project are still present in some CPV products today. Moreover, the silicone on glass primary lenses used by some manufacturers also date back to the early 1980s. However, this 35 years have represented also a tremendous advancement in optical technology. The field of nonimaging optics has been intensively explored to optimize the performance of Fresnel lenses and design secondary optics that constitute optical trains with high transmission (>90%); good spatial uniformity (peak to average ratios below 2.5), little chromatic aberration and acceptance angles in excess of $\pm 0.7^\circ$ for concentrations as high as 1000 suns. And, what is even more important, these accomplishments have been reached while improving the manufacturability, the reliability (UV and weathering resistance) and bringing down the costs for efficient mass production.

Obviously, the field of sun trackers and CPV balance-of-system components has benefited from the tremendous impulse and reduction of costs that microelectronics has experienced over the last three and a half decades.

After two decades in research mode, in the first years of the 21st century, all the progress attained in the different steps of the CPV value chain together with the shortage in silicon supply that was affecting the growth of flat plate PV, brought about a renaissance of CPV technology. Amonix (now Arzon Solar), the CPV industry pioneer founded in 1989, leaped from kW-sized demonstration projects to megawatt ranged power plants. A number of companies fully focused on the CPV business were founded, such as Semprius and Solfocus in the US, Concentrix (later Soitec) in Germany, MagPower in Portugal, Renovalia in Spain, Morgan Solar in Canada, Suncore in China and many others; and companies operating in