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# CURRENT STATUS OF CONCENTRATOR PHOTOVOLTAIC (CPV) TECHNOLOGY



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# CURRENT STATUS OF CONCENTRATOR PHOTOVOLTAIC (CPV) TECHNOLOGY

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## Introductory Note

This report summarizes the status of the concentrator photovoltaic (CPV) market and industry as well as current trends in research and technology. This report is intended to guide research agendas for Fraunhofer ISE, the National Renewable Energy Laboratory (NREL), and other R&D organizations.

Version 1.1 of this report includes recent progress in CPV. The recent record module efficiency of 38.9% at Concentrator Standard Test Conditions (CSTC) is an impressive result, demonstrating the continuing opportunity for CPV technology to improve.

If you have suggestions about this report, additional or updated information, or would like to add your organization's information to our tables, please e-mail [simon.philipps@ise.fraunhofer.de](mailto:simon.philipps@ise.fraunhofer.de). It is our intention to update the report in a regular manner.

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Notable developments in the CPV market and industry in recent years include:

- Cumulative installations (already grid-connected): 340 MW<sub>p</sub>
- Several power plants with capacity  $\geq 30$  MW<sub>p</sub>:
  - Golmud, China, built by Suncore: 60 and 80 MW<sub>p</sub>
  - Touwsrivier, South Africa, built by Soitec: 44 MW<sub>p</sub>
  - Alamosa, Colorado, US, built by Amonix: 30 MW<sub>p</sub>(see installation data base: <http://cpvconsortium.org/projects>)
- Proven reliability and field data for more than 6 years [1]
- Worldwide manufacturing capacities  $\sim 700$  MW per year, but in the near future a reduction is expected

Various developments in CPV research and technology have been achieved as well, including:

- Certified record value for solar cell efficiency of 46.0 % by Fraunhofer ISE, Soitec, CEA-LETI [2,3]
- Certified record value for module efficiency of 38.9 % by Soitec [4]
- Averaged yearly field performance data for power plants with  $> 100$  kWp were reported with performance ratios of 74-80 % achieved [1]
- Recent R&D results can be found in the proceedings of the latest International CPV conference. The next CPV conference will take place in Freiburg, Germany and is planned for April 2016<sup>1</sup>.

## What's New?

Version 1.1 of this report has been thoroughly revised compared to Version 1 from January 2015. The authors like to especially point the reader's attention to the following updates:

- New record of HCPV module efficiency of 38.9% (former record 36.7%).
- Installation data were updated to include the full year 2014.
- Company tables in the appendix were updated and now include links to the company websites.
- The company Soitec S.A. France, a major player in the CPV business, announced in a press release on January 19<sup>th</sup>, 2015 and April 20<sup>th</sup>, 2015 its intentions to refocus on its core business of electronics and to re-structure its solar business (i.e CPV business)<sup>2</sup>. In May 21<sup>st</sup>, 2015 another press release announced that another major player, Suncore, will be the new owner of the Soitec CPV assets<sup>3</sup>. In August 5<sup>th</sup>, 2015 Soitec announced that the closing of the deal will not occur<sup>4</sup>.

<sup>1</sup> <http://scitation.aip.org/content/aip/proceeding/aipcp/1616>; <http://www.cpv-12.org>

<sup>2</sup> <http://www.soitec.com/en/news/press-releases/soitec-reports-q3-2014-2015-consolidated-sales-and-announces-strategic-re-focus-on-its-core-electronics-business-1622/> and <http://www.soitec.com/en/news/press-releases/article-1696/>

<sup>3</sup> <http://www.soitec.com/en/investors/financial-press-releases/soitec-divests-its-solar-system-business-to-refocus-on-its-core-semiconductor-activities-1722/>

<sup>4</sup> <http://www.soitec.com/en/news/press-releases/soitec-announces-the-end-of-negotiations-with-concensolar-regarding-a-sale-of-solar-assets-and-continues-its-refocus-on-electronics-1772/>

- Suncore, China is stopping their CPV production and is re-thinking their CPV strategy.

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Key Facts

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Concentrator Photovoltaic (CPV) technology has recently entered the market as a utility-scale option for the generation of solar electricity. This report explores the current status of the CPV market, industry, research, and technology. The CPV industry has struggled to compete with PV prices, with many companies exiting the market, leading to challenges in raising the capital required to scale. However, CPV modules continue to achieve efficiencies far beyond what is possible with traditional flat-plate technology and have room to push efficiencies even higher in the future, providing a potential pathway for significant reductions in systems costs.

The key principle of CPV is the use of cost-efficient concentrating optics that dramatically reduce the cell area, allowing for the use of more expensive, high-efficiency cells and potentially a levelized cost of electricity (LCOE) competitive with Concentrated Solar Power and standard flat-plate PV technology in certain sunny areas with high Direct Normal Irradiance (DNI) [5]. Figure 1 shows two exemplary concepts using Fresnel lenses and mirrors as concentrating optics.

CPV is of most interest for power generation in sun-rich regions with Direct Normal Irradiance (DNI) values of more than 2000 kWh/(m<sup>2</sup>a). The systems are differentiated according to the concentration factor of the technology configuration (see Table 1). More than 90% of the capacity publicly documented to be installed through end July 2015 is in the form of high concentration PV (HCPV) with two-axis tracking. Concentrating the sunlight by a factor of between 300x to 1000x onto a small cell area enables the use of highly efficient but comparatively expensive multi-junction solar cells based on III-V semiconductors (e.g. triple-junction solar cells made of GaInP/GaInAs/Ge). Low concentration designs – those with concentration ratios below 100x – are also being deployed. These systems primarily use crystalline silicon (c-Si) solar cells and single-axis tracking, although dual axis tracking can also be used.



Figure 1: Left and middle: Example of a CPV system using Fresnel lenses to concentrate the sunlight: FLATCON<sup>®</sup> concept originally developed at Fraunhofer ISE. Right: Example of a mirror-based system developed by the University of Arizona, USA [6].

A key reason for the increasing number of large-scale power plants using HCPV is the significant increase in the efficiency of individual modules, which also leads to a reduction of area-related system costs. Soitec recently demonstrated a CPV module efficiency of 38.9% at Concentrator Standard Test Conditions (CSTC) [4] and efficiencies of commercially available CPV modules exceed 30%. In recent years, AC system efficiencies have also increased, reaching 25-29% and companies predict further increases in efficiency for CPV systems to over 30% in the next couple of years driven largely by improvements in cell efficiency but

also in the optical efficiency [7,8]. In addition to these higher efficiencies, tracking allows CPV systems to produce a larger amount of energy throughout the day in sunny regions, notably during late part of the day when electricity demand peaks. At the same time and in contrast to CSP, the size of the installations can be scaled over a wide range, i.e from kW to multi-MW, and in this way adapted to the local demands. Some CPV systems also disturb a smaller land area, since the trackers, with relatively narrow pedestals, are not closely packed. This makes it possible to continue to use the land for agriculture. Finally, HCPV is advantageous in hot climates in particular, since the output of the solar cells used does not decline as severely at high temperatures as that of conventional c-Si solar modules.

Class of CPV	Typical concentration ratio	Tracking	Type of converter
High Concentration PV (HCPV)	300-1000	Two-axis	III-V multi-junction solar cells
Low Concentration PV (LCPV)	< 100	One or two-axis	c-Si or other cells

Table 1: Description of CPV classes.<sup>1</sup>

Industry interviews indicate that the total capital equipment (capex) requirement, while varying by design and manufacturing process, can be lower for CPV than for traditional flat-plate technologies, including c-Si. Additionally, a bottom-up analysis from NREL based on a specific HCPV system with a Fresnel lens primary optic and refractive secondary lens estimates the total capex for cells and modules in this design (assuming a vertically integrated company) to be around \$0.55/Wp(DC), with a much lower capex for variations on the design. Most HCPV companies have their optics and cells manufactured by a third party, in which case the capital equipment requirements for the HCPV company itself can be quite low.

Reports indicate that the installed system prices for CPV systems have declined significantly since the technology was introduced on the market [9]. In 2013, a Fraunhofer ISE report found that installed CPV power plant prices for 10 MW projects were between €1400/kW and €2200/kW [5]. The wide range of prices results from the different technological concepts as well as the nascent and regionally variable markets. LCOEs based on these systems prices calculated by Fraunhofer ISE [5] range from €0.10/kWh to €0.15/kWh for a location with a DNI of 2000 kWh/(m<sup>2</sup>a) and €0.08/kWh to €0.12/kWh for 2500 kWh/(m<sup>2</sup>a). These numbers provide a basis for comparison of current CPV projects with the analyzed values for utility-scale PV and concentrating solar power (CSP) power plants, as will be discussed in more detail in section 2.2.1. Table 2 summarizes the strengths and weaknesses of CPV.

Although research on cells, modules, and systems for CPV has been ongoing for decades, CPV only entered the market in the mid-2000s. While it has seen strong market growth in recent years, it is still a young and – compared to conventional flat-plate PV – small player in the market for solar electricity generation. This implies a lack of reliable data for market, prices, and status of industry. The aim of this report is to help fill this information void by summarizing and providing reliable data on CPV. The first part of the report focuses on market and industry aspects, which might benefit investors, policy-makers, industry members, researchers who wish to place their research in a larger context, and the general public. The second part deals with research and technology and should primarily be a reference for stakeholders in the CPV industry and research.

<sup>1</sup> Systems with concentration factors between 100 and 300 are not included since their current configurations are not cost-competitive on LCOE-level to other CPV approaches.

CPV Strengths	CPV Weaknesses
High efficiencies for direct-normal irradiance	HCPV cannot utilize diffuse radiation LCPV can only utilize a fraction of diffuse radiation
Low temperature coefficients	Tracking with sufficient accuracy and reliability is required
No cooling water required for passively cooled systems (as is required for CSP)	May require frequent cleaning to mitigate soiling losses, depending on the site
Additional use of waste heat possible for systems with active cooling possible (e.g. large mirror systems)	Limited market – can only be used in regions with high DNI, cannot be easily installed on rooftops
Modular – kW to GW scale	Strong cost decrease of competing technologies for electricity production
Increased and stable energy production throughout the day due to tracking	Bankability and perception issues due to shorter track record compared to PV
Very low energy payback time	New generation technologies, without a history of production (thus increased risk)
Potential double use of land, e.g. for agriculture. Low environmental impact <sup>1</sup>	Additional optical losses
Opportunities for cost-effective local manufacturing of certain steps	Lack of technology standardization
Less sensitive to variations in semiconductor prices	
Greater potential for efficiency increase in the future compared to single-junction flat plate systems could lead to greater improvements in land area use, system, BOS and BOP costs	

Table 2: Analysis of the strengths and weaknesses of CPV.

<sup>1</sup> See e.g.: [http://cpvconsortium.org/pdfs/press\\_releases/CPV\\_Environmental%20Report\\_07-09-11.pdf](http://cpvconsortium.org/pdfs/press_releases/CPV_Environmental%20Report_07-09-11.pdf),  
[http://www.seas.columbia.edu/clca/Task12\\_LCI\\_LCA\\_10\\_21\\_Final\\_Report.pdf](http://www.seas.columbia.edu/clca/Task12_LCI_LCA_10_21_Final_Report.pdf)

## 2 Market and Industry

### 2.1 Status

#### 2.1.1 Status of the Industry

Since 2011, many CPV companies have closed, entered bankruptcy, shifted away from CPV to standard PV, or been acquired by larger firms, some of which continue to pursue CPV while others do not. This type of consolidation is typical of early stage industries. Table 6 and Table 7 give information on the companies that remain open and appear to continue working on HCPV or LCPV modules.

The main challenge cited by the industry is the difficulty of CPV to compete with flat-plate c-Si PV modules on cost, in light of the recent drop in c-Si module prices due to the significant advantage in manufacturing scale that flat-plate currently has over CPV. CPV companies expect that this technology can compete on an LCOE basis with flat-plate PV when installed in sunny areas, but the road to scale has been difficult.

While a breadth of designs in the CPV space exist, the majority of companies are HCPV and most of those employ Fresnel primary lenses in refractive, point-focus systems. Some companies have moved towards smaller cells and higher concentrations in hopes of reducing costs and thermal management requirements. In fact, Table 6 in the appendix shows that almost all HCPV companies now operate near 500x or 1000x. In LCPV, both the designs and concentration ratios shown in Table 7 tend to be much more varied than in HCPV, with groups even targeting building integrated CPV (BICPV) and modules floating on the water.

Despite this convergence within HCPV onto similar module designs, and the recent availability of some standard components, firms continue to use their own custom components. Although many optics suppliers remain enthusiastic about the promise of CPV and the potential for standardized components to help ease growing pains within the industry, there is concern about the existence of a stable market in the future.

Several major blows to formerly leading CPV companies have occurred very recently, shaking confidence in the industry. In 2012, Amonix, now Arzon Solar, closed its 150 MW manufacturing plant in Las Vegas; in 2013, SolFocus, a supplier of systems with a Cassegrain optics, underwent liquidation. In 2014, Soitec was dropped from plans for a 150 MW power plant in the Imperial Valley, California, with the developer opting to use conventional PV modules in its installation. Very recently in August 2015, Soitec announced that the deal to sell its solar system business failed<sup>1</sup>. This means that they will not produce CPV modules anymore. Moreover, Suncore the major Chinese manufacturer also is stopping the CPV module production and is defining a new strategy. It is still unclear how large of an impact these events will have on the CPV industry as a whole.

Anyhow, several companies making III-V multi-junction cells that can be used in terrestrial CPV applications are active, and continue to improve their products, as noted in Section 3. In addition, the total amount of installed CPV has grown significantly since 2011, as can be seen in Figure 2, and large deals, like SunPower's plan to install 40 MW in China and 120 MW of

<sup>1</sup> <http://www.soitec.com/en/news/press-releases/soitec-announces-the-end-of-negotiations-with-concensolar-regarding-a-sale-of-solar-assets-and-continues-its-refocus-on-electronics-1772/>

LCPV in Inner Mongolia, are still being made<sup>1</sup>. Soitec continues to install power plants in South Africa, China and the United States. Suncore has installed 140 MWp at Goldmud, China. Manufacturing capacities are available to produce HCPV systems, e.g. 300 MW/a at Suncore. The future of the existing capacity of 380 MW/a at Soitec is currently unclear. Trackers have also made great strides in recent years, being both more reliable and lower-cost than in the past.

### 2.1.2 Installations and Projects

CPV has only begun to be established in the market in recent years (see Figure 2). A list of CPV power plants with MW capacities can be found in Table 4 in the appendix. The CPV-consortium recently started to collect data on such plants, see: <http://cpvconsortium.org/projects>. The first power plant exceeding the 1 MW-level was installed in Spain in 2006. Since then, an increasing number of commercial power plants have been installed in the MW range annually, with several exceeding 20 MW peak capacity (Figure 3). The largest share, more than 90% of the capacity installed to date, is in the form of HCPV with two-axis tracking. HCPV systems were mostly equipped with c-Si concentrator cells before 2008, but III-V multi-junction solar cells have since become standard. LCPV systems still employ either slightly modified standard or high-efficiency c-Si cells.

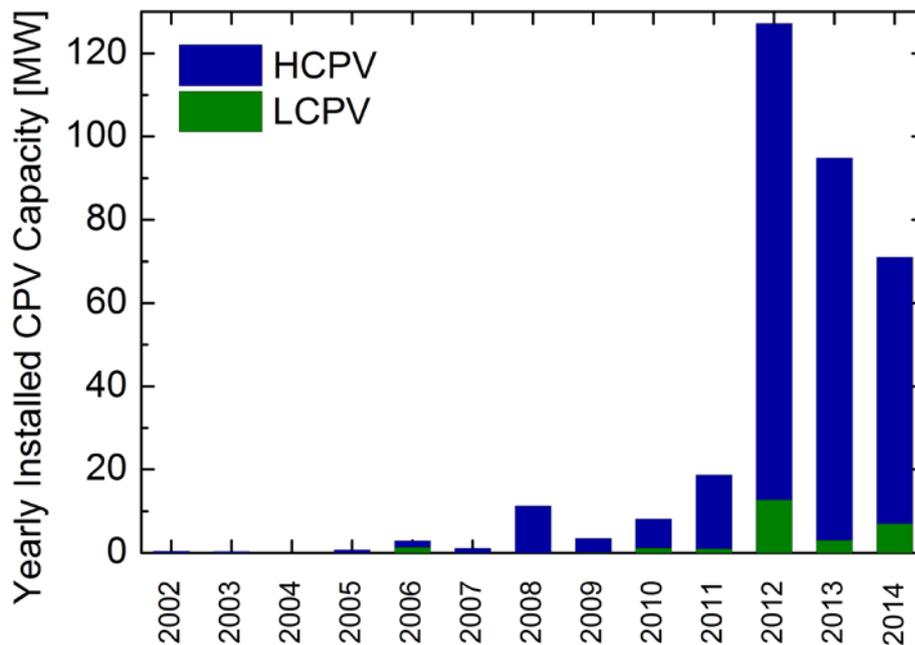


Figure 2: CPV capacity installed each year with indication of the type (HCPV or LCPV), globally, as derived from public announcements.

Along with the trend toward larger power plants, there is a noticeable regional diversification of the market (Figure 4). While the first large power plants were installed solely in Spain, > 1 MW CPV power plants have also been completed in several other countries since 2010. Current regional key areas include the United States, China, Australia, and South Africa.

<sup>1</sup> Sunpower press release of April 16, 2015. <http://newsroom.sunpower.com/2015-04-16-SunPowers-China-Joint-Venture-Partners-with-Apple-to-Provide-Solar-Power-to-the-Environmentally-Preserved-ABA-Region>

Compared to conventional PV, the CPV market is still small, with a market volume around 70 MWp in 2014. For 2015 a total number of new installations between 10 and 25 MWp is estimated.



Figure 3: Examples of large CPV power plants. From top to bottom: 30 MW plant in Alamosa, Colorado, USA (© Amonix); 44 MW in Touwsrivier, South Africa (© Soitec); 140 MW in Golmud, China (© Suncore).

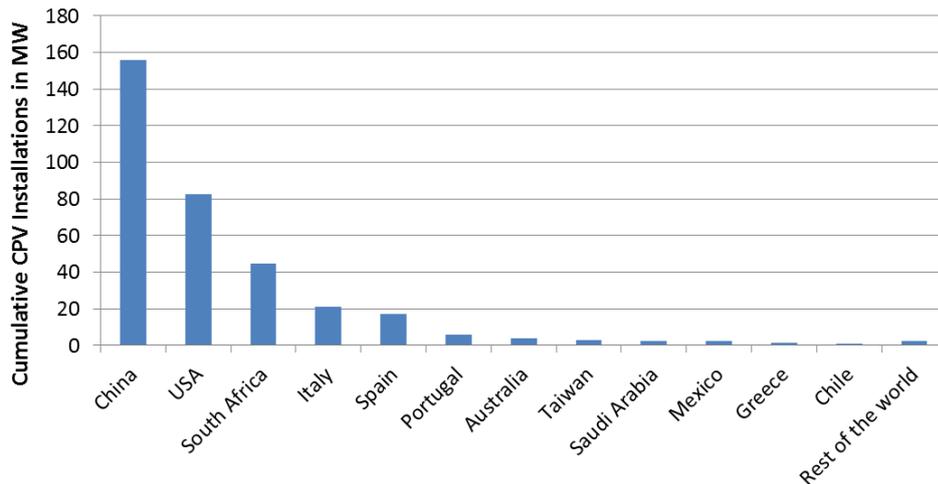


Figure 4: Grid-connected CPV capacity by country through end of July 2015. All countries with a total installation of 1 MWp or more are shown separately.

### 2.1.3 Standards

As with standard PV systems, CPV installations are typically warranted for at least 25 years, thus they have to be reliable. The standard IEC 62108 called “Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval” issued by the International Electrotechnical Commission (IEC) in 2007 is a mandatory step to enter the market. Today many companies have certified their products according to this standard. Please note that additional UL and IEC standards (e.g. for power and energy rating, module safety, tracker, optics, cell assembly) have been published or are under preparation.

## 2.2 Perspective

### 2.2.1 System Costs and Levelized Cost of Electricity

Market prices and cost data for CPV systems are difficult to obtain. This originates from the young market and the comparably low number of installations and companies active in the field. Hence a learning curve is not yet reliable and an analysis of system cost and levelized cost of electricity (LCOE) will include a rather high uncertainty until CPV reaches a high deployment volume.

At the end of 2013 Fraunhofer ISE published an extensive study on the LCOE of renewable energy systems [5]. The study includes also CPV systems. For details about the assumptions made we refer to the publically available study. Recently a group from the University of Ottawa also published gathered data on cost and LCOE for CPV [9].

Based on an industry survey and literature, CPV system prices, including installation for CPV power plants with a capacity of 10 MW, were identified to lie between €1400/kWp and €2200/kWp. The large range of prices results from the different technological concepts as well as the nascent and regionally variable markets. Using technical and financial assumptions specified in [5], the calculations result in LCOE values for CPV power plants from €0.10/kWh to €0.15/kWh at locations with a DNI of 2000 kWh/(m<sup>2</sup>a) and €0.08/kWh to €0.12/kWh with 2500 kWh/(m<sup>2</sup>a) (Figure 5).

For CPV, there are still great uncertainties today concerning the future market development and thus also the possibility of achieving additional cost reductions through technological development. The analysis, however, shows that CPV has potential for reducing the LCOE, which encourages a continued development of this technology. If installations continue to grow through 2030, CPV could reach a cost ranging between €0.045/kWh and €0.075/kWh (Figure 6). The system prices, including installation for CPV power plants would then be between €700 and €1100/kWp.

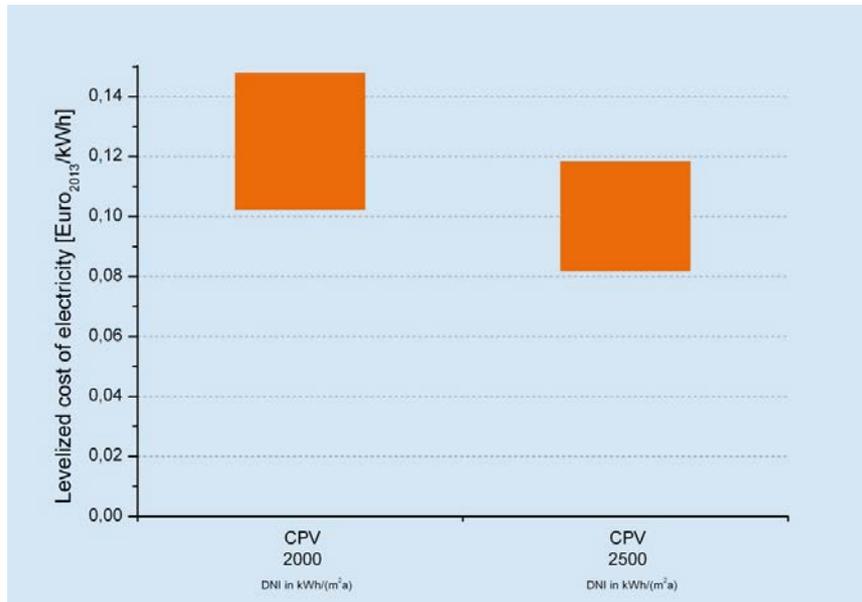


Figure 5: Levelized cost of electricity (LCOE) of CPV systems under high solar irradiation (DNI) of 2000 kWh/(m²a) and 2500 kWh/(m²a) in 2013. Source: [5].

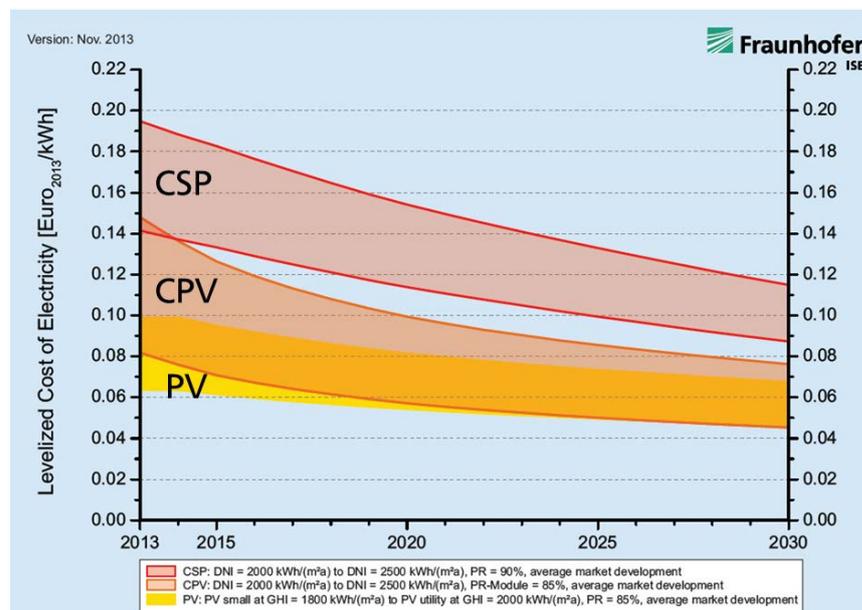


Figure 6: Development of the LCOE of PV, CSP and CPV plants at locations with high solar irradiation of 2000 kWh/(m²a) - 2500 kWh/(m²a). Source: [5].

High efficiency is one of the key drivers to make HCPV more cost-competitive on the LCOE level. Hence the majority of efforts in research aim at increasing the efficiency at all levels from cell to module to system. Figure 7 shows the increase in efficiency since 2000 and underlines the progress made by research and development efforts. The trend lines are based on the expectations of the European Photovoltaic Technology Platform in 2011 [7]. Significant potential for even higher efficiencies than today is foreseen. This chapter aims at summarizing corresponding developments in CPV research and technology in recent years that could lead to additional improvements in efficiency.

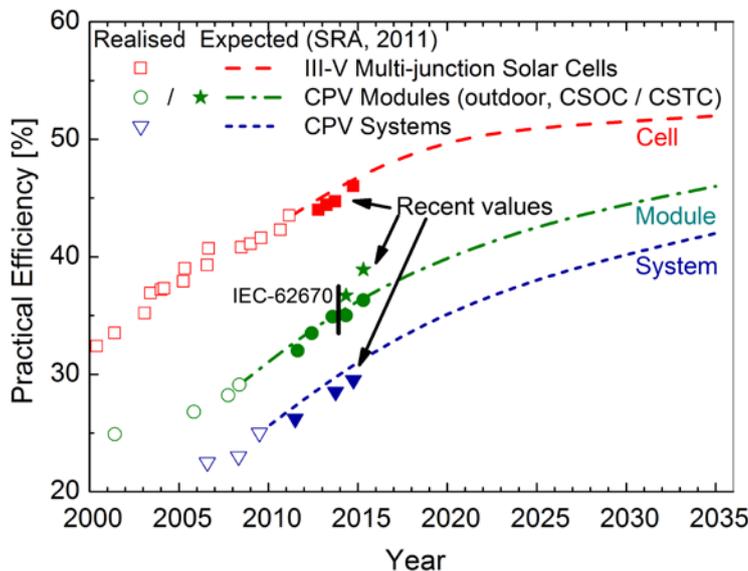


Figure 7: Development of record efficiencies of III-V multi-junction solar cells and CPV modules (cells:  $x^*$ AM1.5d; modules: outdoor measurements). Progress in top-of-the-line CPV system efficiencies is also indicated. (AM1.5d lab records according to Green et al., Solar Cell Efficiency Tables from 1993 [10] to 2015 [3]; CPV module and system efficiencies collected from various publications<sup>1</sup>). The trend lines show expected efficiencies from the Strategic Research Agenda (SRA) developed by the European Photovoltaics Technology Platform in 2011 [7]. Recent efficiency values (full symbols) follow the trend very well.

#### 3.1 Solar Cell Efficiency Status

The efficiency of III-V multi-junction solar cells is the key driver to lower the LCOE of energy produced by HCPV technology. In Figure 8, record efficiencies for these solar cells are displayed. Since 2002 the efficiency has increased by 0.9 % absolute per year. Solar cells made by Sharp [11] and Fraunhofer ISE [2] achieved today’s champion efficiencies of 44.4 %

<sup>1</sup> CPV module efficiencies until 2014 refer to prevailing ambient conditions outdoors. Since 2014 measurements under IEC 62670-1 reference conditions following the current IEC power rating draft 62670-3 are shown. The IEC-norm IEC 62670-1 defines two standard conditions for CPV modules. Concentrator Standard Test Conditions (CSTC) which means DNI of 1000 W/m<sup>2</sup>, 25 °C cell temperature and AM1.5d spectral irradiance and Concentrator Standard Operating Conditions (CSOC) which means DNI of 900 W/m<sup>2</sup>, 20 °C ambient temperature and AM1.5d spectral irradiance.

and 46.0 % for triple- and four-junction solar cells, respectively. As can be seen in Figure 8, commercial cell efficiencies follow R&D results very quickly, indicating that new research in III-Vs is quickly adopted into the production. According to product data sheets of the companies, today multi-junction solar cells are commercially available with efficiencies between 38 % and 43 %. Table 5 in the appendix lists companies with the ability to produce III-V multi-junction solar cells for HCPV.

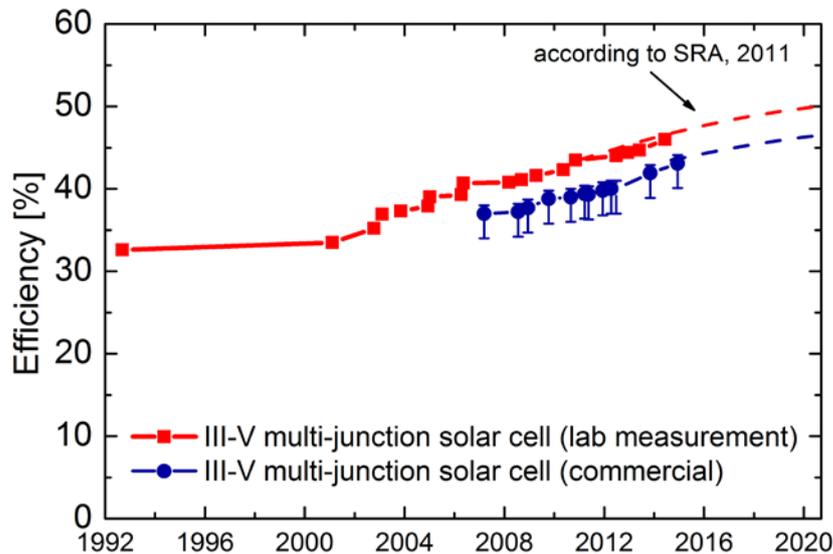


Figure 8: Development of record efficiencies of III-V multi-junction solar cells under concentrated light ( $x^*$ AM1.5d). Examples for average commercial concentrator cell efficiencies (different concentration levels) are also indicated. (AM1.5d lab records according to Green et al., Solar Cell Efficiency Tables from 1993 [10] to 2015 [3] ; AM1.5d commercial efficiencies averaged from company product sheets). The trend lines show expected efficiencies from the Strategic Research Agenda (SRA) developed by the European Photovoltaics Technology Platform in 2011 [7].

There are several main reasons why III-V multi-junction solar cells reach the highest efficiencies of any photovoltaic technology. III-V solar cells are composed of compounds of elements from groups III and V of the periodic table. In the corresponding multi-junction devices, several solar cells made of different III-V semiconductors are stacked with decreasing bandgaps from top to bottom. This reduces thermalisation losses as photometric tons are mostly absorbed in layers with a bandgap close to the photon's energy. Moreover, transmission losses are reduced as the absorption range of the multi-junction solar cell is usually wider than for single-junction devices. Finally the use of direct bandgap III-V semiconductors facilitates a high absorption of light even in comparably thin layers.

The most common III-V multi-junction solar cell in space and terrestrial concentrator systems is a lattice-matched  $\text{Ga}_{0.50}\text{In}_{0.50}\text{P}/\text{Ga}_{0.99}\text{In}_{0.01}\text{As}/\text{Ge}$  triple-junction solar cell. The device is grown with high throughput in commercial metal-organic vapor phase epitaxy (MOVPE) reactors. All semiconductors in this structure have the same lattice constant as the Ge substrate, which facilitates crystal growth with high material quality. However, its bandgap combination is not optimal as the bottom cell receives significantly more light than the upper two cells resulting in about twice the photocurrent of the upper two subcells. Nevertheless, as record efficiency for this triple-junction concentrator solar cell 41.6% (AM1.5d, 364 suns) has been achieved in 2009 [12]. Various approaches are under investigation to further increase in solar cell efficiencies. Table 3 presents cell architectures that have achieved record cell efficiencies above 41%. These use different elements from the wide range of technology building blocks available for III-V multi-junction solar cells. A detailed discussion of each cell structure is out of scope of this paper. A more detailed overview can, for example, be found in References [13-15].

Cell Architecture	Record Efficiency (Accredited test lab)	Institution	Comments
GaInP/GaAs//GaInAsP/GaInAs [3,16]	46.0 @ 508 suns (AIST)	Fraunhofer ISE/ Soitec/ CEA	4J, wafer bonding, lattice matched grown on GaAs and InP
GaInP/GaAs/GaInAs/GaInAs [17,18]	45.7% @ 234 suns (NREL)	NREL	4J, inverted metamorphic
GaInP/GaAs/GaInAs [11]	44.4 @ 302 suns (Fraunhofer ISE)	Sharp	3J, inverted metamorphic
GaInP/GaAs/GaInNAs [19]	44.0% @ 942 suns (NREL)	Solar Junction	3J, MBE, lattice matched, dilute nitrides, grown on GaAs
GaInP/Ga(In)As/GaInAs [20,21]	42.6% @ 327 suns (NREL) (40.9% @ 1093 suns)	NREL	3J, inverted metamorphic
	42.4% @ 325 suns (NREL)  (41% @ 1000 suns)	Emcore	
GaInP-GaAs-wafer-GaInAs [22]	42.3% @ 406 suns (NREL)	Spire	3J, epi growth lattice matched on front and inverted metamorphic on back of GaAs wafer
GaInP-Ga(In)As-Ge [12]	41.6% @ 364 suns (NREL)	Spectrolab	3J, lattice matched, commercially available;
GaInP-GaInAs-Ge [23]	41.1% @ 454 suns (Fraunhofer ISE)	Fraunhofer ISE	3J, upright metamorphic; commercially available from AZUR SPACE, Spectrolab

Table 3: Summary of record concentrator cell efficiencies above 41% based on III-V multi-junction solar cells.

Note that LCPV systems mainly use c-Si solar cells. As this report mainly focuses on the HCPV approach, these solar cells are not described in detail here.

## 3.2 Material Availability

Gallium (Ga), indium (In), and germanium (Ge) are usually employed in current designs for III-V multi-junction cells employed in CPV, and have limited global supplies. The total estimated annual production of Ga and In from byproduct recovery, the primary means of mining these elements, was 280 metric tons and 770 metric tons respectively in 2013 [24]. Current annual production of Germanium in 2011 was estimated at 118 metric tons [25]. These numbers include production of virgin materials only, and not any reclaimed or pre-consumer recycled materials, which are also available.

Assuming a 200 micron thick Ge wafer, about 0.1 g/cm<sup>2</sup> are required if no kerf or dicing losses are assumed. For 30% yield (due to kerf loss, dicing losses, and breakage), about 0.4 g/cm<sup>2</sup> of Ge is required. The true Ge requirement lies somewhere in the middle of these two numbers, depending on how effectively a given company is able to recycle the kerf. Most

companies are able to recycle the majority of the kerf and other material such that total losses are only a few percent. Thus, we would expect less than 4 metric tons of Ge would be required for 1 GW production, assuming 30% module efficiency and 1,000x concentration. The maximum requirement would be approximately 12 metric tons if no material was recycled. The material requirement decreases with increases in efficiency and concentration. It is possible to supply this level of demand with the current production capacity of Ge, but demand from other industries will also significantly impact the supply of Ge available for CPV [25]. Outside of solar, Ge is used for electronics, infrared optics, fiber optics, and polyethylene terephthalate (PET) catalysts. Solar and electronics constitute the fastest growing demand. Therefore, Ge production may need to be expanded in order to support deployment of these cells at large scales. The total worldwide Ge resources are estimated at 35,600 metric tons, with 24,600 metric tons from coal and the rest from lead/zinc, and, thus, is not a limiting factor in expanding production. However, Ge is currently produced as a byproduct of zinc and coal, which have much larger markets and constitute the core focus of most companies mining Ge. It is unclear how much the price of germanium must rise to encourage expansion of Ge production and how much can be produced as a byproduct at prices that do not impair the economics of III-V multi-junction cells employing germanium.

The amount of Ga and In required for a typical III-V multi-junction cell grown on Ge is very small, and is not expected to require an expansion of the supply chain to achieve GW annual production volumes. In addition, the thicknesses of the base layers may be reduced in future designs, further reducing Ga and In material requirements.

For metamorphic or inverted metamorphic cells, the Ga and In used in the MOVPE layers is currently significantly higher than for the lattice matched design on Ge since a thick graded buffer layer, usually GaInP, is required and a GaInAs cell is often employed. However, the total amount used at high concentrations is still very low and not expected to require supply chain expansion at GW annual production for HCPV. The GaAs substrate, however, can represent more significant Ga use if it is not reused. For single-use, 600 micron thick GaAs substrates, less than 0.2 g/cm<sup>2</sup> are required assuming 100% yield. If we again assume 30% yield and no recycling, approximately 0.5 g/cm<sup>2</sup> of Ga is required. We expect the substrate will require less than 5.5 metric tons for 1 GW of production for the case of 30% module efficiency and 1,000x concentration with an effective recycling program. Even without any recycling, no more than 17 metric tons would be required in this case. While this is significant, this still currently represents only about 6 % of the overall annual supply.

Material availability of Ga, In, and Ge for III-V multi-junction cells would be a much more significant challenge if the cells are used for low concentration or one sun applications.

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## 5 Appendix

### 5.1 Data

Data on CPV installations and manufacturing are presented that were collected through the end of July 2015. We are happy to receive comments and additions (simon.philipps@ise.fraunhofer.de).

#### 5.1.1 CPV Power Plants

Table 4 lists all CPV power plants with a capacity of 1 MW or more. Only plants with confirmed completed installation are shown. Plants that are listed in the project library of the CPV Consortium (<http://cpvconsortium.org/projects>) are marked with an asterisk at the end of the online year. Data for these plants are mostly collected from public presentations, press releases, or website announcements.

Company	Origin Company	Power in MW	Appr.	Country	Location	Online year
Soitec	France/ Germany	5.8	HCPV	China	Hami	2014*
Soitec	France/ Germany	44.2	HCPV	South Africa	Touwsrivier	2014*
Soitec	France/ Germany	9.2	HCPV	USA	Borrego Springs	2014*
Soitec	France/ Germany	1.3	HCPV	Portugal	Alcoutim	2014*
Suncore Photovoltaic	China	1.3	HCPV	Portugal	Evora	2014*
Soitec	France/ Germany	1.1	HCPV	Saudi Arabia	Tabuk	2014
Solar Systems/ Silex Systems	Australia	1.0	HCPV	Saudi Arabia	Nofa	2014
SunPower	USA	7.0	LCPV	USA	Arizona	2014
Suncore Photovoltaic	China	79.8	HCPV	China	Goldmud	2013*
Soitec	France/ Germany	2.6	HCPV	China	Hami	2013*
Solaria	USA	2.0	LCPV	Italy	Sardinia	2013
Soitec	France/ Germany	1.7	HCPV	USA	Newberry Springs	2013*
Solar Systems/ Silex Systems	Australia	1.5	HCPV	Australia	Mildura	2013
SolFocus	USA	1.3	HCPV	Mexico	Guanajuato	2013*
Suncore Photovoltaic	China	1.2	HCPV	USA	Albuquerque	2013*
Soitec	France/ Germany	1.2	HCPV	Italy	Saletti	2013
SunPower	USA	1.0	LCPV	USA	Arizona	2013
SolFocus	USA	1.0	LCPV	Mexico	Cerro Prieto	2012*
Suncore Photovoltaic	China	58.0	HCPV	China	Goldmud	2012*

Company	Origin Company	Power in MW	Appr.	Country	Location	Online year
Amonix	USA	30.0	HCPV	USA	Alamosa	2012*
Solaria	USA	4.1	LCPV	USA	New Mexico	2012
Magpower	Portugal	3.0	HCPV	Portugal	Estoi	2012
Solaria	USA	2.0	LCPV	Italy	Puglia	2012
Arima EcoEnergy Tech. Corp.	Taiwan	1.7	HCPV	Taiwan	Linbian	2012
Soitec	France/ Germany	1.2	HCPV	Italy	SantaLucia	2012*
Soitec	France/ Germany	1.2	HCPV	Italy	Cerignola	2012
Soitec	France/ Germany	1.1	HCPV	Italy	Bucci	2012
Solaria	USA	1.1	LCPV	USA	California	2012
BEGI (Beijing General Industries)	China	1.0	HCPV	China	Golmud	2012
Solaria	USA	1.0	LCPV	Italy	Sardinia	2012
SolFocus	USA	1.0	HCPV	Italy	Lucera	2012
Amonix	USA	5.0	HCPV	USA	Hatch	2011
Amonix	USA	2.0	HCPV	USA	Tucson	2011
SolFocus	USA	1.6	HCPV	USA	Yucaipa	2011*
Suncore Photovoltaic	China	1.5	HCPV	China	Xiamen	2011
SolFocus	USA	1.3	HCPV	USA	Hanford	2011*
SolFocus	USA	1.3	HCPV	Greece	Crete	2011
SolFocus	USA	1.3	HCPV	USA	Yuma	2011*
Greenvolts	USA	1.0	HCPV	USA	Yuma	2011
SolFocus	USA	1.0	HCPV	Chile	Santiago	2011
Suncore Photovoltaic	China	3.0	HCPV	China	Goldmud	2010
Soitec	France/ Germany	1.4	HCPV	USA	Questa	2010
SolFocus	USA	1.3	HCPV	USA	Victorville	2010*
Sungrow	China	1.0	LCPV	China	Qinghai	2010
Amonix/ Guascor Foton	Spain	2.0	HCPV	Spain	Murcia	2009
Amonix/ Guascor Foton	Spain	7.8	HCPV	Spain	Villafranca	2008
Amonix/ Guascor Foton	Spain	1.5	HCPV	Spain	Ecija	2006
Abengoa Solar	Spain	1.2	LCPV	Spain	Sanlúcar La Mayor	2006
Sungrow	China	1.0	LCPV	China	Wuwei, Gansu	Unknown

Table 4: Completed CPV power plants with a capacity of 1 MW or more. Power plants marked with an asterisk are listed in the project library of the CPV Consortium (<http://cpvconsortium.org/projects>).

## 5.1.2 CPV companies for cells and systems

Table 5 lists companies with the capability for epitaxial growth of III-V multi-junction solar cells. Table 6 presents companies that manufacture HCPV systems and Table 7 those that manufacture LCPV systems. This information changes rapidly. Data were mostly collected from public presentations, press releases, or website announcements through end of November 2014. Note that companies sometimes refrain from posting information about their deployments, and so might have installed capacity even if not listed here.

Company	Location
<a href="#">Azur Space<sup>1</sup></a>	Germany
<a href="#">CESI</a>	Italy
<a href="#">SolAero</a> (includes Emcore's former photovoltaic business)	USA
<a href="#">Microlink Devices</a>	USA
<a href="#">Sharp</a>	Japan
<a href="#">Solar Junction</a>	USA
<a href="#">Spectrolab</a>	USA
<a href="#">VPEC</a>	Taiwan
<a href="#">Arima</a>	Taiwan
<a href="#">Cyrium</a>	Canada
<a href="#">Epistar</a>	Taiwan

Table 5: Summary of companies with capability for epitaxial growth of III-V multi-junction solar cells. (Companies listed below the bold line (in gray) either seem to have moved away from this approach or do not seem to have production capacities ready for larger quantities, but should not be discounted completely).

Company	Location (HQ)	Conc.*	Type of System	Installed Capacity [MWp]
<a href="#">Suncore</a> Photovoltaic Technology	Huainan, China	1,090	Lens, tilt and roll Dish, HCPVT	144.8 <0.1
<a href="#">Soitec</a>	France	500	Lens, pedestal	79.3
<a href="#">Arzon Solar</a> (previously Amonix)	Seal Beach, CA, USA	HCPV	Lens, pedestal	38.4
<a href="#">Foton HC</a> (previously: Amonix/Guascor)	Bilbao, Spain	HCPV	Lens, pedestal	12.3
<a href="#">Solar Systems/Silex Systems</a>	Victoria, Australia	500-1,000	Reflective dish, dense array, solar tower	4.3
<a href="#">Magpower</a>	Agualva Cacem, Portugal	HCPV	Lens, pedestal	4.2
<a href="#">Arima Ecoenergy</a>	New Taipei City, Taiwan	476	Lens, pedestal	2.1
<a href="#">Abengoa Solar</a>	Madrid, Spain	>1000	Lens, pedestal	0.2

<sup>1</sup> AZUR Space also provides solar cell assemblies as OEM products for various CPV technology platforms, e.g. EFA (Enhanced Fresnel Assembly) for concentrator modules with Fresnel optics and ADAM (Advanced Dense Array Module) for the use in parabolic mirror based CPV systems.

Company	Location (HQ)	Conc.*	Type of System	Installed Capacity [MWp]
<a href="#">RedSolar</a>	Zhongshan, China	HCPV	Lens	0.2
<a href="#">RayGen</a>	Blackburn, Victoria, Australia	HCPV	CSPV: Solar tower with heliostats	0.2
<a href="#">Sumitomo Electric</a>	Osaka, Japan	HCPV	Lens	0.1
<a href="#">Renovalia</a>	Madrid, Spain	HCPV	Dish reflector	<0.1
<a href="#">Pyron Solar</a>	Vista, CA, USA	1,200	Lens, carousel	<0.1
<a href="#">Heliotrop</a>	Lyon, France	1,024	Lens, pedestal	<0.1
<a href="#">Spirox</a>	Hsinchu City, Taiwan	HCPV	Lens, pedestal	<0.1
<a href="#">Airlight Energy</a>	Biasca, Switzerland	600	Reflective dish	
<a href="#">Alitec</a>	Navaccio, Italy	500, 1090	Lens, pedestal	
<a href="#">Angelantoni Industrie</a>	Italy	HCPV	Lens, Pedestal	
<a href="#">Becar-Beghelli**</a>	Italy	HCPV	Reflective	
<a href="#">BSQ Solar</a>	Madrid, Spain	HCPV	Lens, pedestal	
<a href="#">Cool Earth Solar</a>	Livermore, CA, USA	HCPV	Inflated mirrors	
<a href="#">GreenField Solar</a>	Cleveland, Ohio, USA	HCPV	Reflective	
<a href="#">Heliocentric</a>	San Jose, CA	HCPV	Parabolic, reflective dish	
<a href="#">Morgan Solar</a>	Toronto, ON, Canada	HCPV	Planar lens, pedestal	
<a href="#">Rehnu</a>	Tucson, AZ, USA	HCPV	Dish reflector	
<a href="#">Sahaj Solar</a>	Gujarat, India	500	Lens, pedestal	
<a href="#">Sempruis</a>	Durham, NC, USA	>1,000	Microlens	
<a href="#">Sharp</a>	Japan	CPV	Lens, pedestal	
<a href="#">SolarTron Energy Systems</a>	Nova Scotia, Canada	1,000	Reflective dish, dense array	
<a href="#">Solergy</a>	Piedmont, CA, USA	>500	Cone concentrator. CPV and CPV + thermal energy systems, BICPV	
<a href="#">Sun Synchrony</a>	Vallejo, CA, USA	HCPV	Miniaturized reflectors	
<a href="#">SunCycle</a>	Eindhoven, Netherlands	540	Rotating lens/mirror (internal tracking)	
<a href="#">SunFish</a>	Denbighshire, UK	HCPV	Heliostat, hybrid PV and thermal	
<a href="#">Valldoreix Greenpower</a>	Valldoreix, Spain	800	Lens	
<a href="#">ZettaSun</a>	Boulder, CO, USA	Up to 1,000	Lens, internal tracking	

Table 6: Summary of HCPV module companies.

\*If more than one concentration is listed, the company sells multiple modules which each have different concentration ratios. If this column says “HCPV,” that means public information on the exact concentration ratios for that company could not be found.

\*\* Becar-Beghelli is developing a HCPV system within the EU-funded project [ECOSOLE](#) together with other partners.

Company	Location (HQ)	Conc.*	Type of System	Installed Capacity [MW]
<a href="#">SunPower</a>	San Jose, CA, USA	7	Linear reflective trough, c-Si cells	8.0
<a href="#">Abengoa Solar</a>	Madrid, Spain	2-4	Mirror	1.3
<a href="#">Absolicon Solar Concentrator</a>	Harnosand, Sweden	10	Reflective through, Si cells, thermal hybrid	0.1
<a href="#">Whitfield Solar</a>	UK	40	Fresnel lens, c-Si cells	<0.1
<a href="#">Banyan Energy</a>	Berkeley, CA, USA	10	Total internal reflection optics, c-Si cells	
<a href="#">GreenField Solar</a>	Cleveland, Ohio, USA	MCPV	Reflective	
<a href="#">IDHelio</a>	France	50	Fresnel mirror, hybrid PV and thermal	
<a href="#">Pacific Solar Tech</a>	Fremont, CA, USA	Multiple	Dome lens, c-Si cells	
<a href="#">Stellaris</a>	North Billerica, MA, USA	3	Static, “See-through” PV window tiles, c-Si cells, building-integrated CPV	
<a href="#">Sunengy</a>	Sydney, Australia	LCPV	Fresnel, c-Si cells, module floats on water	
<a href="#">Sunseeker Energy</a>	Schindellegi, Switzerland	LCPV	Lens	
<a href="#">Zytech Solar</a>	Zaragoza, Spain	4, 120	Prismatic lens, c-Si cells	

Table 7: Summary of LCPV module companies.

\*If the system is hybrid PV and thermal, only electric energy generation shown in this table