FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE
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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 1.3 of this report includes recent progress in CPV. It is still a difficult time for CPV technology to penetrate the market. However, CPV is not dead! Recently some new CPV installations were realized.

If you have suggestions about this report, additional or updated information, or would like to add your organisation's information to our tables, please e-mail maike.wiesenfarth@ise.fraunhofer.de. It is our intention to update the report in a regular manner.

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Key Facts

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

- Cumulative installations (already grid-connected): >370 MWp
- Several power plants with capacity ≥ 30 MW_p:
  - Golmud, China, built by Suncore: 60 (2012) and 80 MWp (2013)
  - Touwsrivier, South Africa, built by Soitec: 44 MWp (2014)
  - Alamosa, Colorado, US, built by Amonix: 30 MWp (2012)

  (see installation data base: http://cpvconsortium.org/projects)
- Demonstrated reliability, with field data for more than 7 years [1],[2]

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 [3],[4]
- Certified record efficiency of 43.4% for a mini-module consisting of a single full glass lens and a wafer-bonded four-junction solar cell by Fraunhofer ISE [3],[5]
- Certified record value for module efficiency of 38.9 % by Soitec [3],[6]
- Averaged yearly field performance data for power plants with > 100 kWp were reported that achieved performance ratios of 74-80 % [1],[2]
- Recent R&D results can be found in the proceedings of the latest International CPV conference. The next CPV conference will take place in Ottawa, Canada May 01-03, 2017[1].

What's New?

Version 1.3 of this report has been thoroughly revised compared to Version 1.2 (02/2016). The authors like to especially point the reader's attention to the following updates:

- New large installations in China and Morocco with CPV systems delivered by Redsolar (China) and Sumitomo (Japan), respectively
- Soitec´s CPV technology will be continued by Saint-Augustin Canada Electric Inc. (STACE) [7],[8]

  "STACE plans to have completed the installation of its manufacturing line, in Canada, by May 2017. The initial manufacturing capacity of 20 MW per year will ramp up to 70 MW by June 2018 or earlier depending of the order book."
- IEC standard for module power rating 62670-3 was finally published. The standard defines the measurement procedures for the two reference conditions defined in IEC 62670-1 (Concentrator Standard Test Conditions (CSTC): DNI of 1000 W/m², 25 °C cell temperature and AM1.5d spectral irradiance and Concentrator Standard Operating Conditions (CSOC): DNI of 900 W/m², 20 °C ambient temperature and AM1.5d spectral irradiance).
- Installation data were updated to include the full year 2016
- Company tables in the appendix were updated

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[1] http://scitation.aip.org/content/aip/proceeding/aipcp/1616; http://www. cpv-13.org

1 Introduction

Concentrator Photovoltaic (CPV) technology has entered the market as a utility-scale option for the generation of solar electricity with 370 MWp in cumulative installations, including several sites with more 30 MWp. This report explores the current status of the CPV market, industry, research, and technology. The upcoming CPV industry has struggled to compete with PV prices, with some major CPV companies exiting the market, while others face 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 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 standard flat-plate PV technology in certain sunny areas with high Direct Normal Irradiance (DNI) [9]. 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^{2}a). The systems are differentiated according to the concentration factor of the technology configuration (see Table 1). More than 90 % of the CPV capacity that has been publicly documented to be installed through the end of 2016 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® concept originally developed at Fraunhofer ISE. Right: Example of a mirror-based system developed by the University of Arizona, USA [10].

A key reason for large-scale power plants using HCPV is the significant increase in the efficiency of individual modules. High efficiencies lead to a reduction of area-related system costs. In 2015, Soitec demonstrated a CPV module efficiency of 38.9 % at Concentrator Standard Test Conditions (CSTC) [6] 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 [11],[12]. 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 the 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. In some cases, this could allow for continued use of the land for other purposes, for example agriculture, although the relevant benefits of CPV versus flat plate PV in this case is still an active area of research. Finally, HCPV could provide an advantage over traditional c-Si technology in hot climates, because of the lower temperature coefficient.

Table 1: Description of CPV classification.[1]

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

The total capital equipment (capex) requirement for CPV cell and module factories, while varying by design and manufacturing process, can also be lower for CPV than for traditional flat-plate technologies. A bottom-up analysis from NREL in 2014 based on a specific HCPV system with a Fresnel lens primary optic and refractive secondary lens estimated 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 [13]. 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 [14]. In 2013, a Fraunhofer ISE report found that installed CPV power plant prices for 10 MW projects were between € 1400/kW and € 2200/kW [9]. The wide range of prices results from the different technological concepts as well as the nascent and regionally variable markets. 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. With a total of more than 300 MWp it had seen a significant number of installations in the years 2011 to 2014, nevertheless 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. This report intends to fill this information void by summarizing and providing reliable data on CPV. The first part of

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[1] 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.

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.

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

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
Additional use of waste heat possible for systems with active cooling possible (e.g. large mirror systems)	May require frequent cleaning to mitigate soiling losses, depending on the site
Low CapEx for manufacturing infrastructure enables fast growth	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 silicon flat-plate modules makes market entry very difficult for even the lowest cost technologies
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 [15], [16]	New generation technologies, without a history of production (thus increased risk)
Potential double use of land, e.g. for agriculture [17], [18]	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	

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 have 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. 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 water.

Despite this convergence within HCPV onto similar module designs, and the recent availability of some standard components, companies continue to use their own customized components. Although many optics suppliers remain enthusiastic about the promise of CPV and the potential for standardized components to help ease growing manufacturing capacities, 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. However, after this severe setback, we recognize a re-start. For example, the company STACE acquired the IP of Soitec´s CPV technology and announced to set-up a production line.

Also 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. The total amount of installed CPV had grown significantly in the years 2011 to 2014, as can be seen in Figure 2. In 2015 the installed annual capacity reduced significantly down to about 17 MWp which is in 2016 stabilized. A large installation was made by the Chinese company Redsolar (12 MW). Further, several smaller installations e.g. from the companies Sumitomo (1MW), BSQ (several up to 0.25 MW) and ARZON Solar (0.3 MW) were installed. These installations use Fresnel lenses to concentrate the solar radiation. However, the interest in mirror-based CPV systems is growing. Heliostat fields in the tower systems configuration or mirror dishes are used as primary concentrator optics. The PV receiver is water cooled thus providing in addition thermal energy (CPV-T). There are several small companies that offer those systems like Suncore, REhnu, Southwest Solar Technology LLC, Solartron or Raygen (see Table 6). Whereas most of the companies only presented demonstration systems, Raygen has shown already larger installations. So far they have installed 0.4 MW. According to the director John Lasich, Raygen will finish the installation of another MW this year. For LCPV little information is available to the public though Morgan Solar has identified an opportunity for a silicon-based LCPV design. Trackers have also made great strides in recent years, being both more reliable and lower-cost than in the past. This is important as the trackers contribute approximately one third of the costs of the complete system.

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 posts 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, 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, since then III-V multi-junction solar cells have become standard. LCPV systems still employ either slightly modified standard or high-efficiency c-Si cells.

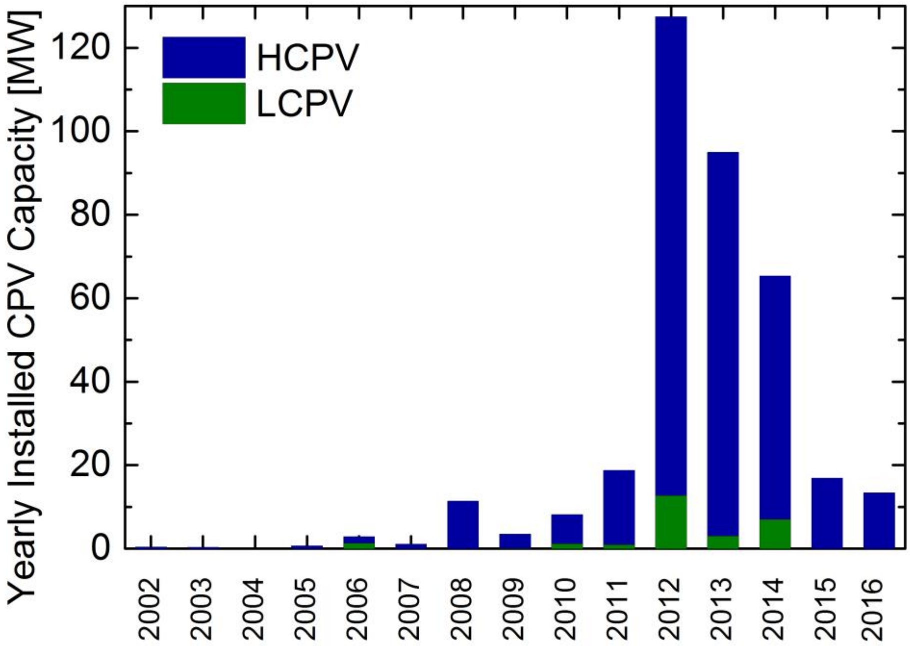

Figure 2: CPV capacity installed each year with indication of the type (HCPV or LCPV), globally, as derived from public announcements, status March 2017.

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

Compared to conventional PV, the CPV market is still small It had a market volume around 70 MWp in 2014. Then the installed capacity decreased. In 2016 CPV systems with a total capacity of 14 MWp were installed. The industry is restructuring and previously small companies are growing, however starting with smaller installations. In 2016, Morocco became a site where CPV has been installed with a capacity of 1 MWp, see also Figure 4.

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); a recent installation from 2016, 12 MW in Delingha City, China (© Redsolar).

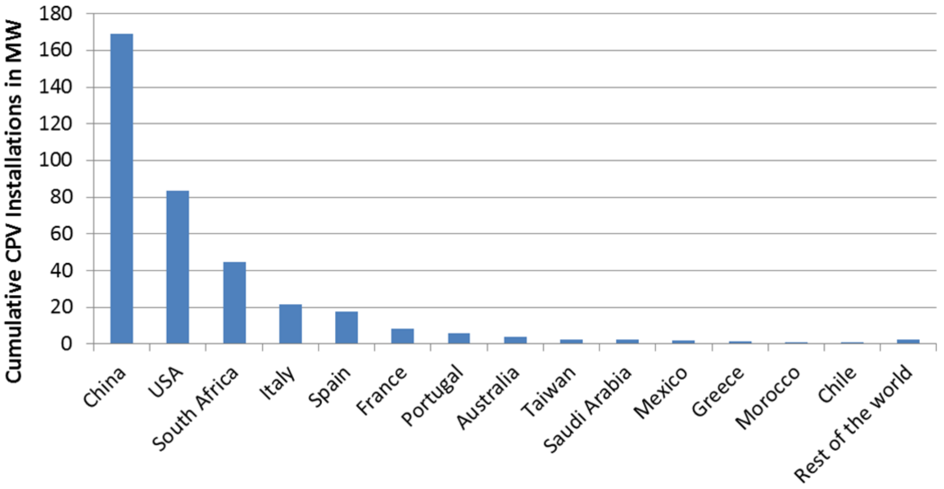

Figure 4: Grid-connected CPV capacity by country at the end of 2016. All countries with a total installation of above 1 MWp are shown separately.

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. Recently the IEC standard for module power rating 62670-3 was finally published. Recently the IEC standard for module power rating 62670-3 was finally published. The standard defines the measurement procedures for the two reference conditions defined in IEC 62670-1 (Concentrator Standard Test Conditions (CSTC): DNI of 1000 W/m², 25 °C cell temperature and AM1.5d spectral irradiance and Concentrator Standard Operating Conditions (CSOC): DNI of 900 W/m², 20 °C ambient temperature and AM1.5d spectral irradiance). In this way the module performance is defined well and is comparable between the designs. Please note that additional UL and IEC standards (e.g. for 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 [9]. 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 [14].

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 [9], 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^{2}a) and €0.08/kWh to € 0.12/kWh with 2500 kWh/(m^{2}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. Today's low costs for flat-plate PV systems have motivated CPV companies to further innovate their designs to reach even lower costs than these, as reflected by the recent decrease in deployment, while the companies reconsider their designs.

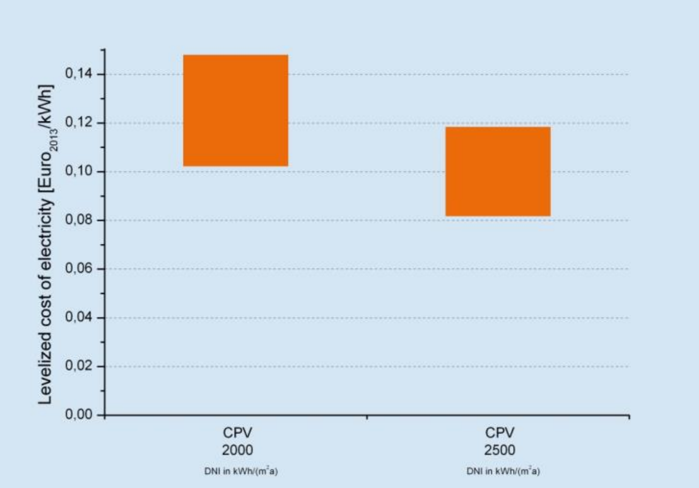

Figure 5: Levelized cost of electricity (LCOE) of CPV systems under high solar irradiation (DNI) of 2000 kWh/(m^{2}a) and 2500 kWh/(m^{2}a) in 2013. Source: [9].

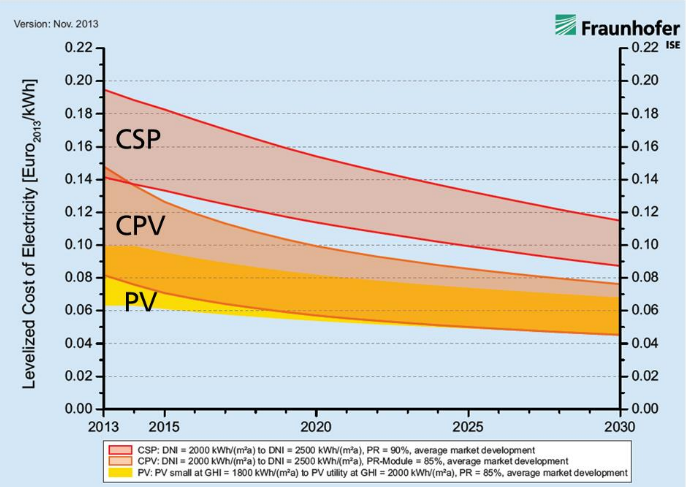

Figure 6: Development of the LCOE of PV, CSP and CPV plants at locations with high solar irradiation of 2000 kWh/(m^{2}a) - 2500 kWh/(m^{2}a). Source: [9].

3 Research and Technology

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 [11]. Laboratory cell efficiency has reached 46.0 % [3], [4] and CPV module efficiency tops at 38.9 % (CSTC) [6]. Note that the latter value refers to large modules with multiple lenses. A mini-module consisting of a single full glass lens and a wafer-bonded GaInP/GaAs//GaInAsP/GaInAs cell has achieved a record efficiency of 43.4 % [5]. 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.

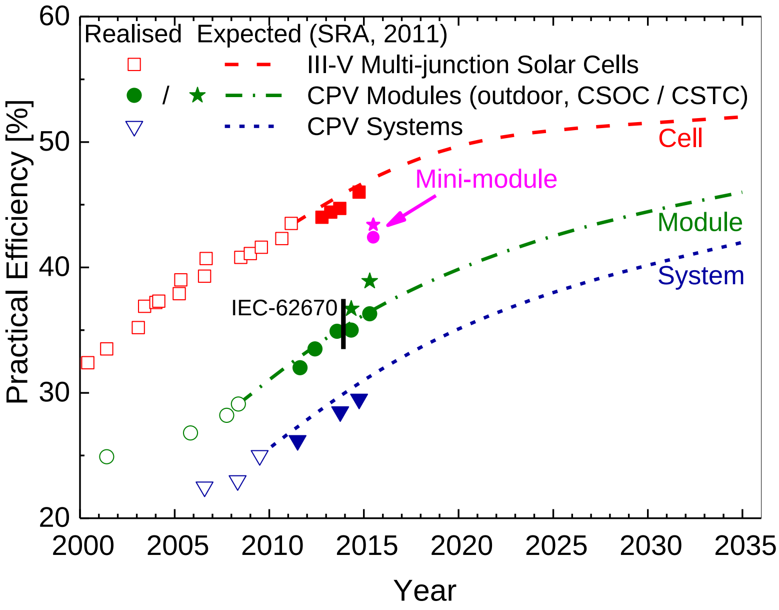

Figure 7: Development of record efficiencies of III-V multi-junction solar cells and CPV modules (cells: x*AM1.5d; modules: outdoor measurements). Progress in top-of-the-line CPV system efficiencies is also indicated. (AM1.5d lab records according to Green et al., Solar Cell Efficiency Tables from 1993 [19] to 2016 [3]; CPV module and system efficiencies collected from various publications[1]). The trend lines show expected efficiencies from the Strategic Research Agenda (SRA) developed by the European Photovoltaics Technology Platform in 2011 [11]. Recent efficiency values (full symbols) follow the trend very well.

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[1] CPV module efficiencies before 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/m², 25 °C cell temperature and AM1.5d spectral irradiance and Concentrator Standard Operating Conditions (CSOC) which means DNI of 900 W/m², 20 °C ambient temperature and AM1.5d spectral irradiance.

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 [20] and Fraunhofer ISE [4] achieved today´s champion efficiencies of 44.4 % 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.

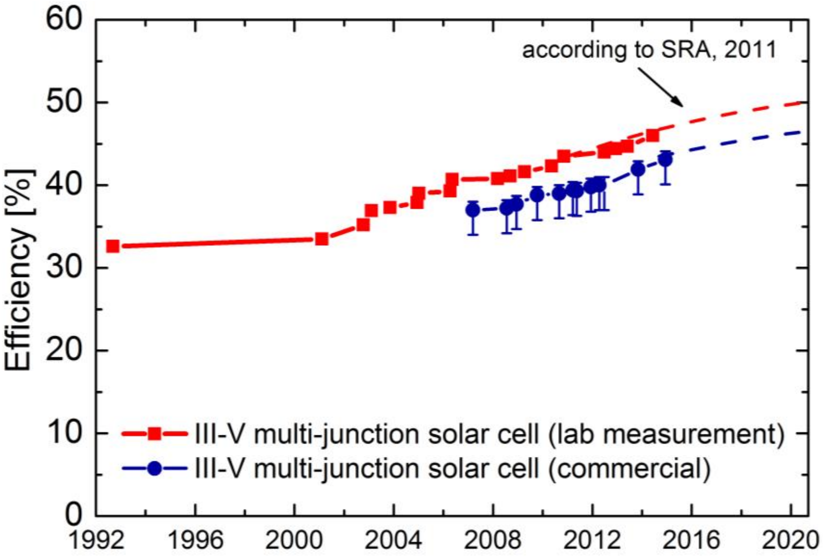

Figure 8: Development of record efficiencies of III-V multi-junction solar cells under concentrated light (x*AM1.5d). Examples for average commercial concentrator cell efficiencies (different concentration levels) are also indicated. (AM1.5d lab records according to Green et al., Solar Cell Efficiency Tables from 1993 [19] to 2016 [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 [11].

There are several 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 group 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 thermalization losses as photons 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. In addition, the efficiency increases when operated under concentrated illumination due to a linear increase of short circuit current and logarithmic increase of voltage.

The most common III-V multi-junction solar cell in space and terrestrial concentrator systems is a lattice-matched $Ga_{0.50}In_{0.50}P/Ga_{0.99}In_{0.01}As/Ge$ triple-junction solar cell. The device is typically 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, a record efficiency for this triple-junction concentrator solar cell 41.6 % (AM1.5d, 364 suns) was achieved in 2009 [21]. 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 [22]–[24].

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

Cell architecture	**Record efficiency (accredited test lab)**	**Institution**	**Comments**
GaInP/GaAs//GaInAsP/GaInAs [3],[25]	46.0 @ 508 suns (AIST)	Fraunhofer ISE/ Soitec/ CEA	4J, wafer bonding, lattice matched grown on GaAs and InP
GaInP/GaAs/GaInAs/GaInAs [26][27]	45.7% @ 234 suns (NREL)	NREL	4J, inverted metamorphic
GaInP/GaAs/GaInAs [20]	44.4 @ 302 suns (Fraunhofer ISE)	Sharp	3J, inverted metamorphic
GaInP/GaAs/GaInNAs [28]	44.0% @ 942 suns (NREL)	Solar Junction	3J, MBE, lattice matched, dilute nitrides, grown on GaAs
GaInP/Ga(In)As/GaInAs [29][30]	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 [31]	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 [21]	41.6% @ 364 suns (NREL)	Spectrolab	3J, lattice matched, commercially available
GaInP-GaInAs-Ge [32]	41.1% @ 454 suns (Fraunhofer ISE)	Fraunhofer ISE	3J, upright metamorphic; commercially available from AZUR SPACE, Spectrolab

Note that LCPV systems mostly 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 primary production of Ga and In from byproduct recovery, the primary means of mining these elements, was 375 metric tons and 655 metric tons respectively in 2016 [33],[34]. The production capacity for primary Ga was estimated at 730 metric tons/year the same year, with the capacity for high-grade, refined Ga appropriate for use in HCPV (from low-grade primary sources) was 320 metric tons/year. Global annual refinery capacity for Germanium production, excluding production in the United States, which is unavailable for reasons of business sensitivity, was estimated by the USGS as 155 metric tons in 2016 [35]. These numbers include production of virgin materials only, and not any reclaimed or pre-consumer recycled materials, which are also available.

Assuming a 200 µm thick Ge wafer, about 0.1 g/cm² 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/cm² 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 [35]. 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 µm thick GaAs substrates, less than 0.2 g/cm² are required assuming 100 % yield. If we again assume 30 % yield and no recycling, approximately 0.5 g/cm² 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 5 % of the overall annual supply.

Material availability of Ga, In, and Ge for III-V multi-junction cells could be a more significant challenge if the cells are used for low concentration or one sun applications, depending on what substrate is used and if it is reused.

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5 Appendix

5.1 Data

Data on CPV installations and manufacturing are presented that were collected through the end of 2016. We are happy to receive comments and additions (maike.wiesenfarth@ise.fraunhofer.de).

5.1.1 CPV Power Plants

Table 4 lists all CPV power plants with a capacity of 1 MWp 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. In 2016 to the best of our knowledge Redsolar and Sumitomo installed systems with a capacity of 1 MWp or more.

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).

Company	Origin Company	Power in MW	Appr.	Country	Location	Online year
Sumitomo	Japan	1	HCPV	Morocco	Ouarzarte City	2016
Redsolar	China	12	HCPV	China	Delingha City	2016
Soitec	France/ Germany	2.2	HCPV	France	Signes Lafarge	2015
Soitec	France/ Germany	3.6	HCPV	France	Aigaliers	2015
Soitec	France/ Germany	1.5	HCPV	France	Grabels	2015
Soitec	France/ Germany	1.1	HCPV	USA	Fort Irwin	2015
Soitec	France/ Germany	2.1	HCPV	China	Hami III	2015
Soitec	France/ Germany	5.8	HCPV	China	Hami II	2015*
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	China	79.8	HCPV	China	Goldmud	2013*

Photovoltaic						
Soitec	France/ Germany	2.6	HCPV	China	Hami I	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*
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/	1.4	HCPV	USA	Questa	2010

	Germany					
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

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 2015. Note that companies sometimes refrain from posting information about their deployments, and so might have installed capacity even if not listed here.

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
Azur Space[1]	Germany
CESI	Italy
SolAero (includes Emcore's former photovoltaic business)	USA
Microlink Devices	USA
San´an Optoelectronics	China
Sharp	Japan
Solar Junction	USA
Spectrolab	USA
VPEC	Taiwan
Arima	Taiwan
Cyrium	Canada
Epistar	Taiwan

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[1] 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.

Table 6: Summary of HCPV module companies. Companies in gray either seem to have moved away from CPV, or are in the process of restructuring their CPV business. Sometimes companies have reentered the business, so are retained in the table with the possibility that their technology may return.

Company	**Location (HQ)**	**Conc.***	**Type of System**	**Installed Capacity [MWp]**
Arzon Solar (previously Amonix)	Seal Beach, CA, USA	HCPV	Lens, pedestal	38.4
Foton HC (previously: Amonix/Guascor)	Bilbao, Spain	HCPV	Lens, pedestal	12.3
RedSolar	Zhongshan, China	HCPV	Lens	12.2
Solar Systems/Silex Systems	Victoria, Australia	500-1,000	Reflective dish, dense array, solar tower	4.3
Magpower	Agualva Cacem, Portugal	HCPV	Lens, pedestal	4.2
Arima Group	New Taipei City, Taiwan	476	Lens, pedestal	2.1
BSQ Solar***	Madrid, Spain	HCPV	Lens, pedestal	1.4
Sumitomo Electric	Osaka, Japan	HCPV	Lens	1.1
Abengoa Solar	Madrid, Spain	>1000	Lens, pedestal	0.2
RayGen	Blackburn, Victoria, Australia	HCPV	CSPV: Solar tower with heliostats	0.4
Rehnu	Tucson, AZ, USA	HCPV	Dish reflector	<0.1
Renovalia	Madrid, Spain	HCPV	Dish reflector	<0.1
Pyron Solar	Vista, CA, USA	1,200	Lens, carousel	<0.1
Heliotrop	Lyon, France	1,024	Lens, pedestal	<0.1
Spirox	Hsinchu City, Taiwan	HCPV	Lens, pedestal	<0.1
Suncore Photovoltaic Technology	Huainan, China	HCPV	HCPVT	<0.1
SunOyster System	Hamburg, Germany	1,000	HCPVT with parabolic mirror and linear lens	<0.1
Airlight Energy	Biasca, Switzerland	600	Reflective dish	
Alitec	Navaccio, Italy	500, 1090	Lens, pedestal	
Becar-Beghelli**	Italy	HCPV	Reflective	
Cool Earth Solar	Livermore, CA, USA	HCPV	Inflated mirrors	
GreenField Solar	Cleveland, Ohio, USA	HCPV	Reflective	
Heliocentric	San Jose, CA	HCPV	Parabolic, reflective dish	
Morgan Solar	Toronto, ON, Canada	HCPV	Planar lens, pedestal	
Sahaj Solar	Gujarat, India	500	Lens, pedestal	

Semprius	Durham, NC, USA	>1,000	Microlens	
Sharp	Japan	CPV	Lens, pedestal	
SolarTron Energy Systems	Nova Scotia, Canada	1,000	Reflective dish, dense array	
Solergy	Piedmont, CA, USA	>500	Cone concentrator. CPV and CPV + thermal energy systems, BICPV	
STACE (Saint-Augustin Canada Electric Inc.)	Saint-Augustin, Canada	HCPV	Lens, pedestal (former Soitec technology)	
Sun Synchrony	Vallejo, CA, USA	HCPV	Miniaturized reflectors	
SunCycle	Eindhoven, Netherlands	540	Rotating lens/mirror (internal tracking)	
SunFish	Denbighshire, UK	HCPV	Heliostat, hybrid PV and thermal	
TianJin Lantian Solar Tech	China	HCPV		
Valldoreix Greenpower	Valldoreix, Spain	800	Lens	
ZettaSun	Boulder, CO, USA	Up to 1,000	Lens, internal tracking, rooftop	

*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.
*** Includes installations of Daido Steel.

Table 7: Summary of LCPV module companies. Companies in gray either seem to have moved away from CPV or are in the process of restructuring their CPV business. Sometimes companies have reentered the business, so are retained in the table with the possibility that their technology may return.

Company	**Location (HQ)**	**Conc.***	**Type of System**	**Installed Capacity [MW]**
SunPower	San Jose, CA, USA	7	Linear reflective trough, c-Si cells	8.0
Abengoa Solar	Madrid, Spain	2-4	Mirror	1.3
Absolicon Solar Concentrator	Harnosand, Sweden	10	Reflective through, Si cells, thermal hybrid	0.1
Whitfield Solar	UK	40	Fresnel lens, c-Si cells	<0.1
Banyan Energy	Berkeley, CA, USA	10	Total internal reflection optics, c-Si cells	
GreenField Solar	Cleveland, Ohio, USA	MCPV	Reflective	
IDHelio	France	50	Fresnel mirror, hybrid PV and thermal	

Line Solar	Netherlands	LCPV		
Pacific Solar Tech	Fremont, CA, USA	Multiple	Dome lens, c-Si cells	
Stellaris	North Billerica, MA, USA	3	Static, “See-through” PV window tiles, c-Si cells, building-integrated CPV	
Sunengy	Sydney, Australia	LCPV	Fresnel, c-Si cells, module floats on water	
Sunseeker Energy	Schindellegi, Switzerland	LCPV	Lens	
Zytech Solar	Zaragoza, Spain	4, 120	Prismatic lens, c-Si cells	

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