Chapter 2
The Case for CPV

The energy-generating potential of photovoltaics is huge—but it does suffer from some practical challenges, particularly related to the required size of generating installations. The solar resource is quite dilute, which means that a photovoltaic power plant needs to occupy a very large area compared to conventional power plants to generate a given amount of output. The amount of space required depends inversely on the efficiency of the solar panels—so a power plant of say, 100 MW that uses panels with 20% efficiency will occupy 25% less space than a plant of the same capacity using panels of 15% efficiency.

As we saw in the last chapter, Si technology, while extremely low in price, is nearing the physical limits of its efficiency potential. CPV has tried to circumvent that by enabling the use of much higher efficiency solar cells which cost a hundred or more times as much as Si cells. Any thorough discussion of CPV needs to start with an understanding of these cells, their operating mechanism and limits, and the forces that led to their development.

2.1 Operating Principles and Limits of Solar Cells

Photovoltaic cells work by absorbing the energy of solar photons to excite electrons in a semiconductor (for in-depth discussion, see, for example, the texts by Nelson or Green on solar cell physics [1, 2]). The basic mechanism is illustrated in Fig. 2.1. A basic solar cell is an extremely simple device—a p-n junction. One of the two main layers, usually the p-type, is much thicker than the other and acts as the "absorber." Incident photons travel through the absorber until they are absorbed by an interaction with an electron. When an electron absorbs a photon, it is excited from the valence band of the absorber into the conduction band, creating a pair of free charge carriers—the conduction band electron and the valence band hole left in its place. The built-in electric field of the p-n junction then separates the

H. Apostoleris et al., *Concentrating Photovoltaics (CPV): The Path Ahead*,
Green Energy and Technology, DOI 10.1007/978-3-319-62980-3_2

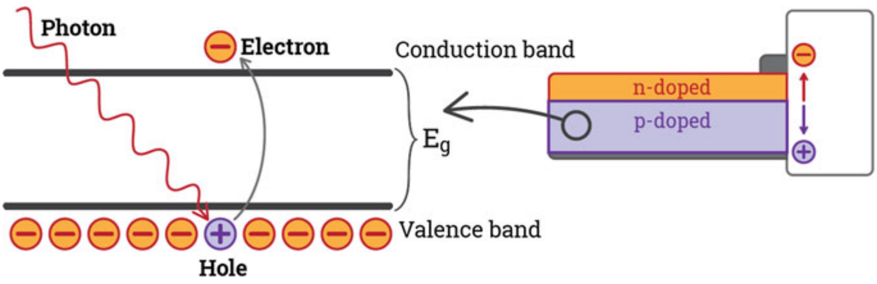
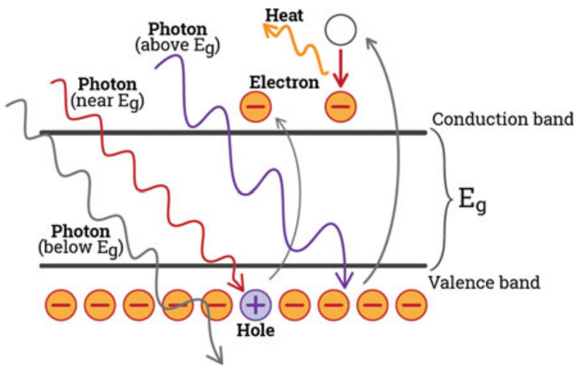


Fig. 2.1 The operating principle of a photovoltaic cell: valence-band electrons in a semiconductor are excited to the conduction band by the energy of incident photons. Conduction band electrons and valence band holes are separated by a PN junction, causing current to flow through the external circuit

Fig. 2.2 Interaction of photons of different energies with a PV cell: photons with energy below the band gap are transmitted; those with energy above the band gap create a carrier pair by promoting an electron, but the difference between the photon energy and the band gap becomes heat



electron-hole pair and drives them into the external circuit, where electrons flow in one direction and holes in the other, producing an electric current.

This extremely basic picture of solar cell operation is sufficient to explain the strongest limits on solar cell efficiency. The critical understanding is how the solar cell interacts with photons of different energies. This is shown in Fig. 2.2. The band gap of the absorber acts as a threshold energy that determines what happens to the energy of an incident photon. First, an electron can only cross the band gap if it absorbs a photon whose energy is greater than the band gap energy E_g. Photons with energy less than E_g do not create carrier pairs, and typically pass through the solar cell entirely to be transmitted out the back side (or absorbed by the back contact). A photon whose energy is higher than E_g can be absorbed, transferring all of its energy to the electron. What happens next also depends on the photon energy. If the photon has energy very close to E_g, the electron is excited to the bottom of the conduction band and essentially all of the photon energy is transferred to the carrier pair. However if the energy is significantly higher than E_g, the electron will be promoted to a higher-energy region of the conduction band. The electron will then seek to minimize its energy by relaxing, very quickly, to a lower-energy state near the conduction band edge. The difference between the photon energy and the band gap energy is dissipated as heat into the solar cell. This energy is not carried by the extracted current and represents a *thermalization loss*.

These two mechanisms—below band gap transmission and above band gap thermalization loss—are the two biggest factors that fundamentally limit the efficiency of an ideal solar cell [3]. There are other fundamental losses, related to recombination of carrier pairs inside the cell, and the mismatch in the entropy carried by light inside and outside of the cell [4]. These will be touched on later, incidentally, but not belabored except where they are directly relevant to the subject under discussion. Because of the combination of these factors, the ultimate limit for a solar cell with a single absorber material—a so-called "single-junction" device—is only 33% at the optimum value of the band gap (about 1.5 eV), and declines further for values of E_g far from this optimum. When accounting for its band gap and additional fundamental loss mechanisms specific to the material, silicon solar cells can be shown, as we noted in the previous chapter, to be limited to 29% efficiency [5]. This value has nearly been reached in the laboratory and the efficiencies of commercial panels continue their climb toward something near these experimental records [6, 7]. In order to go beyond this, different cell technologies are needed.

2.2 Solar Cells to Match the Solar Spectrum

The basic problem of photovoltaic efficiency can be considered in the following way: we are trying to capture a resource with a broad spectrum using a device with a narrow spectral response. Solar photons are distributed over a range of about one order of magnitude in energy. A solar cell, as we have seen, functions best when incident light is as close to its band gap—a single energy—as possible. In order to fully utilize the resource using a photovoltaic converter, we need to broaden its spectral response to match the incoming spectrum of light. This is the concept of so-called "third-generation photovoltaics." [8]

One strategy has come to dominate the push for high-efficiency PV. It grows from the observation from the last section that solar cells are typically transparent to below-E_g radiation. This means that if a second collector—a solar cell, thermal absorber or anything else that might be useful—is added behind the solar cell, the sub-E_g radiation will be collected by this second device rather than the solar cell. This is the key insight that led to the development of the multijunction solar cell. If a number of solar cells are stacked, from top to bottom, in decreasing order of absorber band gap, the incident light will be divided into smaller bands, defined by the band gap energies of the solar cells. Fig. 2.3 illustrates this for a typical combination of band gaps—each cell spontaneously "filters" the above-E_g light for electricity production and transmits the below-E_g to the cell below. This avoids the need for balancing between below-E_g loss and thermalization loss. Multijunction cells offer huge efficiency gains over single-junction: as of this writing the record

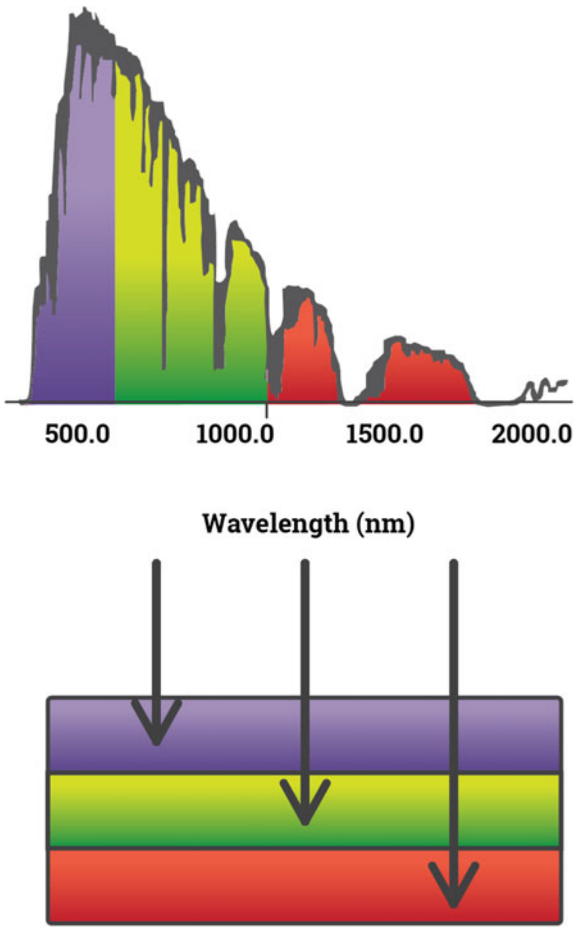


Fig. 2.3 Division of the solar spectrum by a multijunction cell

efficiency of a multijunction cell was just below 39% under unconcentrated sunlight [9] and 46% under light concentrated about 300 times [10]. For comparison, the best-ever single-junction cell is "only" 28.8% [11, 12].

The first key to making this kind of cell is to find combinations of photovoltaic materials with the correct band gaps or ideally, a single family of materials whose band gap can be tuned across the desired range by varying their composition. Several of these material families, in fact, exist. The best-performing and most widely used of these is the III-V alloys—combinations of at least one materials from the III column of the periodic table with at least on from the V column—in particular Ga, In, As, and P in various combinations [13, 14]. While these materials have excellent optoelectronic properties and make high-quality solar cells, they are both extremely expensive due to the scarcity of some of these elements, and require advanced processing techniques to make high-quality solar cells [13, 14]. As a result these cells are more expensive than Silicon cells by a factor of a few hundred.

For this reason these cells have only two practical applications—aerospace, where the cost of solar cells is a secondary concern, and CPV, where concentration allows the cost to be offset by reducing the cell area by 500 times or more. But this imposes its own constraints.

At this point it is worth considering in a bit more detail why it is helpful to have high-efficiency PV cells at all.

2.3 Why Do We Care About High Efficiency?

The high efficiency of multijunction cells makes them enticing to both researchers and manufacturers looking to reach the 30–40% efficiency range that is well beyond the reach of silicon. But what, really, is the value of high efficiency? In research, efficiency is the standard by which all cells are measured. In real-world deployment the value is more dubious. Experts rightly warn against being an "efficiency snob" when selecting solar panels, instead putting the emphasis on cost and reliability (as one would with any other consumer product!) [15]. This is an important caveat for researchers as much as consumers, that advises us against such crazy schemes as trying to overturn the whole PV manufacturing sector by, say, switching from Si to some new material, for the sake of gaining a few points of efficiency. So we should be clear, if we do insist on chasing efficiency, regarding what exactly it is good for.

The basic idea of increasing efficiency is "getting more from less." But what are we trying to use less of? There are two main perspectives to take. One is that we want to use less hardware—fewer solar panels, less racking and mounting material, a smaller number of electrical connections, lower expense in terms of time and money to install. Ultimately this is an argument based on **cost**. We try to get the maximum out of each piece of hardware because we don't want to pay for an extra piece. If hardware and installation cost nothing, or at least if other concerns are more pressing, we don't care so much about optimizing the output of each piece. This scenario would lead to the second perspective: that we are trying to get as much energy as possible from a given amount of **space**. This is relevant on a rooftop or any residential setting, where the guiding question is "can I fit the PV system that I need into the space that I have?"

From a commercial perspective, CPV needs to address one of these needs in order to be useful. Does it?

To answer this we need to look into the unique physical and economic constraints that apply to concentrator systems.

2.3.1 Concentrator Physics: Fundamental Limits of CPV

The thermodynamics of optical concentration have been dealt with rigorously since the 1970s [16]. The basis for this investigation is the principle of etendue conservation: *for any optical system, the product of the spatial extent (beam cross-section or width) and angular extent of the propagating light cannot be decreased*. The consequence of this law is that any concentrator—a system that reduces the spatial extent of light—must have a limited *acceptance angle* (θ_A), or maximum incidence angle which can be concentrated onto the target. An ideal thermodynamic concentrator, which concentrates light in two dimensions, is limited by the fundamental concentration limit

$$C = \left(\frac{1}{\sin(\theta_A)}\right)^2$$

In order to make multijunction cells economically feasible, CPV systems concentrate light by more than 500x, and some systems even reach 1000 times. In commercial systems sub-ideal concentrators based on Fresnel lenses are used for the sake of compactness; however, this reduces the acceptance angle even further below the thermodynamic limit. This is effective at minimizing cell-related costs, but it raises two additional challenge: a requirement of precise sun-tracking, and of mismatch between the light coming from the sun and the acceptance of the concentrator.

Sun tracking is essential for CPV: since the sun (apparently) moves across the sky, and high-concentration optics have an acceptance angle in the range of 1–2° [17], the system must undergo some movement or modification in order to maintain the sun in the acceptance cone of the optics. This is presently achieved by mechanical means: the entire system or module is rotated to maintain normal orientation towards the sun [18]. In some systems that use only low concentration and concentrate light in only one dimension, tracking along a single axis is sufficient; however, for the high-concentration systems that we are primarily discussing here, two axis tracking is used. Because the acceptance cone is small, this tracking must be quite precise, and this requires a heavy piece of machinery which adds a substantial expense. In addition to the cost a conventional tracker is much too bulky and heavy to be used in most residential settings, limit CPV to large-scale fields. This takes CPV out of the running for rooftop installations, where high efficiency would be most useful.

In addition to this, there is a complication in system design that comes from using two-axis trackers. In a field where many CPV modules with trackers are installed, modules tend to shade each other, blocking light from the modules behind them as they rotate. Because a module consists of many cells connected in series, blocking one or two cells may substantially reduce the output of the entire module. Therefore shading should be avoided as much as possible. For this reason trackers are spaced out widely in a commercial installation, meaning that only a small fraction of the land is used to collect light. Shading is avoided when the sun is low, but when it is high most of its light falls on the ground between modules and it lost. Thanks to this spacing, a typical CPV installation does not actually save much space, per unit output, compared with flat-plate, and depending on how widely spaced the modules are, may even require more space! [19]

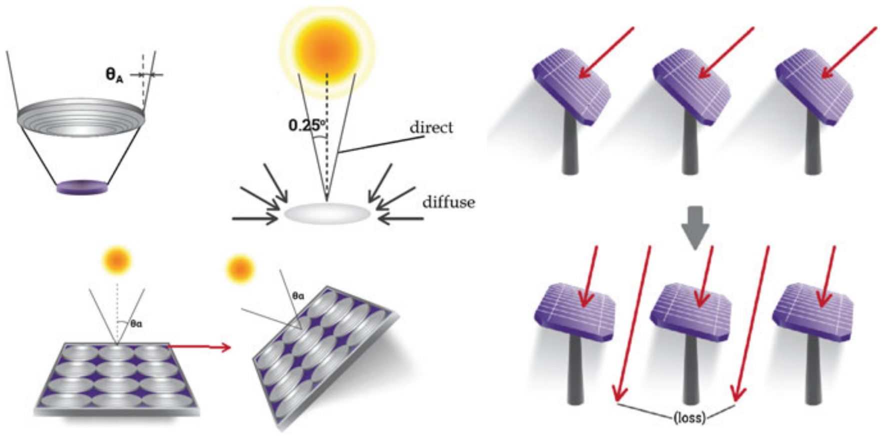


Fig. 2.4 Consequences of restricted acceptance angle in concentrators: since light incident outside the acceptance angle cannot be concentrated, diffuse light is lost and the concentrator must track the sun. To prevent panels from shading each other they are widely spaced, which means that most light incident at midday falls on the ground between the trackers and is lost

Finally, the acceptance angle of the concentrator is under many conditions not well matched to the angular profile of the incident sunlight. The "mismatch" between the incident light and the concentrator acceptance comes from the fact that much of the light coming from the sun is diffused by interactions with particles in the atmosphere. This diffuse light, falling outside of the concentrator's acceptance angle, cannot be concentrated and therefore is lost. So a concentrator actually has access to less light than a flat-plate collector under the same conditions Fig. 2.4.

2.3.2 CPV Economics

If CPV is not so useful as was hoped at reducing the size and space requirements of PV installations, can it reduce costs? That is, after all, what it was primarily designed for.

For an idea of this we can look to a recent NREL analysis of CPV module costs [20]. This study put cell-related costs in a 500X CPV module at roughly the same level, per Watt of output, as cell costs in a standard, non-concentrating module, but the high-concentration optics increase the module cost by nearly $0.20/W. The analysis put the minimum sustainable price of a CPV module at $0.77/W, far above the average market price of PV modules at the time ($0.57/W) [6]. And this is only part of the story. High-precision two-axis trackers impose an additional cost of greater than $0.30/W Fig. 2.5.

What does this mean for the economics of CPV?

The current cost given by NREL to install a large-scale PV power plant, including mounting, power conditioning equipment and installation costs, averages

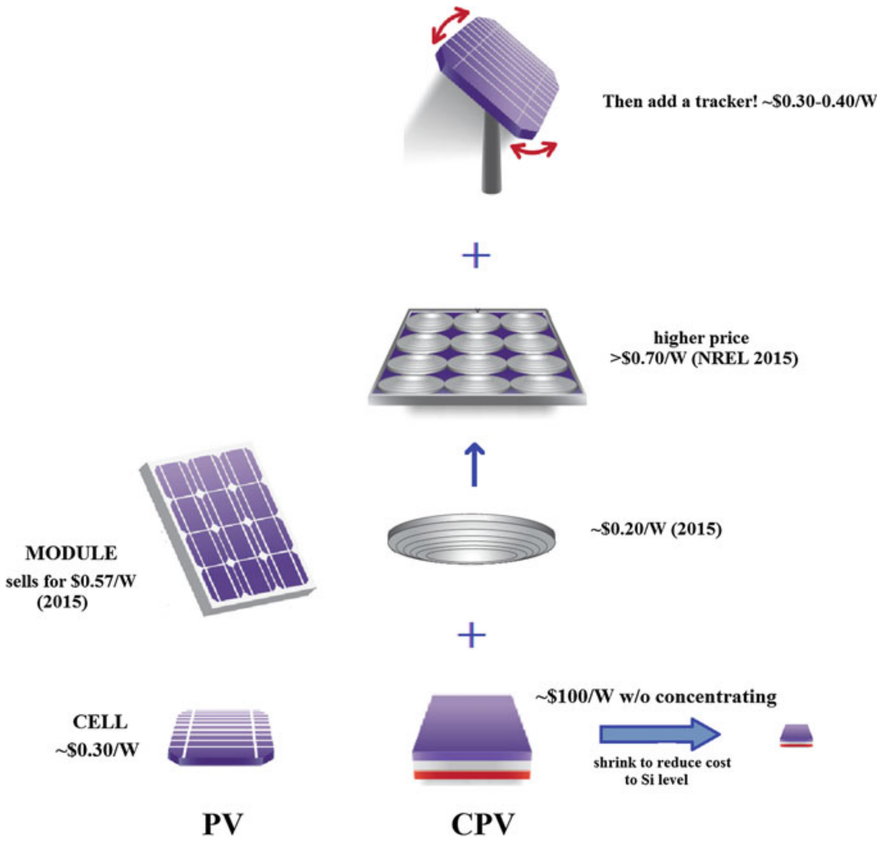


Fig. 2.5 Cost components of CPV versus flat-plate PV. Estimated module costs are somewhat higher for CPV due to the need for high-quality optical materials, and two-axis tracking adds a cost on top of the module that is not present for flat-plate

just under $1.50/W, and is coming down. [21] Pricing estimates for CPV systems are more difficult to come by due to the much smaller size of the market and lack of standardization. However we can get some idea just by naively considering the cost components described above—which represent the difference between CPV and a conventional system. Adding the cost of the tracker and the additional optics-related module cost represents a premium of about $0.50/W to use CPV rather than flat-plate—more than a 30% markup! The PV sector is very price sensitive, with aggressive bidding wars and resultant price reductions driving who gets business and who goes out of business. Add to this that flat-plate PV, as we have seen, is a mature technology riding a smooth learning curve to ever-lower costs as it scales [22]. CPV, as a cost-saving proposition, seems to be dead on arrival.

So what remains?

If we believed CPV were truly dead we would not be writing a book about it! The fact is that the problems we have outlined have been recognized by many researchers and a wide array of creative technological solutions have been proposed. These form the basis for taking bold new approaches to CPV to finally make concentrator technology into affordable PV products, to satisfy niches in the large and growing solar energy market that would otherwise be left unfilled. CPV, we believe, is far from dead; it has simply falle out of step with the realities and needs of today. With appropriate development, CPV can be an extremely versatile technology which opens new dimensions of design space for developing innovative products. The keys to realizing this potential lie in the pages of optics journal, unused patents and overlooked startups. Our purpose here is to collect these bits of creative technological invention and piece them together in new ways that better fit today's economic realities.

The technological components can be broken down into three: cells, optics and tracking. In each area there are exciting developments that, taken together, sketch out a framework for a new CPC paradigm. The three chapters that follow will highlight the themes and innovations in each area, and weave them into a bigger picture that will give context and ground for the main goal of this book—reimagining CPV.

References

1. Nelson, J. (2003). *The physics of solar cells* (Vol. 57). World Scientific.
2. Green, M. A. (1982). Solar cells: operating principles, technology, and system applications.
3. Shockley, W., & Queisser, H. J. (1961). Detailed balance limit of efficiency of p-n junction solar cells. *Journal of Applied Physics, 32,* 510–519.
4. Hirst, L. C., & Ekins-Daukes, N. J. (2011). Fundamental losses in solar cells. *Progress in Photovoltaics: Research and Applications, 19,* 286–293.
5. Kerr, M. J., Cuevas, A., & Campbell, P. (2003). Limiting efficiency of crystalline silicon solar cells due to Coulomb-enhanced Auger recombination. *Progress in Photovoltaics: Research and Applications, 11,* 97–104.
6. Barbose, G. L., & Darghouth, N. R. (2016). Tracking the Sun IX: The Installed Price of Residential and Non-residential Photovalic Systems in the United States (Washington: US Department of Energy). *available at emp. lbl. gov/publications/trackin*.
7. Green, M. A., et al. (2017). Solar cell efficiency tables (version 49). *Progress in Photovoltaics: Research and Applications, 25,* 3–13. doi:10.1002/pip.2855.
8. Green, M. A. (2001). Third generation photovoltaics: Ultra-high conversion efficiency at low cost. *Progress in Photovoltaics: Research and Applications, 9,* 123–135.
9. Chiu, P. et al. (2014). In *Photovoltaic Specialist Conference (PVSC), IEEE 40th.* 0011–0013 (IEEE).
10. Fraunhofer, I. S. E. (2014). New world record for solar cell efficiency at 46%. Press release.
11. Kayes, B. M. et al. (2011). In *Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE.* 000004–000008 (IEEE).
12. Green, M. A., Emery, K., Hishikawa, Y., Warta, W., & Dunlop, E. D. (2015). Solar cell efficiency tables (Version 45). *Progress in Photovoltaics: Research and Applications, 23,* 1–9.
13. Bett, A., Dimroth, F., Stollwerck, G., & Sulima, O. (1999). III-V compounds for solar cell applications. *Applied Physics A, 69,* 119–129.

14. Bauhuis, G., Mulder, P., Haverkamp, E., Huijben, J., & Schermer, J. (2009). 26.1% thin-film GaAs solar cell using epitaxial lift-off. *Solar Energy Materials and Solar Cells, 93,* 1488–1491.
15. Murphy, T. (2011). *Don't be a PV Efficiency Snob* https://dothemath.ucsd.edu/2011/09/dont-be-a-pv-efficiency-snob/.
16. Winston, R., Miñano, J. C., & Benitez, P. G. (2005). *Nonimaging optics*. Academic Press.
17. Shanks, K., Senthilarasu, S., & Mallick, T. K. (2016). Optics for concentrating photovoltaics: Trends, limits and opportunities for materials and design. *Renewable and Sustainable Energy Reviews, 60,* 394–407.
18. Mousazadeh, H., et al. (2009). A review of principle and sun-tracking methods for maximizing solar systems output. *Renewable and Sustainable Energy Reviews, 13,* 1800–1818.
19. Ong, S., Campbell, C., Denholm, P., Margolis, R., & Heath, G. (2013).Land-use requirements for solar power plants in the United States. *Golden, CO: National Renewable Energy Laboratory* **140**.
20. Horowitz, K., Woodhouse, M., Lee, H., & Smestad, G. (2015). Bottom-Up Cost Analysis of a High Concentration PV Module; NREL (National Renewable Energy Laboratory). (NREL (National Renewable Energy Laboratory (NREL), Golden, CO (United States))).
21. Fu, R. et al. (2016). US Solar Photovoltaic System Cost Benchmark Q1 2016. (NREL/PR-6A20-66532. Golden, CO: National Renewable Energy Laboratory (NREL)).
22. Swanson, R. M. (2006). A vision for crystalline silicon photovoltaics. *Progress in Photovoltaics: Research and Applications, 14,* 443–453. doi:10.1002/pip.709.

http://www.springer.com/978-3-319-62979-7

Concentrating Photovoltaics (CPV): The Path Ahead
Apostoleris, H.; Stefancich, M.; Chiesa, M.
2018, VIII, 68 p. 24 illus. in color., Hardcover
ISBN: 978-3-319-62979-7