Introduction

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Abstract Concentrating photovoltaics (CPV) is an alternative to flat-plate module to produce cost-competitive electricity. It is based on the use of an optical system of decreased cost that is able to concentrate solar light on a very small surface (high-efficiency solar cell). It has numerous benefits such as greater energy density, greater efficiency, and lower surface and lower semiconductor material requirements. Nevertheless, some technical and economic barriers must be removed to decrease the electricity production costs using this technology and to make it really cost-competitive. In the past years, researchers in CPV technology have experimented with important technological advances that are mainly focused on the increase the high-efficiency solar cells. Recently, a four-junction solar cell, with an efficiency of 44.7 % under 297 suns and the expectations to reach 50 % in next years, has been developed. Despite such technological advances, CPV technology has a marginal position in the photovoltaic market and must show, even still, a long-term reliability similar to the flat-plane PV module to improve its position in the market. Some arguments could explain this situation: the high competition of the flat-plane PV, the lack of CPV-module testing methods and standards, and the lack of trust of private sector investors. For CPV technology to gain momentum, it is necessary to continue economical and technical support of development and testing of pilot projects to show long-term reliability and achieve a better understanding of the CPV technology performance, which would result in greater confidence of the private sector.

1 Introduction

From the beginnings, CPV technology appeared like a real alternative to flat-plate modules to produce cost-competitive electricity to concentrate the solar light on a very small surface (high-efficiency solar cell). Its benefits are clear: greater energy

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P. Pérez-Higueras and E.F. Fernández (eds.), *High Concentrator Photovoltaics*,
Green Energy and Technology, DOI 10.1007/978-3-319-15039-0_1

density, greater efficiency, and lower surface and semiconductor areas. Comparing its position on the learning curve of flat-plate modules, CPV technology is further behind. Taking into account the continuous increase of solar cell efficiency, CPV technology shows an extremely high potential for a decrease in cost. Nevertheless, linked to these advantages there appear to be some technical barriers that must be eliminated to dramatically decrease electricity-production costs.

When light falls onto a monojunction solar cell, only photons with energy greater than the band gap energy are able to break covalent bonds to create electron-hole pairs, which are separated by the device structure and produce electrical current. This current can be used to power an electric circuit. Photons with lower energy cannot produce more electricity. Multijunction (MJ) solar cells try to eliminate such losses by having various subcells placed of different semiconductor material, and, thus they have a different band gap energy. The subcell placed on the top has the greater band gap energy, and the rest of the subcells are ordered by decreasing band gap. In this sense, spectrum solar range used to produce electricity is wider [1, 2] and the efficiency increases.

The efficiency of MJ solar cells increases with the number of cells that form the stack, but this increase is less each time the overall number of cells increases [3]. In practice, MJ solar cells are limited to five or six subcells, and, in fact, the best results are obtained with triple-junction monolithic solar cells.

Concerning the optical concentrator, it can be simple, or it can consist of primary and secondary optical devices. The primary optical device collects and concentrates direct normal irradiation (DNI), and the secondary optical device distributes light uniformly across the solar cell. The use of a secondary optical device allows an increase of the uniformity of the DNI, thus improving the performance of the system [4, 5]. Currently, research lines are focused to improve the design to decrease the nonuniformity on different subcells [6]. Different optical concentrators are currently being used (parabolic dishes, Fresnel lenses, linear parabolic reflectors, etc.), but most of the CPV systems use optical devices based on Fresnel lenses [7].

In the past years, researcher in CPV technology has experimented with important technological advances mainly focused on two research lines: (1) the increase of high-efficiency solar cells; and (2) the improvement of optical concentrators.

Concerning solar cells, Table 1 shows the evolution of efficiency records from previous years. A relative increase in efficiency, nearly 20 %, has been seen in only 10 years. It is worth mentioning that on 2013, the Sharp Company reached an efficiency of 44.4 % with a three-junction (InGaP/GaAs/InGaAs) solar cell under 302 suns, and Fraunhofer Institute reported an efficiency of 44.7 % with a four-junction (GaInP/GaAs/GaInAsP/GaInAs) solar cell under 297 suns. The efficiency of MJ solar cells not only is the highest in PV technologies, but also there is an expectation to obtain 50 % in following years [8, 9].

These results join together some intrinsic advantages of CPV technology—such as the decrease of solar cell material requirement for the same capacity, lowers balance-of-system costs (BOS), greater energy density, decreased land costs—all of which make this technology very attractive for massive electricity production.

Table 1 Evolution of the indoor efficiency record for 2003–2013

Date	Type of cell	Suns	Efficiency (%)
Q4 2003 [10]	GaInP/GaAs/Ge (2 terminals)—spectrolab	309×	36.9
Q4 2004 [11]	GaInP/GaAs/Ge (2 terminals)—spectrolab	175×	37.3
Q4 2005 [12]	GaInP/GaInAs/Ge (2 terminals)—spectrolab	236×	39.0
Q4 2006 [13]	GaInP/GaInAs/Ge (2 terminals)—spectrolab	179×	39.3
Q4 2007 [14]	GaInP/GaInAs/Ge (2 terminals)—spectrolab	240×	40.7
Q4 2008 [15]	GaInP/GaAs/GaInAs (2 terminals)—NREL	140×	40.8
Q4 2009 [16]	GaInP/GaInAs/Ge (2 terminals)—spectrolab	364×	41.6
Q4 2010 [17]	InGaAp/GaAs/InGaAs (2 terminals)—spire	406×	42.3
Q4 2011 [18]	GaInP/GaAs/GaInNAs (2 terminals)—solar junction	418×	43.5
Q4 2012 [19]	InGaAp/GaAs/InGaAs (monolithic)—sharp	306×	43.5
Q4 2013 [20]	InGaP/GaAs/InGaAs (monolithic)—sharp	302×	44.4
Q4 2013 [21]	GaInP/GaAs//GaInAsP/GaInAs—(Fraunhoffer institute)	297×	44.7

However, despite such technological advances, CPV technology must show, even still, a long-term reliability similar to that of the flat-plane PV module to consolidate a stronger market position.

In the present context—in which the price of conventional crystalline silicon PV modules has decreased sharply from €3.5/W to €0.5/W [22], which is linked to the absence of a small- to medium-size application market, which would in turn facilitate CPV technology to reach a maturity—it is complicated to think about CPV obtaining a solid position in terms of market penetration during the short term. In fact, CPV technology has marginal participation in the global PV market. According to the European Photovoltaic Industry Association (EPIA), the total PV power installed in 2012 was approximately 102 GW, of which only 100 MW can be attributed to CPV technology. These figures show a share participation of <0.1 % [23]. Despite very limited market share, it is worth mentioning that at the end of 2013, the total power of CPV technology was approximately 160 MW [24, 25], which represents a 60 % increase compared with the previous year. The following three arguments could be made for this situation.

Argument No. 1

The first argument is the low cost, the very well-known good reputation, and the highly reliable technology of the flat-plane PV. In fact, in the last 10 years, the market penetration of PV has increased greatly worldwide. Such technology has shown a high degree of maturity and has earned PCV the confidence not only of public institutions but also of private companies regarding its capacity to produce cost-competitive electricity.

Trying to obtain the present privileged position of flat-plane PV has not been easy, and it has required an enduring collaboration of many actors (governmental bodies on both national and local levels, decision makers, private companies, electric utilities, national government organizations, etc.) that were able to launch a wide variety of promotional strategies and dissemination programmes worldwide. In fact, in past years, economies of scale have been a key factor in the sharply decreased the costs of flat-plane PV, and CPV must be able to follow a steeper learning curve [26]. So, for a relatively novelty technology such as CPV to compete in such scenario assumes the facing of manifold challenges.

The use of CPV has numerous benefits such as greater energy density, greater efficiency, and needs for lower surface and semiconductor material requirements, thus resulting in a decrease of the associated costs. Nevertheless, additional costs are needed due to use of optical devices, lenses, trackers, and operation and managements costs, etc. Therefore, it is necessary to remove some technical and economic barriers to decrease the electricity production costs using this technology and to make it truly competitive in the marketplace.

Argument No. 2
The second argument is the lack of CPV-module testing methods and standards [27, 28]. Many years ago, numerous domestic and international consensus standards (IEC 61215, IEC 60904, IEC 61853, etc.) were developed for the design qualification and type approval of terrestrial crystalline silicon for the rating of flat-plane photovoltaic modules under different meteorological conditions, etc. Therefore, based on the use of such testing methods and standards, it is possible to study and compare the performance of different module types and to accurately predict how much energy a PV module will deliver under real meteorological conditions during a specific period of time. This information has been used by government bodies, prospective owners, private companies, etc., to study by means of classical investment analysis in order to project the profitability of PV projects and to analyze the "bankability" of this technology. In general, all of the standards published and elaborated by the International Electrotechnical Commission and different International Organizations (National Renewable Energy Laboratory, ASTM International, Institute for Environmental Protection and Research, etc.) that are relevant for photovoltaics have been well accepted for the PV market. Ultimately, they have contributed to increase the confidence in PCV technology and to pave and make easier the development of PV. In CPV technology, the present situation is far from here, and it can be characterized by a lack of testing methods and standards for rating and studying the performance of CPV modules.

A short time ago, the International Electrotechnical Commission published the first part of IEC-62670 standard [29], which defines standard test conditions under which suppliers must measure the CPV system and deliver the main electrical parameters of CPV modules. The second and third part of this standard was not published until date [30]. Both parts will define the procedure to evaluate generated energy and determine the performance ratio of CPV plants. The lack of standards for CPV modules to analyze CPV modules performance under different meteorological conditions is one of the most important technological barrier, and it would be necessary to remove it as soon as possible to drive the sector to take off.

Argument No. 3

Finally, the third argument is the lack of trust of private sector investors in a relatively new technology that must show a long-term reliability. In this sense, it is necessary to develop a methodology that permits anlaysis of the bankability of CPV projects to decrease the risk of investing in them. Such a methodology would be based on the evaluation of the real performance of a CPV through on-site experimental campaigns [31, 32]. The conducting of experimental campaigns would allow development of a database to deeper analyze CPV performance and to forecast energy production over the long term. An accurate prediction of the energy production of a CPV plant would increase investors confidence in this technology. Table 2 shows some of the strengths, weaknesses, opportunities, and threats (SWOT diagram) to high-CPV technology [33, 34].

Forecasting the evolution of the market for a new technology is a complex issue mainly due to the lack of historical data and because of rapid advances that occur during the first stages of development. In addition, this evolution will be dependent on other factors such as the economic crisis, support programs implemented by several countries, etc. However, the increase forecasts for CPV technology are optimistic, and numerous technical reports have predicted a rapid increase of the global market share [35–37]. To achieve this goal, a crucial issue will be not only to continue the economical and technical support of development and testing of pilot projects but also to foster the installation of multi-MW PV plants. In this way, it will provide establishment of quality, safety, and reliability standards as well as a better understanding of CPV technology performance under real meteorological

Table 2 SWOT diagram for HCPV technology

Strengths	Weaknesses
• High efficiency • Modularity and scalability • Mature technology • Several pilot MW plants installed • Widely used materials (steel, glass, aluminum, plastics) • High-energy yield (kWh/kWp) for high-DNI locations • Low LCOE for high DNI locations • Smaller area per MW than flat plate	• Only suitable for locations with high DNI • Not suitable for building integration • Need for high-accuracy tracking • Higher cost per Wp • Low production and installed capacity • Long-term reliability not proven • Few years of field performance data • Lack of standardization of power rating or system acceptance criteria
Opportunities	**Threats**
• Market emergence of utility-scale projects • Specific political incentives • Perceived as a distinctive technology • Green/local job creation policies • More cost decrease potential than CSP plants • Lower maintenance cost than CSP plants	• Perceived technology risk • Decreasing costs of flat-plate • Perceived high cost • Bankability • Energy storage is easier in CSP plants

LCOE levelised cost of electricity; *CSP* concentrated solar power

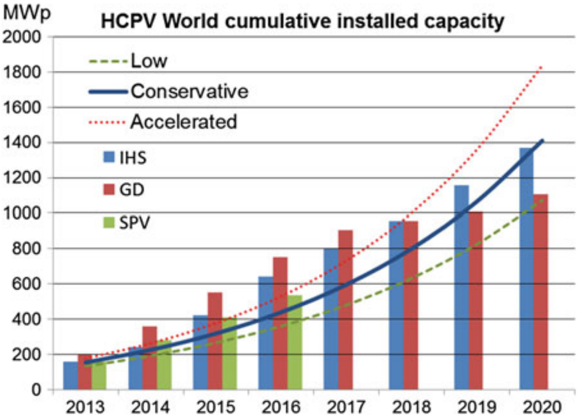

Fig. 1 Market forecast performed by three private companies: GD, and SPV. The forecast of HCPV world cumulative capacity is based on three scenarios: 1 a base case with annual growth of 30 % (*conservative*), 2 a pessimistic case with annual growth of 27 % (*low*), and 3 an optimistic case with annual growth of 33 % (*accelerated*) [39]. solar solution; *GD* Global data; *SPV* SPV market research

conditions. The undertaking of large projects, such as the installation of 44-MW CPV in South Africa or a 50-MW CPV in China, shows the path we must take to allow CPV technology to really gain share in the marketplace [38] (Fig. 1).

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