Executive Summary (1 page)

This proposal has been a coordinated effort between the European Commission and Japanese NEDO in order to advance in the science and technology of concentrator photovoltaics (CPV). Research has covered all relevant areas in CPV, from multi-junction solar cells to CPV systems, including modules, lenses, thermal dissipation, rating, round robin schemes, development of characterization tools for cells, modules and systems (outdoor and indoor), the use of nanostructures, reliability and modeling at all the stages of the CPV chain.

European partners have comprised: 1) Universidad Politécnica de Madrid (UPM, Spain, Coordinator of the European Consortium); 2) the Fraunhofer-Gesellschaft zur Foerderung der angewandten Forschung e.V. (FhG-ISE, Germany); 3) Imperial College of Science Technology and Medicine (ICSTM, UK); 4) ENEA (Italy); 5) BSQ Solar (Spain); 6) PSE (Germany) and 7) CEA-INES (France). Japanesse partners have comprised: 1) University of Tokyo (Coordinator of the Japanese Consortium); 2) Toyota Technological Institute (TTI); 3) AIST; 4) SHARP; 5) Daido Steel; 6) University of Miyazaki; 7) Asahi Kasei; 8) Kobe University and 9) Takano Co. Ltd.

In the field of solar cells, for example, SHARP has reported a 3J multi-junction solar cell with an efficiency of 44.4 % @ 246-302 AM1.5 D ASTM G173-03 1000 W/m2 suns and 37.9 % at one sun as independently measured by FhG-ISE. Progress beyond state of the art of multi-junction solar cell has been pursued by investigating growth on silicon (Asahi Kasei, University of Miyazaki) and the achievement of a novel 4^{th} junction solar cell (FhG-ISE). Moreover, GaAsN (TTI, University of Miyazaki) and multiple quantum well (ICSTM, FhG-ISE and U. of Tokyo) solar cells have been investigated. Solar cells based on quantum dots (intermediate band solar cells) have demonstrated below bandgap two-photon absorption [U. of Tokyo & Instituto de Energia Solar (IES) at UPM]. The experimental techniques developed within the project have allowed also to spectrally resolve this absorption for the first time.

Investigation in modules has allowed for the development of the first prototype of the so-called INTREPID module (Daido Steel and UPM) a module integrating domed shaped Fresnel-Köhler optics developed at CEDINT-UPM and multi-junction solar cells. Modules included some other technologic advances such as anti-soil and heat evacuating coating layers developed by University of Miyazaki. INTREPID modules have been assembled on advanced BSQ Solar trackers leading to the so-called INTREPID systems. A 50 kWp plant has been installed at Villa de Don Fadrique (Spain) and a 15 kWp system at IES-UPM campus using this technology. Efficiency above 28 % at system level under Concentrator Standard Operating Conditions (CSOC) has been reported for this system which is the highest reported in the world at system level.

Tools for the characterization of several CPV elements have also been created. These include, for example: a system for the characterization of multi-junction solar cells (Takano); the Module Optical Analyzer MOA, (a system developed by the Instituto de Energía Solar at UPM capable of characterizing CPV acceptance angle and alignment and integrated in the HELIOS system suitable for its use in industrial environments); Triband-Heliometer (a system developed by Instituto de Energía Solar at UPM for characterizing the irradiance reaching the top, middle and bottom cells); a sensor, developed by BSQ solar, for characterizing tracker accuracy; a meteostation (CEA-INES and IES-UPM) integrated at different levels in the CPV plant with software and hardware capable of remote data acquisition), specialised software (ENEA) that can calculate energetic performance

and losses of CPV plants and model them (SOLCORE software by ICSTM).

Please provide a summary description of the project context and the main objectives. The length of this part cannot exceed 4 pages.

The Project context dates back to March 2007, when the EU's leaders endorsed an integrated approach to climate and energy policies that aimed to fight against climate change and increase the EU's energy security while strengthening its competitiveness. They committed Europe to transform itself into a highly energy-efficient, low carbon economy. To quickly start this process, the EU Heads of State and Government set a series of demanding climate and energy targets to be met by 2020, known as the "20-20-20" targets. These are:

- A reduction in EU greenhouse gas emissions of at least 20% below 1990 levels.
- 20% of EU energy consumption to come from renewable resources.
- A 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.

Concurrently, the Japanese Prime Minister Fukuda presented his vision to the press on June 9th 2008 on "Cool Earth in 2050" where the contribution of PV to this vision was taken into account in several PV programs and taking into account several temporal scenarios. Specific objectives of "Cool Earth in 2050" are:

- A reduction in Japan CO_2 emission of at least 25% below 1990 levels until 2020.
- Cumulative PV capacity with 14GW and 53GW until FY2020 and FY2030, respectively.

RTD is one of the key factors for achieving this goal. The Directorate-General Research, with the support of the several services of the EC including the Joint Research Centre and in particular of the Institute of Energy together with the New Energy and Industrial Technology Development Organization (NEDO) of Japan, devised a cooperative strategy that was materialized by the issue, on July 20th, 2010, of the call FP7-ENERGY-2011-JAPAN: Ultra-high Efficiency Concentration Photovoltaics (CPV) Cells, Modules and Systems /EU-Japan Coordinated Call. NGCPV answered to this Call and, with its results is expected to have contributed to the achievement of both the "20-20-20" and "Cool Earth in 2050" targets.

Following the content and scope of the Call, NGCPV objectives have focused on the development of new material processes for highly efficiency cells and modules for CPV systems, on the development and demonstration of new concepts for devices and processes for very high efficiency photovoltaics and on new characterisation techniques suitable for such solar cells and systems. Our research on novel materials and quantum nanostructures has aimed to clarify the requirements for III-V-based multi-junction solar cells to enable a 50% cell efficiency. By researching on the full production line that goes from cells to modules, NGCPV aimed to identify and evaluate all losses factors whose minimization should enable module efficiency beyond 35 %.

Solar cells are at the base for the achievement of a high efficiency in a photovoltaic system. Our experimental activity plan towards the achievement of 50 % efficient solar cells has included in their objectives the research on the improvement of the current matching between cells in a multi-junction solar cell, the use of Si substrates, the use of more than 3 junction solar cells (in particular metamorphic quadruple solar cells) and the use of nanostructures.

NGCPV objectives also contemplated the integration of high efficiency cells in CPV modules aiming to advance towards a final 40% efficiency target. Research towards this goal has demanded the development of new optics for concentration and reliable characterization techniques for CPV modules and cells. Reliable characterization of solar cell materials and devices is essential to the progress of the research. Prior to NGCPV, many semiconductor characterization techniques, even conventional ones, had still not been used as routinely as they should for the characterization of solar cells. The reason was often the poor understanding of how the results of the measurements should be interpreted when applied to the peculiarities of photovoltaic devices, in particular, when nanostructures were involved. Reliable determination of the module and cell efficiencies is essential for later planning of PV systems. Setting as one of our objectives the agreement in a round robin scheme was considered as one of the best ways for achieving this reliability.

To progress beyond the integration of cells and modules, NGCPV stated as one of its objectives the installation of a 50 kWp CPV plant. This plant should serve also as bench mark to test the methods proposed in the Project for predicting its energy forecast. Also in this direction, characterization of cells, optics and single concentrators should be carried out both indoor and outdoor in order to unveil all the aspects of their performance. The existence of this plant would also support the development of the testing and certification procedures and the determination of the standard for the definition of the power supplied by a CPV plant and the procedures to predict its energy output. By achieving the integration of characterization tools in the manufacturing process NGCPV aimed to progress a step forward beyond the development of characterization tools at laboratory level.

Please provide a description of the main S & T results/foregrounds. The length of this part cannot exceed 25 pages.

NGCPV has provided significant results that have contributed to the development of a new generation of concentrator photovoltaics (CPV). CPV can be structured into four conceptual areas: concentrator solar cells, concentrator modules, concentrator plants and quantum nanostructures for solar cells. We also group next the main results/foregrounds obtained by NGCPV according to these categories. The important topic of standardization and development of characterization tools will also be described accordingly to this classification being the main results in this field also described within each category.

Concentrator solar cells. Current state of the art of concentrator solar cells is based on multi-junction solar cells (MJSC) and to their development and efficiency improvement the project has devoted significant efforts**.** Hence, at the early stages of the Project, research focused on improving former world record solar cell architectures that are based on the so-called up-right metamorphic (UPR) approach consisting of three solar cells (3J). FhG-ISE carried out a modeling effort and concluded that, using realistic parameters in the simulation, the UPR approach could lead "only" to 44.4 %. In order to approach 45 %, FhG-ISE studied the potential of inverted metamorphic (IMM) approach concluding that this approach, again using realistic material and device parameters and 3J, could lead to 45.1 % efficient solar cells. To progress further, it was concluded that 4 junction solar cells (4J-MJSC), based on the UPR approach, could be one of the approaches to be followed. In this case, the potential efficiency of the cell was calculated to 49.1 % when using Ge substrates. The structure of the cells we have mentioned is illustrated in Fig. 1 and all of them have been experimentally studied in NGCPV. Additional studies revealed that the use of GaSb or InP substrates could increase the efficiency above 50.5 %. All these efficiency figures refer to operation at 500 suns AM1.5D ASTM G173-03 1000 W/m2 (AM1.5D for short in what follows).

Concerning the 3J-UPR approach, FhG-ISE was able to upgrade their technology from 3 inch wafers to 4 inches wafers while increasing the efficiency (41.4 % @ 500-600 suns AM1.5D), see *Fig. 2*. To achieve this goal, for example, metallic fingers were shaped with 67º facets in order to reflect the light from the metal fingers towards the cell surface (Fig. 2). The anti-reflecting coating of some of these cells was optimized taking into account the secondary optical element used in Daido modules. These cells exhibited an average efficiency of 39.5 % in the range from 400 to 1000 suns.

Fig. 3 illustrates the inverted metamorphic approach for manufacturing a multi-junction solar cell. Following this approach SHARP obtained a world record efficiency (44.4 % @ 246-302 AM1.5 D suns and 37.9 % at one sun) as independently measured by FhG-ISE (Fig. 4). It is remarkable that, at the beginning of this Project, SHARP started with 35.8 % efficiency cells at one sun and 43.5 % under concentrated light. Progress in efficiency improvement along the Project has been possible thanks to the optimization of several elements in the cell structure such as reduction of the series resistance of the tunnel junction, optimization of the anti-reflective coating, optimization of the window layer of the top cell, fine tuning the InGaAs bandgap and reduction of the width of the top contact layer.

Multi-junction solar cells have also gone through reliability tests involving climatic chambers with temperature cycling (IES-UPM, FhG-ISE and SHARP), high current injection and electroluminescence analysis (FhG-ISE). Both cells by FhG-ISE and SHARP demonstrated reliability equivalent to more than 30 years of operation.

Accuracy and reproducibility in the characterization of multi-junction solar cells has been assessed by means of a round robin scheme between AIST and FhG-ISE. After a careful process in which aspects such as lamp spectrum control, temperature, instruments and probes have been controlled, an excellent agreement has been found between solar cell calibration between FhG-ISE and AIST as demonstrated by the results in Fig. 5.

In NGCPV roadmap towards 50 % efficiency, the use of silicon substrates and the development of 4J multi-junction solar cells on Ge substrates have also been investigated. GaAsN (TTI and University of Miyazaki) and multiple quantum well solar cells (ICSTM, FhG-ISE and U. of Tokyo) have been investigated [1, 2] in order to implement the required 4^{th} solar cell. In the case of the GaAsN, both the nature of the defects [3] associated to the introduction of N as well as their concentration were studied by advanced characterization techniques such as real time X-ray diffraction topography (U. Miyazaki) [4, 5], deep level transient spectroscopy and infrared spectroscopy [6, 7] (Toyota Technical Institute). To implement multiple quantum well solar cells into a high efficiency triple-junction structure, the wafer-shuttle concept has been implemented. Thereby monolithically integrated multi-junction cells were created by sequential growth in different epitaxy reactors [8] in Europe and Japan (FhG-ISE, University of Tokyo and SHARP). The use of silicon substrates has also been investigated. In this respect, growth on silicon substrates have proven to proceed with a threading density dislocations lower than 1E6 cm-2. GaAs pn-junction solar cells grown on Si (111) fabricated by Asahi Kasei were evaluated by surface photovoltage (SPV) by U. of Miyazaki. Ge based 4J multi-junction solar cells have also been manufactured using the wafer bonding (the concept is illustrated in Fig. 6). Within this Project, the best result has been a 4J solar cells 38.5 % efficiency @ 188 suns AM1.5D (FhG-ISE).

CPV modules. The development of high efficiency CPV modules includes cell and optics integration into the module and the development of suitable tools for their characterization.

Concerning cells and optics integration, advanced primary and secondary optics [named Domed shaped Fresnel-Köhler (DFK)] (Fig. 7) were developed. The optimization process included, for example, outdoor studies were the impact of soiling was studied by comparing the performance of modules were periodic cleaning had been carried out with others in which have not [9]. The modules also incorporated special coatings, designed by the University of Miyazaki, in order to minimize soiling [10], at the time that enhanced the optical properties of the lenses, and facilitate heat dissipation. The coating designed to facilitate heat thermal dissipation decreased module temperature of operation by 10 C [11] increasing module efficiency by 0.5 points. The properties of these layers remained stable with time. At the end of these optimization process and after been integrated in the system and carefully optimizing also the total balance of systems, the INTREPID CPV system exhibited a 28 % efficiency under CSOC which, as advanced before, is the highest reported in the world at system level.

The DFK primary and secondary optical elements (POE and SOE) were designed by CEDINT Group at the Universidad Politécnica de Madrid on the basis of LPI's Fresnel-Köhler concentrator technology [12]. Fig. 8 shows an illustration of these POE and SOE. The manufacturing tolerance of these optical elements was kept within +/- 0.015 mm for the SOE and +/- 0.3 mm for the

POE. One of the aims of their design was the achievement of good spatial and spectral uniformity of the irradiance on the cell surface (Fig. 9).

Development of characterization tools for cell and module characterization has also played an important role within NGCPV. In this respect:

- CEA-INES has developed the tool, called "OSFAM" (One Size Fits All Module) designed for the outdoor characterization of cells and modules (Fig. 10). The tool is versatile and can hold modules with Voc ranging from 3 V to 200 V, short-circuit currents from 0.5 A to 10 A, primary lenses can exhibit sizes from several to hundred cm2,

- CEA-INES has also developed a tool with the capability of characterizing 6 different module technologies under the same conditions (Fig. 11) and a software (MAGIC) for module analysis.

- The Instituto de Energía Solar at the UPM has also carried out intensive work in order to develop characterization tools suitable for indoor characterization compatible with their use at industrial level. In this respect, this Group has developed HELIOS and MOA (Module Optical Analyze). HELIOS (Fig. 12) allows determining module efficiency. MOA, applying the Luminescence-Inverse (LI) method, can measure the optical-angular properties of a CPV module in few seconds without the need of any illumination nor module movement (thus, fulfilling the requirements for being used in production line). In this way, MOA can investigate, for example, the concentrator photovoltaic (CPV) module optical-angular performance (in particular, misalignments between the main optical components comprising the module) at different temperature conditions (in a wide range of actual operating conditions) [13]. MOA concept is illustrated in Fig. 13.

Reliability in the characterization of CPV modules have been achieved also by following round robin schemes between IES-UPM, CEA-INES, FhG-ISE and ENEA. The lessons learnt will be introduced in the normative IEC62670 that is developing the standards for CPV module characterization. One of these lessons, for example, refers to the importance of achieving a spectral matching ratio (SMR) close to one between the top and middle cell. The kind of thermal probe to be used and its placement also needs to be very accurately defined in order to measure the temperature of operation of the module.

In the area of modeling, U of Miyazaki has developed tools for modeling temperature effects in CPV modules that included heat transfer models (Fig. 14). This task is necessary in order to reduce temperature induced efficiency losses. Results have been compared with field data giving as result that the model can be applied to estimate the operating temperature and conversion efficiency of cell or module. The model also allows for determining the thermal stress on the cell.

CPV plants. A 50 kWp CPV plant, compromising 5x10kWp CPV trackers have been installed at Villa de Don Fadrique (Fig. 15) using Daido CPV modules and trackers developed by BSQ Solar. Modules operate at 820 suns and can be remotely monitorized. As one of its most significant results, during its first two years of operation, the plant has demonstrated a 74 % AC performance ratio (the ratio between the number of plant working hours at nominal power generating the actual AC energy and the number of equivalent solar irradiation hours at 1000 Wm-2, Fig. 16). Accompanying this deployment, several tools have been developed in order to characterize and model CPV plants. These tools compromise:

- A Triband-Heliometer, developed by researchers at the Instituto de Energía Solar of the Universidad Politécnica de Madrid for characterizing the irradiance reaching each one of the cells in the 3J multi-junction stack (Fig. 17a)
- A sensor, developed by BSQ Solar, for characterizing tracking accuracy (Fig. 17b)
- Meteostation, with software and hardware for remote data acquisition (Fig. 18) developed by CEA-INES and IES-UPM that has allowed studies related to the impact of wind [14] and temperature on the performance of the plant [15]. The station can monitor wind speed and direction, ambient temperature, relative humidity, global, diffuse and direct normal radiation as well as spectral radiation. It incorporates, as one of its elements, the Triband-Heliometer mentioned above.
- Specialized software (ENEA) that can calculate energetic performance and losses of the plant distributed as spectral, electrical conversion, thermal, ohmic and mismatch losses. Fig. 19 shows one of the plots generated by this software representing a summary of the losses contribution normalized to the incident solar energy. ICSTM has developed SOLCORE, a software tool for modeling CPV plants.

The data obtained from the 50 kWp [16] plant allowed the verification of models, new techniques and new tracking system and contributed to better module manufacturing skills.

A second 15 kWp system (called INTREPID) was installed at IES-UPM Campus incorporating the latest version of Daido modules and BSQ Solar trackers. This system has demonstrated system efficiencies above 28% under CSOC conditions (Fig. 20). As a result of the study of the experimental results, a model has been developed that allows to reliable predict the efficiency of a CPV system (Fig. 21).

Quantum nanostructures. Two kinds of nanostructures have been studied in NGCPV for two different main applications: quantum wells, for the achievement of the 3rd or even 4th cell in a multi-junction solar cell scheme and quantum dots (QDs), for the implementation of intermediate band solar cells .

U of Tokyo and ICSTM have been successful in manufacturing a multiple quantum well solar cell (comprising 70 QW layers) with a 1.15 eV bandgap (Fig. 22a) [17]. It has been predicted (ICSTM, FhG-ISE, U. Tokyo) that, when incorporated in a 4J- MJSC, a QW with this bandgap can lead to solar cells with efficiencies above 50 % [18]. The implementation of this 4J- MJSC implies the growth of the MQWs on Germanium substrates. In order to prevent the formation of anti-phase domains, the choice of 6 degrees off Ge substrates has been investigated. Interestingly, research in this field has unveiled that, under certain growth conditions, quantum wires instead of quantum wells, with interesting optoelectronic properties for solar cell applications, can be grown [19].

Concerning quantum dots for intermediate band solar cell applications, research in this Project has resolved spectrally for the first time (IES-UPM and U. Tokyo) the generation of photocurrent as a consequence of photon absorption in the intermediate band to conduction band transitions. University of Kobe as carried out pump-probe experiments that have allowed the estimation of the absorption coefficient related to IB to CB transitions [20]. In this respect, the importance of inserting the so-called "field damping layers"[21] in the solar cell structure in order to take the quantum dots into a flat band potential region has also been experimentally revealed [22] in InAs/AlGaAs quantum dot solar cells. In addition to the insertion if these damping field layers, the improvement in the solar cell performance has been produced thanks to the use of higher band gap semiconductors barriers (that reduces thermal escape) and the doping of the quantum dots (that increases the absorption of photons related to the intermediate band to conduction band transition).

Several models have been developed along the Project to model quantum dots in solar cells [23, 24]. These models have allowed to identify what are the technological demands in order to approach efficiencies above 40 % in InAs/GaAs quantum dot solar cells (these are, mainly, the use of light management structures that increase optical length by a factor of 50 and the growth of quantum dot structures comprising 100-300 layers of QDs) [25].

Please provide a description of the potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and the exploitation of results. The length of this part cannot exceed 10 pages.

Socio-economic impact

Decarbonizing the electric sector is one of the main objectives of current governmental energy research plans. As a consequence of this policy support, the share of renewables in the gross EU energy consumption has increased from 10% in 2007 to 14.1% in 2012. In the electricity sector, the share of renewables has increased from 16.1% in 2007 to 23.5% in 2012. Photovoltaics (mostly flat-plate silicon modules) have played a significant role in this increment, ranging amongst the two most installed sources, together with wind energy, of electricity during 2011-2013 in the EU. As a consequence, PV electricity already accounts for 3% of the EU electricity demand. Globally, solar PV electricity achieved more than 38 GW of new installed capacity worldwide in 2013 (11 GW in Europe and 6.9 GW in Japan), reaching a global cumulative capacity of almost 140 GW [26]. In US solar PV accounted for 36% of the new installed capacity in the first three quarters of 2014 [27].

However, although PV markets are progressing very rapidly towards competitiveness in the electricity sector, in most of the countries PV remains a policy-driven market. According to the EPIA Global market outlook for photovoltaics 2014-2018 [26], “declining political support for PV has led to reduced markets in several European countries (Germany, Italy, Belgium, France and Spain for instance) while the implementation of new feed-in tariff policies has led to a dramatic increase of the markets in other countries (such as China and Japan)”. Therefore, reducing the cost of PV electricity is still necessary to make it completely independent of governmental support.

In this concern CPV technology is expected to play an important role. Several market research reports have predicted that CPV electricity will reach lower costs than conventional PV by the end of this decade [28, 29]. Some authors claim that this is already the case in some regions with very high direct normal irradiance (DNI) conditions. In any case, reducing the capital cost of CPV technology (in €/W) is essential in order to reduce the cost of CPV electricity (in €/kWh), and this must be accomplished by progressing through the learning curve of the CPV technology.

With a CPV global cumulative capacity of only 358 MW, the CPV system capital costs is already below 3 $/W [30]. Notice that in 1998, when flat-plate silicon PV installations had a similar global cumulative capacity, the PV system capital cost was above 10 $/W [31]. Assuming the same learning rate for CPV than for PV (14%) [30], it is expected that the capital cost of CPV electricity will be halved (down to 1.5 $/W) after the installation of only 9 GW of new CPV capacity worldwide. Thus, CPV technology offers a great opportunity to reduce the PV electricity cost in the very short-term. In this concern, the main challenge is to progress rapidly through the learning curve of CPV technology. In this aspect, NGCPV project has played an important role, as explained below.

Impact on reducing the capital cost of CPV technology

At the beginning of the NGCPV project, in early 2010, the CPV market was very small, with a cumulative installed capacity of only 20 MW, and the capital costs ranged from 4 to 10 €/W [30]. In these conditions, CPV could not compete with conventional solar PV systems. During the course of this project the CPV market has grown up to 358 MW (18 times greater) and the CPV system cost has been reduced below 3 $/W, according to several market research reports [30].

The reduction of the CPV capital cost is attributed mainly to the progress through the learning curve of CPV technology. In this concern, CPV offers a great advantage respect to conventional PV systems: the upper bound in the conversion efficiency. Increasing the efficiency is an effective way to reduce the capital cost, since it enables the reduction of the overall system size (affecting to the tracker, number of modules, labor costs, etc.) per unit of output power. Increasing the CPV overall system efficiency has been one of the main assets of the NGCPV project.

At the time NGCPV project proposal was written (late 2009), the highest efficiency reported for a CPV cell was 41.6% (Spectrolab, US) and at the time the project started (March 2010) the highest efficiency was already 43.5% (Solar Junction, US) and the record efficiency for a full CPV system was 25%. As a result of the NGCPV project the Japanese partner SHARP reported a new world record efficiency of 44.4% (April 2013) which is the today's highest conversion efficiency for a triple junction solar cell. As one of the main CPV cell providers, SHARP is now capable of delivering extremely high efficient CPV cells to the CPV module manufacturers worldwide, meaning that NGCPV project has had a direct impact to the cost reduction of the CPV technology that has taken place in the last few years. Very high cell efficiencies, above 40%, have been also achieved by Fraunhofer-ISE in the framework of this project.

However, highly efficient CPV systems require not only highly efficient cells, but also highly efficient concentrating optics and accurate tracking systems. Advanced optical systems designed by UPM have been incorporated in the so-called INTREPID CPV modules, developed by Daido within the NGCPV project, and accurate tracking strategies have been developed by BSQ Solar. Both have been combined in a full CPV system that has demonstrated an overall conversion efficiency of 28%, one of the highest CPV system efficiencies reported so far.

CPV technology has potential to increase the overall system conversion efficiency beyond 35%. In this concern, a roadmap to progress towards higher CPV efficiencies has been developed within NGCPV project. In a paper published in the early stages of the project titled "Will we exceed 50% efficiency in photovoltaics?" by Prof. Antonio Luque, it was already anticipated that triple junction solar cells have already approached their maximum potential in terms of conversion efficiency. Therefore, novel CPV solar cell structures have to be explored. In this concern, two novel CPV solar cell structures, with potential of exceeding 50% conversion efficiency, have been investigated in NGCPV project: four-junction solar cells and intermediate band solar cells.

To fabricate these novel cell structures, NGCPV project has investigated two groups of novel materials: dilute nitrides and quantum nanostructures. This research has also required the development of new advanced characterization techniques. These activities have been carried out at a more fundamental research level in order to identify the actual potential of these materials for developing novel CPV cell structures. Therefore, these activities have been documented in more than 100 publications.

CPV technology represents an opportunity for EU and Japanese industries to get the leadership in the future of solar power generation technologies. NGCPV project has enabled both EU and Japanese stakeholders to acquire valuable CPV technological know-how, which has positioned them in a leadership starting position, just before the eventual imminent take-off of CPV industry.

In this framework, our Project has impacted the development of the concentrator photovovoltaic industry by:

- Developing high efficiency multi-junction solar cells (44.4 %)
- Effectively integrating all CPV elements (lenses, trackers, cells) in a CPV system and achieving 28 % system efficiency (under CSOC)
- Developing standards for energy forecast and power rating in CPV systems
- Identifying the roadmap towards 50 % cell efficiency
- Advancing in the science stated by this roadmap such as the research related to the manufacturing of the 4th junction in the multi-junction solar cell stack
- Increasing our understanding of the role of quantum structures in photovoltaic energy conversion
- Developing new tools for the characterization of elements involved in the CPV chain and, in particular, of those involved in CPV module characterization at industrial level.
- Verifying the reliability of solar cells by finding out that this exceeds 3 years of operation.
- Favoring the interchange of researches and collaboration between EU and Japan.

Impact on reducing the levelized cost of electricity (LCOE) of CPV electricity

Capital cost (in €/W) is not the adequate parameter for comparing different power generation technologies. In contrast, the levelized cost of electricity (LCOE), i.e. the cost of the produced electricity along the full life of the power plant, must be used. LCOE, which is given in €/kWh, takes into account not only the capital cost, but also the power plant yield during its full life and the maintenance costs. Thus, LCOE determines whether a power plant is profitable in a particular location given the local price of the electricity.

Calculating the LCOE of CPV electricity is not straightforward because it strongly depends on the meteorological conditions of the particular location. Especially important parameter is the direct-normal irradiance (DNI) but there are other parameters affecting the LCOE, such as wind velocity, sunlight spectrum, ambient temperature, rain frequency, etc.

In this context, a confident forecast of the CPV plant productivity is essential to accurately estimate the LCOE and consequently, determine the profitability of a CPV installation. Within the NGCPV project, several predictive models have been developed in order to forecast the productivity of CPV power plants under certain meteorological conditions. To validate these models, an experimental 50 kWp CPV plant was built by BSQ Solar in Villa de Don Fadrique (Toledo, Spain) and is being continuously monitored since October 2012. Based on an exhaustive meteorological characterization, IES-UPM and ENEA obtained the translating equations from standard to real operating conditions. This model is a valuable tool, now available for CPV stakeholders to perform accurate LCOE predictions.

Another important aspect affecting the LCOE of CPV technology is the reliability of CPV cells and modules. High performance is expected for the CPV cell during all the life of the CPV power plant in order to pay-back the initial capital cost of the system. A number of experiments have been carried out by IES-UPM on multijunction CPV cells provided by the partners, concluding that multijunction solar cells can operate for more than 30 years.

Environmental issues

Solar energy is a very disperse resource. This makes solar PV electricity very intensive in the use of some kinds of natural resources such as silver, tin, aluminum, land area, etc. In this concern, the higher conversion efficiency of CPV systems enables the use of fewer amounts of materials and less land area, and consequently it enables a lower environmental impact than flat-plate PV systems [32]. Thus, NGCPV project has also indirectly played a role in reducing the environmental impact of CPV technology by contributing to the increment of the CPV conversion efficiency.

NGCPV project has also anticipated solutions to future challenges of CPV concerning scarcity of constituent materials such as germanium, which is commonly used as substrate in current state-of-the-art multijunction solar cells. Unfortunately, germanium is not an abundant material and could not be used in a scenario in which CPV technology becomes a leading player in the electricity generation worldwide. In this concern, silicon is the ideal substitute due to its great abundance on earth. During this project, several strategies have been explored to grow III-V semiconductors on silicon substrates, the key challenge being the lattice mismatch between silicon and III-V semiconductor layers. As the key result, a novel buffer scheme has been developed by Asahi-KASEI that enables to grow GaAs on Silicon with a surface defect density less than 1E6 cm-2.

Please provide the public website address (if applicable), as well as relevant contact details.

www.ngcpv.org

Partners and contact details

European Coordinator:

- Instituto de Energía Solar -Universidad Politécnica de Madrid, Spain. Contact: Prof. A. Luque (a.luque@upm.es)

Japanese Coordinator:

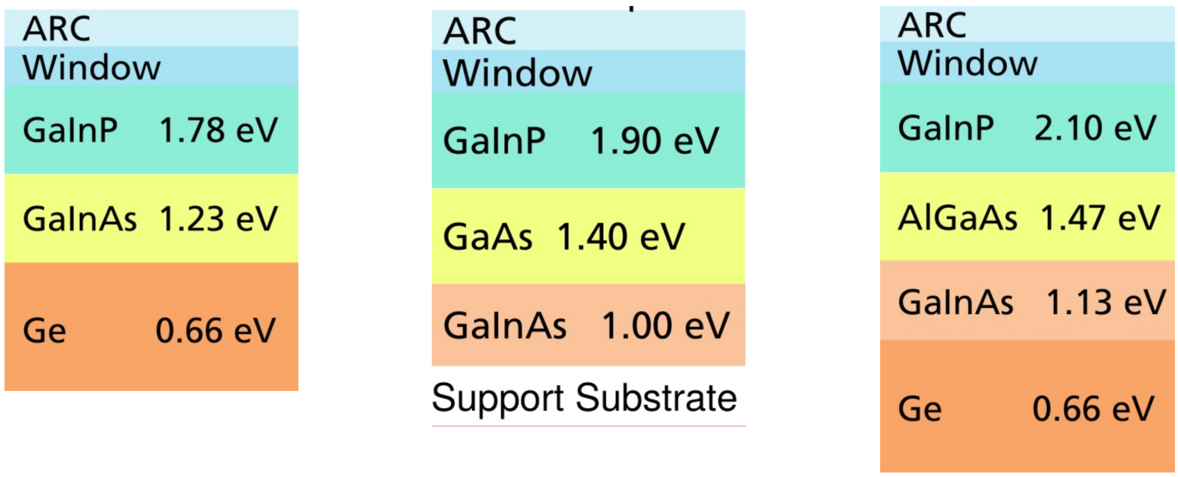
- University of Tokyo: Prof. Masafumi Yamaguchi.(masafumi@toyota-ti.ac.jp)

Partners

- Fraunhofer-ISE, Germany. Contact: Dr. A.Bett (andreas.bett@ise.fraunhofer.de)
- Imperial College of Science Technology and Medicine, UK Contact: Prof. Ekins-daukes (n.ekins-daukes@imperial.ac.uk)
- ENEA, Italy. Contact: Dr. Carmine Cancro (carmine.cancro@enea.it)
- BSQ Solar, Spain. Contact: Dr. Ignacio Luque (iluque@bsqsolar.com)
- PSE, Germany. Contact: Dr. Warmuth Werner (wewa@pse.de)
- CEA-INES, France. Contact: Prof. Jens Merten (jens.merten@cea.fr)

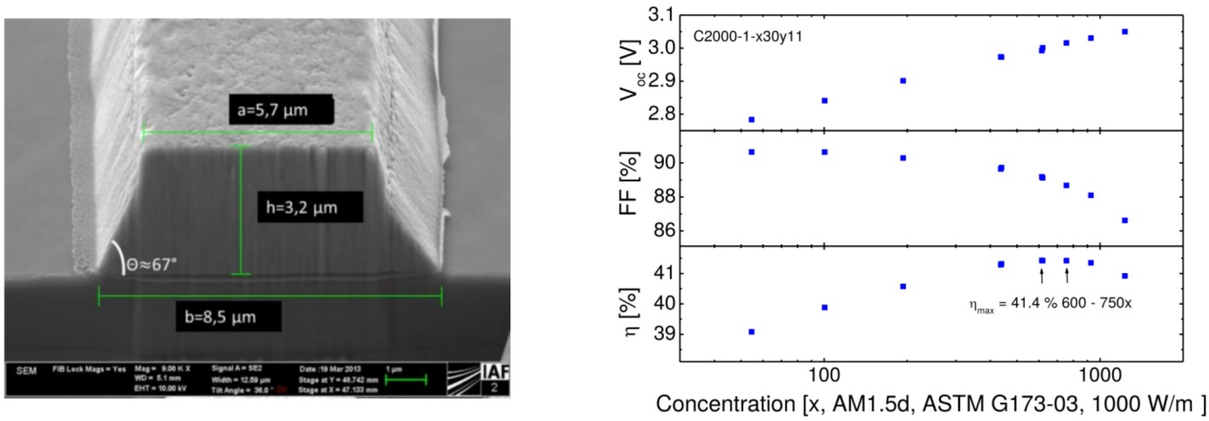
- Toyota Technological Institute (Japan). Contact: Prof. Masafumi Yamaguchi.(masafumi@toyota-ti.ac.jp)
- AIST (Japan). Contact: Dr. Yoshihiro Hishikawa (y-hishikawa@aist.go.jp)
- SHARP (Japan). Contact: Dr. Takamoto Tatsuya (takamoto.tatsuya@sharp.co.jp)
- Daido Steel (Japan). Contact: Dr. Kenji Araki (k-araki@ac.daido.co.jp)
- University of Miyazaki (Japan). Contact: Prof. Atsuhiko Fukuyama (a-fukuyama@cc.miyazaki-u.ac.jp)
- Asahi Kasei (Japan). Contact: Prof. Yoshitaka Moriyasu (kuze.nb@om.asahi-kasei.co.jp)
- University of Kobe (Japan). Contact: Prof. Takashi KITA (kita@eedept.kobe-u.ac.jp)
- Takano Co. Ltd. (Japan). Contact: Dr. Akira Kotagiri (Kotagiri@takano-net.co.jp)

FIGURES



(a) (b) (c)

Fig. 1. Different MJSC optimized structures: (a) 3J Up-right approach, theoretical efficiency 44.4 % @500 suns AM1.5D; (b) 3J inverted metamorphic, theoretical efficiency 45.1 % @500 suns AM1.5D; (c) 4J Up-right approach, theoretical efficiency 49.1 % @500 suns AM1.5D. (After modeling by FhG-ISE using realistic material and device parameters).



(a) (b)

Fig. 2. (a) 67 º faceted metallic fingers for FhG-ISE high efficiency 3J-UPR approach. (b) Efficiency, open-circuit voltage and fill-factor results for best cells as a function of the solar AM1.5 D ASTM G173-3 1000 W/m2 concentration ratio.

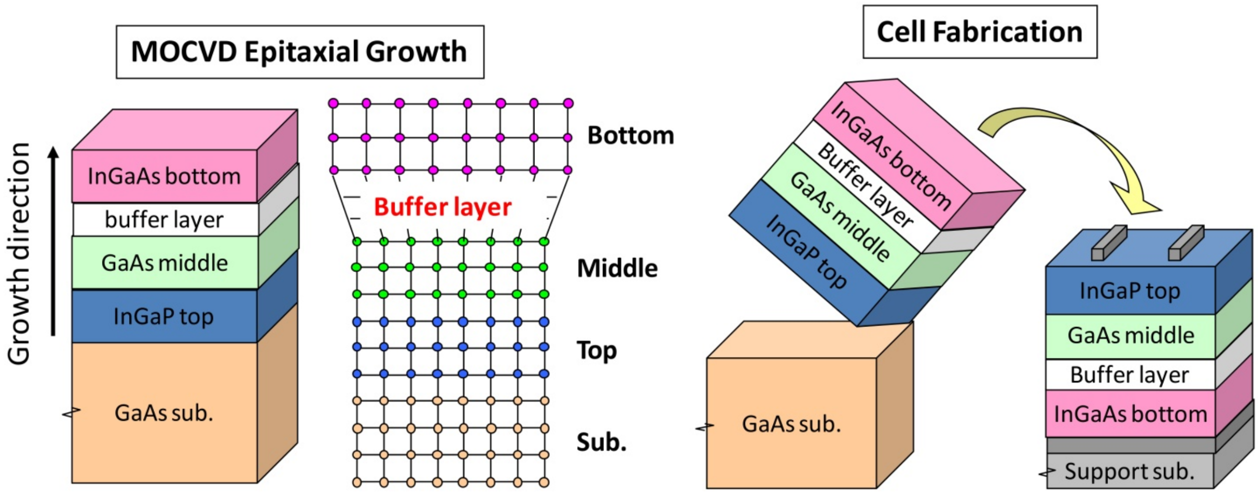


Fig. 3. Inverted metamorphic approach for manufacturing a multi-junction solar cells (illustration by SHARP).

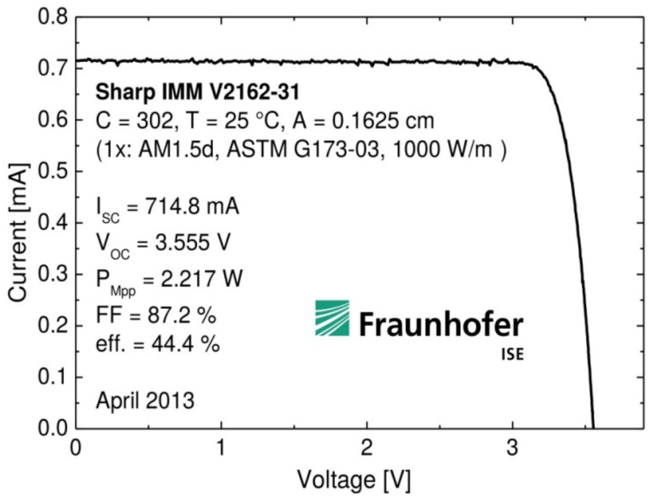


Fig. 4. Current-voltage characteristic of the world record efficiency solar cell by SHARP based on the inverted metamorphic approach. Efficiency independently confirmed by FhG-ISE.

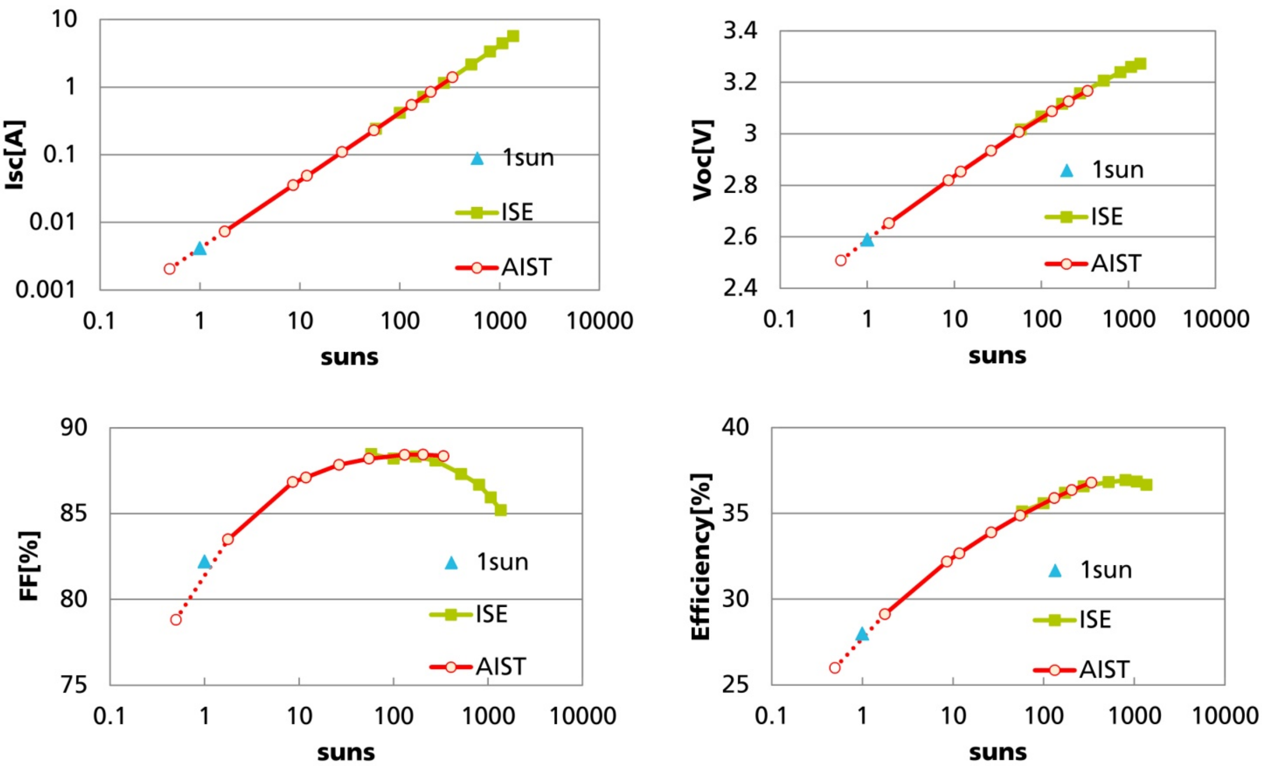


Fig. 5. Comparison of results of multi-junction solar cell calibration between AIST and FhG-ISE.

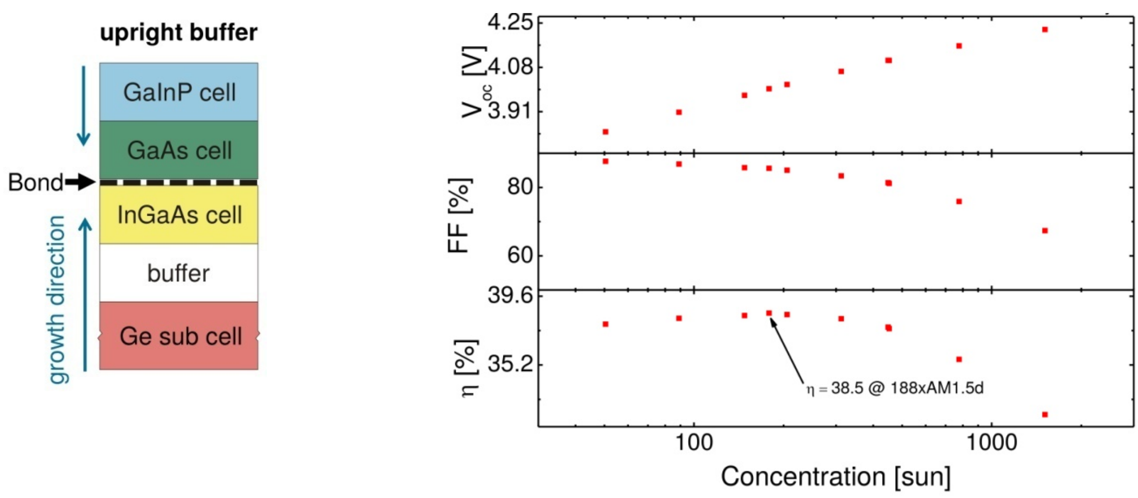


Fig. 6. (a) Schematics of the wafer bonding approach for implementing 4J multi-junction solar cells. (b) Best result obtained during the Project (FhG-ISE).

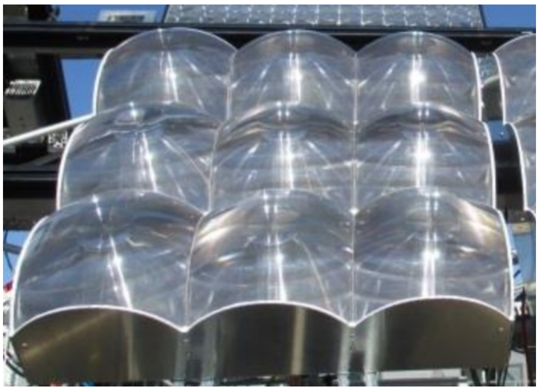
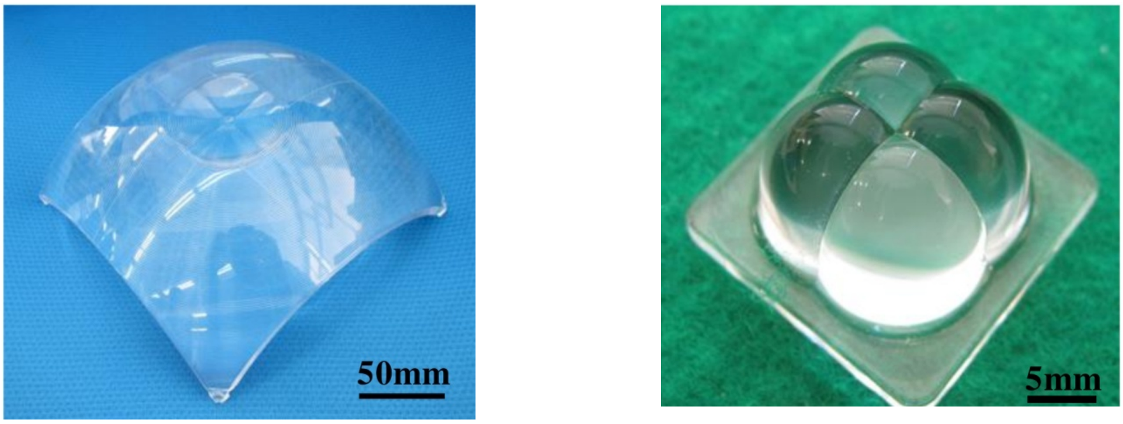


Fig. 7. Daido CPV module integrating FhG-ISE multi-junction solar cells and using DFK optics.



(a) (b)

Fig. 8. Details of the (a) POE and (b) SOE designed for the INTREPID CPV module. ([H. Nagai, K. Araki, K. Hobo, P. Zamora, P. Benitez, J. C. Miñano, K. Nishioka, Y. Ota, I. Luque-Heredia, J. Hashimoto, T. Ueda, Y. Hishikawa, R. Herrero, S. Askins, I. Antón, R. Núñez, G. Sala, M. Steiner, M. Niemeyer, G. Siefer, and A.W.Bett, "Development of the New DFK CPV Module by NGCPV Japan-EU Collaboration," 6th World Conference on Photovoltaic Energy conversion, Kyoto, 2014).

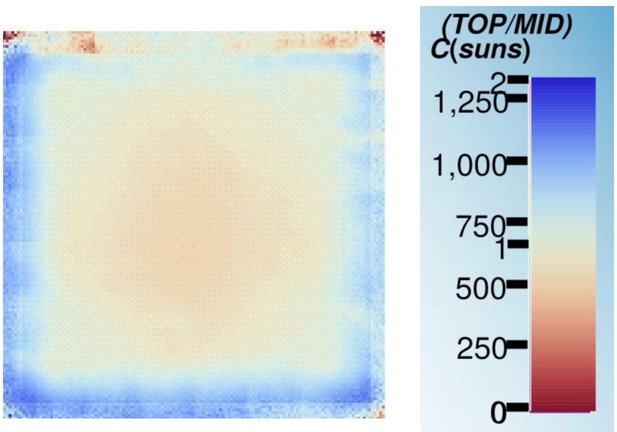


Fig. 9. Uniformity achieved by the DFK primary and secondary elements on the concentrator solar cell. The scale indicates the irradiance ratio between the top and middle cells (CEDINT Group at the UPM).

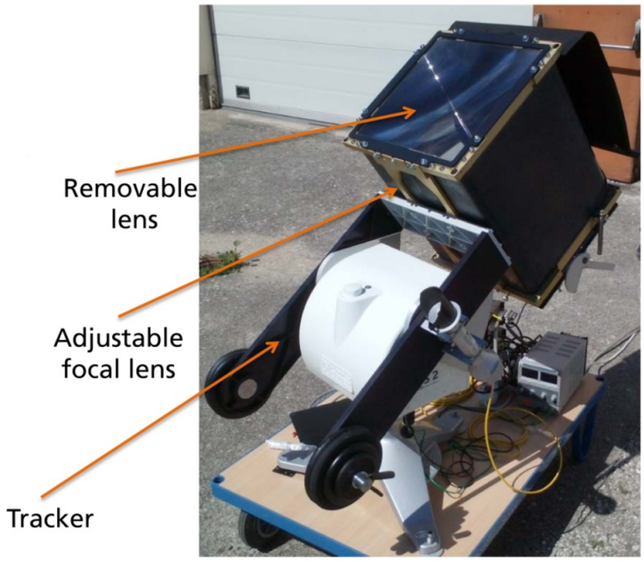


Fig. 10. OSFAM (One Size Fits All Modules), an outdoor characterization tool for cells and modules developed by CEA-INES.

Fig. 11. Outdoor CPV test facility at CEA-INES.

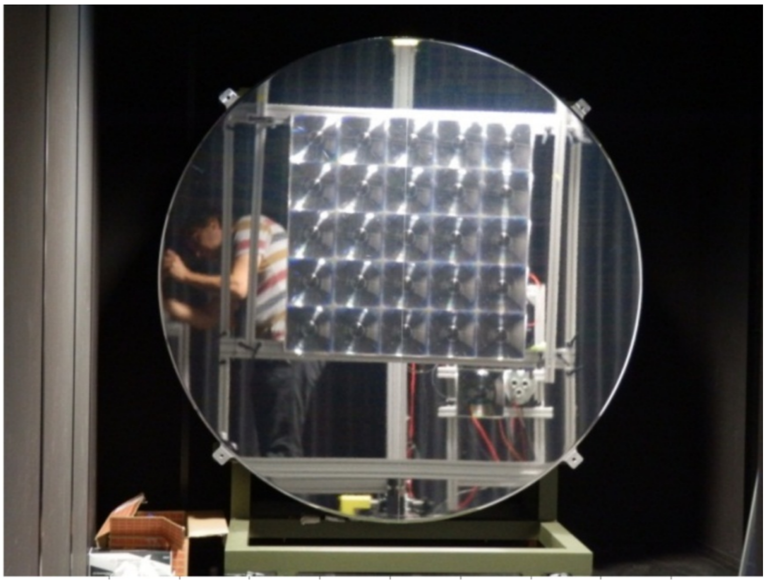


Fig. 12. Detail of the mirror of the HELIOS system, developed by IES-UPM, for the indoor characterization of CPV modules at industrial level (The picture shows the reflection of a CPV module in the mirror).

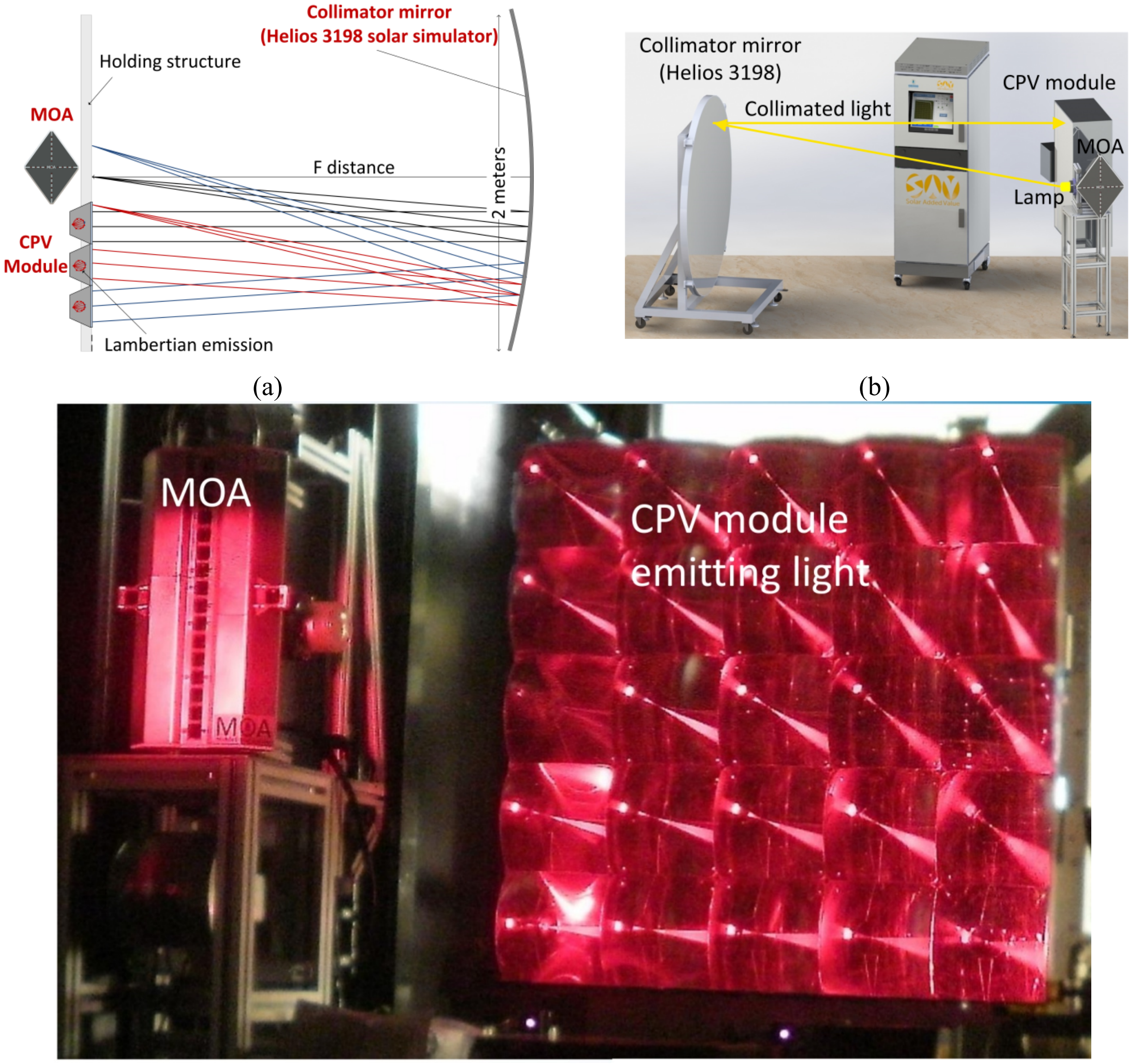
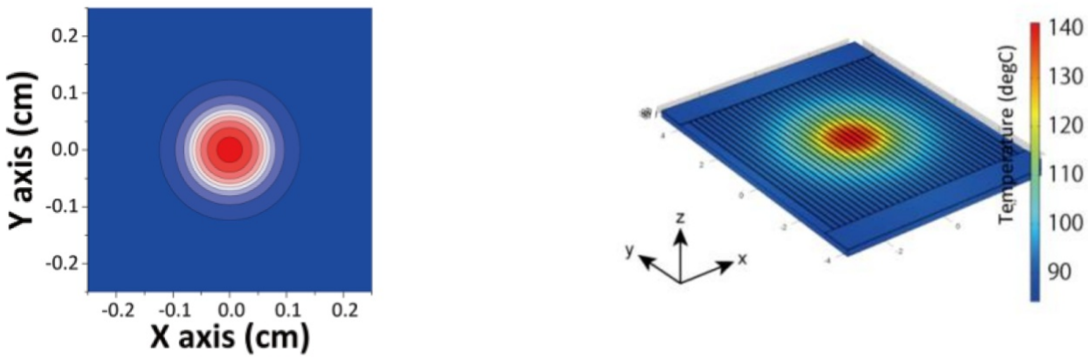


Fig. 13.(a) Measurement scheme of the Module Optical Analyzer tool (MOA) developed at the Instituto de Energia Solar of the Universidad Politécnica de Madrid, capable of analyzing the angular acceptance of CPV modules at the production line (b) Illustration of the MOA system coupled to the HELIOS system (after R. Herrero et al. "Evaluation of Misalignments within a CPV module by the Module Optical Analyzer (MOA): A Case of Study Concerning Temperature Effects on the module Performance. ," 6th World Conference on Photovoltaic Energy conversion, Kyoto, 2014.) (c) MOA in operation



(a) (b)

Fig. 14.(a) Irradiance distribution on a concentrator solar cell and (b) temperature distribution according to the modeling tool developed by the University of Miyazaki.

Fig. 15. 50 kWp CPV plant installed at Villa de Don Fadrique. Modules by Daido. Trackers and installation by BSQ Solar.

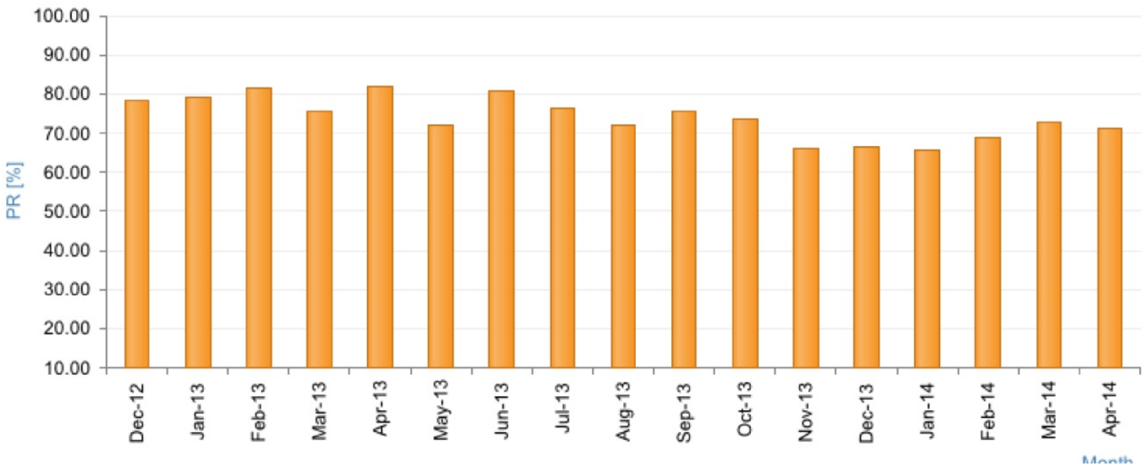
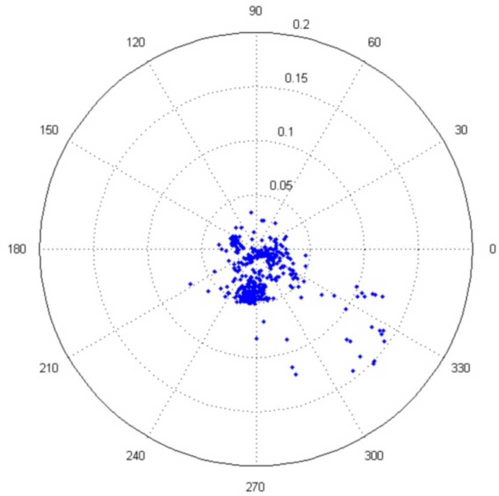


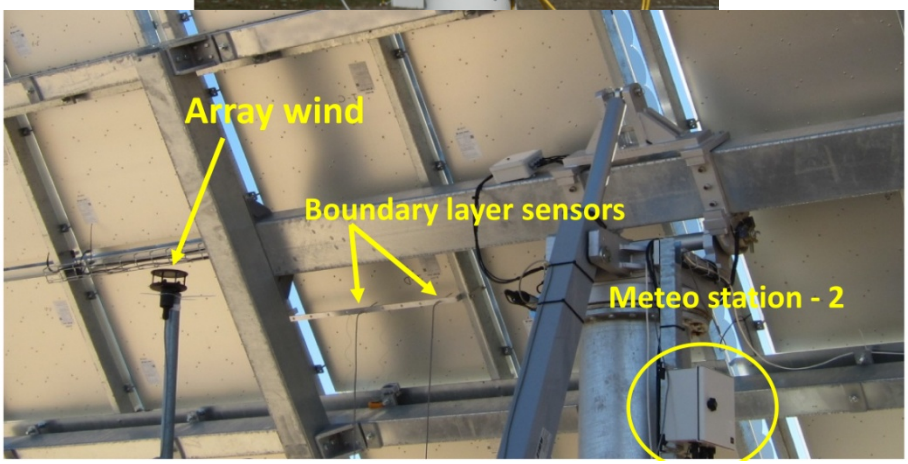
Fig. 16. Performance ratio of the 50 kWp CPV plant.



(a) (b)

Fig. 17. Tools for the characterization of CPV plants: a) Triband-Heliometer, developed by IES-UPM that allows characterizing the irradiance in each of the cells in the 3J multi-junction stack; b) results obtained by the tracker accuracy sensor (BSQ Solar).

(a)



(b)

Fig. 18. (a) One version of the meteo-estation for meteorological data acquisition and correlation against plant performance (CEA-INES) (b) Another meteostation, with sensors located close to the modules, for data correlation against module performance (IES-UPM).

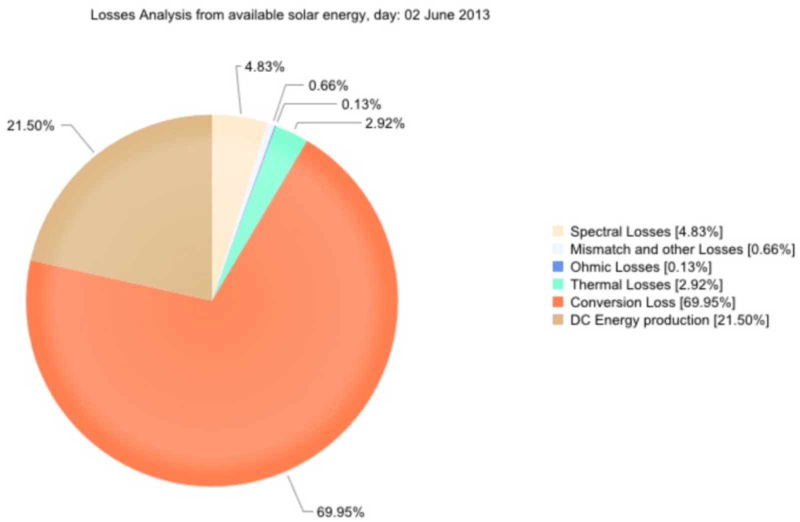
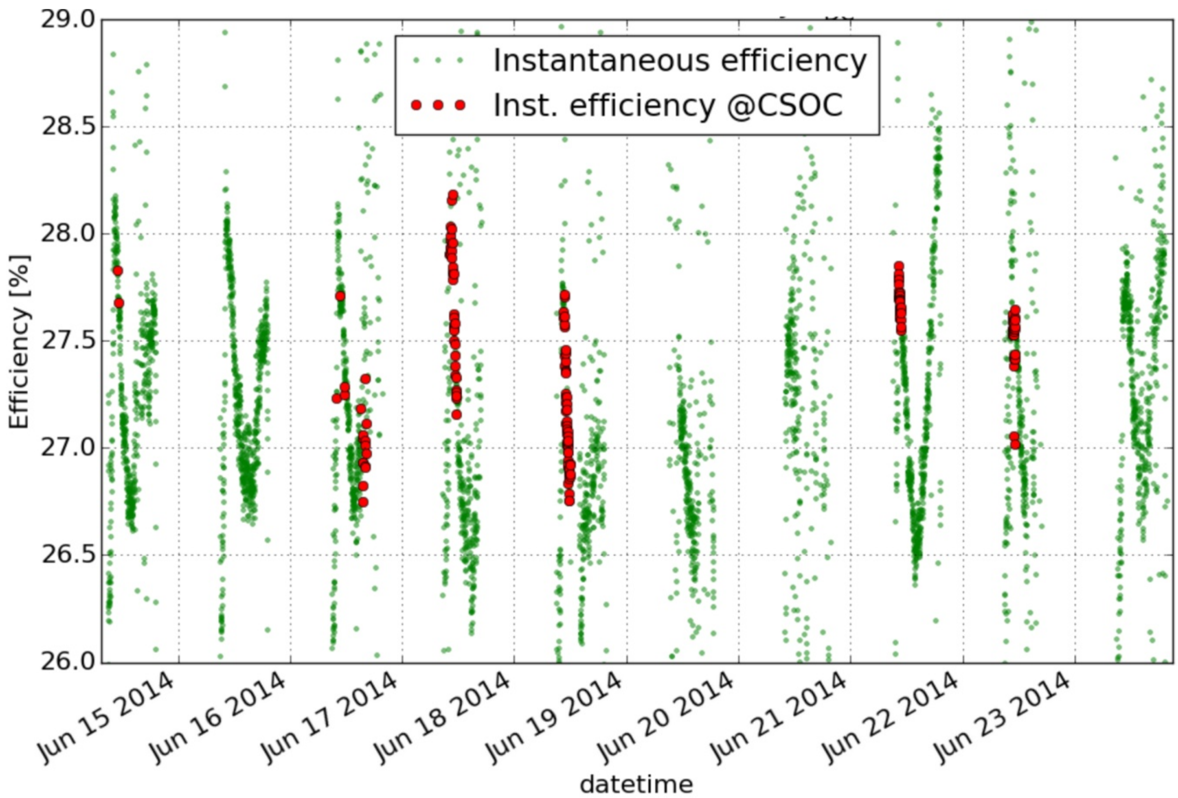


Fig. 19. Output plot generated by the analysis software developed by ENEA representing the summary of the losses in the 50kWp plant contribution normalized to the incident solar energy

(a)



(b)

Fig. 20. (a) 10 kWp system installed at IES-UPM campus with Daido modules and BSQ Solar

trackers. (b) Instanteneous efficiency record.

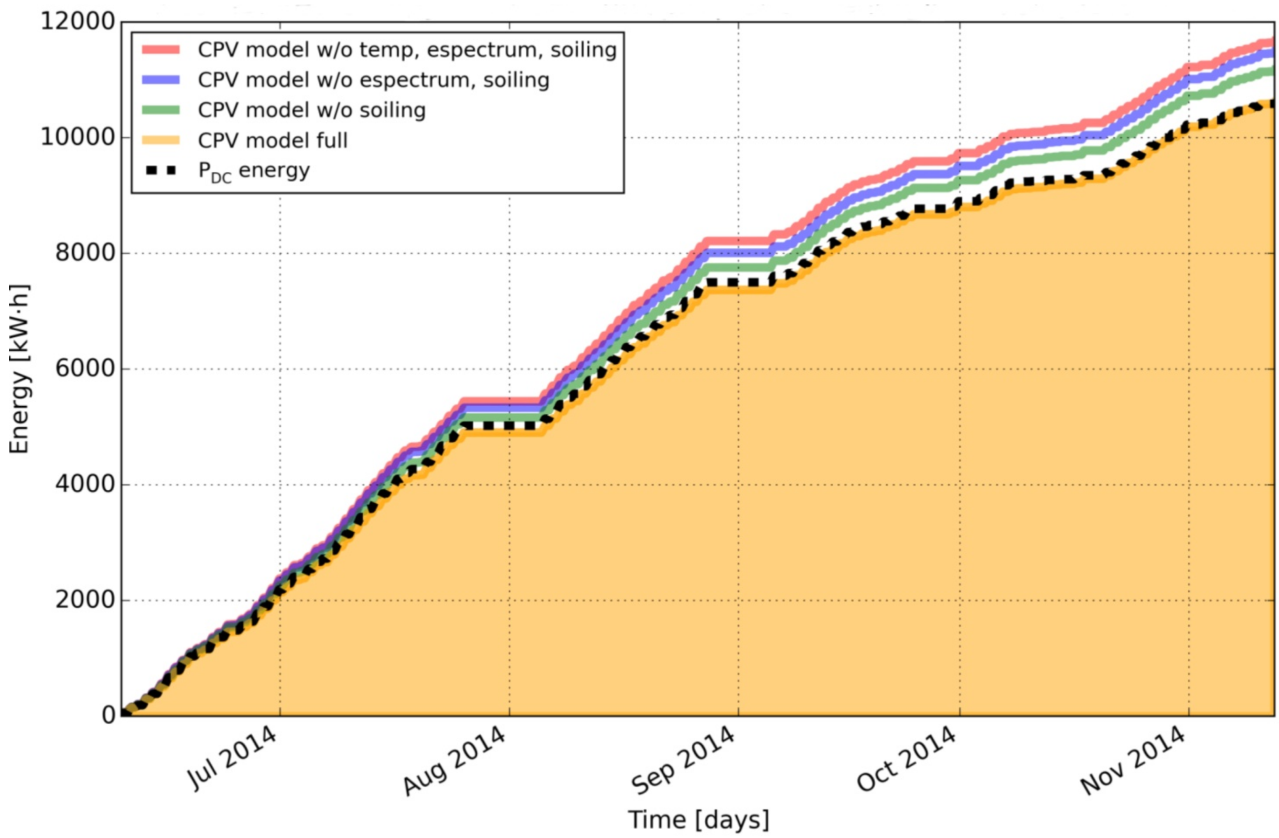
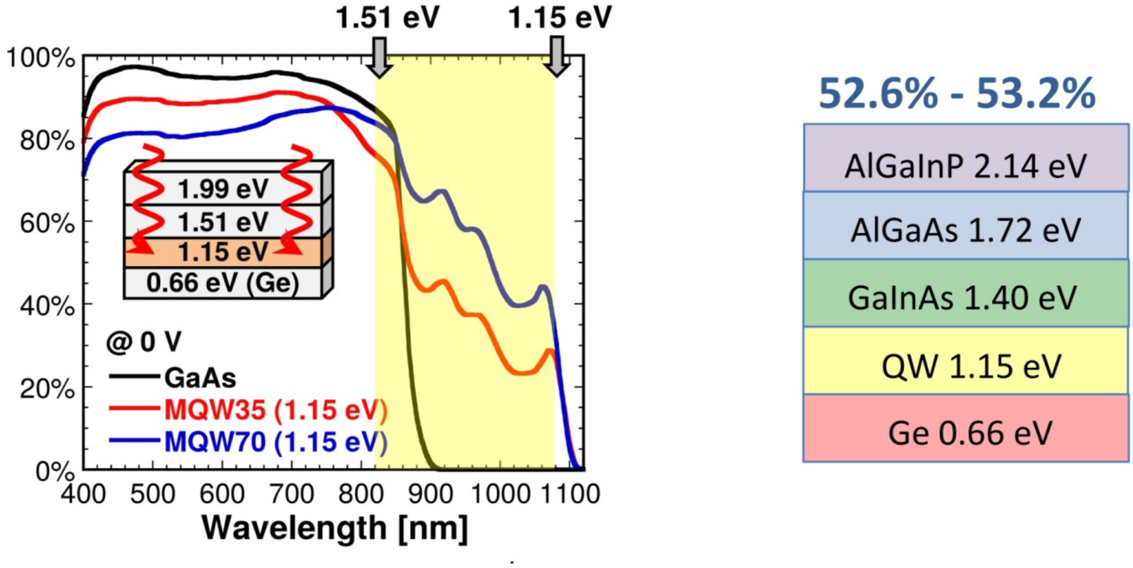


Fig. 21. Application of the energy model developed in the project to the prediction of the accumulated energy produced by the INTREPID plant installed during the Project development.



(a) (b)

Fig. 22. (a) Quantum efficiency of a MQWSC compromissing 70 QW and engineered to exhibit a 1.15 eV effective bandgap (K. Toprasertpong, H. Fujii, T. Thomas, M. Führer, D. Alonso-Álvarez, D. J. Farrell, K. Watanabe, Y. Okada, N. J. Ekins-Daukes, M. Sugiyama, and Y. Nakano, "Proc of the EU PVSEC 2014 " 2014) (b) Proposed structures, with the QW solar cell integrated in it, to achieve a solar cells with an efficiency that exceeds 50 %. (T. Thomas, M. Führer, D. A. Alvarez, N. J. Ekins-Daukes, D. Lackner, P. Kailuweit, S. P. Philipps, A. W. Bett, M. Sugiyama, and Y. Okada, "Potential for Reaching 50% Power Conversion Efficiency Using Quantum Heterostructures," Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto, 2014)

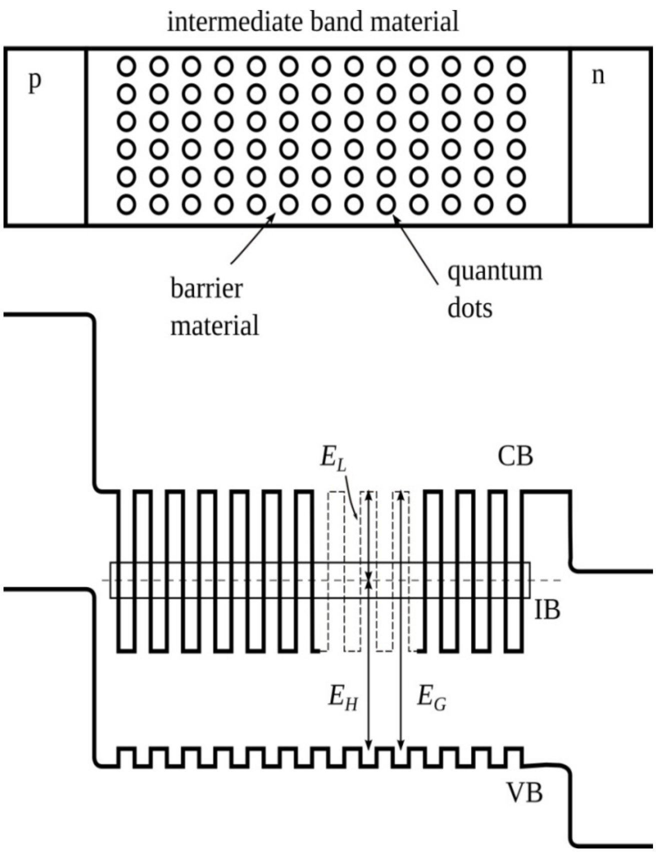


Fig. 23. Schematics showing the basic layer structure (above) of an intermediate band solar cell implemented with quantum dots and (below) the related simplified bandgap diagram (Instituto de Energía SOlar – UPM) [A. Martí, L. Cuadra, and A. Luque, "Quantum dot intermediate band solar cell," Conference Record of the Twenty-Eighth IEEE Photovoltaic Specialists Conference, 2000., pp. 940-943, 2000].

REFERENCES

[1] H. Suzuki, T. Yamauchi, T. Haraguchi, A. Fukuyama, and T. Ikari, "Si Doping in Atomic Layer Epitaxy of GaAsN Thin Films For Multi-Junction Solar Cells," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[2] T. Aihara, T. Murakami, H. Kuradome, T. Sugimoto, H. Suzuki, A. Fukuyama, T. Ikari, K. Toprasertpong, M. Sugiyama, and Y. Nakano, "Demonstration of the Mini-band Investigation in Strain-Balanced InGaAs/GaAsP Quantum Well Solar Cells by Combination of a Piezoelectric Photothermal and Photoreflectance Spectroscopies," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[3] H. Suzuki, D. Ito, A. Fukuyama, and T. Ikari, "Reduction of rotational twin formation by indium pre-evaporation in epitaxially grown GaAs films on Si (111) substrate," *Journal of Crystal Growth,* vol. 380, pp. 148-152, 2013.

[4] W. Ding, K. Kawano, Y. Li, H. Suzuki, A. Fukuyama, T. Ikari, O. Morohara, H. Geka, Y. Moriyasu, K. Ikeda, N. Kojima, and M. Yamaguchi, "Non-Destructive Investigation of Photovoltaic Performance of GaAs p-n Junction Grown on Si Substrate Using Surface Photo-voltage Spectroscopy," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[5] D. Kodera, T. Nishi, K. Ikeda, T. Sasaki, M. Takahasi, H. Suzuki, H. Nakamura, Y. Ohshita, N. Kojima, I. Kamiya, and M. Yamaguchi, "In situ X-ray Diffraction Study of Strain Relaxation Process of Lattice-mismatched InGaAs / GaAs," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[6] K. Demizu, K. Ikeda, N. Kojima, Y. Ohshita, E.Omar, H. Machida, M. Ishikawa, H. Sudoh, and M. Yamaguchi, "Investigation on the Origin of N-H Complex in GaAsN Grown by Chemical Beam Epitaxy Using Deuterated Trisdimethylaminoarsenic," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[7] K. Ikeda, K. Demizu, N. Kojima, Y. Ohshita, and M. Yamaguchi, "Polarization of N-H Bond in Growth Process of GaAsN by Chemical Beam Epitaxy," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[8] D. Lackner, S. P. Philipps, F. Dimroth, H. Sodabanlu, K. Watanabe, N. Miyashita, M. Sugiyama, Y. Okada, and A. W. Bett, "Monolithically Integrated Multi-Junction Cells built by Multiple Separate Growths in Different Epitaxy Reactors," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[9] H. Nagai, K. Araki, K. Hobo, P. Zamora, P. Benitez, J. C. Miñano, K. Nishioka, Y. Ota, I. Luque-Heredia, J. Hashimoto, T. Ueda, Y. Hishikawa, R. Herrero, S. Askins, I. Antón, R. Núñez, G. Sala, M. Steiner, M. Niemeyer, G. Siefer, and A.W.Bett, "Development of the New DFK CPV Module by NGCPV Japan-EU Collaboration," *6th World Conference on Photovoltaic Energy conversion, Kyoto,,* 2014.

[10] T. Sueto, Y. Ota, and K. Nishioka, "Suppression of dust adhesion on a concentrator photovoltaic module using an anti-soiling photocatalytic coating," vol. 97, pp. 414-417, 2013.

[11] K. Nishioka, Y. Ota, K. Tamura, and K. Araki, "Heat reduction of concentrator photovoltaic module using high radiation coating," *Surface and Coatings Technology,* vol. 215, pp. 472-475, 2013.

[12] P. Benítez, J. C. Miñano, P. Zamora, R. Mohedano, A. Cvetkovic, M. Buljan, J. Chaves, and M. Hernández, "High performance Fresnel-based photovoltaic concentrator," *Optics Express,* vol. 18, 2010.

[13] R. Herrero, S. Askins, I. Antón, and G. Sala, "Evaluation of Misalignements within a CPV module by the Module Optical Analyzer (MOA): A Case of Study Concerning Temperature Effects on the module Performance. ," *6th World Conference on Photovoltaic Energy conversion, Kyoto,,* 2014.

[14] M. Castro, C. Dominguez, R. Nuñez, I. Anton, G. Sala, and K. Araki, "Detailed effects of wind on the field performance of a 50 kW CPV demonstration plant," *AIP Conference Proceedings,* vol. 1556, pp. 256-260, 2013.

[15] R. Nuñez, I. Anton, S. Askins, G. Sala, and K. Araki, "Characterization of CPV arrays based on differences on their thermal resistances," *AIP Conference Proceedings,* vol. 1616, pp. 144-148, 2014.

[16] C. Cancro, S. Ferlito, G. Graditi, R. Nunez, I. Antón, G. Sala, M. Castro, and K. Araki, "Energetic Performances of the 50kW CPV Plant Realized within NGCPV Project," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[17] K. Toprasertpong, H. Fujii, T. Thomas, M. Führer, D. Alonso-Álvarez, D. J. Farrell, K. Watanabe, Y. Okada, N. J. Ekins-Daukes, M. Sugiyama, and Y. Nakano, "Proc of the EU PVSEC 2014 " 2014.

[18] T. Thomas, M. Führer, D. A. Alvarez, N. J. Ekins-Daukes, D. Lackner, P. Kailuweit, S. P. Philipps, A. W. Bett, M. Sugiyama, and Y. Okada, "Potential for Reaching 50% Power Conversion Efficiency Using Quantum Heterostructures," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[19] D. Alonso-Alvarez, T. Thomas, M. Führer, N. P. Hylton, N. J. Ekins-Daukes, D. Lackner, S. P. Philipps, A. W. Bett, H. Sodabanlu, H. Fujii, K. Watanabe, M. Sugiyama, L. Nasi, and M. Campanini, "InGaAs/GaAsP strain balanced multi-quantum wires grown on misoriented GaAs substrates for high efficiency solar cells," *Applied Physics Letters,* vol. 105, pp. -, 2014.

[20] T. Kada, S. Asahi, T. Kaizu, T. Kita, R. Tamaki, Y.Okada, and K. Miyano, "Efficient Two-step Photon Absorption in InAs/GaAs Quantum Dot Solar Cells," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[21] A. Martí, E. Antolín, E. Cánovas, N. López, P. G. Linares, A. Luque, C. R. Stanley, and C. D. Farmer, "Elements of the design and analysis of quantum-dot intermediate band solar cells," *Thin Solid Films,* vol. 516, pp. 6716--6722, 2008.

[22] Y. Shoji, R. Tamaki, A. Datas, A. Martí, A. Luque, and Y. Okada, "Effect of Field Damping Layer on Two Step Absorption of Quantum Dots Solar Cells," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[23] A. Luque, A. Mellor, E. Antolín, P. G. Linares, I. Ramiro, I. Tobías, and A. Martí, "Symmetry considerations in the empirical k.p Hamiltonian for the study of intermediate band solar cells," *Solar Energy Materials and Solar Cells,* vol. 103, pp. 171-183, 2012.

[24] A. Luque, A. Mellor, I. Tobías, E. Antolín, P. G. Linares, I. Ramiro, and A. Martí., "Virtual-bound, filamentary and layered states in a box-shaped quantum dot of square potential form the exact solution of the effective mass Schrödinger equation," *Physica B,* vol. 413, pp. 73--81, 2013.

[25] A.Luque and A.Martí, "Spectrum and Light Absorption in Nanostructured Photovoltaics," *Proc of 6th World Conference on Photovoltaic Energy Conversion, Kyoto,* 2014.

[26] EPIA, "Global market outlook for photovoltaics," 2014.

[27] SEIA, "U.S Solar Market Insight," 2014.

[28] G. Research, "Roadmap for CPV Technology," 2011.

[29] C. Today, "The concentrated photovoltaics industry report 2010," 2010.

[30] J. E. Haysom, O. Jafarieh, H. Anis, K. Hinzer, and D. Wright, "Learning curve analysis of concentrated photovoltaic systems," *Progress in Photovoltaics,* 2014.

[31] IRENA, "Renewable Energy Cost Analysis - Solar Photovoltaics " 2012.

[32] V. M. Fthenakis and H. C. Kim, "Life cycle assessment of high-concentration photovoltaic systems," *Progress in Photovoltaics,* vol. 21, pp. 379-388, 2013.