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Concept of a methodical process for the design of concentrating photovoltaic systems according to the context of use

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ABSTRACT

Concentrating Photo Voltaic (CPV) systems maximize energy harvested from the sun with multi-junction solar cells of less area, reducing related implementation costs and reaching energy production thresholds up to 38,9 %.
Nowadays, CPV systems are generally implemented in solar energy farms in a permanent location, however, these systems could be used in other dynamic contexts, such as vehicles or portable devices. In this way, mechanical and geometrical parameters related to manipulation, transportation and installation should be carefully considered at the design stage. Besides, each condition of use presents different variables affecting these parameters. In all, there is not an established architecture for these systems, opening up the possibility of radically changing their use, geometry and components.
Therefore, a concept of a methodical process for designing of CPV systems is proposed in order to predict their behavior in terms of implementation and energy production. This might allow the development of robust concepts that can be adapted to different context of use as required, providing an itinerant character and thus extending the field of implementation of these systems beyond a static use.
The relevant variables for the use of CPV systems are determined through experimentation considering the implementation of Fresnel lenses as light concentrators. This allows generating a structured design guide composed of different methods of measurement, selection and development. The methodical process is based on a perspective of functional modules considering needs, technical aspects and particular usage conditions of each design and it would provide appropriate guidelines in each circumstance.

Keywords: Concentrating Photo Voltaic (CPV), Fresnel lens, Alignment process, Design and assembly, Context of use, Tolerances ratio (TR), Performance Index

1. INTRODUCTION

*A **Concentrating Photo Voltaic** (CPV) system converts light energy into electrical energy in the same way that **conventional photovoltaic technology** does, but uses an **advanced optical system** to focuses a large area of sunlight onto each cell for maximum efficiency. Different CPV designs exist, sometimes differentiated by the concentration factor, **such as low-concentration** (LCPV) and **high concentration** (HCPV).* [1]

There are many types of CPVs differentiated by their components, architecture or physical configuration and some values of characteristic parameters. A CPV has three essential components: first, an optical element that can work by refraction or reflection to redirect and concentrate the sunlight, so this element can be a lens or a mirror with different forms and geometries. The second component is the photovoltaic element that transforms the sunlight redirected by the optical element in electrical energy and, for these applications, this is usually a high-performance small solar cell of GaAs or multi-junction. The last component is an interface element, which integrates the other components to define the final geometry of the CPV. This last element varies according to the CPV type or optical element used. The implementation of various CPVs in a same interface element integrates a functional module allowing the achievement of high energy standards specifically developed for punctual requirements.

By Implementing these systems properly, it is achieved a better balance of cost/benefit ratio, obtaining increased energy production without incurring in the high cost associated with photovoltaic elements. However, the implementation of the

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concentration systems brings new challenges related with parameters and exclusive conditions of use, which have been studied and solved progressively seeking to strengthen the use of this technology.

It should be mentioned that the CPV systems generally come with a solar alignment or a solar tracker system [2] because they work exclusively with the component of direct light from the sun, i.e., the rays of light coming out from the sun and enter the optical element perpendicularly. Therefore, this relative position should ensure the operation of the system all the time. This type of solar aligners has been vastly studied and currently various related technological developments are presented, where active components represent an energy expenditure of the system. In this sense, the component of the weight of CPV systems is important because in order to move more weight it is required a greater energy expenditure, also, lighter systems facilitate handling on the part of operators or final users. This paper proposes a new methodical process to design and integrate CPV systems considering real efficiencies of the components and including environmental variables.

Section 2 presents the background of the CPVs and their principal parameters, methods for development, aligning, and assembly of CPV systems based on lenses performance, measurement and control of the different variables that affect the behavior of these, and, finally, a practical case demonstrating the need to improve the predictions of power production. Section 3 exposes the proposed methodical process beginning with the definition of the main variables included in the approach and explaining each stage composed by different steps ending with an algorithm that related all the analyzed parameters for the power prediction. Finally, section 4 presents some conclusions about the proposed method.

2. BACKGROUND

The parameters governing the performance of the CPV systems vary to some extent by the elements used and the functional principles of these. However, for more configurations there are parameters that can be generalized. Anyway, elements that most variation present are the optical ones, and these type of components have behaviors defined by the same physical principles. Figure 1 presents three types of optical elements used in CPV systems: parabolic mirrors on the left, reflectors or flat mirrors in the center and Fresnel lenses on the right [3].

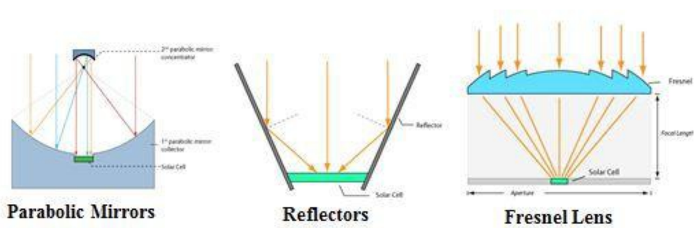


Figure 1. Some types of optical elements used for CPV systems [3].

One of the most important parameters in all CPV systems is the Concentration Factor (CF), defined in Equation 1, that determines the level of energy production of the system and corresponds to the ratio between the area of the optical element and the area of the photovoltaic element.

$$CF = \frac{Optical\ element\ area}{Photovoltaic\ element\ area} \quad (1)$$

According to Chemisana, there are three main levels of CF: high concentration factor when the factor is greater than 100 (CF > 100), medium concentration factor when the factor is between 10 and 100 (10 < CF < 100) and low concentration factor when the factor is less than 10 (CF < 10) [2].

High CF allows theoretically much greater energy production; however, systems with these configurations have higher requirements. On the one hand, a factor of very high concentration also represents a high temperature, which could result in degradation in the solar cell if the temperature is not properly controlled; on the other hand, these concentration factors determine a parameter known as the acceptance angle. According to Chemisana, high concentration factors always require a solar tracker of two axes with a margin of error in the acceptance angle less to 0.2°, while the middle and lower factors have lower tolerances and can work with trackers of a single axis or even eliminate these systems [2].

Although this parameter is common in any CPV system, the use of certain optical elements or certain configurations of use facilitates or restricts the reach of high concentration factors because for these levels it is required the most possible difference between the optical and photovoltaic areas. So, in optical systems with line focus or line-shaped, the difference of areas is much smaller compared to optical systems with shaped focus point. These configurations are shown in Figure 2 with Fresnel lenses of line and point focus on the left and reflectors or parabolic mirrors of line and point focus on the right [2].

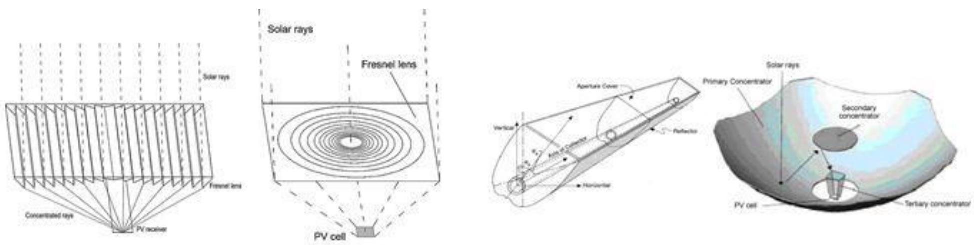


Figure 2. CPVs with lenses Fresnel and parabolic mirrors with line and point focus [2].

Another important parameter is the focal length, which must be ensured between the optical element and the photovoltaic element to focus the light exactly on the photovoltaic cell. This parameter arises directly from the focal length featured at any optical element that presents a focus, but in CPV systems, it is directly related to the alignment of the components. In Figure 3 the most relevant general parameters for CPV systems are summarized.

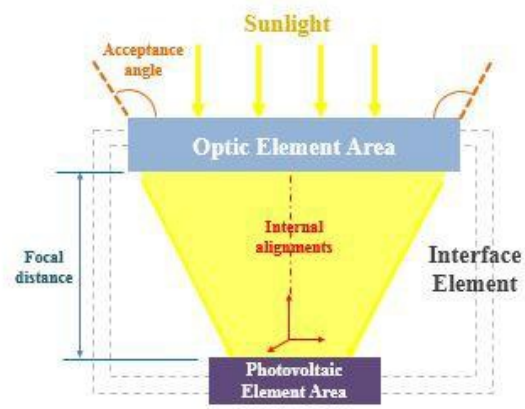


Figure 3. Main components and parameters of a CPV.

In order to capture as much energy as possible, there must be a precise alignment between the used optical systems and photovoltaic cells, which is achieved through a strategy of assembly, and alignment that allows finding the position of better efficiency of the cell in relation to the focal point of light. Likewise, it is evident the need to develop an interface element that serves to integrate other components, giving structural character and a defined architecture to the CPV and preserving alignment conditions according to the design and conditions of use. The implications of bad processes of design, manufacturing, assembly and alignment are illustrated in Figure 4.

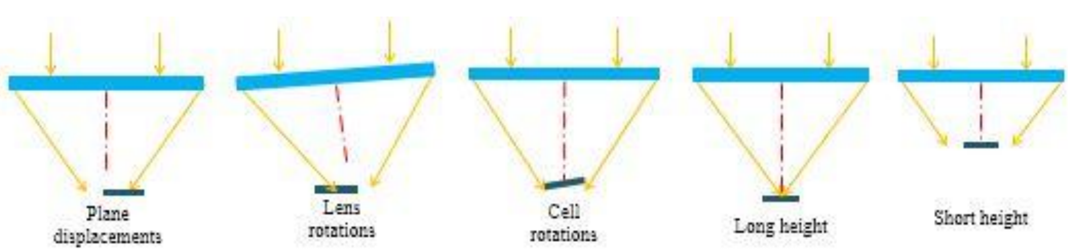


Figure 4. Assembly errors that can be present in CPVs.

For several decades, CPV systems have been the center of attention of institutions and researchers around the world [4]. However, only in recent years this knowledge has been moved to industry which have begun to market these systems, presenting them as a real highly useful alternative that offers great benefits compared to traditional photovoltaic systems, as they have the potential to reduce costs associated with the production of solar energy by making it more affordable and competitive in terms of renewable energy. This added to a model for large-scale energy production can lead to a significant increase in cost-benefit terms.

Contemporary companies like “SEMPRIUS”, “MORGAN SOLAR”, “AIRLIGHT”, “SOLFOCUS”, “AZUR SPACE” and “SOITEC” [5] [6] [7] [8] [9] manufacture and market CPV systems and high efficiency photovoltaic cells. Most of these companies are focused on solar power plants and large-scale installations, including solar tracking system and assembly and installation services. Most commonly used optical technologies are the Fresnel lenses, plane-convex lenses and parabolic mirrors or faceted parabolic mirrors.

2.1 Focus of lenses

The main manufacturers of CPV systems for high-energy production plants use Fresnel or plane-convex lenses shown in Figure 5. However, these elements have facilitated the development of CPV technology of smaller scale, through smaller functional units that can be integrated, strengthening more their scalability for different approaches.

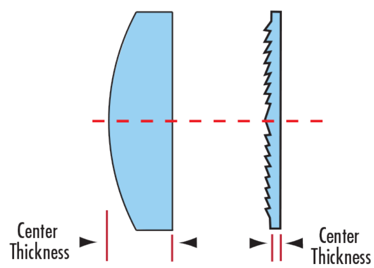


Figure 5. Plane-convex and Fresnel lenses [10].

Plane-convex lenses have good optical efficiency allowing the penetration of most light into the cell except what is lost by absorbance due to the material properties of the lens. Nevertheless, the biggest disadvantage of the plane-convex lenses is its large volume due to the relationship between the diameter and height of the lens for a given focal point. This situation limits the dimensions of these elements by weight and production cost, limiting the possibility of achieving high concentration factors with largest photovoltaic cells [4].

Meanwhile, Fresnel lenses allow to reach a wide range of concentration factors varying the diameter of the lens freely without disproportionate increasing in weight and production cost. Although they lose a little more efficiency compared with plane-convex lenses, this loss can be included in the functional model of the systems to overcome it.

The application of technologies such as CPV systems have promoted the creation of companies that develop and distribute Fresnel lenses with a variety of options; including lenses designed specifically for solar concentration. Thanks to their thin geometry, companies have been able to make developments in different materials such as PMMA or PC, materials that do not affect significantly the optical properties of lenses compared with glass, but reduce its weight and fragility. This market simplifies the process of design and development of CPV systems eliminating the need to design and produce their own lenses.

In order to propose a methodical process of design, manufacture and assembly, it was decided to focus the proposal on CPV systems with Fresnel lens due the advantages exposed. To develop the proposal it was necessary to study methods and tools existing for the development of CPVs and how the different variables and parameters are analyzed and integrated in these processes.

First, it was performed a research of existing methods of development and assembly of CPV systems based on refractive optical elements such as Fresnel lenses or plane-convex lenses, starting from the three basic elements that make up the CPVs (Photovoltaic Element, Optical Element and Interface Element). In addition, methods and tools used for align optical elements developed for CPV systems and finally, the existing methods to determine the impact of different variables related to the use conditions and manufacture of CPV systems based on design and assembly tolerances were studied**.**

2.1.1 Methods of development and assembly of CPV systems based on refractive optical elements

In terms of technological development, two approaches clearly characterized in the design and manufacture of CPVs based in refracting optical elements can be identified.

The first is the development of a highly industrialized level CPVs with micro-components. These CPVs are currently governing the market and are developed by companies like "SEMPRIUS" or "SOITEC" [5] [9] which use highly technological and automated processes based on printing methods and Surface Mount Technology (SMT) for cells and other electronic elements [11] [12]. These methods are traditionally used for electronic assemblies on a small-scale (micrometers or millimeters) requiring high precision, giving this type of CPVs a robust character that improves efficiency, reliability and performance. Figure 6 Shows a CPV module of “SEMPRIUS” [5].

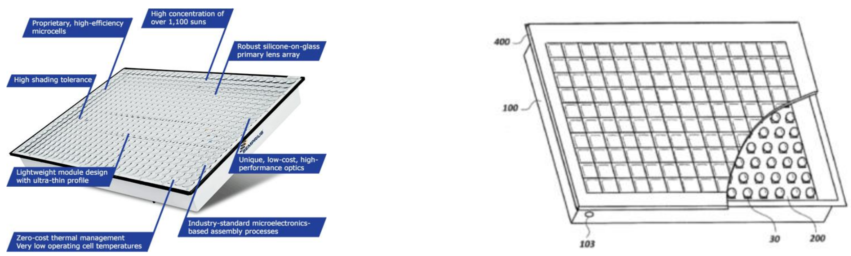


Figure 6. CPV module of “SEMPRIUS” [5] [12].

This approach of CPVs does not present details about the primary lens, their manufacture and proper assembly in relation to the photovoltaic cell and just indicates the use of panels of Fresnel lens or plane-convex lenses aligned with the cells. However, it is perceived the use of secondary lenses bonded on the photovoltaic cell. These elements increase the acceptance angle of the CPV in relation to light beams reducing the degree of precision required to assemble and align the primary lens relative to the cell, also distributing homogeneously the light incident on the photovoltaic cell to improve the performance of the system [11] [12] [13].

For the chassis, these designs have a geometry of tray-type formed in one piece and in various plastic and metal materials. These kind of chassis have bearing surfaces at the edges to assemble the primary lenses and create together a closed module but there are not many details of this.

Despite its great benefits, such CPVs are highly expensive and their manufacture requires very specialized and complex machinery, which represents a significant barrier if manufacturers want to implement these processes for local development of CPVs.

The second approach of development CPVs is based on less sophisticated and automated processes where larger scale components are used and essentially a process of integration of components may be defined, as it is presented in Figure 7. These developments have a more investigational character and less industrialized and different developments focused on the different components of the CPVs, lenses, cells and chassis [14] [15] [16] [17].

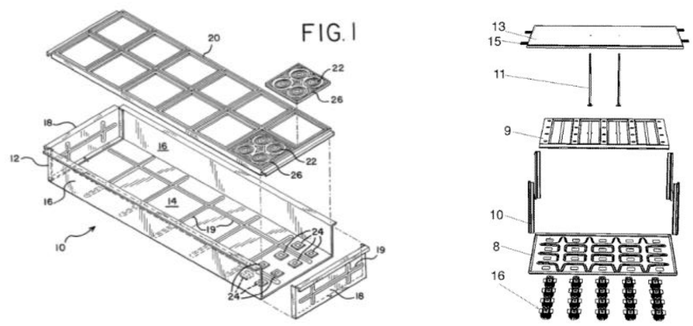


Figure 7.CPV modules developed by components integration [15] [16].

Generally, modules of photovoltaic cell ready for connection and installation are used and in some cases are assembled in thermal dissipation structures and with secondary lenses, as optical elements. With or without secondary lenses, these CPVs use mainly Fresnel lenses in form of panels or arrays composed by many lenses and individual assembly lenses [15] [17] [18].

The interface element or chassis of these designs presents the form of boxes and most times the faces are developed separately and assembled with mechanical elements or adhesives, sometimes these have frames in rigid materials such as steel in order to integrate walls of lighter materials [14] [15] [16] [17].

Assembly and alignment processes of these CPVs are based primarily on the development of components manufactured through CNC technologies that ensure greater precision in the pieces that can be used as aligners. Sometimes the use of jigs, dies or external fixtures, like work tables previously aligned and designed, is specified to provide reference structures for the assembly of CPVs. Kinematic joints, conical aligners or reference holes are used to ensured exact positions of the parts which are assembled with mechanical components such as rivets, screws or adhesives. Lenses are aligned using lasers properly positioned perpendicularly to show focal points, besides using guides and reference surfaces [16] [17] [18].

2.1.2 Methods and tools used for aligning optical elements for CPV systems

Methods and tools, with more information from the literature, for alignment of concentration systems have been developed especially for systems with faceted mirrors [19]. In terms of alignment with lenses of CPVs there is very little information. However, some of the methods found can be adapted for use in aligning lenses of CPVs.

Starting with the most basic methods like visual alignment or alignment with inclinometers where simple accessible tools are used and sometimes for not depending on the sun, lasers are used to perform visual alignments. These systems are easy to implement and are not expensive, but their cost can see reflected in the time required to perform the alignment processes and greater possibility of error by the person involved [19].

Position Sensing Detector (PSD) are often used as precision systems in combination with lasers and prisms, and, more recently, cameras and systems of image processing have been used as methods of photogrammetry and fringe reflection, making developments of specialized software to refine alignment processes through computer media [19]. Some methods for alignment are presented in Figure 8.

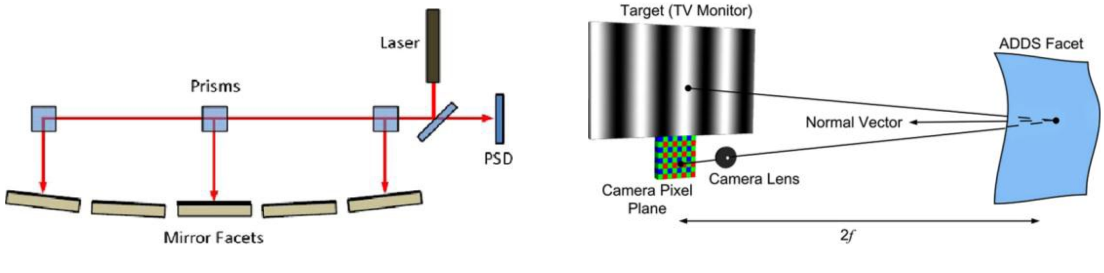
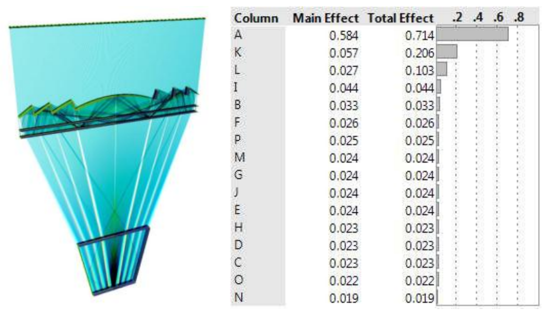


Figure 8. Some methods for alignments of mirrors [19].

2.1.3 Methods for measuring impact of variables related to the use conditions and manufacture of CPV systems

Numerical methods and analysis of computational models can perform simulations of cases and scenarios to determine the impact of different conditions and variables on the behavior of the modeled systems. This is the case of “MORGAN SOLAR INC.”, where a sensitivity analysis process, supported by a simulation tool called MSOS, simulates the impact of different parameter values to determine the performance of the systems developed. Such analysis is presented in Figure 9. In this way, it is possible to see the most sensitive points in the development, assembly and implementation process of systems and identify the most influential parameters without making constant real tests [20].



Column	Main Effect	Total Effect
A	0.584	0.714
K	0.057	0.206
L	0.027	0.103
I	0.044	0.044
B	0.033	0.033
F	0.026	0.026
P	0.025	0.025
M	0.024	0.024
G	0.024	0.024
J	0.024	0.024
E	0.024	0.024
H	0.023	0.023
D	0.023	0.023
C	0.023	0.023
O	0.022	0.022
N	0.019	0.019

Figure 9. Sensitive analysis performed by “MORGAN SOLAR INC.” through MSOS software [20].

To measure and predict some of the most complex variables such as the environmental variables, actual standardized tests are usually carried out over a period of six months to one year. During this period, the studied systems are positioned in a solar tracker with two axes and data of misalignments, meteorological variables, current-voltage curves and data of Direct Normal Irradiance (DNI) are taken. After testing, a data analysis is performed in order to find possible correlations between variables measured and finally, the results can be extrapolated to different locations to predict specific behaviors of the systems [21]. An example of such characterization is presented in Figure 10.

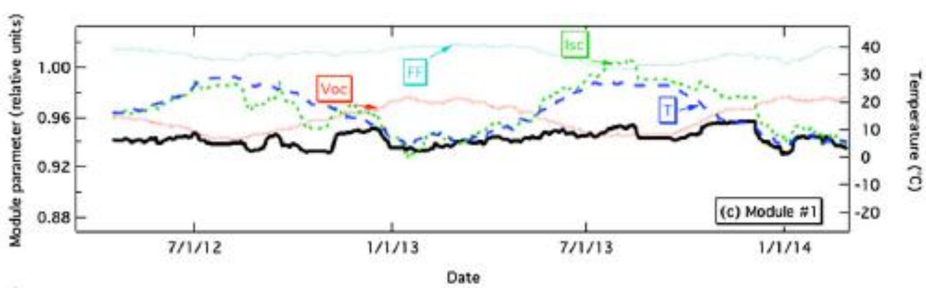


Figure 10. Characterization data of a CPV tested [21].

From these analyses it is possible to identify that the environmental variables affecting the behavior of CPV systems are [21] [22]:

- The temperature, not only at the level of the photovoltaic cell. Although cells compromise their efficiency as a function of temperature, must be considered that the lenses suffer deformations that can change their refractive properties. This type of phenomena has not yet been deeply studied.
- The humidity and dust or solid material can cause damage to systems, corrosion, and even affect the passage of light from the lens to the cell by dirt or condensation effects.
- The rainfall can cause structural damage, shorts circuits and indirectly determine the level of sun that receives the system. Therefore, places with high rates of rainfall will present higher index of cloudiness and, furthermore, low levels of Direct Normal Incidence (DNI) required for the system to function properly.

2.1.4 Theoretical development and practical case

The authors developed a CPV system to be used in the World Solar Challenge 2015. Theoretical calculation was carried out with Equation 2 [23] in order to describe the behavior of the system and predict its energy production.

$$E = (A_c * S * R * \eta_c * \eta_{ot} * \eta_s * N_{CPV} * t_{CPV}) \quad (2)$$

For the basic calculation of the potential theoretical energy of CPV systems the values of the most important parameters are operated, such as A_c = photovoltaic area, S = number of suns or concentration factor, R = solar radiation and efficiencies of the components, η_c = cell efficiency, η_{ot} = optical efficiency, η_s = system efficiency, such as electrical components, N_{CPV} = quantity of CPVs and t_{CPV} = time of use ot the system [23].

The CPV system was designed with 60 CPVs, triple-junction cells of 5,5x5,5 mm^2 of 42% of efficiency, concentrator factor of 437,2 suns, Fresnel lenses of acrylic (PMMA) of 115x115 mm^2 and 180 mm of focal length and optical efficiency of 92% approx., as it is presented in Figure 11. The efficiency of the system by connections was calculated in 90 % approx.

Figure 11. CPV module designed and developed by the authors.

For the design and manufacture of the system, tools, such as a laser aligner for Fresnel lenses, were created and the interface element was designed to be rigid and lightweight, as it is shown in Figure 12. The geometry was based on two functional modules with tray form where the photovoltaic cells were manually assembled.

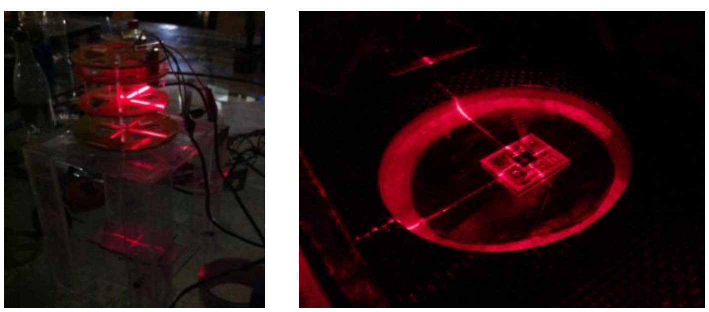


Figure 12. Laser aligner for Photovoltaic cells and Fresnel lenses developed by the authors.

According to Equation 2, the power production of the system was calculated excluding the time factor and the result suggests 276 Watts of power including the data of desing mentioned before. However, the real power measured was 110 Watts, 40% less than the theoretical prediction.

After testing the designed CPV system it was concluded that since the high-energy production come from the integrated work of each cell, the proper alignment of each one is fundamental to improve the performance of the system. For a specific purpose, not only a correct assembly and alignment process is necessary, but also the design of an interface element capable of keeping this alignment condition is required. Because of this, the rigidity is the most important property needed for the interface element for CPV systems.

The theoretical model of the Equiation 2 does not include factors such as temperatures and deformations effects. Also, the solar radiation factor should be delimited only for the DNI that is the real light component used by the CPV systems. However, DNI can vary drastically with time, so that this function in terms of energy is assumed for constant DNI or an average during used time. For the immediately verification of the calculation error, the power can be a more useful value because it is measured in a specific instant with the real value of DNI.

The improvement of prediction methods and also the development of a method to obtain a best performance of CPV systems are evident. For this reason the methodical process is proposed in the next section.

3. METHODICAL PROCESS PROPOSAL

The variables identified can be separated in three groups:

1) Component variables, considering the cell efficiency, the lens efficiency and the interaction between the integration cell-lens. Efficiencies of the components, given by their manufacturers in a datasheet. They represent an initial value to approximate the real performance of a CPV system but, due to the interaction between these elements, they can present a different behavior with the theoretical properties of each component separately. It is necessary to understand the impact of this interaction in the energy production and finally in the real performance of the system.
2) Geometrical variables, which are composed by three displacements for each axis (x, y, z) and one rotation in relation to the cell-lens couple. This group of variables is determined specifically by the manufacture and assembly process and can be traduced in tolerances.
3) External variables or environmental variables like work temperature, wind forces, humidity levels and precipitation levels. These variables are obtained from the context or contexts of use and they must be included, since these values have strong influence in the design and manufacture stage and later they have direct impact in the behavior of the CPV system.

With the identified groups of variables, the methodical process of design and integration for CPV systems based on design methodologies is defined. The variables are separated in design stage and the specifics steps of the process try to control each variable. Figure 13 shows a conceptual diagram, which simplifies the complete process proposed in this paper.

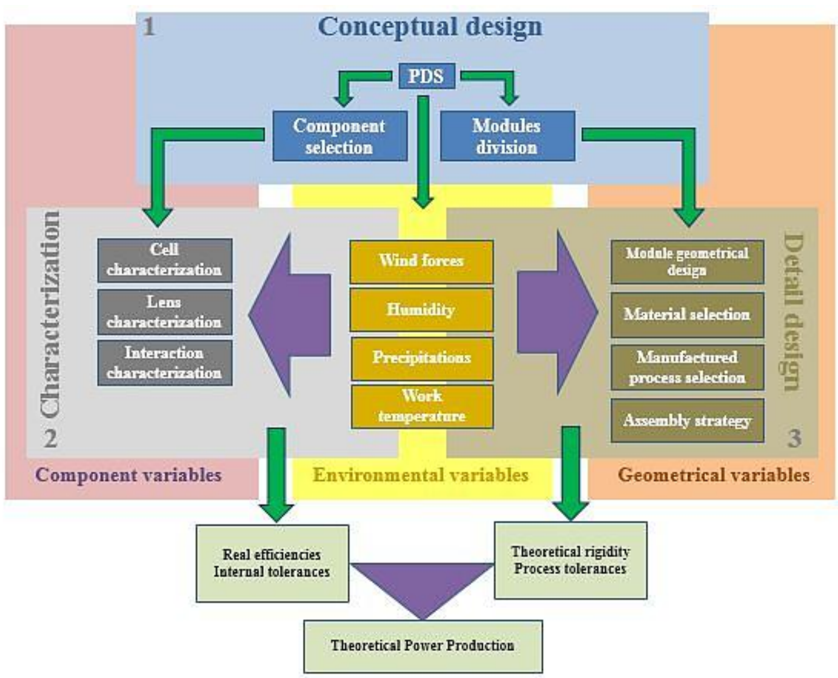


Figure 13. Graphic summary of the methodical process proposed.

The methodical process consists in three main stages: the conceptual design, the characterization and the detail design. The groups of variables mentioned before are implicit in each stage, except the group of environmental variables since these are transversal to the whole process, as it is exposed in the Figure 13.

In this way, with the characterization stage in co-analysis with the environmental variables, the real efficiency of the interaction lens-cell, called performance index, is achieved depending on the internal tolerances of this interaction described in the second group of variables. On the other hand, the detail design stage, considering the environmental variables, allows to get the deformation tolerances of the system to keep an energy production limit in determined use conditions, and the tolerances of the process of manufacture and assembly which must be compared with the internal tolerances of the system, in order to determine the energy production that can be reached by process limits and predict a real performance of the designed system. Therefore, the context of use is not just included in the environmental variables but it is also included the context of development and production.

Figure 14 presents the flux of the proposed process along with the results of the stages. This can be an iterative process that can return to any stage at any time.

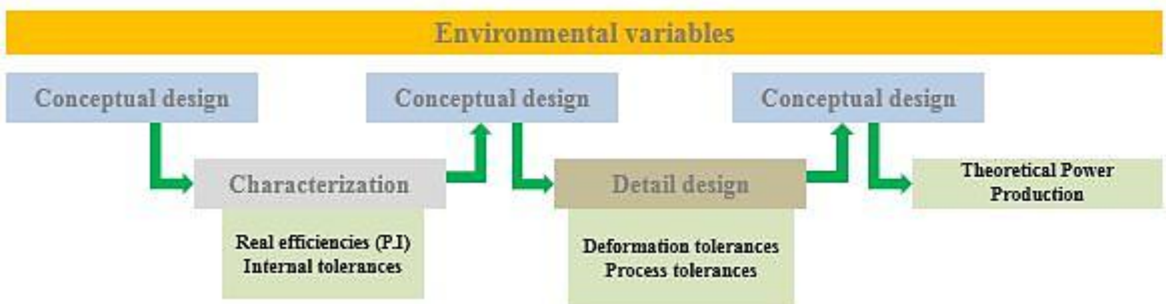


Figure 14. proposed flux for the omplementation of the methodical process.

3.1 Conceptual design

This stage transforms the requirements of the system in a basic conceptual design considering the main elements of a CPV system, the optical element and the photovoltaic element.

3.1.1 Product Design Specifications

The conceptual design begins with the definition of a Product Design Specification (PDS), according to Pugh [24], where he identified 32 basic elements that can be specified, in order to get the better possible description of the requirements of any product and generates a more complete concept that satisfies all the needs for which it was created.

In this case, the PDS can be reduced to the next basic specifications:

- Performance: this parameter describes the energy requirements of the system, and it can be expressed as power in Watts or as energy in Watts per unit of time. It is the most important requirement because is the value that can be reached with the design process.
- Size: in some cases, the space available for the system can be limited in terms of either area or volume, even in different moments of the use of the system, for example, there can be a limitation for the storage space to transport the system.
- Working environments: the contexts of use of the system must be described in terms of variables that have direct relation with the energy production. In this way, the main environmental variables are the working temperature, the wind forces, the humidity levels and the precipitation levels. These conditions can suggest the use of heat dissipater in the cell, the necessary rigidity for the system alignments, possible materials for the interface element and duty or water conditions that can affect the performance of the system and cause damage. This could be prevented with additional elements that guarantee some levels of International Protection (IP) according to the international regulation IEC 60529.

3.1.2 Component selection

In this step, the general components must be selected according to the PDS. First, it is recommended to select the photovoltaic cell because there is less offer and variation for these elements in the market and they usually have higher costs. These components determine other considerations for the rest of elements, the photovoltaic cells for CPV systems are usually small cells based on more photovoltaic materials besides Silicon, which leverage more wavelengths of the light, managing to reach efficiency levels up to 40%. This efficiency is used in relation to the cell area and the concentrator factor to calculate a first theoretical power production. Therefore, their selection is determined mainly by the energy requirements in the PDS; as it is shown in Figure 15 [8].

Sun Concentration	I_{sc} [A]	V_{oc} [V]	I_{MPP} [A]	V_{MPP} [V]	P_{MPP} [W_{MPP}]	FF [%]	D [%]
Version MC/Air Grid optimized for medium concentration + Antireflective Coating adapted to air							
X 250	1,16	3,07	1,14	2,82	3,21	90,1%	42,0
X 500	2,33	3,11	2,29	2,79	6,40	88,3%	41,9
X 1000	4,68	3,13	4,57	2,70	12,33	84,2%	40,4
Version MC/Glass Grid optimized for medium concentration + Antireflective Coating adapted to glass							
X 250	1,15	3,07	1,13	2,81	3,18	90,1%	41,7
X 500	2,31	3,10	2,27	2,80	6,35	88,7%	41,6
X 1000	4,61	3,13	4,52	2,71	12,24	84,8%	40,1

Figure 15. Datasheet of a triple-junction photovoltaic cell manufactured by "AZUR SPACE" [8].

Each manufacturer describes the behavior of the cells in terms of power production with standards of solar irradiation of 1000 W/m^2. The typical areas of these cells are $10mm^2$, 5 mm^2 or less because while smaller the cell, higher concentrator factors can be obtained with smaller optics elements.

With the photovoltaic cell defined, the next step is to define the Fresnel lens. The first consideration is the concentrator factor, which determines the lens area to get a specific energy production. Then, there are other important aspects like the optical efficiency, the material, grooves density, the transmittance, etc. Some of these aspects are presented in Figure 16 [10]. Fresnel lens can be designed specifically for solar energy applications, but the most common and cheapest lenses are for optical applications, which are not highly efficient compared to the lenses designed for solar applications. For CPV systems, it is recommended to use non-imaging Fresnel lens, with less grooves density and high F number, i.e., less diameter and higher focal length [4]. Finally, the efficiencies of these two components, cells and lenses, are the first real approach to the efficiency of the CPV system, and Equation 2 can be used as a first approach for energy calculation.

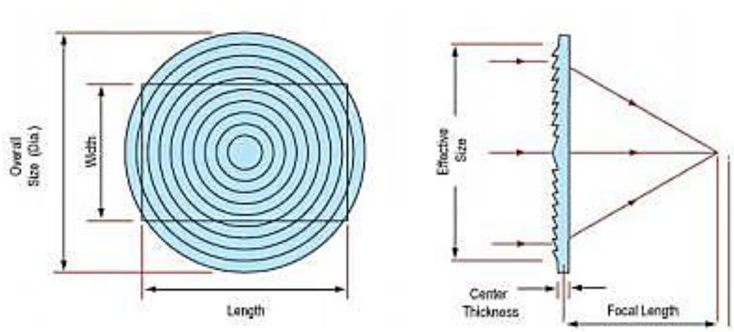


Figure 16. typical Fresnel lens graphic by "EDMUND OPTICS INC" [10].

3.1.3 Module division

To generate functional modules of CPVs, first, it is necessary to determine the quantity of the individual CPVs that will be used to integrate the whole system. This number depends on the energy requirements described in the PDS. In this way, the number of CPVs is obtained dividing the needed power between the maximum power of a CPV, as it is shown in the Equation 3.

$$N_{CPV} = \frac{W\ needed}{Wmpp} \tag{3}$$

Typically, the CPV systems are separated in functional modules and this division allows building units perfectly functional with the possibility to scale them integrating various modules to conform bigger systems in order to generate more energy.

Additionally, requirements of size related with storage dimensions or deployment dimensions can limit the minimum functional module size, the number of functional modules or, even, the number of CPVs, also limited by the available area for lenses. These limitations are represented in Equations 4 and 5.

$$N_{CPV} = \frac{Deployment\ area}{Lens\ area} \tag{4}$$

$$N_{Modules} = \frac{Deployment\ area}{Storage\ area} \tag{5}$$

3.2 Characterization

This stage is oriented to test the real behavior of the selected components under an approach of the environmental variables in order to get a more exact prediction of the expected power. Therefore, it is necessary to get some samples of the main elements of the CPV system. Through the Performance Index (PI) a conceptual coefficient that can be operated in the energy calculation is obtained.

3.2.1 Cell characterization

This process allows checking the behavior of the cells under real or simulated work conditions having the data of performance from the manufacturers as starting point. In this way, it is possible to adapt the efficiency of the cells through the Equation 6, where η is the percentage efficiency; P_m is the real power obtained from the cell; E is the sun irradiation and A_c is the photovoltaic area.

$$\eta = \frac{P_m}{E * A_C} \tag{6}$$

3.2.2 Lens characterization

With the selected lens, it is necessary to analyze its real behavior standing between the light and the photovoltaic cell. For this reason, it is important to know its response in terms of temperature variation and deformations, humidity, wind forces, dust and rain. Under these conditions, the chromatic aberrations or differential focal points, performance to different wavelengths and mainly the optical efficiency or energy that crosses by the lens through tests of transmittance can be determined. Many of these tests can be carried out in simulation software and real tests with controlled environmental conditions.

3.2.3 Interaction characterization

This characterization allows getting a PI in terms of power, according with the real behavior of the integration between lens-cell. The main measure is the power of a cell in function of the displacements in each axis (*x*, *y* and *z*). For each position in each axis, there will be a corresponding power value and there will be a value or range of maximum power production as it is shown in Figure 17. This process determines the sensibility of the system in function of the alignment errors. In this way, it is possible to select the interval of positions that keeps the power level of the whole system within the energy or power requirements, getting a set of maximum internal tolerances for each measured axis.

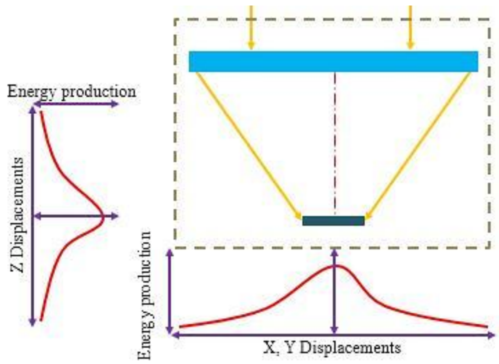


Figure 17. Graphics of the CPV energy production in function of the displacement in each axis.

Finally, to correct the error of the theoretical power and the real power, a PI is calculated according to the Equation 7.

$$PI = \frac{Real\ Power}{Theoretical\ Power} \tag{7}$$

3.3 Detail design

The final stage of the process is oriented to design an appropriate interface element satisfying the requirements presented in the PDS through the correct inclusion and control of the different variables that affect the systems. For design of this element, environmental conditions focused on the need of a rigidity level to keep the manufacture and assembly conditions are taken into account. Essentially, the geometry of the elements, the material and the manufacturing process define the rigidity. For this reason, in this stage the different steps could be worked in parallel.

Looking forward to simplify the designs and improve the control of the different parameters, some design guidelines to generate a more functional concept are considered. These guidelines are minimum quantity of parts, minimum quantity of mobile parts and auto-alignment assemblies.

3.3.1 Module geometrical design

The geometry of the modules refers to the dimensions and the kind of profiles and geometrical elements that conform the design. All of these are defined by the PDS requirements and use conditions.

Basically, the main dimensions of the CPV systems are given by the lenses selected and the specifications of energy or power requirements and maximum areas for deployment and storage. These dimensions are represented in Figure 18, and according to them, the next relations are obtained:

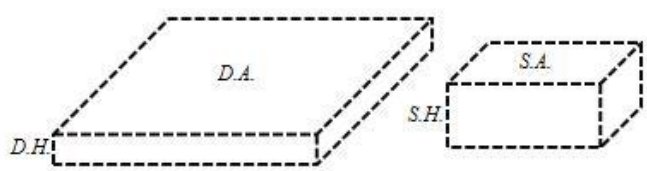


Figure 18. Volumes of deployment and storage of a CPV system.

- Deployment Height (D.H.): Focal length lens * lens thickness * base thickness.
- Storage Area (S.A.): Deployment area / modules number.
- For Storage Height (S.H.), two cases may occur: By stacking the modules one on another, with its own height fixed.
    - Storage Height (S.H.) = Deployment Height * modules number

Or in case of restrictions of space and the height storage is less than the height of stacking. For this case, it is necessary to develop a way to vary the height of modules for storage times without affecting its functionality for deployment times as it is shown in Figure 19.

- Storage Height (S.H.) < Deployment Height * modules number

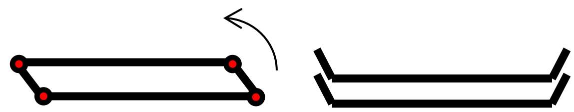


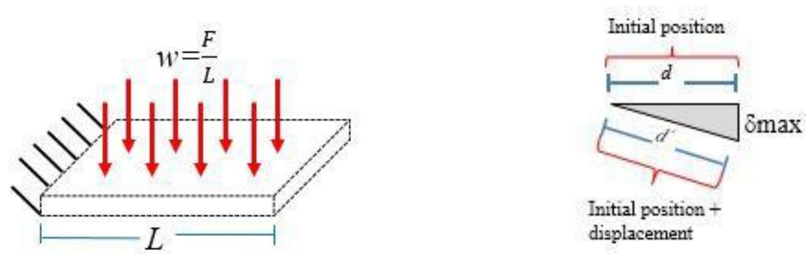
Figure 19. Proposal of CPV modules with variable height.

The profiles, transverse sections or geometrical elements determine the geometric rigidity in presence of forces or loads. The main loads, which the modules will be subjected, are its weight and wind forces, so the rigidity of the modules must overcome them. The first load can be approximated by adding the individual weight of each component, and then this value has to be corrected with the calculation of the weight of the interface element.

The wind forces can be obtained from the maximum wind speed registered in the context of use, through Equation 8, where ρ = Air density, *D.A.* = Deployment area, Cd = Coefficient of aerodynamic drag (Cd = 2 for rectangular shapes) and *W.Speed* = Maximum wind speed

$$Wind\ F = \frac{1}{2} * \rho * D.A. * Cd * W.Speed^2 \quad (8)$$

For practical purposes, the analysis can suppose a configuration of maximum load as it is shown in Figure 20(a) where the modules are rigidly wardrobes in its shorter side and there is a distributed load in the top of them. This configuration can be solved with the Equation 9 to calculate the rigidity of a beam in terms of δmax (maximum deflection in length units), distributed load, L = length, E = rigidity module of material and I = inertia given by used geometric elements. In this way, a maximum deflection value can be calculated according to the internal tolerances of the system from the interaction characterization step as it is shown in Figure 20(b). With the resultant inertia, a specific geometrical profile or transverse section can be designed. The material for E is specified in the next step.



(a) (b)

Figure 20. (a) Configuration for the module analisys, and (b) diagram of displacement errors presented by deflections.

$$I = \frac{-w * L^4}{8 * \delta max * E} \quad (9)$$

3.3.2 Material selection

This step complements the last step for the expected rigidity levels. Taking into account the temperatures, humidity and precipitation levels, it is possible to propose some materials adapted to these environmental conditions with specific E values. Then, the Equation 9 is used to determine a rigidity module for the previously calculated inertia and finally the correct material in concordance with the requirements is selected.

3.3.3 Manufacture process selection

The process of manufacture depends on the manufacture capabilities, the selected material and the geometry, among others. However, not only the environmental conditions should be considered, but also the internal tolerances from the characterization stage, in order to guarantee the needed tolerances for the components in relation to the positions of the lenses and cells.

3.3.4 Assembly strategy

This step is strongly related with the manufacture process considering that it is a method focused on the lens and cell assembly. For this step, it is necessary to review the internal tolerances of the system and the process of manufacture, determining the appropriate method for assembly:

- Centered assembly in the interface element: assembling many cells in one-step through molds, jigs or some tools developed. For this procedure, it is necessary to ensure that the manufacture process, to make the assembly tools, has tolerances inside the range of internal tolerances of the system.
- Centered assembly in photovoltaic element: assembling the cells or the lenses one by one to ensure the perfect alignment between lenses and cells. This method is recommended when the process tolerances are outside the system tolerances or when there is not enough control of the process tolerances.

3.3.5 Theoretical energy production

Finally, it is possible to approach a theoretical adjusted power knowing all the details for the design of the interface element and with the measured PI.
It is necessary to calculate the Tolerances Ratio (TR) between the tolerances needed for the system and the tolerance levels of the process with Equation 10.

$$TR = \frac{Internal\ Tolerances}{Process\ Tolerances} \tag{10}$$

The TR factor is integrated to the power calculation. In this way, when the minimum level of process tolerances is bigger than the maximum level allowed by the internal tolerances of the system, the Theoretical Power (TP) will be reduced by these factors. This calculation is shown in Equation 11 where the PI summarizes the efficiency factors of the cells and lenses, the other factors are: A_{cell} = cell area, N_{sun} = number of suns or concentration factor, DNI = Direct Normal Irradiation measured, η_{sys} = efficiency of electrical components of the system and N_{cpv} = number of used CPVs.

$$TP = (A_{cell} * N_{sun} * DNI * PI * \eta_{SYS} * N_{CPV}) * (TR_{x,y}) * (TR_{z}) \tag{11}$$

The TR factor is divided in two parts: tolerances for *x* and *y-axes*, which may be equivalent, and tolerances for *z* axis. All these tolerances are affected by the tolerances of the process of the parts related with the position of the cells and lenses and by the maximum deflection levels, as it was presented in the Module geometrical design step.

4. CONCLUSIONS

- The power calculation results can vary significantly because of the way in which the design process is developed. The proposed approach is presented only as a suggestion of steps to improve the prediction of the behavior of systems before running the construction design. However, in some cases, acquisition of some components to perform real tests such as internal tolerances of the lens-cell integration might not be viable and for these cases, the appropriate use of secondary lenses can provide a lower sensitivity of the system against displacement. It is also recommended to carry out a deep search of simulation methods for different cases and required components.

- Main environmental variables that affect energy production of a CPV are presented as time changing variables that may or may not adversely affect the system at a specific time. The temperature is a variable that can be easily characterized and integrated as a constant environmental variable in the interaction of the components. However, the relative humidity and the level of precipitation suggest the implementation of levels of protection or impermeability according to the most extreme case, since through these protections the effect of these variables can be ignored.

- The proposed process is specific for CPV systems with Fresnel lenses; however, its main steps can be easily adapted to systems using other optical elements, mainly by adjusting the selection parameters of the optical component and defining ways to characterize components and correct assembly processes.

- Further research is oriented to perform a practical case study using the proposed methodical process in order to validate its real advantages and to determine the error level between the theoretical power obtained through the process and the real performance of a CPV system designed using the process.

5. REFERENCES

[1] CPV Consortium, "cpv technology," cpvconsortium, September 2013, http://www.cpvconsortium.org/cpv_technology (15 May 2016).

[2] Chemisana, D., "Building integrated concentrating photovoltaics: a review," Renewable and Sustainable Energy Reviews, vol. 15, no. 1, 603-611 (2011).

[3] Green Rhino Energy Ltd, "pv concentration," greenrhinoenergy, April 2013, http://www.greenrhinoenergy.com/solar/technologies/pv_concentration.php (27 May 2016).

[4] Xie, W., Dai, Y., Wang, R. and Sumathy, K., "Concentrated solar energy applications using Fresnel lenses: A review," Renewable and Sustainable Energy Reviews, vol. 15, no. 6, 2588-2606 (2011).

[5] Semprius Inc., "products," semprius, August 2006, http://www.semprius.com/products (15 February 2016).

[6] Morgan Solar Inc., "how it works;" morgansolar, May 2007, http://www.morgansolar.com/how-it-works/ (15 February 2016).

[7] Airlight Energy, "cpv-process system," airlightenergy, February 2008. http://www.airlightenergy.com/cpv-process-system (15 February 2016).

[8] AZUR SPACE Solar Power GmbH,"cpv assemblies," azurspace, Apil 2014, http://www.azurspace.com/index.php/en/products/products-cpv/cpv-assemblies (23 Nobember 2015).

[9] Soitec, "omponents," soitec, Februart 1997, http://www.soitec.com/en/technologies/concentrix/components/ (29 October 2015).

[10] Edmund Optics Inc., "advantages-of-fresnel-lenses," edmundoptics, March 2016, http://www.edmundoptics.com/resources/application-notes/optics/advantages-of-fresnel-lenses/ (27 May 2016)

[11] HASIN, S. and Helfan, R. "Photovoltaic Module Assembly," United States Patente US 20130319507A1, May 29 2013.

[12] Seel, S., Menard, E., Kneeburg, D., Kendrick, B., Furman, B., Wagner, W., Jasinski, R. and Burroughs, S., "High concentration photovoltaic modules and methods of fabricating the same," United States Patent US 20130146120A1, Dicember 5 2012.

[13] Menard, E., Bower, C., Burroughs, S., Carr, J., Conner, B., Dets, S., Furman, B., Meitl, M. and Sullivan, M. "Concentrator-Type Photovoltaic (CPV) Modules, Receiver and Sub-Receivers and Methods of Forming Same," United States Patent US 20100236603A1, February 9 2010.

[14] D. Fork, D. Duff, M. Weisberg, T. Zimmermann and S. Horne, "Solar concentrating photovoltaic device with resilient cell package assembly," United States Patent US 20070256725Al, May 5 2006.

[15] Jiménez, S. E. C., Pardo, A. D. D., Maroto, C. M., Sáez, E. J. and Botts, A., "Mounting procedure of a high-concentration photovoltaic solar module and module thus mounted," United States Patent US 20140182655A1, March 4 2013.

[16] Olah, S. "Solar energy module and fresnel lens for use in same," United States Patent US006399874B1, June 4 2002.

[17] Miller, W., Ocegueda, V., Dittmer, J., Sinsheimer, R., and Prucha, M., "Alignment of photovoltaic cells with respect to each other during manufacturing and then maintaining this alignment in the field," United States Patent US 20120152309A1, September 8 2011.
[18] Mughal, H., "An innovative design of a low cost 120x concentrating system based on proven one sun technologies," in Photovoltaic Specialists Conference (PVSC) 2009 34th IEEE (2009).
[19] Ren, L., Wei, X., Lu, Z., Yu, W., Xu, W., and Shen, Z. "A review of available methods for the alignment of mirror facets of solar concentrator in solar thermal power system," Renewable and Sustainable Energy Reviews, vol. 32, 76-83 (2014).
[20] Drew, K., Morris, N., Sinclair, M., Myrskog, S. and Morgan, J. P. "Sensitivity Analysis Applied to a Concentrator Photovoltaic System," in 2014 IEEE 40th Photovoltaic Specialist Conference (PVSC) (2014).
[21] Kurtz, S., Muller, M., Jordan, D., Ghosal, K., Fisher, B., Verlinden, P., Hashimoto, J. and Riley, D., "Key parameters in determining energy generated by CPV modules," Progress in Photovoltaics: Research and Applications, vol. 23, no. 10, 1250-1259 (2015).
[22] Muller, M., "Experience with CPV Module Failures at NREL," Reliability Workshop, Golden CO, (2012).
[23] Rosales, A. A., Velásquez, J. B., Gómez, G. O. and Gutiérrez, R. M., "Designing a concentrating photovoltaic (CPV) system in adjunct with a silicon photovoltaic panel for a solar competition car," SPIE Sensing Technology+ Applications (2014).
[24] Pugh, S., [Total Design: Integrated Methods for Successful Product Engineering], Addison-Wesley Publishing Company, Addison Wesley, (1990).