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Design and analysis of photovoltaic surfaces based on a multiphysics approach

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Abstract

(In English)

Every day, the cost of photovoltaic (PV) solar energy decreases significantly, which facilitates its acquisition and use. Globally, the construction and transportation sectors have a high energy demand, so the use of surfaces exposed to solar radiation could generate electricity on site to act as a "prosumer node". However, flat shapes of most commercial solar panels hinder the integration with possible variable geometric shapes, so the objective of this work is to analyze the energy generation potential of photovoltaic modules with adaptive morphologies and the implications they have in terms of manufacturing and energy performance using different manufacturing materials than the commercial ones. Firstly, the mechanical effects of monocrystalline solar cells are studied in order to estimate the flexibility capacity when encapsulated, which gives a maximum curvature radius of $6.51m$. At the same time, a multiphysical model is proposed to estimate the efficiency and energy losses associated with temperature and optical phenomena. This analysis allows determining the influence of the manufacturing materials on the overall efficiency of the system, for which their properties were characterized through laboratory tests. Based on the above, a first case study is proposed which corresponds to the modeling of the PV system of an electrosolar-boat (Vehicle Integrated Photovoltaics VIPV) in which important inventive and manufacturing findings related to the manufacturing process of rigid and semi-flexible modules with monocrystalline cells (c-Si) were made. Then, a second case study is proposed through an genetic algorithm (GA) to determine PV surfaces with optimal generation geometries associated to the use of space in constructions (Building Integrated Photovoltaics BIPV). For the VIPV application case, a double curvature PV module was designed with 3,97% more electricity generated than a flat PV module for the same area constraints, while for the BIPV case, an optimal PV surface with 22,5% additional energy was fabricated.

Keywords: Building Integrated PV, Vehicle Integrated PV, Curved PV surfaces, PV module morphology, Optimal PV surface, Multiphysics PV modelling

Resumen

(En Español)

Cada día, los costos de la energía solar fotovoltaica (PV) disminuyen de manera importante, lo cual, facilita su adquisición y uso. A nivel global, los sectores de la construcción y del transporte, tienen una gran demanda energética por lo que, el aprovechamiento de superficies expuestas a la radiación permitiría generar energía eléctrica en sitio para suplir necesidades como "nodo prosumidor". Sin embargo, las formas geométricas planas de la mayoría de los módulos PV solares comerciales dificultan la integración con posibles formas geométricas variables, por lo que, el objetivo de este trabajo es analizar el potencial de generación que presentan módulos PV con morfologías adaptativas y las implicaciones que tienen en cuanto a fabricación y comportamiento energético utilizando materiales de fabricación no convencionales. En primera instancia, se estudian los efectos mecánicos de las celdas solares monocristalinas con el fin de estimar la capacidad de flexibilidad al ser encapsuladas, lo cual da un radio de curvatura máximo de $6,51m$. Paralelamente, se plantea un modelo multifísico que permita estimar la eficiencia y las pérdidas energéticas asociadas a temperatura y fenómenos ópticos. Dicho análisis, permite determinar la influencia de los materiales de fabricación en la eficiencia global del sistema, por lo que se caracterizaron propiedades de los mismos a través de ensayos de laboratorio. A partir de lo anterior, se plantea un primer caso de estudio que corresponde al modelamiento del sistema fotovoltaico de una embarcación electrosolar (Fotovoltaica Integrada a Vehículos VIPV) en el cual se hicieron hallazgos inventivos y de fabricación importantes relacionados al proceso de fabricación de módulos rígidos y semiflexibles con celdas monocristalinas (c-Si). Después, se plantea un segundo caso de estudio a través de un algoritmo genético (GA) para determinar superficies PV con geometrías óptimas de generación asociado al aprovechamiento de espacio en construcciones (Fotovoltaica Integrada a Construcciones BIPV). Para el caso de aplicación VIPV, se diseñó un módulo PV de doble curvatura con un 3.97% de mayor electricidad generada que un módulo PV plano para las mismas restricciones de área, mientras que el caso BIPV, se fabricó una superficie PV óptima con un 22,5% de energía adicional.

Palabras Clave: PV integrada a edificios, PV integrada a vehículos, superficie PV curva, morfología módulo PV, Superficie PV óptima, Modelamiento PV Multifísico

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Chapter 1

Introduction

Nowdays, the trend of energy consumption in the world is increasing due to the growth of the world's population and the invention of new electronic devices such as cell phones, vehicles, computers, home appliances etc (Kiatkittipong et al., 2008). From this demand, about 73.8% is met by non-renewable electricity, while the remaining 26.2% corresponds to renewable electricity. (Abdmouleh et al., 2015). This increases the interest of countries in using Renewable Energies (REN's) whose costs has been decreasing in recent years, especially solar energy, which is currently the most economical renewable energy, even lower than wind energy (Cubillos, 2014), (Hauff et al., 2011). For these reasons, solar energy can be considered as one of the Renewable Energy Sources (RES) with higher potential in future, thanks to its capacity to supply the worldwide energy demand and availability (Zobaa and Bansal, 2011).

The use of photovoltaic (PV) solar energy is largely provided by solar farms, which are large tracts of land, covered by PV modules, producing up to 2,245MW (Kumar, 2022). Considering the prosumer nature of solar energy, it is possible to think of more localized applications, with lower energy consumption and solar resource as applications in Building Integrated Photovoltaics (BIPV) and Vehicle Integrated Photovoltaics (VIPV) which have geometric shapes established for aesthetic, technical or functional requirements. Thus, it is reasonable to think about new applications involving the use of surfaces exposed to solar radiation, however, most high-efficiency commercial PV modules are of rigid geometry, which limits their design, applicability, integrability and adaptability. The possibility of having adaptable curved PV modules, allows to think on having PV surfaces for localized energy production, in order not to depend exclusively on solar farms. This localized applications can be seen on roofs, amorphous facades and transportation vehicles. Currently, only 0.3% of the energy consumed by vehicles is generated without causing any additional impact(Murdock et al., 2020).

In this way, PV energy presents a great advantage to distributed and democratized energy generation and use, because it is produced at the same site of consumption, so losses from the generation

chain are minimized and the surpluses can be traded. This is the so-called **Prosumer** concept (Diahovchenko and Petrichenko, 2022). Most of the solar panels found commercially and in the literature have completely flat geometries. However, for applications in transportation systems and buildings, it is possible to propose curved geometries that allow a better adaption to the required complex shapes. This fact has severe implications in terms of manufacturing and modelling of shape of PV module. This way, we seek to contribute to the solar energy sector, specifically in localized applications with low power requirements in restricted spaces with established geometrical shapes using PV technology to maximize electricity generation.

1.1 Background

Use of PV solar energy dates back to the 20th century with the discovery of the photoelectric effect, which granted Albert Einstein the Nobel Prize for Physics. Until then, it was only shown that it was possible to transform the sun's light energy into usable electrical energy. However, through the development of new materials, these phenomena began to be harnessed on a larger scale (Deshmukh and Venkataraman, 2006). Firsts PV modules had low efficiencies, and their manufacture was quite complex, which made their application at industrial level and on a large scale unthinkable. Over the years, new solar cell technologies has been developed and allowed them to increase their production and consequently their use in the different sectors. Currently, the most widely used and most cost-effective type of cell is still monocrystalline silicon (c-Si). This type of cell offers an efficiency near 25% (Green, 2009) and is normally used in the manufacture of flat geometry solar panels, due to its low thickness and fragile behavior, which makes it difficult to obtain curved PV surfaces.

1.2 Problem Statement

The geometry of surfaces exposed to solar radiation can have irregular shapes or contours with curvature. Consequently, there is an opportunity to implement PV modules with adaptive curved geometry, so the energy performance can change substantially. Thus, it is necessary to analyze the energy transformation behavior of any given geometry, from radiation capture to materialization, in localized power generation applications.

1.3 Research justification

PV potential is a measure of the average irradiance that occurs at certain coordinates, i.e., is the characteristic of a terrestrial coordinate to generate electricity according to the incident radiation throughout the year, depending on the hours of solar incidence and weather conditions. Thus, ob-

jects exposed to radiation with low average shading could be potential nodes of power generation, particularly in architecture with BIPV and Building Adapted Photovoltaics (BAPV), in transportation sector through VIPV and Vehicles Adapted Photovoltaics (VAPV), also applications emerges in other contexts such as works of art (Apostolou, 2016) as murals, sculptures and uses in architecture (Farkas, 2011). However, most of these applications do not have completely flat geometries, as in the case of residential roofs, which are vivally based on a combination of planes at different inclinations, compared to vehicles where the available PV area smooth curvatures along the fairing. Thus, the ability to generate adaptive shapes using PV modules enable to rethink conventional manufacturing processes. Additionally, the geometric shape of objects can determine technical aspects of the power generation potential:

- Portions of area where the average irradiance is higher than in others.
- Partial Shading (PS) that could have thermal implications in terms of hot spots
- Optical phenomema related to the incidence of radiation and electrical analysis using conventional connections

These facts allows rethink the connection strategy between solar cells.

The Design Engineerring Research Group (GRID) of EAFIT University has developed sustainable mobility projects as solar cars Primavera I-II (Arévalo-Molina et al., 2014), in which they have implemented PV modules to be integrated in automobiles fairing, through the use of composite materials and resins. Also, interconnection strategies were implemented in order to avoid energy losses due to shading for slightly curved contours. Based on the above, the way of using these materials was rethought in order to manufacture semi-flexible PV modules, that allow the solar cells to be positioned on exposed surfaces to solar radiation while they adapt to curved shapes, ensuring adequate reliability. This fact makes it possible to search for materials that satisfy required mechanical functions, which may have important implications in manufacturing industry, specifically in the development of rigid, semi-flexible and flexible PV modules. Thus, a multi-physical study for curved PV surfaces will allow determining their power generation in function of location, geometry, materials and manufacturing process.

1.4 Research question

Based on the experience gathered by the GRID throughout the projects carried out with solar PV energy, has allowed the manufacturing of PV modules of Si cells with a certain degree of flexibility and capacity to adapt to established contours; however, the electricity generation ability related to their geometry has not been studied in depth. Therefore, the following research question arises.

- How to improve the overall performance of a photovoltaic surface?

1.5 Objectives

1.5.1 General objective

To develop a method to find optimal PV surfaces by considering multiphysic phenomenons in order to maximize solar energy collection

1.5.2 Specific objectives

- To analyze the models that explain the operation of PV surfaces through a search of the state of art in order to differentiate and select different physical phenomenons involved in solar energy.
- To design a tool to find adaptive PV surfaces through an optimization algorithm that allows to maximize captured radiation while adapting its forms to the available area.
- To propose a multiphysical analysis through the correlation of variables in order to estimate the energy transformation in the obtained PV surfaces
- To apply geometric surface generation tool and the multiphysics method through case studies in order to generate and adapt new morphologies of PV modules.

1.6 Methodology

Different methodologies are used to provide a solution to each of the objectives of this work in a specific way. These methodologies are based on the practice of research in design, a subject in which GRID has had great experience. The methodologies are shown in Fig 1.1

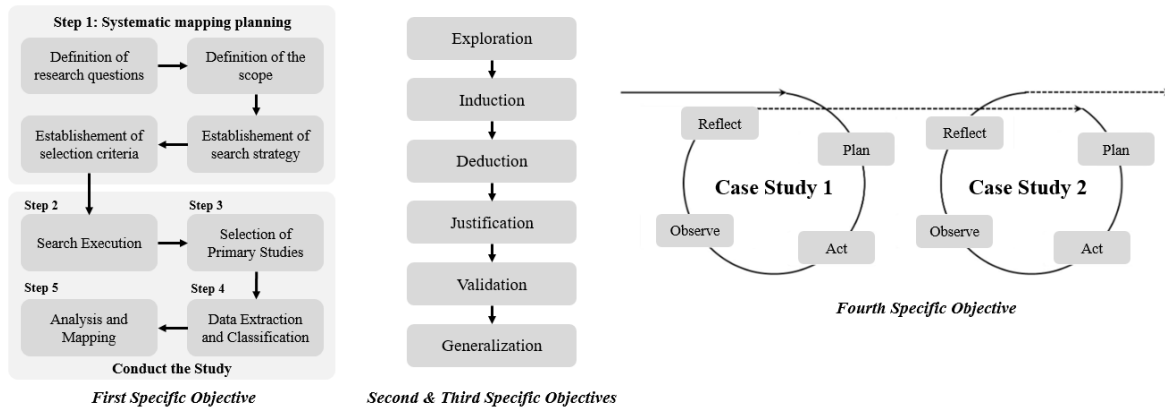


Figure 1.1: Methodologies (Salama et al., 2015; Horváth et al., 2007; McNiff, 2016)

For the first specific objective related to the search for the State of Art, the "Systematic Mapping Study" methodology will be used (Salama et al., 2017). "Research in Design Context" will be the methodology for the second and third specific objectives (Horváth et al., 2007). For the fourth specific objective related to the case studies, the "Action Research" methodology will be used (McNiff, 2016), this is observed in the development of the case studies, initially for a PV system for an electrosolar boat (in which there is a fixed geometry) and finally for a PV module integrated to building terraces (in which there is no established geometry and it must be generated).

From the development of the work, according to the proposed methodologies, different tools will be used. Software packages such as: Ansys® , TracePro® and Matlab® will allow the validation of physical phenomena in controlled environments. Regarding the numerical development, Python™ will be used as the main tool. Material properties will be found from laboratory tests using Standards and finally real time data acquisition devices will be implemented to perform experimental validations.

1.7 Research Scope

It is expected to obtain a model to evaluate the power generation capacity of adaptive PV modules that allows to analyze the effects of the properties of materials, location site and the given geometry. It is also expected to develop a numerical optimization tool to generate optimal PV surfaces according to the given constraints. Finally, is proposed a manufacturing process that allows the solar cells to take the required adaptive shapes without compromising their structural integrity. For future research, it is recommended to evaluate the potential of the interconnection strategies on the optimal surfaces obtained, as well as to perform a deeper analysis of the bending effects on the c-Si cells, in order to evaluate their real energy performance.

1.8 Manuscript Organization

The following is the content of each of the chapters and appendix that compose this manuscript.

Chapter 1: Introduction The general aspects of the project and the description of the problem are presented. The objectives, methodology and research question are also presented.

Chapter 2: Theoretical Background All the theoretical and conceptual aspects that allow the understanding of the physical models implemented in the work are described. It begins with a description of the different types of solar cells, commercial PV modules and the most used types of connections. Then, the concept of solar resource is presented from the point of view of the sun's

movement and the available radiation for given coordinates. Finally, the different physical phenomena presented in the operation of a PV module are discussed.

Chapter 3: State of the Art The uses of PV modules in vehicle and building applications are addressed, identifying different manufacturing processes. Then, aspects related to the physics of the problem and the approach of multiphysics models for the understanding of the global operation of PV modules are deepened. Finally, the most commonly used numerical strategies in the context of solar PV energy are presented.

Chapter 4: Proposal In this chapter, the general approach to the solution of the problem from the 3 major analyses is presented. Then, the procedural approach for the design of PV surfaces with curvature, which will be used in the case studies, is presented.

Chapter 5: Case Study VIPV The case study of the electrosolar boat is presented from the geometrical design of the curved PV modules to the different physical analysis of operation. The manufacturing method used for the 14 PV modules is presented and finally, operation tests are performed in a controlled environment.

Chapter 6: Case Study BIPV Like the electrosolar boat, the procedural approach is applied to a case study of PV systems integrated to constructions in a context of Colombian terraces. The analysis starts with the generation of the geometry and then the physical performance of the optimal surface found is analyzed. Finally, the optimal surface is fabricated and then subjected to experimental tests.

Chapter 7: Conclusions and Further Research The final conclusions and future work are presented.

Appendix A: Characterization of PV module manufacturing materials The measured optical and mechanical properties of the fabrication materials of the semi-flexible PV modules are shown.

Appendix B: Performance and experimental testing of curved PV surfaces. The design of the measurement circuit and the different experimental tests on the PV modules with curvature are presented.

Chapter 2

Theoretical Background

In this chapter, some basics concepts of photovoltaic (PV) modules will be addressed, in order to understand the problem from a more general point of view. Then, based on energy transformation in PV modules, it is necessary to review theoretical aspects related to the physical phenomena and sun's movement, which are presented during the operation of a solar panel, in order to understand the incidence of the geometric shape over the overall performance. Likewise, a search for different types of Optimization Algorithms (OA) that allow the formulation of a model to find a PV optimal surface is carried out, extending the search to numerical techniques used in solar energy sector. Based on this knowledge, will be possible to propose a model that allows the energetic characterization of PV module according to the established geometry. Finally, in order to materialize adaptive PV surfaces, it is necessary to review the way in which solar panels are currently manufactured, taking into account the requirements of solar cell types and final geometric shapes. These topics will be discussed below.

2.1 Photovoltaic System

Solar energy is obtained by transforming sunlight radiation into electricity, which is possible by photoelectric effect (Hofman and Rosselli, 2002). Due to incidence of photons, these allow the movement of free electrons on the photovoltaic cell surface between *N-type* and *P-type*, which translates into small differences in electrical potential, which, throughout the day, give rise to significant energy gains (Joyce et al., 2001). In general, there are two main uses of solar energy:

- **Solar thermal energy** which generates heat due to solar incidence, typically used in water heaters
- **Solar PV energy** which it will be discussed in this work, transforms sunlight into electricity through the use of solar cells (Sarver et al., 2013)

Fig 2.1 shows the operation of a typical PV system.

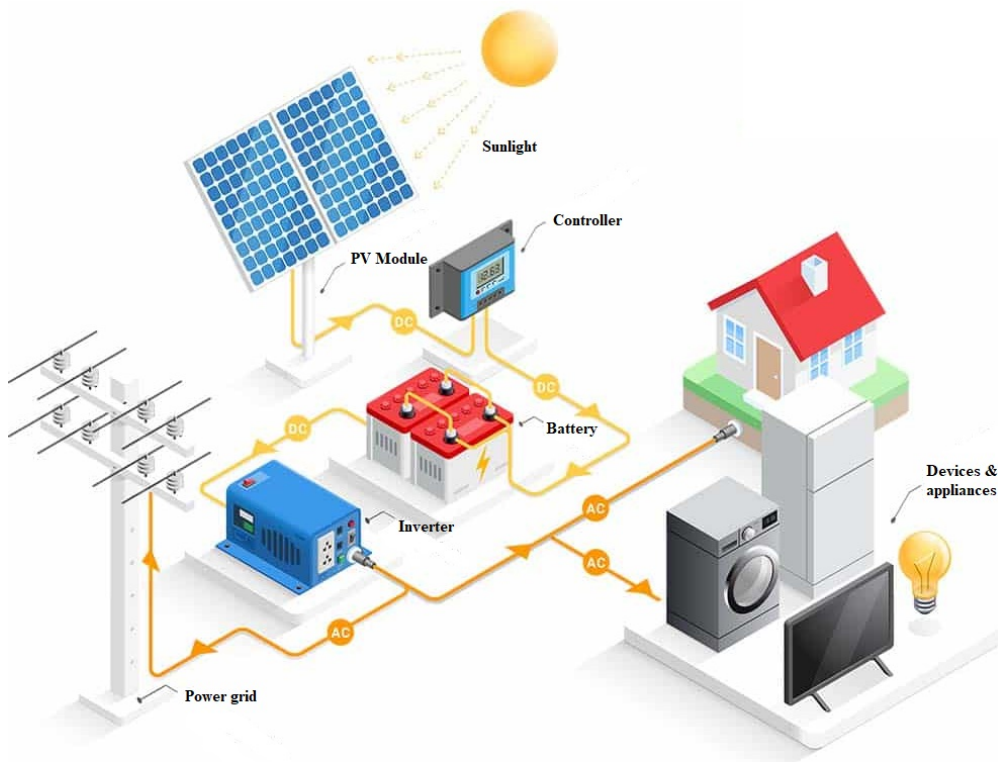


Figure 2.1: Schematic diagram of PV system (Enghenaria, 2022)

Initially, sunlight is captured by the PV modules, which transform this radiation into DC electricity, which goes to a controller that controls the energy flowing between the battery and PV modules to avoid discharges and over-discharges. The battery is responsible for energy storage for later consumption, usually at night, then this energy goes to an inverter which converts the DC electricity generated by the PV modules into AC current, which can be sold to the grid or consumed by appliances and basic needs such as lighting and others. In this research, PV modules will be specifically studied, taking into account its surface geometry, energy efficiency and manufacturing characteristics. Therefore, the types of solar cells existing in the market and most typical ways of interconnecting them, according to the given applications, will be explained and finally, different geometrical configurations of commercial PV modules are presented according to their flexibility or capacity of adaptation to other surfaces.

2.1.1 Photovoltaic Cells

Photovoltaic solar cells are the most important elements of a PV module, because they have the ability to convert sunlight into electricity. They are manufactured from very thin wafers on the order of mi-

crons and are made of different materials, usually semiconductors, which have different characteristics of efficiency, size, color and mechanical behavior. Fig 2.2 shows the historical development of PV cell materials and their corresponding efficiency.

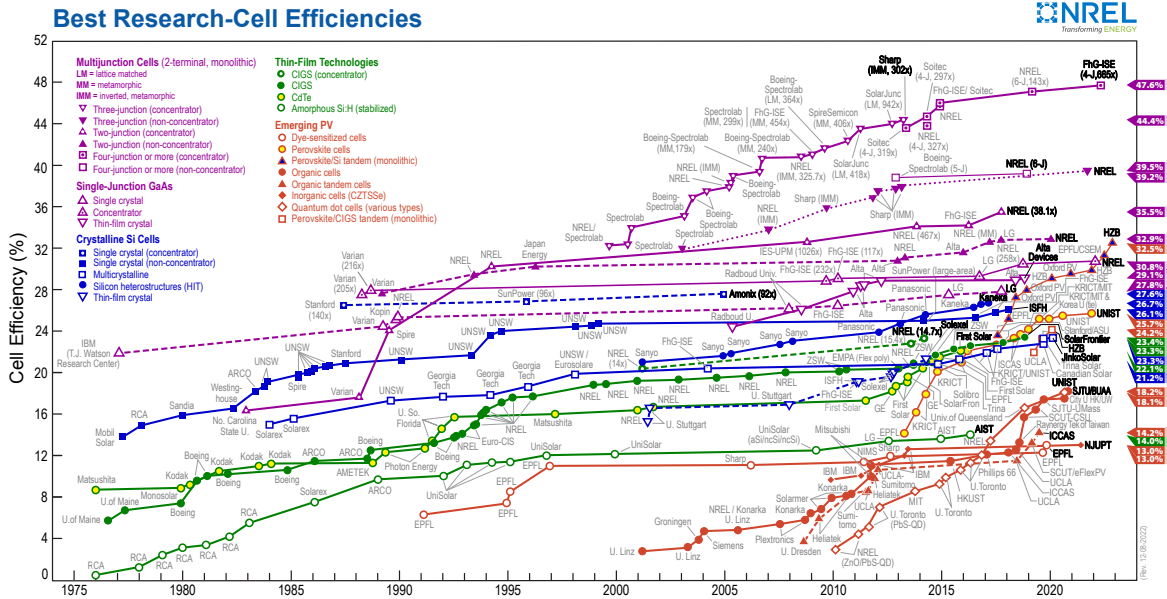


Figure 2.2: Historical development of solar cells (Elmore and Kubik, 2020)

Based on the above, it can be seen that there are a large number of PV materials developed; however, the main characteristics of the most widely used and available solar cells are shown in Fig 2.3 and described below

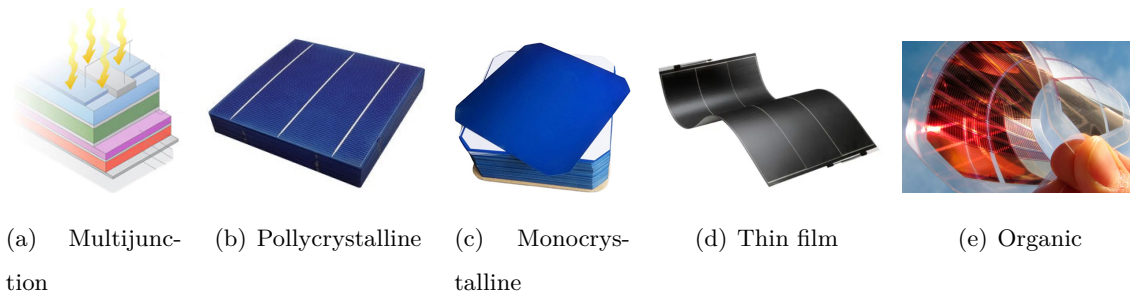


Figure 2.3: Different types of solar cells (PVcells, 2022)

Multijunction solar cell This type of solar cell has the capacity to produce different wavelengths of incident radiation because it has multiple layers, which gives it an efficiency of almost 40%. It is made of semiconductor materials such as Gallium Indium Phosphide (GaInP), Indium Gallium Arsenide (InGaAs) and Germanium (Ge), which are arranged in layers and respond to different

wavelengths of light (Muniz da Silva et al., 2011). Fig 2.3 shows the cross section of a multijunction solar cell.

Polycrystalline silicon solar cell Are obtained by melting silicon and then arranging it in molds to take its final shape. Due to the grain growth of the cooled silicon and possible impurities, the efficiencies of polycrystalline solar cells are in the order of 15% (Soto, 2005) which is lower than monocrystalline cells. A typical polycrystalline solar cell is shown in Fig 2.3.

Monocrystalline silicon solar cell The cells are obtained from wafers cut from cylindrical silicon ingots in very small thicknesses, so that, when rounding the corners, an octagonal figure is left, which has an efficiency of approximately 20%. This efficiency is higher than polycrystalline cells because it is a single crystal, so there are no grain boundaries in the area of the cell as we can see in Fig 2.3. Its efficiency is in the order of 23,2% are the most cost-efficient solar cells on the market today (Płaczek-Popko, 2017).

Thin Film solar cell It is a solar cell manufactured by arranging thin layers whose thickness varies from nanometers to micrometers, hence the name thin film cells (Dimmler, 2014). They are manufactured in various materials such as amorphous Silicon (a-Si) and Thin Film Silicon (TF-Si), Pervoskita (CaTiO_3), Galio (Ga), Cadmium Telluride (CdTe), Copper Indium Gallium and Selenium (CIS or CIGS), the latter reaching up to 21% efficiency and it is shown in Fig 2.3 (Aberle, 2009).

Organic solar cell Has 3 types: molecular type, hybrid type and organic polymer type, which are the most commonly used and achieve efficiencies of up to 16% (Rivas, 2018) and is shown in Fig 2.3. Plastic substrate films such as Polyethylene Naphthalate (PEN) or Polyethylene Terephthalate (PET) are used, which are manufactured by liquid solution deposition, which facilitates their mass production, reducing production costs (Hu et al., 2020).

2.1.2 Interconnection of solar Cells

The array of a PV module is formed by the interconnection of solar cells in order to collect the energy generated by each one, accumulate it and deliver it to an end user so that it can be used. Based on the operating requirements and weather conditions, it is possible to modify the way in which the cells are connected to each other, in order to satisfy energy delivery characteristics, avoid obstacles such as shadows and reduce the impact of possible failures in the system. Some typical interconnection strategies for the above cases are presented in Fig 2.4 and presented below.

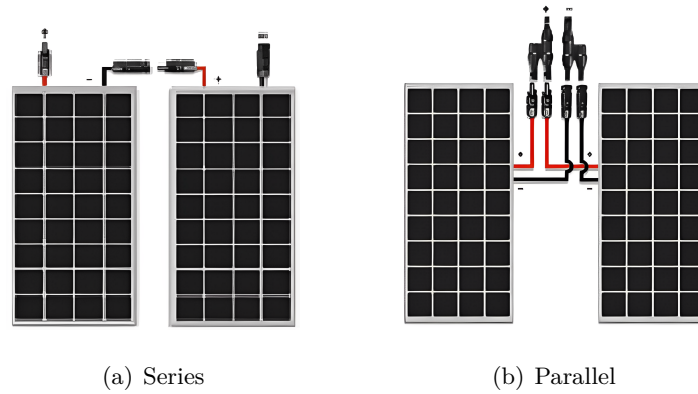


Figure 2.4: Typical connections in PV modules (SunFields, 2020).

Series Is the most typical connection found between solar panels. Normally, photovoltaic cells are also connected in this way in order to add the voltage of each cell while the current remains constant (Mejía et al., 2009). A schematic of the connection is depicted in Fig 2.4

Parallel It can be understood as a case contrary to the serious connection, whereby the currents are added and a minimum operating voltage given by the technical characteristics of the cell is managed (Mejía et al., 2009). This arrangement is shown in Fig 2.4.

2.2 Solar resource

Since the use of solar energy depends on the presence of the sun, it is necessary to determine the time and amount of available radiation to know the potential for electricity generation from the use of a PV module for a specific site. This will depend on many factors, among which are: the location along the planet of the PV system and the amount of incident radiation, which in turn depends on atmospheric factors (cloud cover, ambient temperature, environmental cleanliness and humidity). The following are the basic concepts related to the movement of the sun with respect to a fixed point of installation of a PV module, as well as some external factors that affect the amount of available radiation.

2.2.1 Movement of the Sun

The estimation of the duration of the day is a function of the movement of the sun, understanding that this body also moves in relation to other stars and that a PV module is on the ground in a fixed position. In this way, it is possible to estimate the average hours of sunshine as a function of the coordinates of the location of a PV module through the coordinate systems shown below.

Ecliptic Coordinate System Is a celestial coordinate system used to represent apparent positions, orbits and pole orientations of solar system objects. The origin of the system can be the center of the sun or the earth, its main direction is towards the vernal equinox and it has a right hand convention (Moraño Fernández, 2021), this is shown in Fig 2.5.

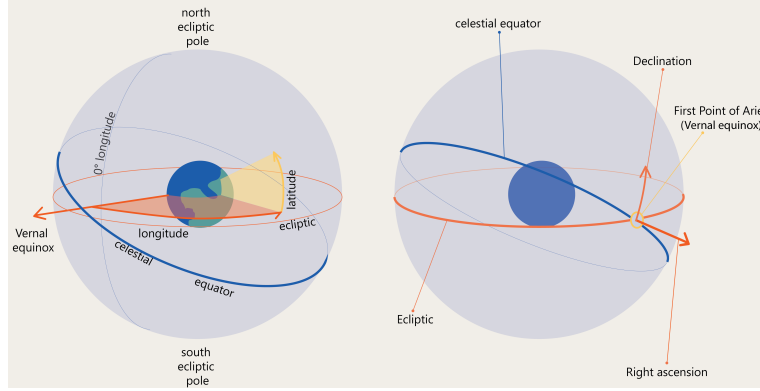


Figure 2.5: Ecliptic and equatorial coordinate system. Source: created by the authors

Equatorial coordinate system It is shown in the right of Fig 2.5 and it is used to specify positions of celestial objects. It can be implemented in spherical or rectangular coordinates and in both cases defined by an origin at the center of the earth, a fundamental plane consisting of the projection of the earth's equator onto the celestial sphere and a primary direction towards the vernal equinox (Moraño Fernández, 2021).

Horizontal coordinate system Is a celestial coordinate system that refers to the observer's horizon and its vertical. These coordinates are local and depend on the observer, because the sun is observed under different horizontal coordinates by different observers located at different points on the Earth. It is the most widely used and intuitive coordinate system to know the trajectory of the sun for a specific location, which is exposed in Fig 2.6.

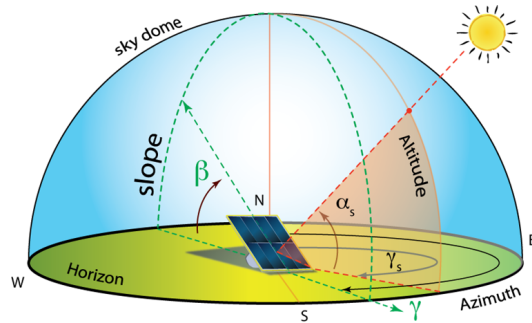


Figure 2.6: Horizontal coordinate system (SunTheory, 2020)

From the altitude angle, the slope of the PV module is generated and the azimuth angle allows the location based on a rotation axis perpendicular to the ground. This information is collected in a traditional way, from solar charts, however, nowadays there are databases such as suncalc (Thieurmél et al., 2019), which allows to obtain this data for a specific location. Fig 2.7 shows an example for the city of Magangué, Colombia.

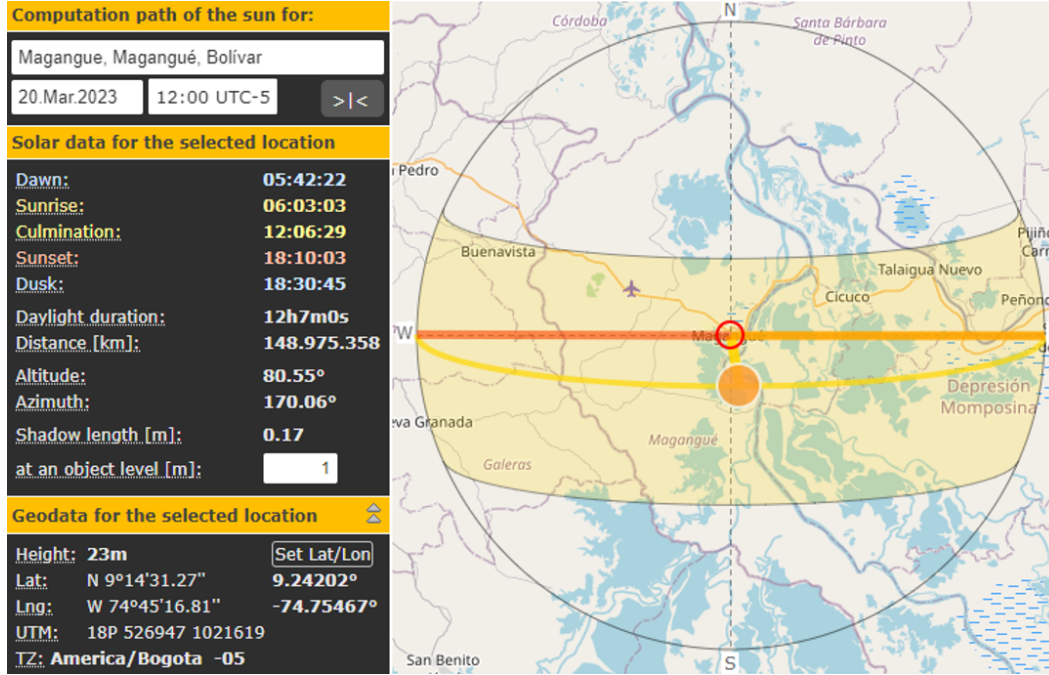


Figure 2.7: Position of the sun in Magangué for the March equinox (Thieurmél et al., 2019)

The chosen day was the March equinox at 12:00 noon, because it is the same duration of the day as the night. It is observed that general data of the day (such as sunset, sunrise, etc.) are available. Also, there is an altitude angle of 80.55° , which suggests an approximate slope of 10° and south oriented.

2.2.2 Solar radiation

From the position of the sun during the year, it is necessary to know the magnitude of the amount of radiation energy that reaches the surface of a PV module in order to know the energy contribution of solar energy for a given site. It should be taken into account that the sun radiates a large amount of energy that reaches the atmosphere, which takes an approximate value of $1367W/m^2$ and is called solar constant (Hsieh, 1986). However, this value decreases when reaching the PV module caused by environmental phenomena that attenuate such radiation, mainly due to cloudiness and particles in the environment. These facts enables to think about the different forms of radiation given for a fixed point (Nelson, 2003), which are shown in Fig 2.8.

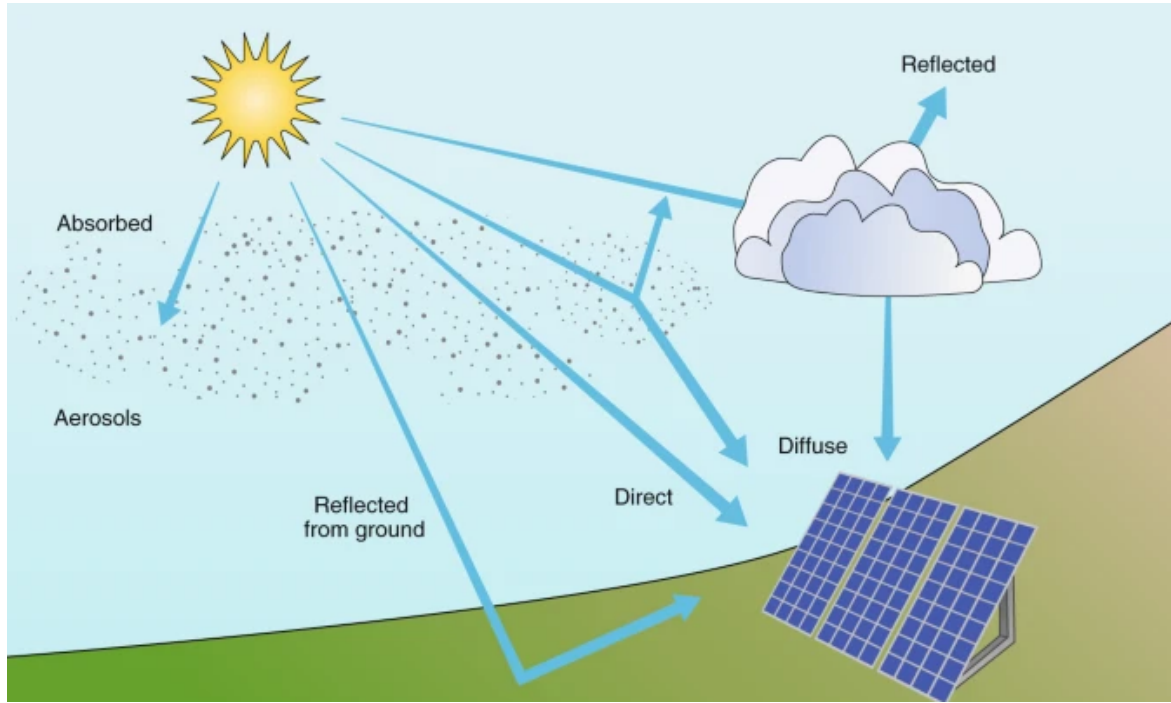


Figure 2.8: Types of radiation (Ekins-Daukes and Kay, 2019)

The sun's rays reach the atmosphere and there is a component absorbed by the air and other particles such as pollution aerosols. However there is a large part that is not absorbed and reaches the ground surface in the form of direct radiation, which impacts on the PV module. The remaining rays are reflected on the ground and this is known as reflected radiation or albedo radiation. It is also known that, due to the presence of clouds, the light is attenuated generating diffuse radiation. In general terms, the effective radiation incident on the area of a PV module is given as a function of the irradiance, which is different for each geographical location. Fig 2.9 shows a normal irradiance map for Colombia generated by *solargis* (Šúri et al., 2011)

It is observed that the greatest photovoltaic potential is found in the areas of the caribbean, orinoco and amazon regions of colombia. This fact reaffirms Magangué as a site of interest for this project. Considering the above, it is necessary to further analyze the behavior and its dependence on atmospheric factors, with respect to the production of electricity within the PV module, these considerations will be analyzed below.

Spectral dependence: The electricity generated through PV modules is highly dependent on the wavelength of the incident radiation. Consequently it is necessary to know the spectrum of the sun, establishing its dependence on the time of day, seasons, orientation of the PV module and atmospheric conditions (González, 2001). In order to understand the incidence of the spectrum in silicon, with

SOLAR RESOURCE MAP

DIRECT NORMAL IRRADIATION**COLOMBIA**

ESMAP

SOLARGIS

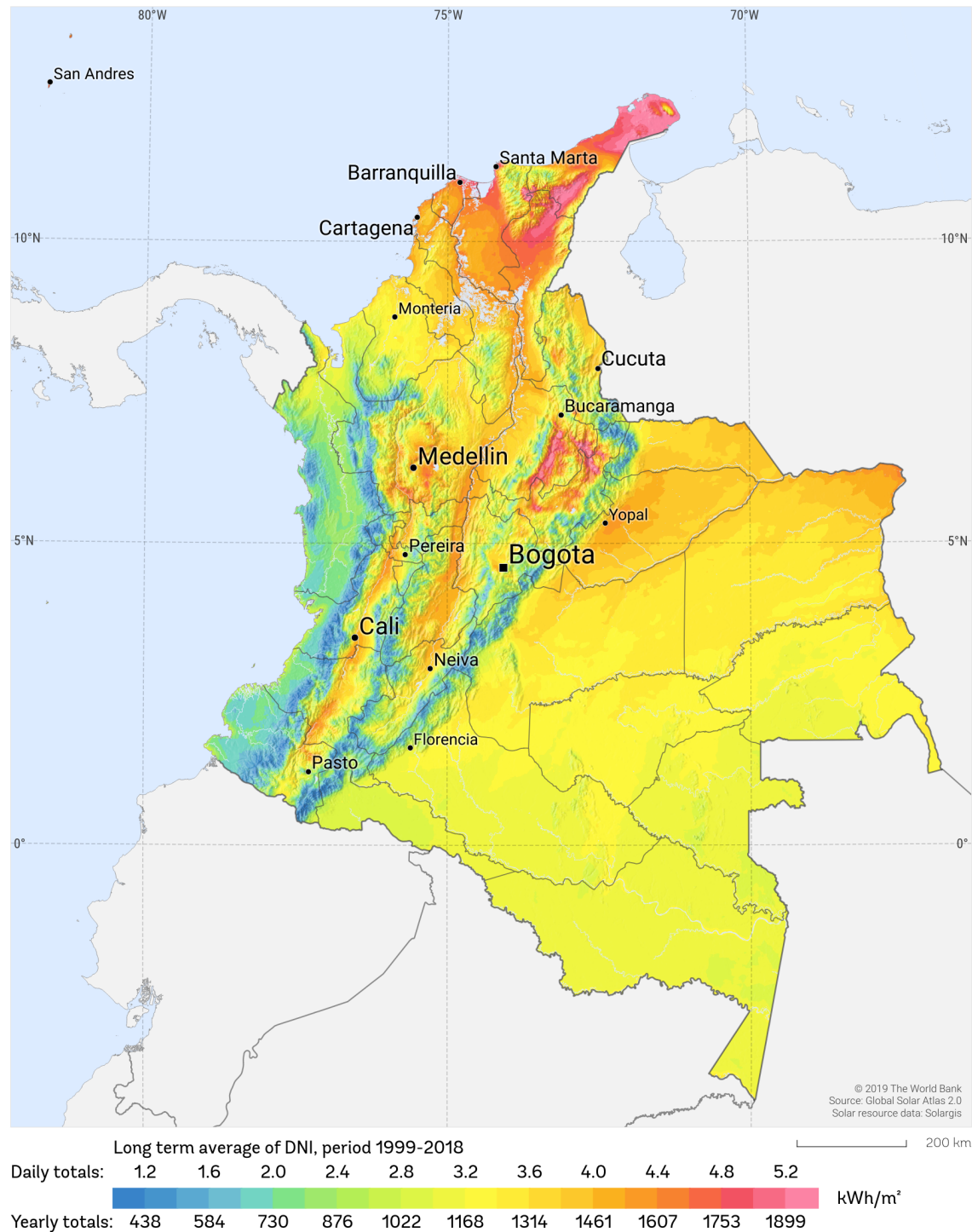


Figure 2.9: Normal irradiance map for colombia (Šúri et al., 2011)

respect to meteorological conditions, an *AM1.5* condition is considered, in Fig 2.10 the spectrum of the sun is shown for this condition.

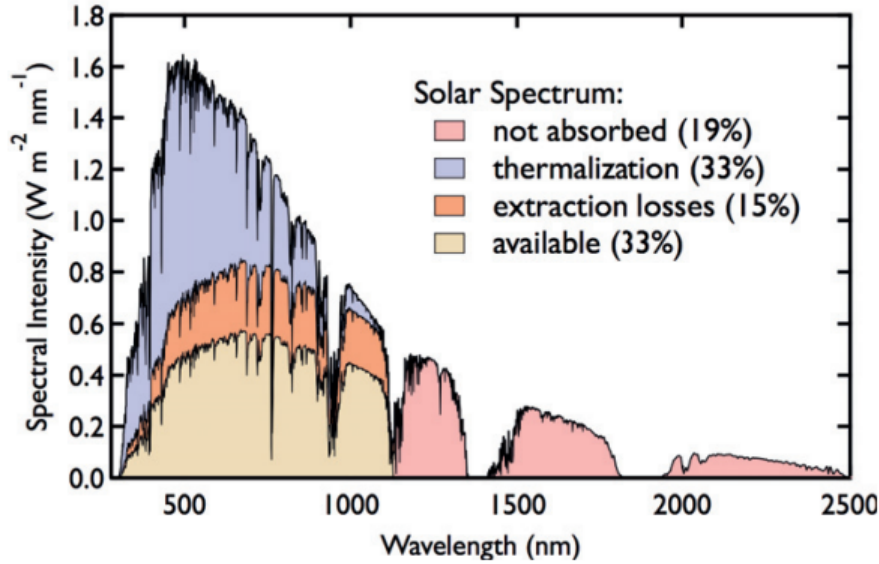


Figure 2.10: Spectral distribution in *AM1.5* condition (Semonin et al., 2012)

The entire area under the curve corresponds to the radiation energy on the earth's surface, i.e., the radiation remaining after considering the part absorbed by the atmosphere. Of this area, 33% of the energy is due to the heat generated by the photoelectric effect, which corresponds to thermodynamic losses. Similarly, there are 15% extraction losses due to optical and resistive phenomena inside the PV module. In the infrared range, i.e., above approximately 1000nm , silicon does not have the capacity to absorb energy, so about 19% is converted into heat and does not generate electricity. Therefore, in theory, only 33% of the incidental radiation can be used in electricity, a limit established by Shockley-Queisser for first-generation cells. Currently, most commercially available PV modules are below this efficiency value, so for the purposes of this work, this spectral distribution will be considered.

2.3 Commercial presentations of PV modules

Photovoltaic cells, being electrically conductive materials, cannot function properly without being isolated from the environment because they can short circuit. In addition, if there is a large number of interconnected cells without encapsulation, they can cause electric shocks to the people who handle them, not to mention that they can deteriorate when exposed to the environment. Likewise, the manipulation of the cells is very complex if there is nothing to package, assemble and position them into a complete part. For this reason, manufacturing techniques have been developed in order to isolate the cells from the environment through encapsulation processes, which are discussed below

for the different geometric configurations of solar panels. Taking into account the types of solar cells and their performance characteristics described above, it is possible to find different configurations of commercial solar panels, which, depending on the type of solar cell used and its manufacturing materials, present geometric attributes in terms of the final shape in which they operate, which are described below.

2.3.1 Rigid photovoltaic Modules

Rigid PV modules are usually made of typical monocrystalline and polycrystalline solar cells, so their flexibility is very limited. Its manufacturing is made from an aluminum frame in which a sheet of tempered glass is placed on top (Mughal et al., 2018). Then, the solar cells are encapsulated between two layers of Ethylene Vinyl Acetate (EVA), which is a material made from a type of lightweight, porous plastic (Jiang et al., 2015). At the lower part of the encapsulation, the frame is reinforced with a sheet of aluminum as is shown in Fig 2.11.

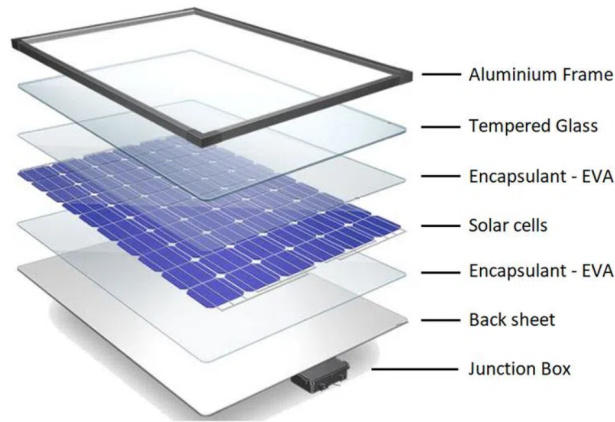


Figure 2.11: Rigid PV module fabrication (CER, 2019)

This is the way in which most PV modules are manufactured. They are highly resistant to mechanical and environmental effects, and the metal frame helps them to dissipate heat, which has a positive effect on power generation. Likewise, this rigid configuration only allows installation in rigid frames or on surfaces with flat geometry, which makes it difficult to adapt to contours with geometries other than flat or curved.

2.3.2 Flexible photovoltaic Modules

Flexible solar panels belong to the family of "thin film" panels and are constructed with monocrystalline silicon layers 300 times thinner than standard solar panels, which allows them to be flexible while maintaining their functionality. They have a good ability to adapt to established contours, they also have an efficiency of approximately 7% to 15% and a lifetime of 15 to 25 years (Li et al., 2021b).

Flexible PV modules are manufactured using the sandwich assembly principle, which is exposed in Fig 2.12. They are composed of a sheet of Ethylene TetraFluoroEthylene Tetraethylene (ETFE), which is a material used as an ecological alternative to glass and also improves energy performance. Then, the solar cells are placed between two EVA sheets and a Tedlar Polyester Tedlar (TPT) sheet as reinforcement (Li et al., 2021b)

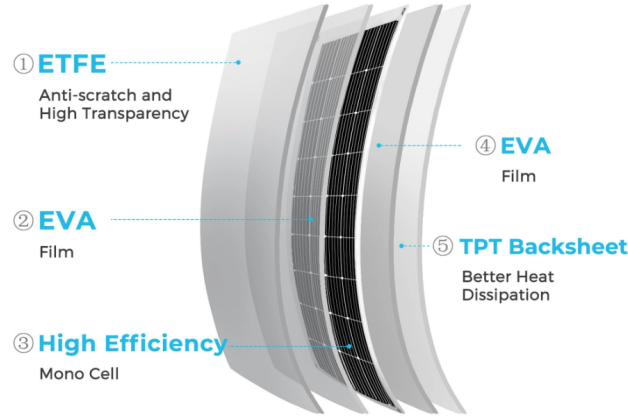


Figure 2.12: Flexible PV module fabrication (Renogy, 2020)

The flexibility of these PV modules allows adaptation to curved or irregular contours without compromising the structural integrity of the photovoltaic cells, which offers an important advantage for localized applications integrated with other devices. The type of cells used in this PV module configuration are thin film or CIGS (Segarra Balaguer, 2021), so high efficiencies are not achieved. However, they can reach up to 30cm radius of curvature, which is a value that allows a high range of adaptation to curved surfaces.

2.4 Physical Phenomena Involved

From the energetic transformation of sunlight into electricity within a photovoltaic module, a series of physical phenomena occur that have important implications on the overall performance of the system. Thus, the energy behavior depends largely on the materials used for its manufacture and the final geometric shape of the solar panel during its operation. Consequently, understanding the effects and analyzing the consequences of each of these phenomena, will provide a deeper insight into the performance and reliability of the system. These physical phenomena are analyzed below.

2.4.1 Optical Phenomena

The optical phenomena present in a PV module, makes it possible to study the incidence of light waves as a function of the electromagnetic spectrum. In this way, it is possible to study the estimation of optical losses in encapsulation and as well as in the cell due to the geometry of the panel and the material of which it is composed. The most commonly used simulation method is ray tracing. The most commonly used mathematical models for the characterization of the optical behavior of a PV system are Beer-Lambert Law, Snell's Laws, Fourier Optics and Fresnell's Laws which are the most important optical model used in this work whose scheme is shown in Fig 2.13:

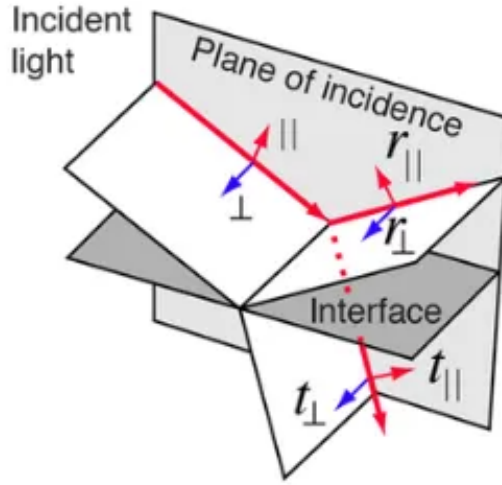


Figure 2.13: Scheme of Fresnell's laws (Jenkins and White, 1957)

Fresnell equations or coefficients are defined as the ratio between the electric field of a reflected and transmitted wave, with respect to the electric field of the incident wave. They describe the reflection and transmission of light when it strikes a surface between 2 different mediums. Thus, when light strikes a dielectric surface, it will reflect and refract as a function of the angle of incidence (Jenkins and White, 1957). The Fresnell equations are as follows:

$$t_{\parallel} = \left(\frac{2n_i \cos \theta_i}{n_i \cos \theta_i + n_t \cos \theta_t} \right) \quad (2.1)$$

$$t_{\perp} = \left(\frac{2n_i \cos \theta_i}{n_t \cos \theta_i + n_i \cos \theta_t} \right) \quad (2.2)$$

$$r_{\parallel} = \left(\frac{n_t \cos \theta_i - n_i \cos \theta_t}{n_t \cos \theta_i + n_i \cos \theta_t} \right) \quad (2.3)$$

$$r_{\perp} = \left(\frac{n_i \cos \theta_i - n_t \cos \theta_t}{n_i \cos \theta_i + n_t \cos \theta_t} \right) \quad (2.4)$$

$$r_{total} = \frac{R_{\parallel} + R_{\perp}}{2} \quad (2.5)$$

Expressions 2.1, 2.2, 2.3 and 2.4, will be used in Chapter 6 in order to estimate the total transmitted component of light to the solar cells and the associated losses with reflection and absorption within the encapsulation.

2.4.2 Thermal Phenomena

This phenomena allows to analyze the evacuation of the heat generated by the photoelectric effect and the evaluation of cooling strategies in order to increase the efficiency of the system. The most commonly used simulation methods to analyze the thermal performance of solar panels are the Finite Element Methods (MEF) and Computational Fluid Dynamics (CFD). The main mathematical models used for the analysis of these physical phenomena are Energy Balance, Heat Exchangers Design, Enthalpy Methods and Empirical relationships of natural convection. However, it is possible to estimate these energy exchanges in the form of heat, from the knowledge of the heat transfer modes, which will be the most used analysis in this work and which are shown in Fig 2.14.

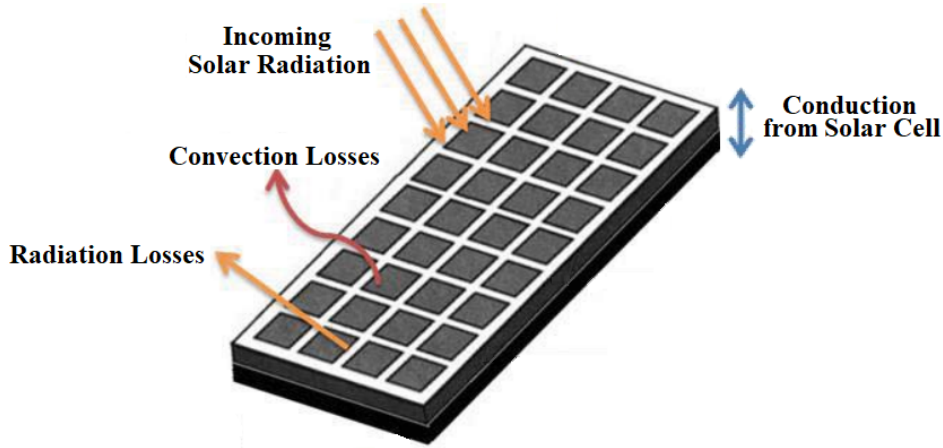


Figure 2.14: PV module thermal scheme (Siddiqui and Arif, 2012)

Considering that the solar cell generates electricity, by receiving solar radiation, it behaves as a heat source. So, there is heat transfer by conduction from the cells to the encapsulation and the reinforcement, which finally release this heat to the environment by radiation and convection. The equations governing these phenomena are shown below.

$$q_{cond} = -\frac{kA}{\Delta x} (T_2 - T_1) \quad (2.6)$$

$$q_{conv} = hA_s (T_2 - T_\infty) \quad (2.7)$$

$$q_{rad} = A\varepsilon (T_s^4 - T_{surr}^4) \quad (2.8)$$

From equations 2.6, 2.7 and 2.8, it is possible to estimate the energy performance from the thermal point of view (Cengel and Ghajar, 2007), which allows to know the mechanisms of energy loss by heat depending on the properties of the materials of manufacture of the PV module and the surrounding atmospheric conditions.

2.4.3 Mechanical Phenomena

Although this phenomena is not directly linked to the operation of the PV system, the study of mechanical phenomena allows the correct operation of a solar panel, because they allow to evaluate the performance of the PV array under operating conditions. In addition, the mechanical analysis guarantee the structural integrity of the solar cell, which is characterized by its high fragility. The most commonly used simulation strategy is the FEM and the associated mathematical models are Macromechanics and Micromechanics models based on Hooke's Law, which is shown below in its general form.

$$\{\sigma\} = [E] \{\varepsilon\} \quad (2.9)$$

The forces associated to the operation or the mass of the PV modules cause strains as a function of the stiffness of the material. Equation 2.9 is used to study the behavior of the encapsulation and solar cell, considering an isotropic behavior of the materials. However, in order to analyze reinforcements made of composite materials, it is necessary to include models from macromechanics (Barbero, 2010) as exposed in 2.10.

$$\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} \quad (2.10)$$

The values of the matrix S are a function of Young's , Poisson's and Shear Modulus of a given material. This assumption enables to analyze the reinforcement of a PV module made of composite material, which considers a transversely isotropic material due to the symmetry condition in the lamination of fibers and fabrics (Voyiadjis and Kattan, 2005).

2.4.4 Electrical Phenomena

This phenomena is used in the estimation of usable electrical energy from the modeling of electrical behaviour. They are also allow the evaluation of strategies to increase efficiency due to shading conditions. They are used to design the arrangement of the photovoltaic cells, in addition to estimating the performance with respect to the other physical phenomena presented. Usually, mathematical modeling methods are used for their implementation, which are single and double diode models and 3 to 7-parameter models. For the purposes of this study the single diode model will be analyzed due to the availability of data from the manufacturer and its scheme is shown in Fig 2.15.

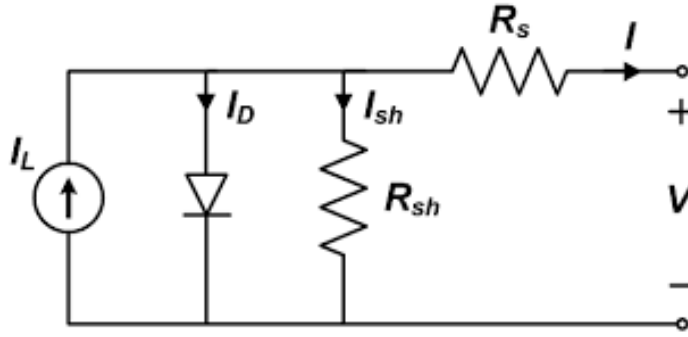


Figure 2.15: single diode model schematic (Ghani et al., 2014)

This model is widely used for typical conditions of temperature and irradiance, which allows estimating the conditions of electricity generation when solar radiation strikes the surface of the photovoltaic cells, generating voltage and a current flux along the cells. Equation 2.11 governs this electrical phenomenon (Ghani et al., 2014).

$$I = I_L - I_0 \left[e^{\frac{V + IR_s}{nV_T}} - 1 \right] - \frac{V + IR_s}{R_p} \quad (2.11)$$

The total current generated is then directly proportional to the incident radiation on the cell. Likewise, the cell temperature is taken into account in the inverse saturation current as well as in the shunt current. This model allows generating the VI curve, which are shown in Fig 2.16 below.

This graph provides a general understanding of the operation of a PV module and is provided by cell manufacturers as it shows the Short-Circuit Current (I_{sc}), which occurs when the voltage is zero, and conversely, shows the open-circuit voltage (V_{oc}) when the current is zero. It also shows the Maximum Power Point (P_{max}), which is the best combination of voltage and current in the operation of the PV module (Das, 2013).

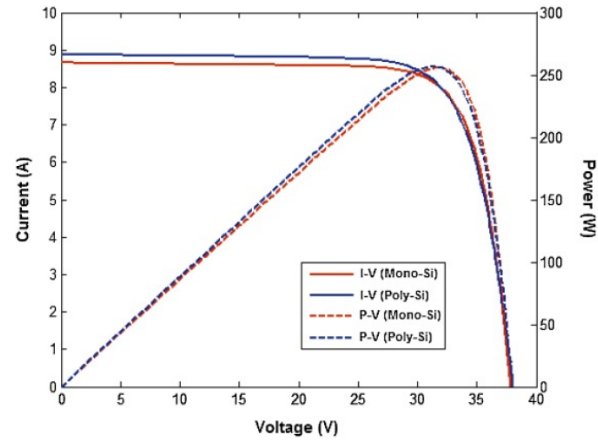


Figure 2.16: VI and PV Curves per silicon cells (Aslam et al., 2022)

Analyzing the previous subsections about the involved phenomena, we have an understanding of the most important aspects related to the operation of a PV module, according to the efficiency of the different types of solar cells and how these are interconnected to form solar panels (which can have rigid or flexible geometries). Likewise, the concept of solar resource is presented, as the combination between the movement of the sun and the aspects that influence the irradiance in a specific location. Finally, an analysis of the physical phenomena involved in the operation of a PV module is made in 5.5.3 and 6.5.3, in order to know the aspects that define the energy transformation from solar radiation to electricity, including its structural integrity.

2.4.5 Morphological Analysis

Although it is not specifically a physical phenomenon, the definition of curvature is necessary to include it in multiphysics analyses in order to know its role in the generation of electricity and in PV surfaces with curvature. To determine the curvature of a surface it is necessary to intersect a point with 2 planes orthogonal to the normal vector to the surface: the curves generated in the section are perpendicular and indicate the directions of the main curvature. This is shown in Fig 2.17.

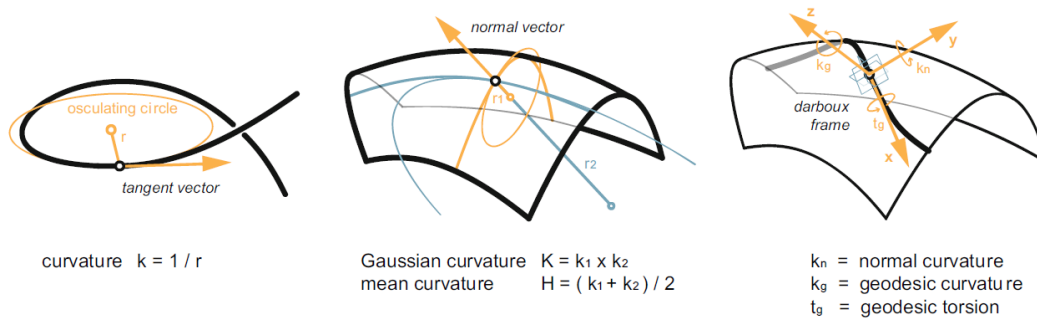


Figure 2.17: Curvature definition (Schling et al., 2018)

Through the 2 principal curvatures k_1 and k_2 , the Gaussian curvature $G = k_1 k_2$ and the average curvature can be estimated by $H = (k_1 + k_2)/2$. If k_1 and k_2 have opposite directions, their osculating circles have opposite sides, so the Gaussian curvature is negative. If k_1 and k_2 have opposite directions and the same absolute value, the average curvature is equal to zero. For this research, it is proposed the use of developable surfaces, i.e., that can adapt to a curved contour without undergoing membrane stresses (Dvorkin and Bathe, 1984), which is achieved when $G = 0$.

Chapter 3

State of the Art

The review presented in Chapter 2 about theoretical context of the problem, allows understanding the aspects related to the operation of photovoltaic (PV) systems, taking into account manufacturing characteristics, geometry and numerical modeling framed in the field of solar energy. Based on the above, a search of the State of Art about surfaces exposed to solar radiation is carried out, in order to determine the influence of curvature shapes in the behaviour of different physics phenomena. Also a search related to optimization algorithms is made in order to analyze their implications in the problem modelling and its manufacturing.

3.1 Adaptive or Curved Photovoltaic Surfaces Applications

In order to know the existing applications that use PV modules integrated to geometric surfaces of prosumer systems, a search is carried out based on the objects or devices that operate in conditions of exposure to radiation. Based on the reviewed context, the applications found in which PV modules are implemented as an additional function of electricity generation (other than structural or protective functions) are categorized as Vehicle Integrated Photovoltaics (VIPV) applications and Building Integrated Photovoltaics (BIPV), which are analyzed from geometric, functional and adaptive aspects.

3.1.1 Vehicle Integrated Photovoltaics (VIPV)

Vehicle Integrated Photovoltaics (VIPV) is a technology that can make a significant contribution to the consumption of transport vehicles as prosumer systems, due to the reduction of costs and the development of solar cell technology, the integration of PV systems in vehicles allows reducing greenhouse gas emissions because they can be charged from natural light, so that solar energy is transformed into movement without the need for any combustion process (Motahhir and Eltamaly, 2021). The most common uses of vehicle-integrated photovoltaics are shown below in Fig 3.1.

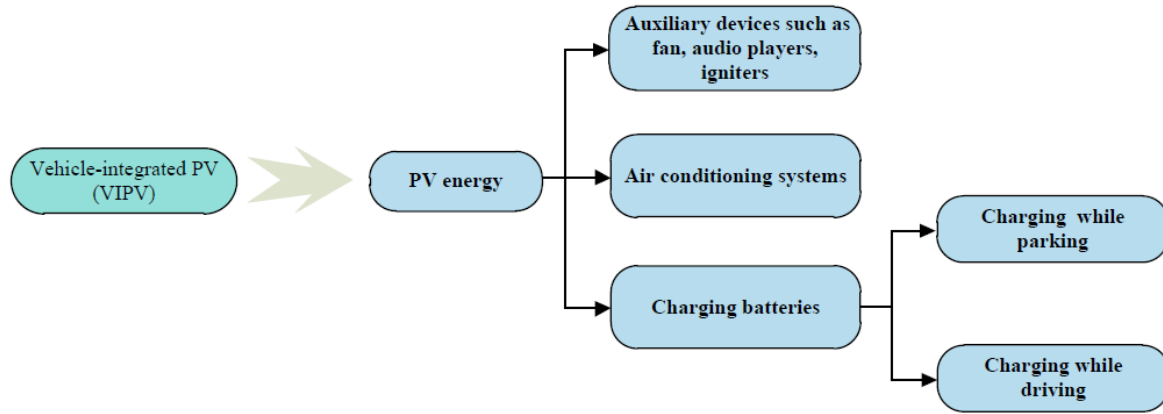


Figure 3.1: VIPV uses. (Motahhir and Eltamaly, 2021).

Usually, due to the limitations of the power generated by the PV modules, they are used to power auxiliary systems such as fans, audio reproduction equipment and air conditioning. However the final objective is to help to charge the batteries when the vehicle is parked or in motion (Thiel et al., 2022). In (Sagaria et al., 2022) it is integrated PV systems to batteries, cover up to 35% of the energy needed for its autonomy in operation, which can vary by a factor of 2.5 depending on weather conditions.

Additionally, vehicles do not have a fixed position, so the radiation incident on the generation area can vary substantially. Also, available area to integrate PV modules on vehicles tends to be small and is limited to the surfaces exposed to radiation. Fig 3.2 shows the number of vehicles integrating PV technology according to the type of means of transport and area available.

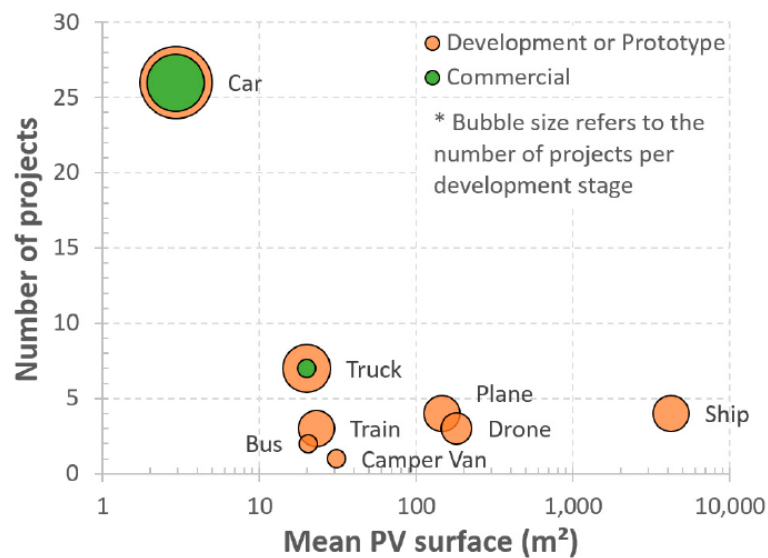


Figure 3.2: VIPV projects according to PV area (Commault et al., 2021)

Cars are the most developed vehicle in technical and commercial terms, although they have the smallest available PV area. Also, there are trucks with integrated PV modules that have some commercial development, but for the rest of the vehicles, which include trains, buses, drones, airplanes and boats, there is not much commercial development. Some studies related to the type of vehicle will be shown below.

3.1.1.1 PV applications in Cars

Among electric vehicles (e.g. autos, buses, trucks and camper vans) those classified as Hybrid Electric Vehicles (HEV), have another supporting energy source, which in most cases is combustion and assists the charge of battery. Electric vehicles (EV) operates in fully electric mode from the recharging of their batteries to a charging stations (Brito et al., 2021). Also, combustion cars are being developed with integrated PV systems. In Fig 3.3 is shown some commercial cars with integrated PV systems.



Figure 3.3: Commercial PV cars

In order to maximize the contribution of solar energy to the operation of a car, it is necessary to take advantage of as much area as possible for the installation of PV modules. Fig 3.4 shows a scheme in which the use of different PV technologies is proposed according to the functional, geometric and formal design attributes given for the vehicle parts in which PV modules are integrated.

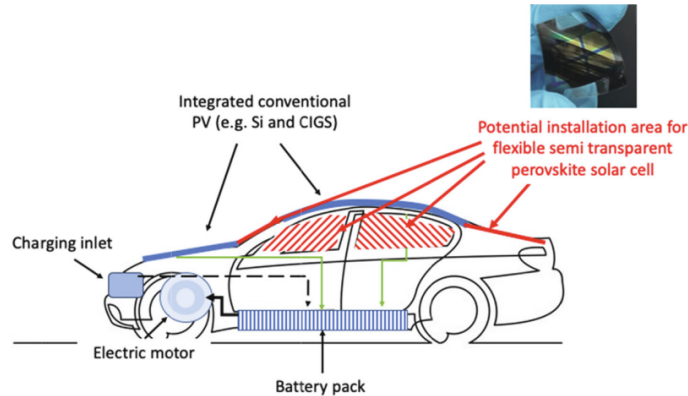


Figure 3.4: Available PV area on car (Nukunudompanich et al., 2022).

This configuration is proposed so that the PV systems installed do not affect the usability, aesthetics and drivability of the vehicle. Thus, for the roof and the hood, it is suggested to install c-Si and CIGS PV modules, given that its orientation to the sun and available area allows maximizing electricity, in addition to their opacity does not affect in any aspect due to its position with respect to the driver. Regarding to the windows, semitransparent perovskite modules are suggested so as not to affect the visibility of the passengers and with respect to the car doors, these also represent a significant area although they are not very well oriented as is shown in Fig 3.5.

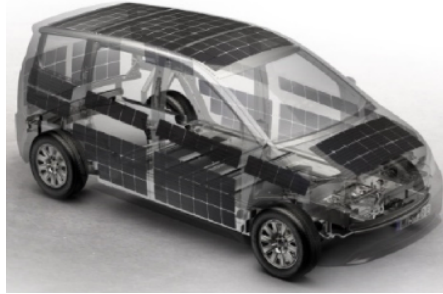


Figure 3.5: Car with PV modules integrated in its doors (Sagaria et al., 2022)

As can be seen, most of the available area of the car body in Sagaria et al. (2022), is used from the installation of PV Modules. It should be noted that the orientation of the vehicle with respect to the sun is very random due to the fact that the vehicles are continuously moving in different topographies throughout the day, which makes the electricity generated from the PV systems installed vary according to their location on the car as shown in Fig 3.6.

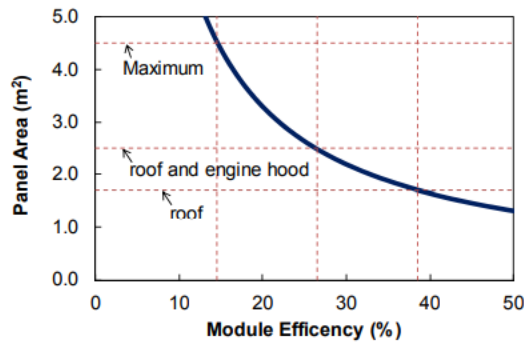


Figure 3.6: Overall PV efficiency in a car depending of the area (Masuda et al., 2016)

Just the use of the roof area offers a better overall performance of 40% because it is the most exposed area of the car and has no obstacles that generate self-shading. In second place is the roof area plus the hood which although it is a larger area, the performance falls below 30% and finally there is the use of the entire area of the car with a 14%. Based on the above, it is convenient to integrate PV systems to vehicle roofs, which normally have curved geometries, so it should be taken into account

that adapting flexible flat PV modules to this surface leads to a development of the geometric shape, this fact is shown in Fig 3.7.



Figure 3.7: Deployment of a flat PV module on a curved surface (Ota et al., 2022b).

Taking into account the geometric shape of the car roofs, the manufacturing of the PV module was made flat and then adapted to contour of the fairing, which has some implications from an assembly and mounting point of view. The roof of a car is an ideal place but normally, the geometry of the roof of the cars is not flat so the deployment of the PV module to be assembled to a curved contour must be taken into account (Ota et al., 2022b). In solar competition cars where the energy demand is satisfied only with integrated PV modules, the roof area is maximized as shown in Fig 3.8.



Figure 3.8: Primavera II, solar competition car (Guzmán Garzón, 2016).

In addition to the large PV area, this vehicle was designed with a low weight chassis and an aerodynamically shaped fairing to reduce aerodynamic resistance. Likewise, the dome where the pilot's seat is located was moved to one side in order to reduce the effects of shadows on the generation of electricity from its PV modules. Also, the PV array was divided into sub-modules, based on an irradiance analysis in order to avoid current drops by self shadows (Guzmán Garzón, 2016).

3.1.1.2 PV applications in airplanes

Solar airplanes take advantage of wider wing enabling installation of PV modules to meet the energy demand for operation of vehicle (Sun et al., 2019). Most of these applications correspond to unmanned vehicles for uses in monitoring, archeology and disaster relief among many other uses (Hoffborn, 2009). Fig 3.9 shows some of the aerial vehicles developed in the last decades.



Figure 3.9: Unmanned aerial vehicles. (Noll et al., 2007; Noth et al., 2004)

The Helios project, developed by NASA, has a single $75m$ wingspan housing a total of 62000 solar cells, which feed 14 electric motors with a total of $40kW$ of power (Noll et al., 2007). Sky Sailor is an unmanned aircraft designed to perform operations on Mars, which has a wingspan of $3,2m$ and a power of $9W$ (Noth et al., 2004) while the solar impulse is a project that allows to have 1 pilot for its management, which has a mass of $2300kg$ and a wingspan of $71.9m$ in which a total of 17248 solar cells are accommodated supplying a power of $13kW$ (Impulse, 2011; Pultarova, 2014). Fig 3.10 shows applications of aerial vehicles of different sizes.

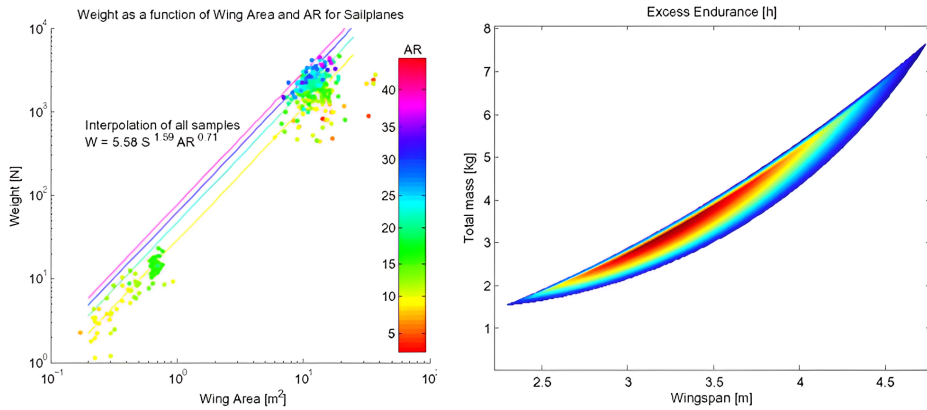


Figure 3.10: Geometrical and operational characteristics of a solar airplanes (André, 2008).

As expected, the weight of the aircraft increases with its wingspan. Likewise, the wing area is proportional to the Aspect Ratio (AR), which is the ratio between the wingspan and the wing chord. Therefore, larger wingspans result in higher endurance, enabling more flight time. This fact is interesting because, in general, for larger aircraft there are longer flight times, therefore, the use of lightweight composite materials, such as carbon fiber, shown in Fig 3.11, can substantially improve the overall performance of solar air vehicles.

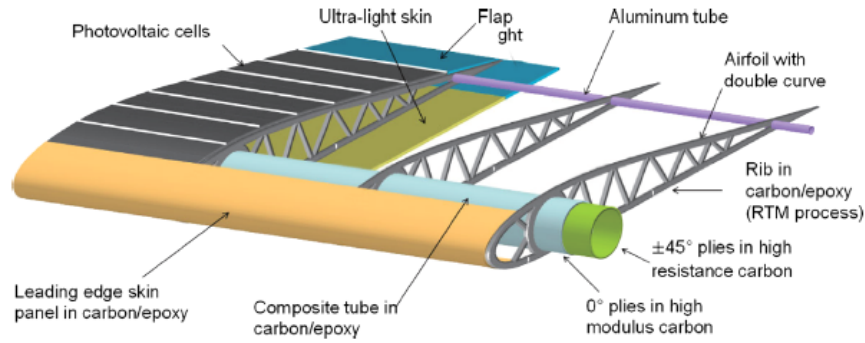


Figure 3.11: Layout for a solar airplane wing (Zhu et al., 2014).

In addition to carbon fiber, the use of non-ferrous alloys of low density and high specific resistance is recurrent in order to minimize weight and increase flight time. Likewise, the installation area of solar cells is given in the upper area of the wing where the exposure to the sun is higher, just after of slats where the wind pressures are higher.

3.1.1.3 PV applications in boats

Boats and, in general, maritime and river vehicles are the ones with the largest effective area for the installation of PV systems, this represents a great opportunity in the market, although there are not a large number of projects implemented to date. The applications of PV boats are mainly for transportation of people (46%), recreation 8% and private use and research 46% (Gorter et al., 2010). Fig 3.12 shows some important solar boat projects.



Figure 3.12: Projects of solar boats (Gorter et al., 2011; Thwaites, 2006; Zhang and Shi, 2020)

"Elp Czeers Mk1" was the first electrosolar speed boat in the world, the monohull made entirely of carbon fiber, has a length of 10m, a top speed of 55km/h and a power of 80kW (Gorter et al., 2011). "Solar Sailor" is a passenger transportation boat made of composite materials, with a length of 24m and a capacity of 100 passengers at a cruising speed of around 10km/h (Thwaites, 2006). The largest electro-solar boat manufactured is the "Planet Solar", which has a length of 31m and moves at a speed of around 15km/h. Its PV system consists of a total of 127 PV modules, covering an area

of $537m^2$, powering 4 engines with a total power output of $176kW$ (Zhang and Shi, 2020). Fig 3.13 shows the location of the PV modules within the areas available on boats.

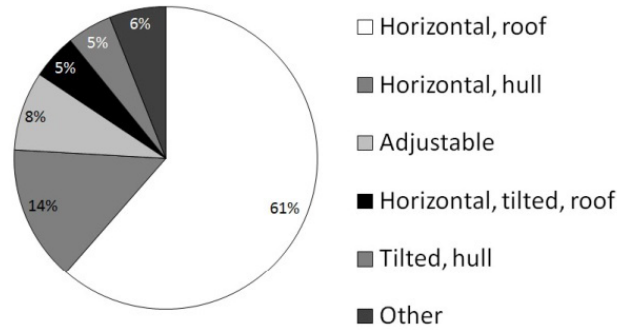


Figure 3.13: PV modules placement on PV boats (Gorter et al., 2010).

The most used area for the installation of PV systems in solar boats is the roof with about 61%, followed by the hull with 14%. The rest of the modules are used in the same areas but with a certain inclination of the PV modules due to the geometry of the boat itself (Gorter et al., 2010). This fact suggests that solar panels on boats tend to be installed horizontally, due to the adequate exposure to sunlight, which allows maximizing the power generated. Fig 3.14 shows the PV power installed as a function of the weight of the boat.

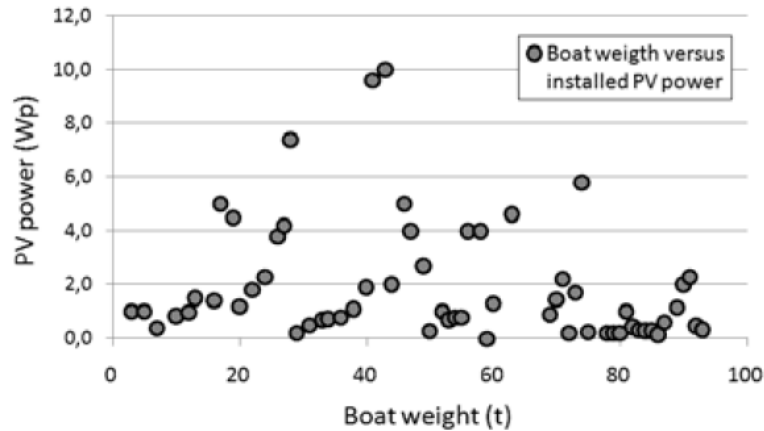


Figure 3.14: Installed PV power vs. weight of solar boats (Gorter et al., 2010).

It is observed that the trend is to have a low PV power output in heavy boats, which is counter-productive due to increased energy consumption. This fact has allowed exploring the fabrication of PV modules with lighter weight materials in order to increase the contribution of the PV modules in the overall performance of the boat, this is shown in Fig 3.15.

The commercial configuration of PV modules shown in 2.3, establishes a metallic reinforcement frame and a PV glass above the cells that plays the role of encapsulation, however, this glass normally

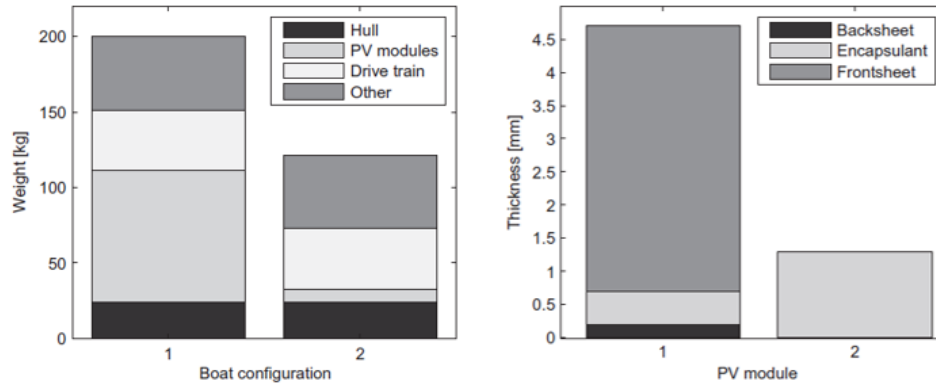


Figure 3.15: Weight reduction of PV modules in solar boats (Gorter and Reinders, 2012)

has thicknesses in the order of 4,5mm, which significantly increases the weight of the PV system (Boat Configuration 1). This fact allows us to propose manufacturing processes using encapsulation materials that allow to reduce the thickness of the PV module (Boat Configuration 2) and also satisfy the functional requirements of the system, mainly the structural integrity of the cells, obtaining lighter solar panels (Gorter and Reinders, 2012). In Section 3.2, an analysis of the PV module manufacturing processes will be made.

3.1.2 Building Integrated Photovoltaics (BIPV)

In buildings and constructions, any surface exposed to radiation during the day is potential electricity generator. Consequently, functional elements such as roofs, terraces and facades are important elements of study, because they are directly integrated into of residents basic needs such as lighting and appliances (Martín-Chivelet et al., 2022). In addition, BIPV applications are stationary and have geometries that are not necessarily impacted by radiation during the whole day. These types of applications usually require basic design requirements for their construction in order to integrate, form or replace a product. For the different applications, it is necessary to establish basic conditions for their implementation, as shown in Fig 3.16, where some characteristics of integrated PV systems are presented according to the level of customization required (Kuhn et al., 2021).

Depending on the implementation specifications, available budget and design requirements established in the development of the application, the following application levels are available for BIPV applications, which are presented below:

- **Standard size:** conventional PV modules are used and integrated to an already established contour without giving an aesthetic added value.
- **Custom size:** in addition to offering electricity from the integration of PV modules, the aim is to replicate the conventional appearance of the element that is being replaced, so it must have



Figure 3.16: Installation features of BIPV applications (Kuhn et al., 2021)

the same mechanical performance and appearance, which gives an aesthetic added value.

- **Adaptable standard dimensions:** offers a higher degree of functionality, allowing to generate PV systems with adaptability to unknown contours and also with aesthetic attributes.
- **Sophisticated design:** allows the development of specific manufacturing processes to achieve the aesthetic design requirements in art and architecture contexts.

In all these BIPV applications, particularly for roofs and facades, the use of different solar cells technologies depends on the requirements and attributes that device designed must achieve. Fig 3.17 shows the use of these types of PV materials in this sector.

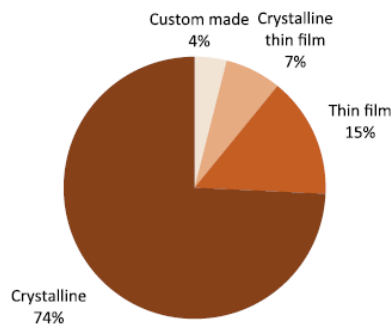


Figure 3.17: PV cell types most commonly used in BIPV applications (Frontini et al., 2015)

It is observed that for both applications, crystalline cells predominate in their use, with 54% for roofs and 74% for facades. The second place is occupied by thin film crystalline cells with 21% for

roofs, while in facades, the second most used technology is thin film with 15%. This fact allows to analyze that the trend in the use of photovoltaic technology in this type of application is towards crystalline cells (Frontini et al., 2015). The following is an analysis of the different types of applications in relation to the above-mentioned characteristics.

3.1.2.1 PV applications in facades

In Assoa and Levrard (2020), it is presented a energetic analysis of a PV system integrated to a building based on triangular geodesic shapes including an electrical and thermal analysis. Similarly, in vertical facades, (Jayathissa et al., 2018) implements an adaptive kinetic PV system based on flat PV modules, which change their inclination throughout the day, maximizing the electrical energy generated, which is shown in Fig 3.18.

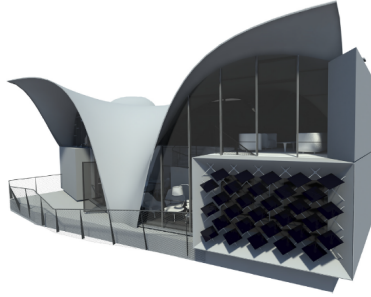


Figure 3.18: Integrated PV wall (Jayathissa et al., 2018)

Also, in Liu and Chow (2020), it is presented solar walls with integrated thermal systems for domestic use of hot water and for thermal comfort. In Alhammadi et al. (2022), was conducted an experimental comparative study of PV modules integrated to the vertical facade of a house called "The Cube" with Copper Indium Gallium Selenium (CIGS) and mono-crystalline Silicon (c-Si solar) cells, in which the effects of the orientation of the sun, with respect to the position of the PV system were analyzed obtaining a better performance for the facade oriented to the southeast. The physical implementation of this work is shown in Fig 3.19.



Figure 3.19: "The Cube" (Alhammadi et al., 2022)

Taking into account that there are several PV elements that can be functionally integrated into a building in Vahdatikhaki et al. (2022), a sensitivity analysis is made. They analyzed the best location and technology that can be integrated into a building depending on its location, orientation, size and shape, as shown in Fig 3.20.

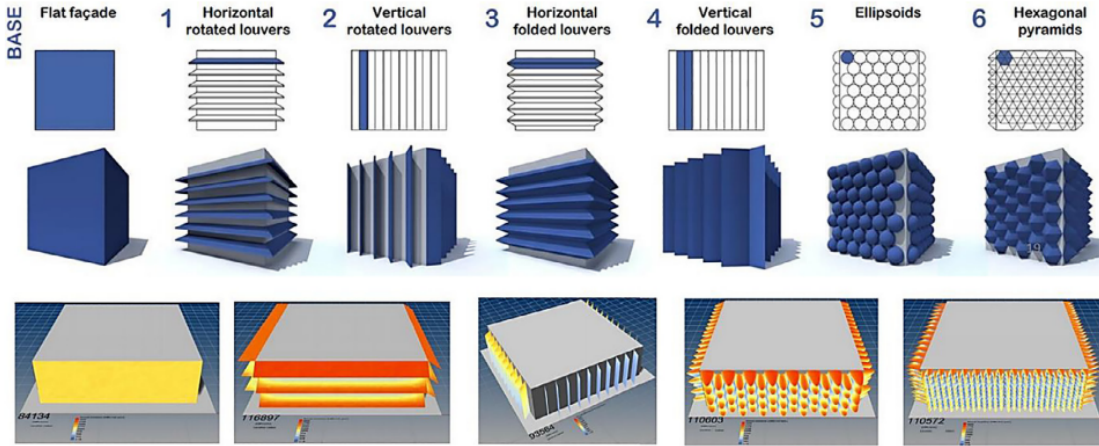


Figure 3.20: Exploration of optimal geometries for solar facades (Vahdatikhaki et al., 2022)

For the geometric shapes shown, a radiation analysis is carried out in order to know the potential of each one of them according to the characteristics of the application site. This study demonstrates that finding optimal geometries can add value to the performance of integrated PV systems.

3.1.2.2 PV applications in roofs

Regarding PV roofs, in Tian et al. (2023), there is an electrical and experimental analysis of curved PV modules integrated to traditional Chinese architecture using CIGS cells for different inclinations. Here the PV module with flat geometry had better performance but the curved PV module had better annual performance due to the excellent performance in the summer for high values of inclination. The schematic of this work is shown in Fig 3.21.

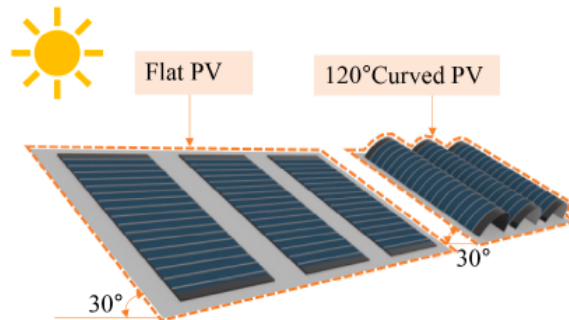


Figure 3.21: Analysis between flat and curved PV modules integrated to roof. (Alhammedi et al., 2022)

With respect to hybrid applications (Yadav et al., 2018), there is a Photovoltaic/Thermal (PV/T) module that seeks the optimal inclination and includes the effect of shadows and uses the energy generated by heat to satisfy basic domestic needs. (Calcabrini et al., 2021) shows different topologies of connection in order to avoid the drop in electricity generation, due to the self-shadows generated by the same geometry of the roof, generating an additional 25% of yield throughout the year. The topologies proposed in the study are shown in Fig 3.22.

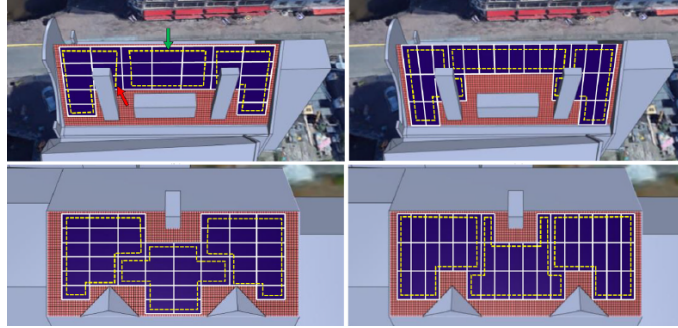


Figure 3.22: Sunroof interconnection topologies. (Calcabrini et al., 2021)

(Tian et al., 2022) implemented a comparative study of PV modules integrated to roofs with flat and curved geometry, which are analyzed in different inclinations, showing that annually, the curved PV module presents better performance. (Esfahani et al., 2021) performs a geometric optimization study of the roof of a building in order to maximize the catchment area, which is an important reference for the development of this work because it explores geometrical shapes that increase the radiation captured, the obtained geometry is shown in Fig 3.23.

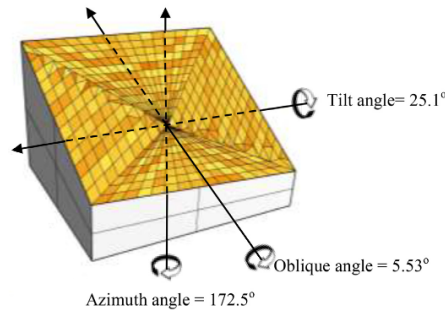


Figure 3.23: Roof geometry that maximizes irradiance capture (Esfahani et al., 2021).

The potential use of flexible roof-integrated PV modules, which offer certain performance advantages throughout the year, is then analyzed. Similarly, due to the shading of the same elements, it is possible to implement interconnection strategies to maximize electricity generation at certain times of the year. Also, the optimization of geometric shapes is explored in order to maximize the captured radiation, which creates challenges in terms of fabrication and implementation.

3.1.2.3 PV applicacioints in Windows

In relation to elements integrated to walls such as windows, in Paydar (2020) and Lee and Lee (2022), an analysis is made of a device that allows varying the position of the windows to reflect the inside of the house and reduce electricity costs and takes into account shading patterns and the seasons of the year for thermal comfort in the houses. The scheme of this device is shown in Fig 3.24.

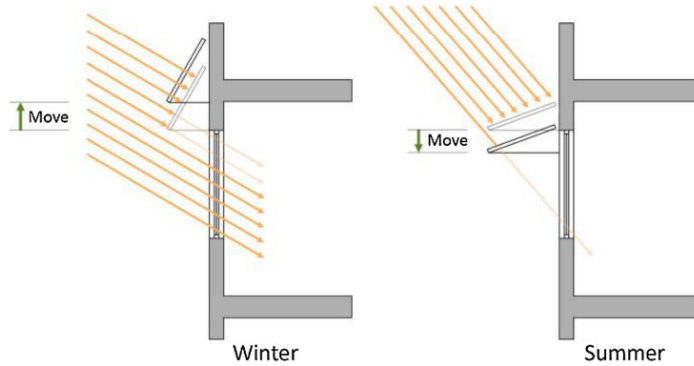


Figure 3.24: Solar windows with motion(Paydar, 2020).

The described movement is achieved by implementing bar mechanisms to a commercial PV module. There are also applications of windows integrated to cogeneration systems, which take advantage of the heat generated by the photoelectric effect, allowing the generation of microclimates in residential environments. The use of thermal energy is provided by a heat exchanger, which saves between 9.15% and 63.71% in energy consumption for thermal comfort (Chen et al., 2021), the scheme of this work is shown in Fig 3.25.

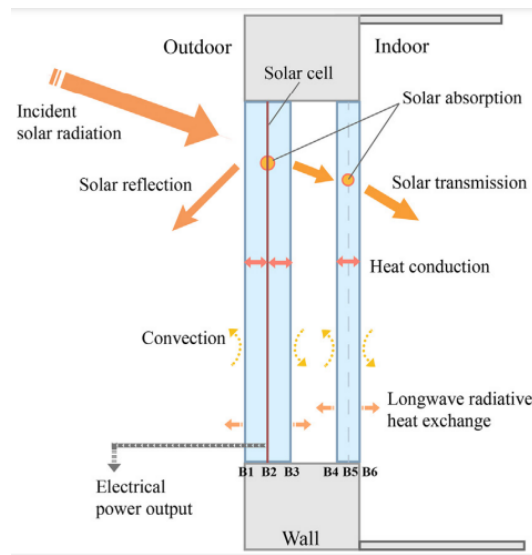


Figure 3.25: Integrated solar thermal windows.(Chen et al., 2021)

In general, windows with PV integrated can generate electrical and thermal energy for the satisfaction of basic needs, also, there is a common denominator and that is that these applications have additional functionalities, given by the thermal comfort and lighting according to the season of the year. This is an important fact, because integrated PV systems offer energy solutions giving a specific added value in their implementation.

3.2 Manufacturing Processes of PV modules

From the review of the applications, in which PV systems are integrated, it is observed that the used PV modules, have specific characteristics for the operating environment of the application, from the geometrical point of view, since they must adapt to already established contours due to aesthetic and functional requirements, which can be flat or curved geometries. Also, in terms of performance, it is useful for VIPV systems to be lightweight, in order to increase the overall efficiency of the PV modules by decreasing the additional mass inertia. This fact allows exploring other types of PV module manufacturing processes in order to find a combination of materials to meet structural, functional and performance requirements. From a search of the State of the Art, a review was carried out about different layouts, data sheets and patents of manufacturing processes for adaptable PV modules to curved geometric shapes. Although some of the manufacturing processes found are for very specific applications, in general, solar cells are assembled from sandwich and encapsulated processes, using layers of different characteristics and properties. In general, two families of materials used to encapsulate and sandwich photovoltaic cells have been identified: glass and plastics. These forming processes will be discussed in more detail below.

3.2.1 Glass-based PV Module Manufacturing

To produce curved PV modules from glass, a precise thermal molding process is required. In patent *US4655811A* a method is proposed to produce transparent curved glass from a surface treatment of flat glass with a layer of indium oxide, then materials with high carbon content are applied on the treated surface and then introduced into a furnace where bending is performed, reaching radii of up to $6,5m$ in applications such as windshields and aircraft windows (Bitter, 1987). An analogous process occurs in patent *US4717790*, in which previously interconnected cells are laminated between a thermosetting polymer and a glass that from the action of an external contour is molded according to the given radius of curvature, the scheme of this configuration is shown in Fig 3.26.

This process is applied to the manufacture of PV modules integrated into automobiles and boats. In order to increase the flexibility capacity of PV modules, it is recurrent to find the implementation of very thin layers of encapsulation material. Patent 4625070 (Berman and Eisner, 1986) proposed



Figure 3.26: Layout patent US4717790 (Gochermann, 1986)

the encapsulation of monocrystalline silicon PV cells between a sheet of tempered glass and another untempered, joined through adhesive materials, which add up to 1.1mm thickness. Fig 3.27 shows the manufacturing scheme of this invention.

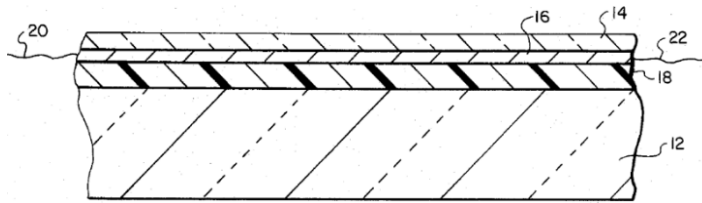


Figure 3.27: Layout patent 4625070 (Berman and Eisner, 1986).

For PV modules integrated into the roof of vehicles, there is a method for curving the surface of the glass within the assembly, which is proposed in patent US5059254. This is achieved by heating the glass sheet to between 500°C and 600°C, obtaining bending radii of up to 0.5m for a thickness of between 1 and 5mm (Pohle, 1995), the schematic of this process is shown in Fig 3.28.

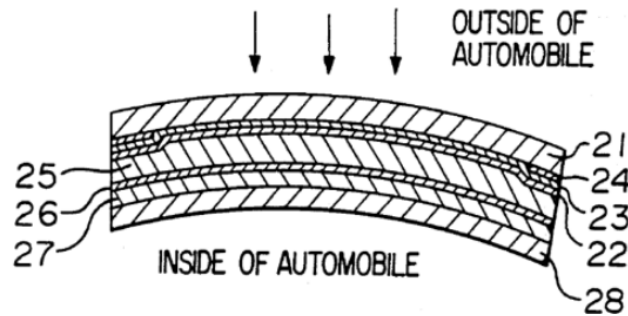


Figure 3.28: Layout patent US5059254 (Pohle, 1995).

Most of the manufacturing processes analyzed for the fabrication of curved PV modules using glass require specialized tooling and equipment, which increase the cost and level of technical expertise required to obtain them.

3.2.2 Plastics-based PV Module Manufacturing

Generally, curved solar panel forming processes using plastics require less sophisticated equipment. In patent US2010/0031996A1, a process is shown in which solar cells are thermoformed in polymeric

material, which provides certain ranges of flexibility for different types of cells, the schematic of this process is shown in Fig 3.29. A similar process is proposed in patent US 8607510B2, where cells are encapsulated in thin flexible sheets of polymeric material, such process is designed for BIPV applications.

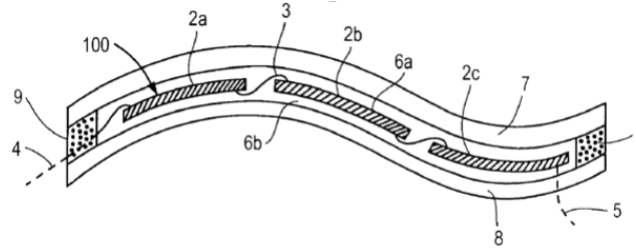


Figure 3.29: Layout patent 2010/0031996 (Daniels, 2007)

The use of composite materials is also recurrent. In patent US3565719 (Du Pont, 1971), fiber-glass fabrics are arranged on a mold with the desired curvature, which are stacked and impregnated until reaching the desired thickness. Then it becomes the sheet that goes underneath the solar cells previously interconnected. Finally, the cells are sealed using an adhesive, which is poured on top of the cells as shown in Fig 3.30.

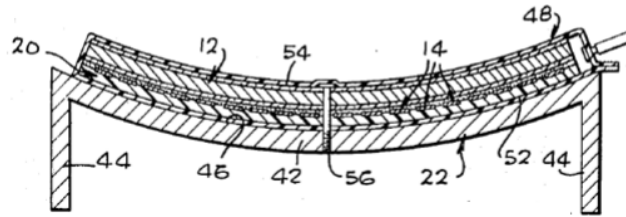


Figure 3.30: Layout patent US3, 565, 719A1 (Du Pont, 1971)

Using thermosetting polymers, patent EP2068375A1 propose first casting of the desired thickness is made until cured. Subsequently, the solar cells are positioned and then a second layer of thermosetting polymeric material is deposited, which is in contact with the first layer. Finally, both layers are hardened and a flexible PV module is obtained. The scheme of this process is shown in Fig 3.31.

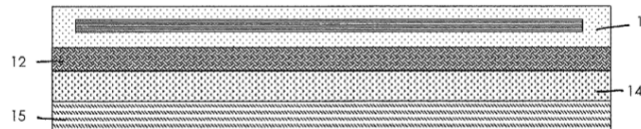


Figure 3.31: Layout patent EP2068375A1 (Brouwer, 2008)

The use of engineering plastics in fabrication of curved PV modules is relatively simpler than glass, because they use conventional equipment and tooling. Those processes require a lower level

of technical knowledge, allowing the generalized fabrication of these systems. Similarly, the optical, thermal, mechanical and electrical properties of these materials have an important influence on system performance, because they determine the behavior of the physical phenomena associated with the overall efficiency. This fact is discussed in the following section.

3.3 Physics analysis of PV surfaces

The general behavior of a PV module is given from the understanding of the physical phenomena involved in the operation of a PV module, which were previously explained in Section 2.4. From the above, a search of the most important works related to each of these phenomena is carried out, in order to expose their influence within the development of PV surfaces with curvature. Finally, the interactions and coupling among them are analyzed from multiphysics models.

3.3.1 Mechanical Analysis

The mechanical phenomena within a PV module are associated with the capacity of the solar cell to withstand loads due to forces generated by velocity changes in vehicle applications, dead loads due to its own weight or critical static conditions and impacts by external elements, such as hail, stones, fruits, animals, etc (Makarskas et al., 2021). However, the most critical loads for a PV module are due to bending effects, condition shown in Fig 3.32.

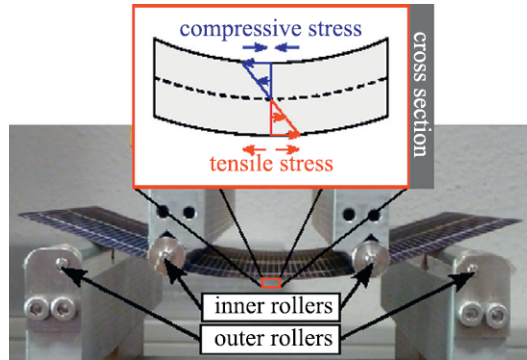


Figure 3.32: Flexion condition in PV modules (Kaule et al., 2014)

The bending condition shown above is common in structural strength analysis for commercial PV modules. This condition is extremely damaging due to the high forces generated by bending moments, which generate tensile-compressive stresses in solar cell, which depend on thicknesses used in the manufacturing materials and their mechanical properties (Kaule et al., 2014). Fig 3.33 shows a more detailed diagram of the stresses and deformations presented in a cross section of a conventional PV module.

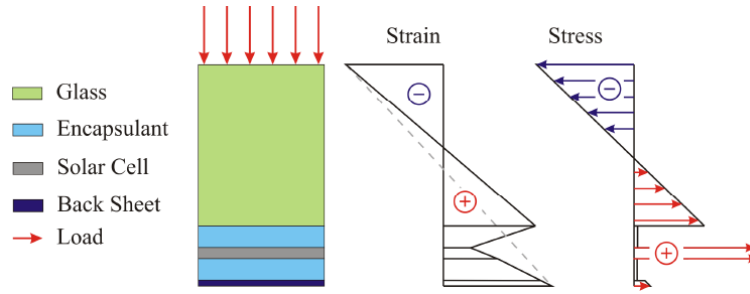


Figure 3.33: Stress and Strain in solar cell (Dietrich et al., 2010)

For a bending condition, the stresses generated in the solar cell will be highly dependent on the location of the materials and the given thicknesses. It is observed that the stresses and deformations are similar along the glass, however this condition changes when reaching the encapsulation due to the difference in Young's modulus. Something similar occurs in the cell, although strains are small, stress presents a large increase due to the mechanical properties of silicon, which is the critical condition that must be minimized. An analysis presented in Sander et al. (2013), exposes the fracture stresses associated to polycrystalline and monocrystalline solar cells, whose distribution is shown in Fig 3.34

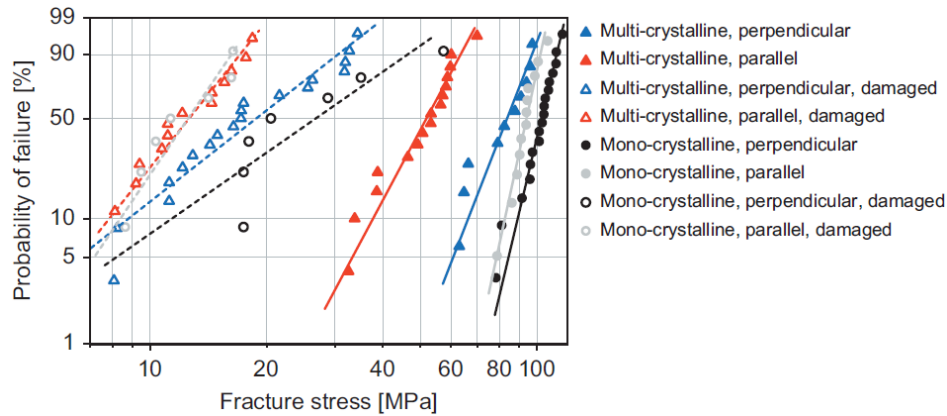


Figure 3.34: Fracture stress vs Probability of failure in silicon solar cell (Sander et al., 2013).

The Weibull distribution diagram showed in Fig 3.34 allows to know the fracture stress of silicon solar cells, used or new, as a function of a failure probability and a load direction given by the PV module orientation. This information allows to establish Safety Factors (SF) in cells and PV modules in order to validate the design of PV systems integrated to buildings and vehicles. Likewise, these stresses allow to establish critical structural conditions in curvature. In addition to the operating loads and flexural stresses, the aging of the PV modules leads to a decrease in the delivered electricity due to snail trail and microcracks effects. Fig. 3.35 shows the results of a power analysis of four polycrystalline PV modules under snail trail condition.

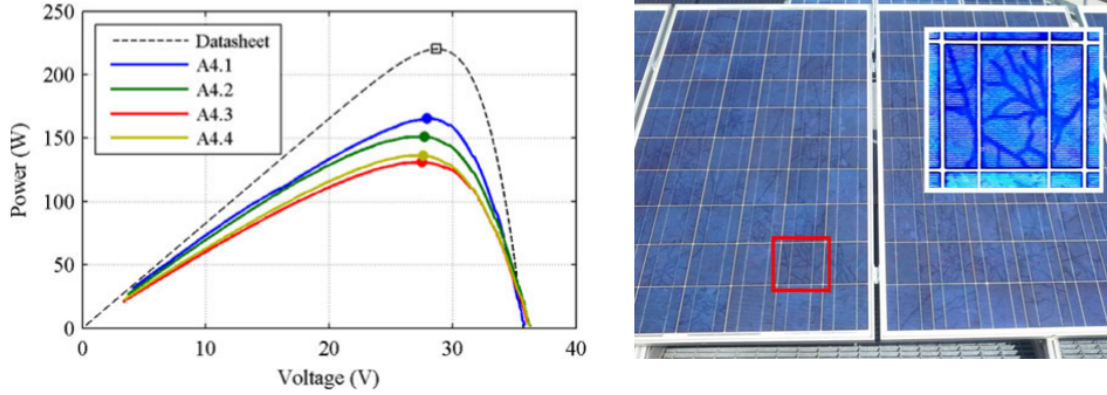


Figure 3.35: Power drop with snail trail condition (Dolara et al., 2014)

The behavior of four PV modules with snail trail condition is observed together with the maximum power of the data sheet, which are below the benchmark. This drop is mainly related to the photo-generated current reduction while the open circuit voltage coincides with the reference value (Dolara et al., 2014).

3.3.2 Thermal Analysis

Thermal study in PV systems is related to the comprehension of energy losses associated to the different mechanisms of heat transfer within of PV module and its relation with the operating environment. Fig 3.36 shows thermal phenomena in a cross section of a conventional PV module.

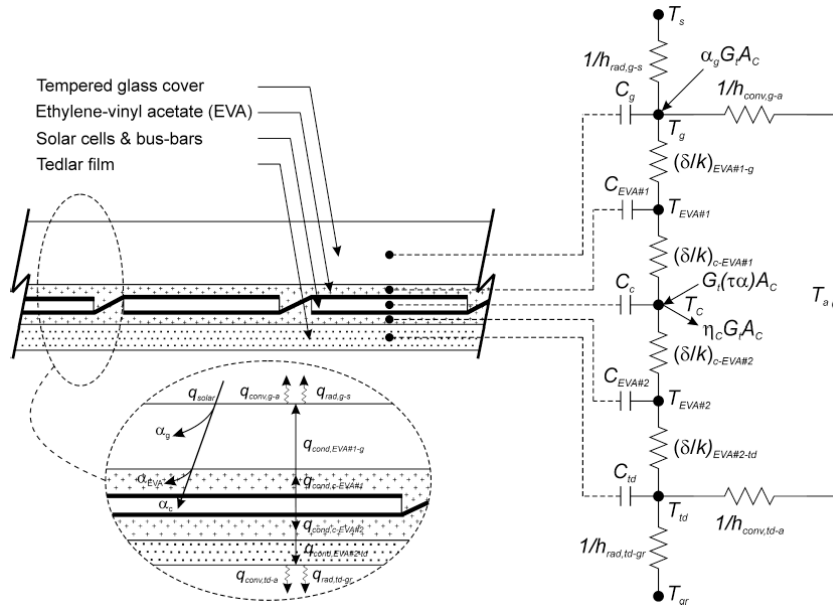


Figure 3.36: Thermal resistance circuit in a PV module (Yaman and Arslan, 2021)

It is observed that the solar cell behaves as a heat source, which generates a flow towards the reinforcement and the encapsulation in the form of conduction that is finally exchanged with the environment by convection and radiation. Similarly, temperature directly affects some parameters of electricity generation. Fig 3.37 shows the relationship between power of PV modules as a function of temperature.

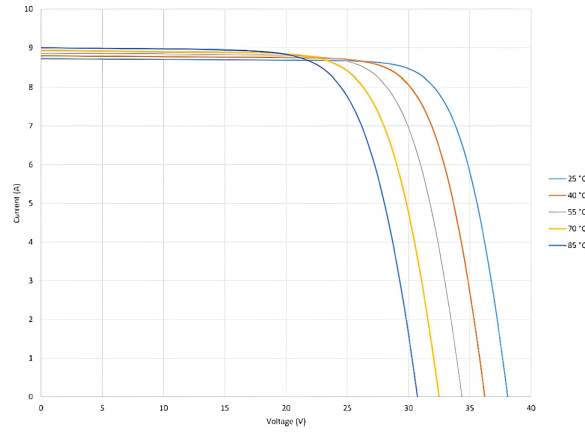


Figure 3.37: Voltage and current drop due to temperature (Gholami et al., 2022)

Voltage is affected by temperature and current also decreases, but not drastically. Thus, a large variation of the delivered power occurs throughout the day, due to changes in solar radiation and heating (Gholami et al., 2022). At the beginning and ending of the day, the highest efficiencies are obtained due to there is only diffuse radiation. It should be noted that in the afternoon the efficiency is slightly lower than in the morning due to the thermal inertia, caused by the heating throughout the day. At dawn and dusk, there are changes in efficiency due to the presence of direct radiation, which takes a maximum value at midday, causing the greatest drop in performance (Krauter and Hanitsch, 1996). Fig 3.38 shows an analysis of cell and ambient temperature as a function of irradiance.

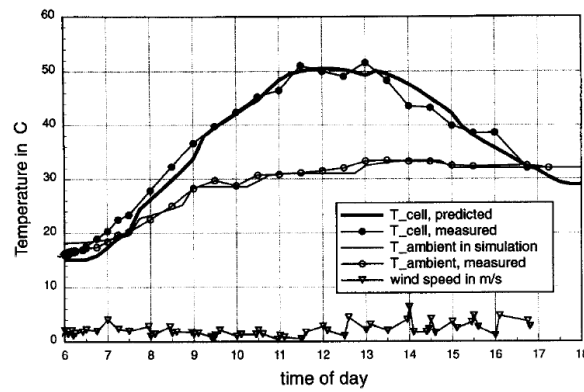


Figure 3.38: Cell and ambient temperature vs. irradiance (Krauter and Hanitsch, 1996)

It is observed that at the beginning of the day, the temperature of the cell and the environment coincide, however when there is direct radiation, the cell heats up due to the radiation itself and the current generated, reaching a separation of almost 20°C at midday. The cell temperature decreases throughout the afternoon while the ambient temperature remains constant. Fig 3.39 shows a thermal analysis of the PV module through FEM for shown layer configuration.

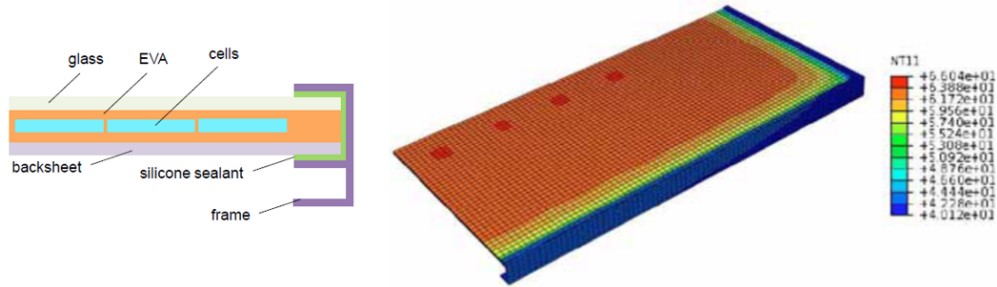


Figure 3.39: Temperature distribution in commercial PV module (Lee and Tay, 2012)

Due to the presence of the metal frame, it allows a greater heat exchange with the environment due to its high thermal conductivity, which translates into areas of approximately 15°C cooler close to the solar cells. The hottest points are found in the cells, with a temperature of approximately 55°C.

3.3.3 Optical Analysis

Optical analysis the radiation before and after it reaches the PV module. It is related with the study of atmospheric phenomena on the incident irradiance and the optical phenomena presented when the light enters to the encapsulation, which are shown in Fig 3.40.

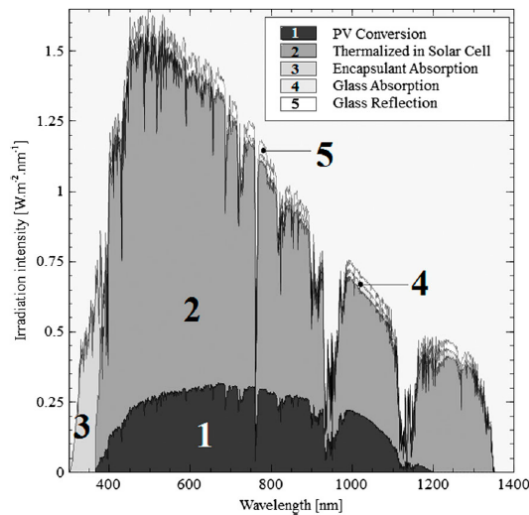


Figure 3.40: Spectral irradiance including PV module optical and thermal losses (Weiss et al., 2016)

The area under the spectrum curve corresponds to the total radiation energy incident on a surface, the bigger area **2** is due to thermal losses, area **1** corresponds to electricity and resting small portion areas due to optical losses by reflection and absorption, (Dupeyrat et al., 2011), which are shown in Fig 3.41.

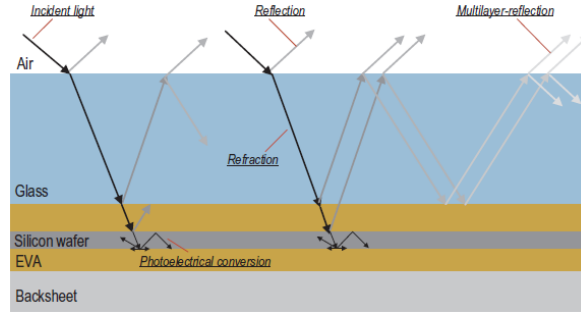


Figure 3.41: Optical losses in conventional PV module (Shen et al., 2020)

When radiation strikes the surface of a PV module, there is a portion of the light that is transmitted onto the glass and continues its path to the encapsulant, while there is a portion reflected onto the surface of the glass. Part of the transmitted portion of light through the glass is transmitted to the encapsulant and another part is reflected on the surface of the glass, similarly occurs when the light crosses the cell generating a third reflection. Final losses correspond to light that is absorbed in the glass and the encapsulant before reaching the solar cell (Saw et al., 2017). The estimation of these losses depends on the optical properties of the materials that make up the solar panel, as shown in Fig 3.42.

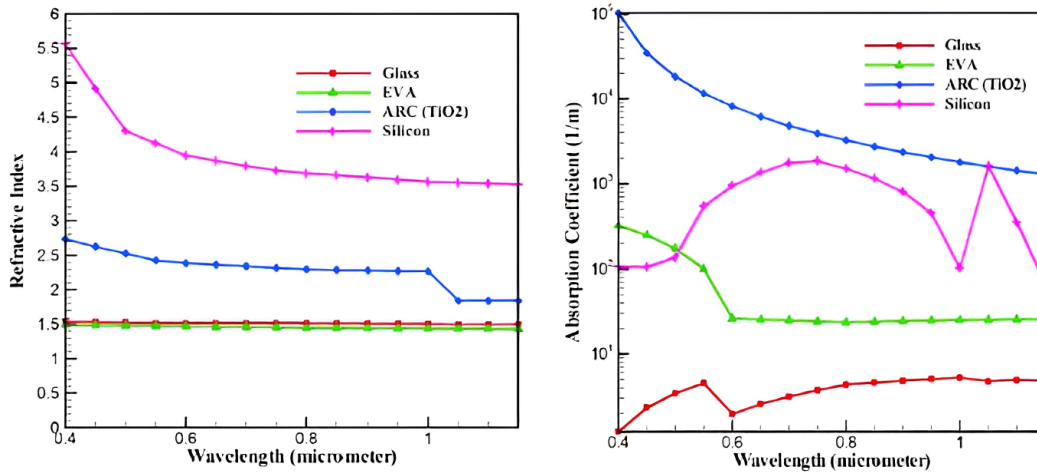


Figure 3.42: Optical properties in conventional PV module (Abdolzadeh and Zarei, 2017)

Taking into account these properties and additionally the transmittance and reflection and using the equations presented in Section 2.4.1, it is possible to estimate the losses due to optical phenomena

throughout the day, which also depend on the angle of incidence of the sun, as shown in Fig 3.43.

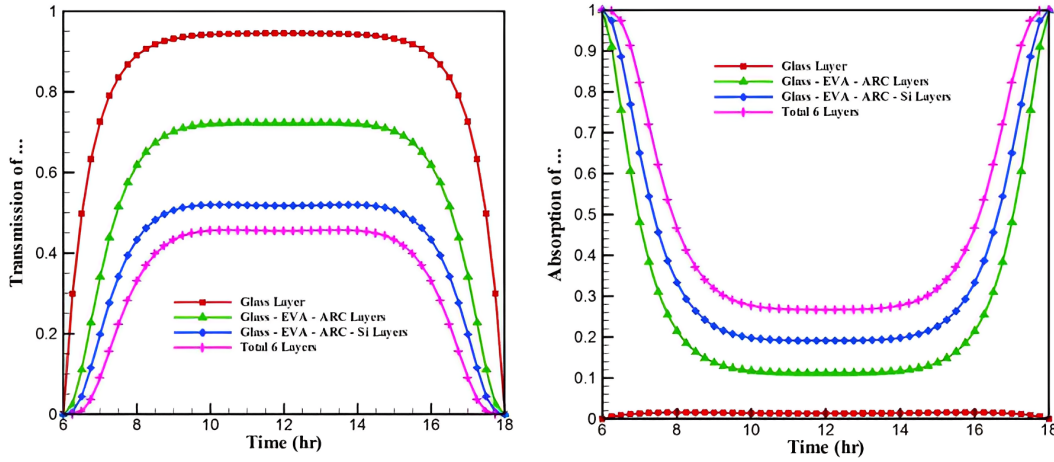


Figure 3.43: Transmission and absorption during the day in a PV module (Abdolzadeh and Zarei, 2017)

Transmission is at its maximum between approximately 8 and 16 hours, and tends to be very small at the end of the day due to the low elevation angles of the sun at those times. However, absorption behaves in the opposite way, being maximum in the early morning and late afternoon and taking the minimum value in the middle of the day. Knowledge of the optical phenomena and properties within the materials of a PV module allows estimating the total reflection and absorption losses and thus, proposing energy improvement scenarios in order to maximize electricity generation.

3.3.4 Electrical Analysis

Electricity is the most commonly used energy output of the PV module, so its analysis is a very important aspect. In section 2.4.4, the simple diode model and the VI and PV plots were shown to understand the performance of a PV module under typical operating conditions. However, in practice, the performance of PV modules can change due to the presence of external agents such as dust, water vapor and snow. Also, sudden changes in radiation and shading, can lower the performance substantially. Shades are a common problem in PV modules and big plants, because if one of the modules or cells has less irradiance (e.g. by shadows) than another one with which it is connected, the performance drops in the whole system. This can generate a reverse-biased condition that causes overheating of the cell as is shown in Fig 3.44 where the VI curve in reversed bias region is observed.

It is found that for an unshaded condition, the VI curve behaves in a typical way and the PV module, or solar cell, delivers power normally. However, when shading occurs, the voltage drops, increasing the reverse-biased condition which initially translates as a power drop and temperature increase, causing hot spots, which can lead to a breakdown voltage condition and damage the PV module completely. To avoid these conditions there are numerous strategies (Das et al., 2017), such

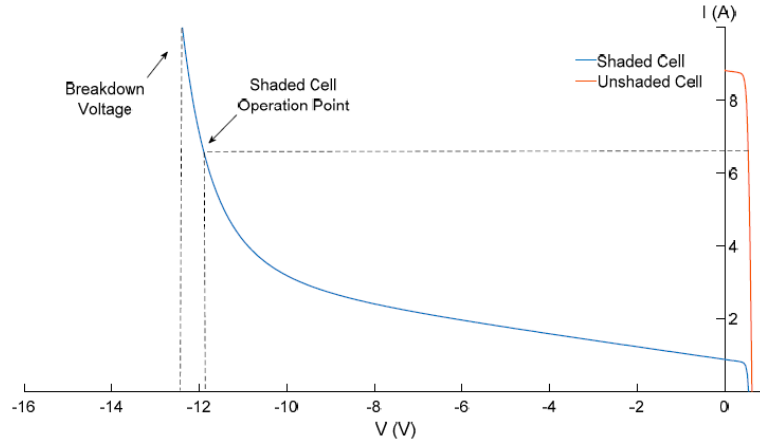


Figure 3.44: I-V curve of a PV module in a reverse bias region (Vieira et al., 2020).

as those shown in Fig 3.45 where different circuit topologies to mitigate the effect of shadows are presented.

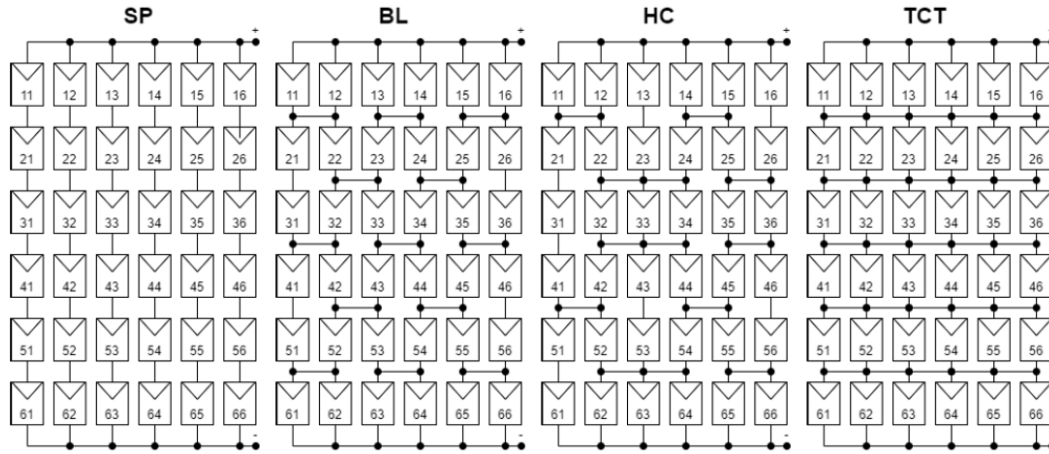


Figure 3.45: Interconnection strategies for shading conditions (Acosta and Mejía-Gutiérrez, 2022)

The acronyms correspond to the connection types SP: Series-Parallel, BL: Bridge-Link, HC: Honeycomb and TCT: Total Cross Tied, which are fixed connections within the PV array, i.e., they are implemented during module manufacturing as well as bypass diodes (Vieira et al., 2020). Fig 3.46 shows the VI and PV curve for a PV module connected with SP, which has cells with different incident irradiance.

In conventional interconnection topologies, the power tends to drop completely due to low irradiance values due to shading, however, the used SP connection helps to avoid the reversed bias condition, obtaining an output power of 974,6W. In Kaushika and Gautam (2003), it is established that the TCT and BL connection types are superior and have better performance under shading conditions

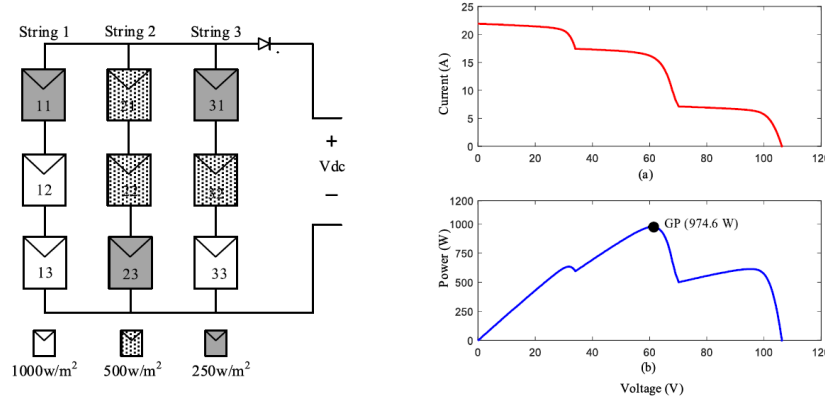


Figure 3.46: VI and PV curves of PV module connected with SP topology (Mehedi et al., 2021)

and do not represent major cost overruns, making them excellent implementation options.

3.3.5 Multiphysics Analysis

PV modules have the capacity to generate electricity from solar radiation through internal energy exchanges, which on the one hand manifests itself in heat, part of which is exchanged with the environment, and on the other hand, due to the change in direction of the sun's rays throughout the day, energy losses are generated by absorption and reflection. Fig 3.47 shows a scheme of the exchange and relationship between different physical phenomena of the PV module and the environment.

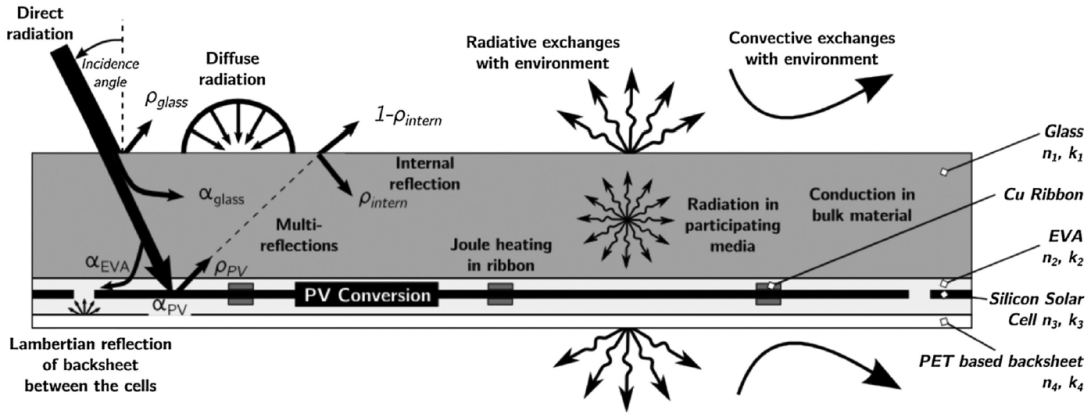


Figure 3.47: Relation between physical phenomena in a PV module (Weiss et al., 2016)

When direct radiation is incident on the glass, there are optical losses from the air to the panel and along the encapsulation until it reaches the photovoltaic cell. Similarly, heat is generated in the cell and is transmitted from the inside to the outside, generating radiation and convective cooling. To estimate the total energy mechanisms that compose the total losses, it is necessary to perform a deeper analysis, the scheme of which is shown in Fig 3.48.

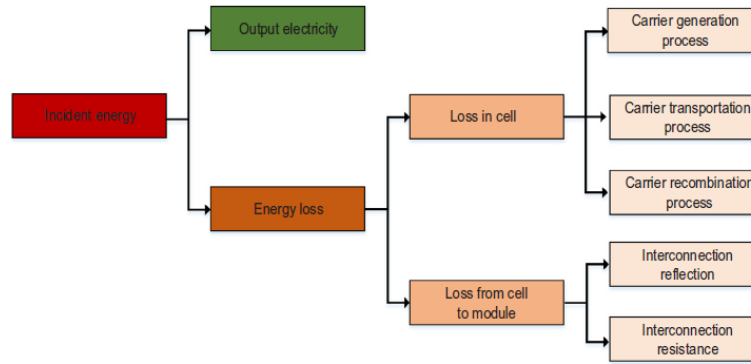


Figure 3.48: Distribution of total incident energy. (Shen et al., 2020).

The incident radiation is transformed into electricity and the rest are losses associated with the cell and its interaction with the complete module. Within the losses in cell, first is the carrier generation process that includes optical losses in encapsulation and thermalization due to sub-bandgap. Then, is the carrier transportation process that includes series resistance due to dissipation in the elements that integrate the circuit and shunt resistance due to lack of current. Finally there are the losses in the carrier recombination process that include the Carnot loss, angle mismatch and non-radiative recombination (Gagliardi and Paggi, 2019). While losses from the cell to the module are given from the interconnection elements from the reflection on its surface and thermal losses due to resistance (Shen et al., 2020). In summary, the energy transformation of a PV module is reduced to electricity (17.44%), heat (75.58%) and reflection (6.98%) (Hanifi et al., 2018), Fig 3.49 shows the different loss mechanisms, both optical and thermal, and their percentage.

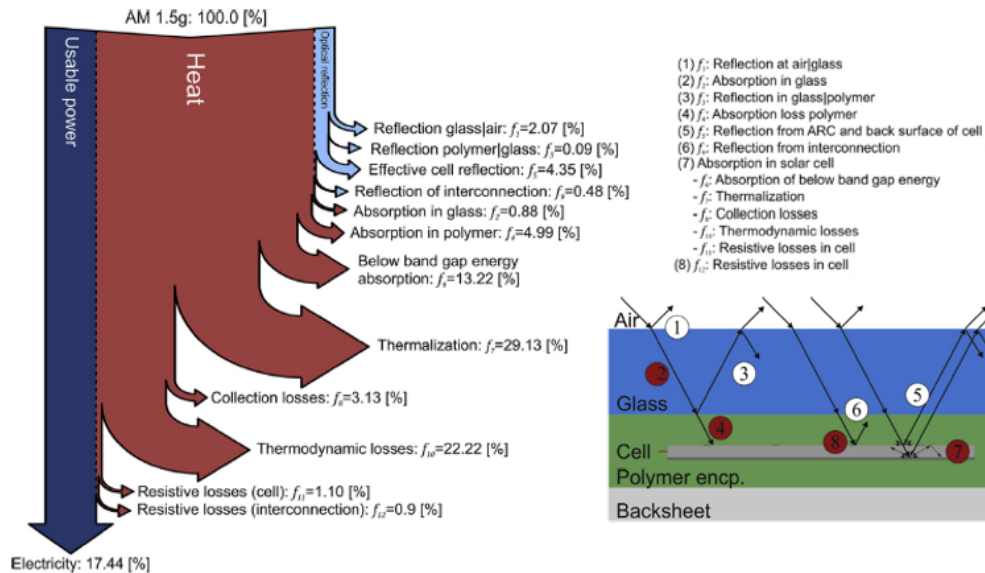


Figure 3.49: Energy transformation in a PV module (Hanifi et al., 2018)

It is evident that the overall performance of a PV system is managed by different physical phenomena that are closely related to each other, allowing multiphysical coupling between 2 or more of them. This combination of physical phenomena allows to understand the characteristics of the coupling in order to propose strategies to improve the overall performance. Taking into account that the total energy of the spectrum for 1.5AM is the radiation incident on the PV module, it is possible to show the percentages of energy losses associated with the different phenomena within the area of the incident radiation curve. Within the VI curve it is also possible to show some loss mechanisms, which are shown in Fig 3.50.

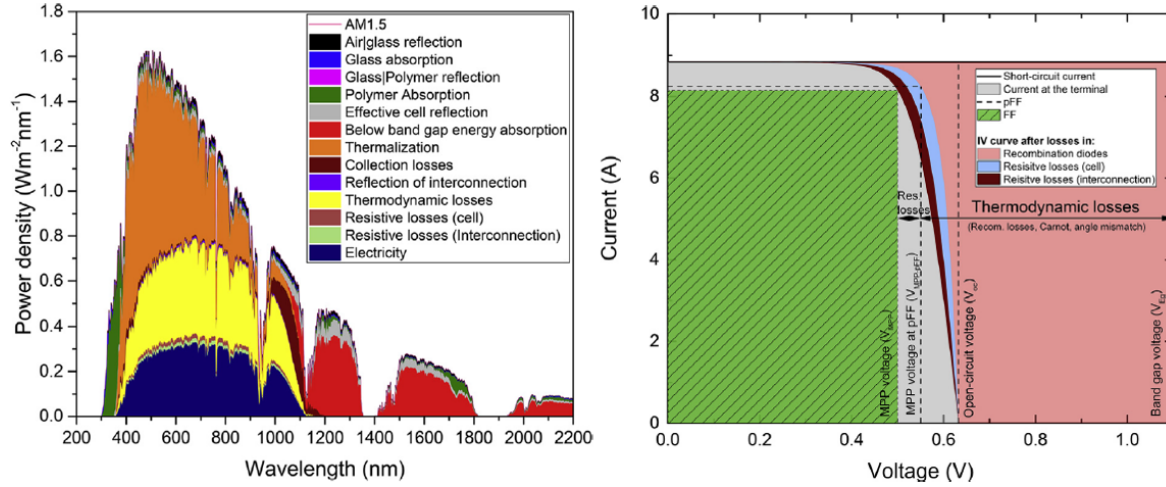


Figure 3.50: Energy transformation in spectrum and VI curve (Hanifi et al., 2018)

The graphs shown allow a detailed understanding of the energy transformation within a conventional PV module, so that energy improvement strategies essentially decrease the area of some loss by increasing the area of electricity. Among the different improvement strategies, the most recurrent is the implementation of PV/T modules, to which heat exchange devices are integrated in order to reduce heat losses and that these can be used in electricity (Hu et al., 2021; Maadi et al., 2019; Hu et al., 2021).

3.4 Numerical Optimization Strategies

The harnessing of solar energy into electricity involves the interaction between various physical phenomena of different types, nature and behavior. In practice, the solar radiation for a point can vary in position and the magnitude of the irradiance depends on atmospheric factors (Ahmad et al., 2003). The electricity generated in the PV modules is analyzed from the diode model (see Section 2.4.4), while the losses of thermal and optical nature are explained through heat transfer (see Section 2.4.2) and geometrical optics (see Section 2.4.1) models, accordingly.

Thus, analyzing the complete performance of a PV module, including energy exchanges to and from the solar panel, is a complex task. Although the problem of estimating energy losses within a PV module is solved through the use of analytical and experimental models, analyzing actual irradiance and environmental conditions of a site and their relationship with the PV module can be very unpredictable due to sudden changes in weather conditions (Fröhlich, 2000). Additionally, during the operation of PV modules, external factors such as clouds, dust and shadows can affect the performance by causing voltage spikes, mismatch, different temperatures and stray currents inside the cell, which gives a stochastic essence to the problem, in addition to its multiphysical nature (Elsheikh et al., 2019). Therefore, solving a problem that integrates all these phenomena from an analytical model is a complex mission due to the difficulty in its implementation and the multiple assumptions (Wang et al., 2020). To satisfy these conditions, metaheuristic methods are employed because they are better adapted to this type of conditions (Garud et al., 2021). In Fig 3.51, a taxonomy of metaheuristic algorithms used in the field of PV is shown.

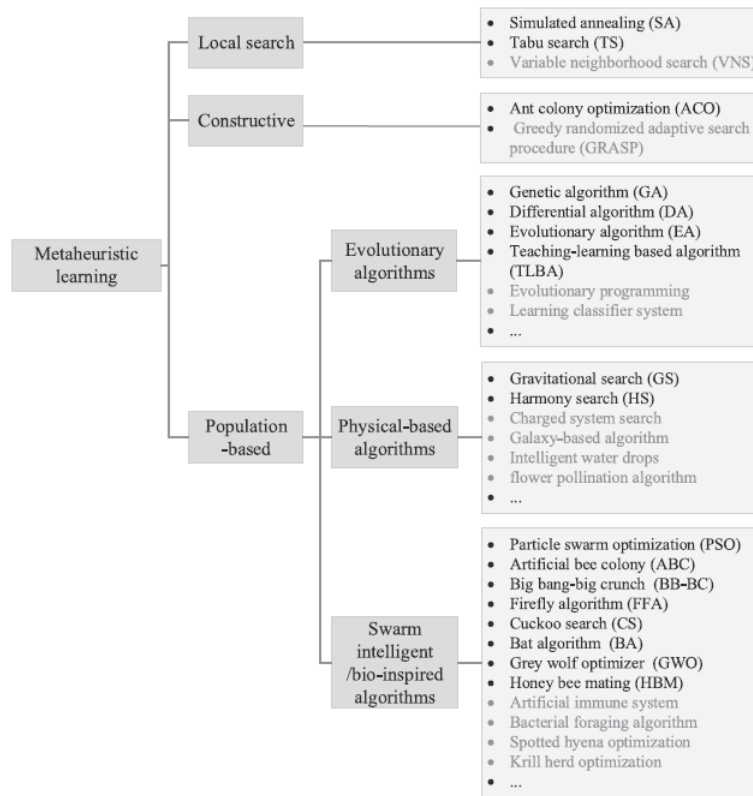


Figure 3.51: Taxonomy of metaheuristic techniques implemented in the field of PV (Feng et al., 2021).

From the distribution proposed by (Feng et al., 2021), a large number of metaheuristic learning techniques applied to solar energy problems were identified, which are divided into local search algorithms, constructive methods and population-based methods. These types of optimization strate-

gies are generally used in the field of PV to deal with problems related to maximum power point (MPPT), fault detection, shadow incidence, and PV system design and sizing (Al-Shahri et al., 2021) and generating hybrid models (Mellit and Kalogirou, 2008). In Fig. 3.52, an analysis of the most used metaheuristic methods in PV modules applications is made.

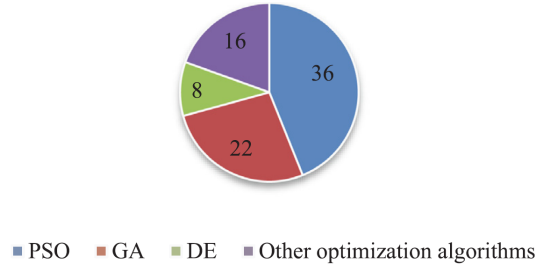


Figure 3.52: Metaheuristic population-based methods used in solar energy (Feng et al., 2021)

It is observed that the population-based technique Particle Swarm Optimization (PSO) is the most used of all the metaheuristics in the solar energy field with 36%, followed by Genetic Algorithms (GA) with 22% and Differential Evolution (DE) with 8%, while the rest of the studies in (Feng et al., 2021), implement other types of optimization algorithms. Based on the above, a deeper analysis will be made considering these 3 types of metaheuristic learning techniques, in order to analyze their characteristics and problems solved by their implementation.

3.4.1 Particle Swarm Optimization (PSO) in PV systems

PSO is a metaheuristic algorithm used in solar energy (Khare and Rangnekar, 2013), that approaches the search in a solution space using individual agents (particles), which are formed by quasi-static positional vectors (Li et al., 2021a). The particle motion is composed of a stochastic and a deterministic parts, in which each particle i is attracted to its position due to the best global current g^* and its best location along the history x_i^* , while it tends to move randomly, as shown schematically in Fig 3.53

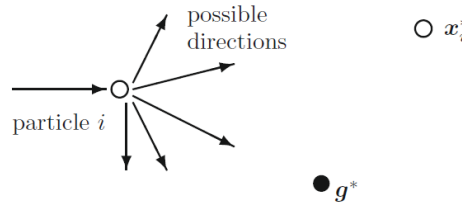


Figure 3.53: Schematic representation of the motion of a particle in PSO (Yang, 2020).

When a particle finds a better position, it updates that position as the current best location, this happens while other n particles have iterations in a certain time. Fig 3.54 shows a study of interconnection to reduce losses due to current differences in PV modules in a solar plant.

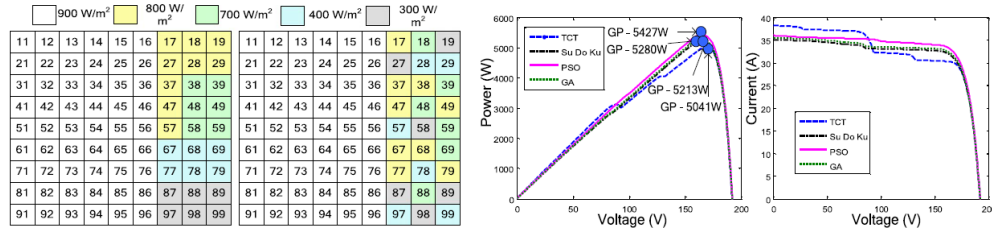


Figure 3.54: Electrical performance from interconnection strategies using PSO (Babu et al., 2017)

For shadow pattern shown, interconnection strategies modeled from metaheuristic techniques and fixed connections are shown, in which PSO shows the best results, even above TCT. Also, PSO is used in solar cell parameter determination (Nunes et al., 2018).

3.4.2 Genetic Algorithm (GA) in PV systems

GA and their variants are among the most popular of the evolutionary algorithms, because they are found in a wide variety of applications within PV modules (Ahmed et al., 2020). It is based on biological evolutionary processes, they have an excellent performance under random conditions, since among their advantages is the ability to deal with complex problems, ease of parallelization in their execution and the ability to adapt to other models (Yang, 2020). Fig 3.55 shows typical steps in GA.

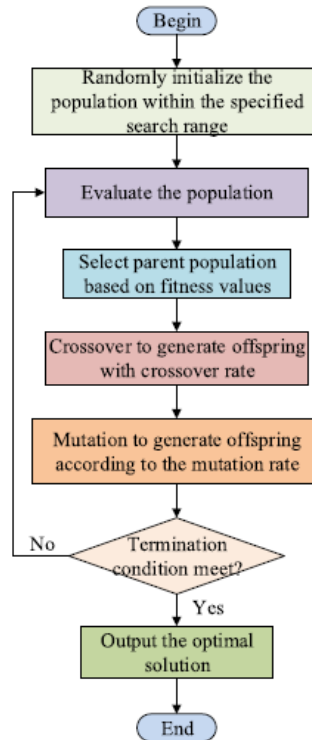


Figure 3.55: Flowchart of GA (Li et al., 2021a).

The algorithm starts from a population of individuals, which are evaluated and ranked in a fitness function, then these elements are reproduced, the offspring are assigned mutations and then re-evaluated in the objective function, choosing the best ones. Similarly in Fig 3.56, an optimization of the geometry of a building in order to provide comfort to its inhabitants, save energy and space in the cold areas of China using a Multi-Objective Genetic Algorithm (MOGA), which shows with respect to a cubic shape, the best shape obtained has an increase between 30% to 53% of incidental radiation (Zhang et al., 2016).

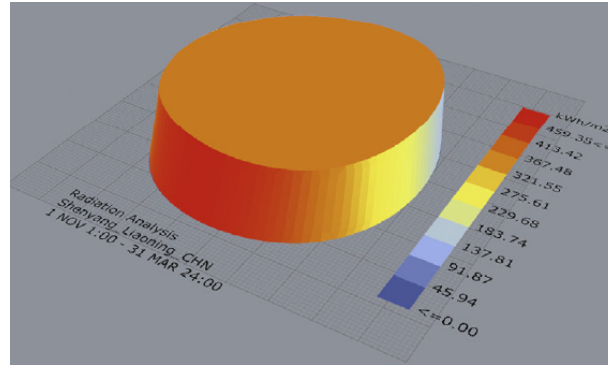


Figure 3.56: Geometric optimization of a building (Zhang et al., 2016)

In (Chen et al., 2019), a GA is implemented to find the necessary parameters to model the VI curve to evaluate failures in PV arrays. This same type of algorithm was implemented for geometric optimization of a residential roof in the southern hemisphere where the optimized shape found has 15.7 times more uptake than conventional roof geometries in Australia (Esfahani et al., 2021).

3.4.3 Differential Evolution (DE) in PV systems

DE is a population-based method that, like the previously described algorithms, has a wide use in different disciplines due to its good convergence properties, in addition to its multiple variants. A schematic diagram is shown in Fig 3.57

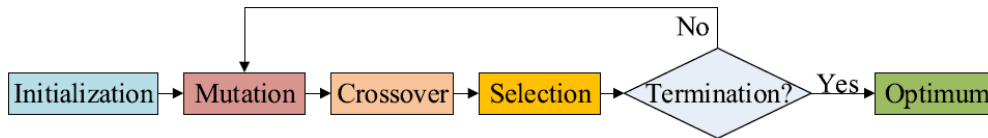


Figure 3.57: Flowchart of DE (Biswas et al., 2019).

This algorithm has 4 stages in the following order: initialization, mutation, crossover and selection. In the initialization, the population size is kept constant and each individual is considered as a solution vector of decision variables, then, the mutation is given by taking the difference between two vectors

and adding a third vector with a certain weight, it is the main operation in DE. Finally, to maintain the diversity of the population, using trial vectors after mutation (Zhang et al., 2016). DA algorithm was implemented to find optimal geometrical parameters of a Solar Air Heater (SAH) whose results indicate that the optimized geometry has a higher performance with the reference geometry by about 16.5% (MesgarPour et al., 2021). The applied geometrical scheme is shown below in Fig 3.58.

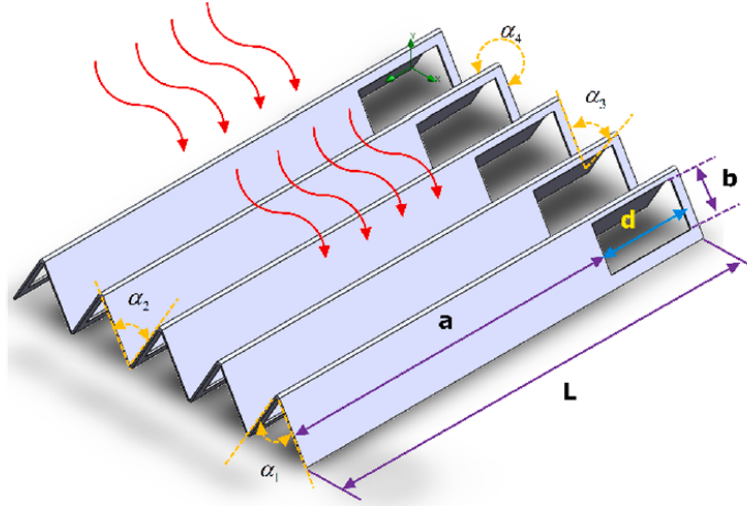


Figure 3.58: DE optimization of a solar heater using DE (MesgarPour et al., 2021),

The use of Artificial Intelligence Techniques (AIT) and Hybrid Modeling (HM) in solar PV problems is growing every day, due to the stochastic nature of some of the physical phenomena involved in operation. The use of these methods allows better results to be obtained in very complex and highly variable problem environments, so that algorithms with learning capabilities end up being an excellent option. The use of Artificial Neural Networks (ANN) has also been extended to the field of solar energy, which deserves to be mentioned. Unlike the previous metaheuristic methods, ANN is a heuristic technique that minimizes errors by the iterative trial-error method, presenting good results and approximations in some types of problems (Yang, 2020). Its approach and application in the context of the PV system problem will be discussed below.

3.4.4 Artificial Neural Networks (ANN) in PV systems

ANN is the emulation of a biological neural network which has a natural ability to store and ascertain valid experimental knowledge for use. This technique has high information processing speed, mapping capability, fault tolerance and adaptability, no explicit mathematical model is needed and there are numerous variations and types. Therefore, ANN is an excellent tool for modeling, predicting and optimizing systems. Fig 3.59 depicts the typical ANN model.

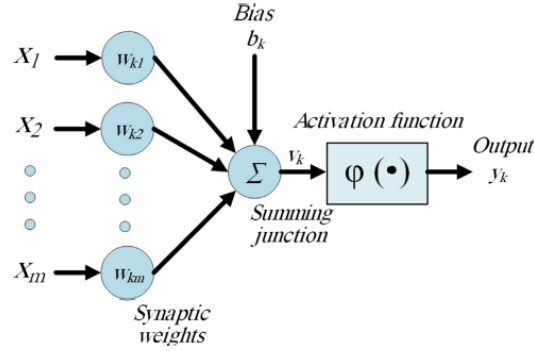


Figure 3.59: Scheme of a ANN (Elsheikh et al., 2019)

ANN models consist of a set of links called synapses, each of which has its own weight w_{kj} , which is multiplied by its own input x_j . These results are summed externally with a bias b_k , which is responsible for decreasing or increasing the sum of the output v_k . A gamma activation function is applied to the output to decrease the amplitude range of the output signal y_k and identify relevant or irrelevant values, these activation functions can be of different types (Haykin, 2009). Through the implementation of ANN in the PV sector, it is possible to provide solutions to problems of different nature. Some examples of ANN applications can be the use in the diagnosis of failures of PV modules of street lights (Hwang et al., 2019) and PV plants considering the effect of shadows, cracks or dust on the surface of the solar panels (Espinosa et al., 2020), where the ANN topology used in this study is shown in Fig 3.60.

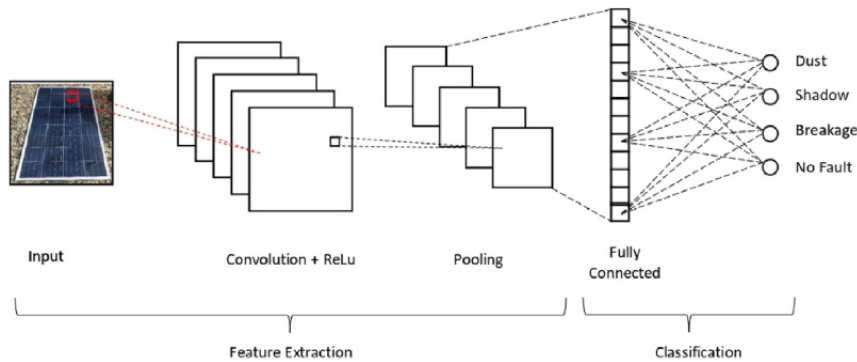


Figure 3.60: Performance analysis of PV plant using ANN (Espinosa et al., 2020)

About variations of ANN, a Neural Network Estimator (NNE) is implemented in MATLAB-Simulink™ to find the Maximum Power Point Tracking (MPPT) (Saidi et al., 2021) and considering shadows (Zandi and Mazinan, 2019). ANN are also used to determine the parameters of PV modules (Karamirad et al., 2013), estimate the effects of relative and absolute humidity on solar panels (Sohani et al., 2020) and assist in the design of PV experiments (Moreira et al., 2021).

Based on the previous sections, a state of the art is presented in which current issues that put into context the problem of the use of PV surfaces are addressed. Also, the way in which the different physical phenomena are analyzed in a PV module and the numerical strategies mostly found in this sector were exposed, which allows to have a general understanding of the problem and to obtain tools for the approach of solutions. However, it is necessary to analyze how these works are related to each other, exposing their main attributes in order to find the contribution of this work, which is presented below.

3.5 Conclusions of the literature review and contribution

From the development of the chapter, it is evident that the most frequently used applications that integrate PV systems in prosumer nodes are given in transportation vehicles and sustainable construction. Also, the use of different PV technologies is observed according to the characteristics of the study performed and the available resources of the authors, developing different strategies and solution approaches based on the point of view of the problem and the variables of interest. Thus, in Table 3.1, the most representative works found in the state of the art in relation to the use of PV surfaces in prosumer nodes are presented in order to analyze the scopes obtained and identifying potential future works that can contribute to this research.

Although PV systems do not have the capacity to completely satisfy the energy demand of a vehicle due to the limited area available for their installation, there are works that integrate PV modules mainly on the roofs of automobiles. Because the design of these must have aerodynamic attributes, almost 67% of the PV modules presented in VIPV applications are non-flat geometries, while for BIPV applications only 20% have geometries with curvature. With respect to the solar cells used, only 15.8% of the papers used silicon cells in curved PV surface applications due to their limited flexibility, likewise, only 1 of the papers manufactured their own PV modules with plastic based processes, the rest used commercial PV modules. The solution approach presented in the papers is usually accompanied with at least two tools among which are: numerical models (based on analytical models), simulation (based on software packages) and experimental models, among which, about 84.2% of the papers present numerical solutions, 47.3% experimental models and 36.8% simulations. With respect to future works, only 21.05% performed irradiance analysis as a function of geometric shape.

Finally, the contribution of this work is focused on the development of PV surfaces with curvature in VIPV and BIPV applications through the approach of a hybrid model that allows:

Ref.	Applic.	Cell	Geom.	Sol.	Contributions	Future work
(Ota et al., 2022b)	Car roof	c-Si	Curve	Exp.	Optical analysis for a radius of 1m	Perform electrical analysis
(Birnie III, 2016)	Car roof	c-Si	Curve	Num.	Energy recharging during parking	Manage shadows during day
(Tomita et al., 2019)	Car roof	p-Si	Flat	Num.	Shade management strategies	Inconstant energy for shading
(Araki et al., 2020)	Car roof	Multi	Curve	Sim.	Analysis of a car PV module	Validation curved PV Module
(Tiano et al., 2020)	Car roof	c-Si	Flat	Sim.	Heat effects in car PV modules	Include a cooling device
(Masuda et al., 2016)	Car roof	c-Si	Flat	Sim.	Concentrator layers in modules	Experimental validation
(Ota et al., 2022a)	Car roof	c-Si	Curve	Sim.	Exploring PV geometric shapes	Experimental validation
(Tayagaki et al., 2019)	Car roof	Multi	Curve	Num.	Performance on non-planar shapes	Experimental validation
(Yamada, 2020)	Car roof	c-Si	Curve	Num.	Cell adaptation to 3D shapes.	Thermal model
(Chen et al., 2021)	Window	Thin	Flat	Num.	Optical- thermal in PV windows	Study geometrical shape
(Paydar, 2020)	Window	P-Si	Flat	Num.	PV device integrated to windows	Experimental validation
(Liu et al., 2020)	Window	CdTe	Flat	Num.	Study transparent PV materials	Study geometrical shape
(Stoichkov et al., 2019)	Facade	Org	Flat	Num.	Organic cells BIPV applications	Study geometrical shape
(Martín-Chivelet et al., 2018)	Facade	c-Si	Flat	Exp.	PV ventilated systems in facades	Low yield by shadows.
(Shahrestani et al., 2017)	Facade	NA	Flat	Num.	Facades naturally ventilated	Study geometrical shape
(Tian et al., 2022)	Roof	CIGS	Curve	Num.	Flat vs. curved PV modules	Study bending PV module
(Calcabrini et al., 2021)	Roof	NA	Flat	Sim.	PV modules in urban scenarios	Study geometrical shape
(Ahmed-Dahmane et al., 2018)	Roof	p-Si	Flat	Esp.	Increase efficiency in 0.35%.	Inconsistency of results
(Tian et al., 2023)	Roof	CIGS	Curve	Exp.	Curved PV modules in BIPV	Analyze tilt angle

Table 3.1: Literature review of PV surfaces in VIPV and BIPV applications.

- Generate the geometry of PV surfaces with curvature from given requirements, guaranteeing the structural integrity of the solar cells.
- To know the energetic behavior of the PV surfaces as a function of the given or obtained curvature geometry.
- Validate the behavior of PV surfaces from their fabrication and experimental measurements.

To achieve this, an approach will be proposed that allows the integration of these 3 elements through a series of phases that include the collection of initial information, generation of the surface geometry, structural and energy analysis and finally the fabrication of the PV surface. This will be analyzed in greater depth in the following chapter.

Chapter 4

Proposed Multi-Physics approach for variable PV surface design

In order to meet the objectives in the introduction section and the challenges of the contribution, we analyze the research works found that relate the ease of adaptation of solar panels to surfaces, the materials and processes used, mathematical methods of solution and the analysis of the related physical phenomena in order to present this proposal. It was found then, that a great potential to generate electricity using solar energy is in the use of available area in some devices through the integration of photovoltaics (PV) systems with surfaces exposed to radiation as Vehicle Integrated Photovoltaics (VIPV) and Building Integrated Photovoltaics (BIPV), whose geometry is given most of the times by the detailed design or by external clients, which constraints the performance of PV modules to the already established form. Based on the above, a research work is proposed to include the performance characteristics of the solar panel in the end-use device, in order to integrate the PV module within the design, according to the geometric shape for a given surface area and operating conditions.

4.1 Proposed Approach

In order to design and develop geometric PV modules that can adapt to contours or variable morphologies, it is necessary to integrate different knowledge about the physical phenomena, applications, morphology and numerical solution strategies which were previously exposed in Chapter 3. Thus, in order to generate adaptive PV surfaces, it is necessary to know the geometrical shape that the PV surface will have according to known parameters as irradiance, available space and operating conditions, to which it will be necessary to analyze its capacity to generate electricity according to its

morphology. Then the implications that the geometric shape has on the surface fabrication will be analyzed. From the above, 3 major analysis are presented that allow to focus this work, which are set out and shown in Fig 4.1

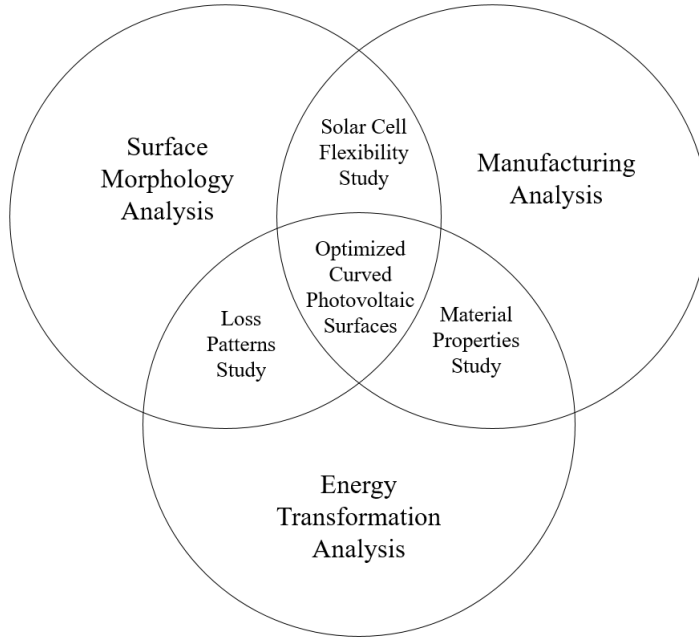


Figure 4.1: Major analyses and interactions

From the above, it can be seen that each of the 3 major analyses is connected to each other through different studies due to the intersection of the circles, in which, the contribution of this work focuses on obtaining curved optimal PV surfaces. In the following subsections, a detailed explanation of each of the 3 major analyses and their connections will be given.

4.1.1 Surface Morphology Analysis

To analyze this problem it is necessary to define the mathematical condition of curvature and its influence with the manufacturing characteristics. Curvature condition must be integrated to a numerical ray tracing tool that allows knowing the amount of irradiance captured, which is based on historical of the application site. The morphology of the PV modules will depend on the context and use of the surface exposed to radiation. Usually, most solar panels used on a large scale, such as in solar farms, have flat geometry. However, in smaller applications, the PV module must have the capacity to adapt to the contours of the prosumer devices. This allows to assume that there are surfaces exposed to radiation with previously defined geometries that have a different function than generating electricity, such as the fairing of cars or building facades.

For available areas exposed to radiation that do not have established geometries, it is necessary to define methods to find surfaces that best fit these spaces. From the above, it is necessary to implement intelligent algorithms that enables to search for the optimal geometries. It must also have the ability to adapt to phenomena and models of different nature enabling to evaluate the power captured by any surface. Thus, due to the amount of data and its characteristics, metaheuristic algorithms have very good capabilities to easily find a solution to this type of problem. Starting from a known and conventional flat geometry of PV modules, the algorithm must gradually search for a solution from the evaluation of the surface in a fitness function. Among the metaheuristic algorithms analyzed in Section 3.4. Particle Swarm Optimization (PSO) works well, however the swarm particles have their own intelligence, which does not apply very well to our problem, because the geometrical implications of a PV module, with respect to power harvesting, are not known. Differential Evolution (ED) has the mutation before the crossover, which is not very convenient in our problem because it starts from known mathematical functions which can abruptly change the nature of the surface obtained. Genetic Algorithms (GA) could easily evaluate each surface locally and reproduce from known mathematical functions and allow progressive development to find optimal surfaces. In addition, GA have a good ability to integrate with models of different nature with each other, so it better fits for applications where PV morphology is not constrained, such as BIPV, where on the contrary, non flat surfaces may be appreciated from an architectural perspective.

4.1.2 Energy Transformation Analysis

The optimal curved PV surface is expected to generate more electricity than a conventional flat PV module, so it is necessary to analyze the energy behavior of such an increase. Thus, it is expected to analyze the geometric effects of a curved PV surface and its relationship with the associated optical and thermal losses, taking into account the arrangement of materials and the manufacturing process used. This is achieved through the implementation of computational simulations and using multiphysics and experimental models.

4.1.3 Manufacturing Analysis

By modeling the morphology of the PV surface and analyzing the energy potential, it is proposed a fabrication process that allows adaptation to the shape of prosumer devices, which is given by design requirements or spatial constraints in strategical areas with solar radiation incidence. From the review of the State of Art in Chapter 3, it is decided to use manufacturing processes based on the use of engineering plastics, due to the experience gathered by GRID and the difficult access to PV glass forming technology (Kurtz et al., 2018) which represents an important opportunity for PV module

manufacturing in developing countries, where glass-based solar panel manufacturing technology is not commonly available. Within this study, it is necessary to ensure structural integrity for the cells operating loads, on the other hand, it is required to maximize flexibility in mono-crystalline Silicon (c-Si) cells with used materials, in this way, some mechanical and optical properties were measured thorough laboratory test in Appendix A. The chosen process has the capability to achieve these required attributes.

4.1.4 Analysis interactions

Finally, there are important relationships between each of the 3 major analyses exposed above, which allow to connect and integrate them in order to obtain curved photovoltaic surfaces with c-Si cells. In order to model the behavior, shape and manufacturing of photovoltaic surfaces with curvature in a general way, it is proposed to execute different application cases that allow to develop the related topics gradually and thus, to know the problem in a deeper way. As it was seen in Chapter 3, most of the applications that involve the energetic use of surfaces exposed to radiation as prosumer node are found in sectors of transportation (VIPB) (see subsection 3.1.1) and construction (BIPV) (see subsection 3.1.2).

Keeping in mind that the case studies developed in this research are solutions presented for a specific need, the process of finding a solution follows a series of progressive steps that include: gathering the necessary information for the problem, generating the surface geometry, analyzing the performance of the surface found as a function of physical phenomena, and finally fabrication. Each of these steps is discussed in more depth in the next section using the procedural approach proposed.

4.2 Procedural Approach

Based on the 3 major analyses presented above, a flow chart is proposed to methodically address each of the steps necessary to obtain a PV surface depending on the application and location conditions. The nomenclature used is shown in Fig. 4.2

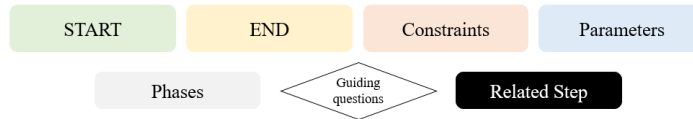


Figure 4.2: Nomenclature of the Procedural Diagram

Such a procedural approach begin with *START*, which belongs to the first stage called Identification of the Application Environment (see Subsection 4.2.1) in which all the information necessary to

carry out the cases study is gathered, which is classified into the following categories:

- **Application context:** refers to the identification of the characteristics of an Existing Geometry to which it is required to adapt a PV surface with curvature, which can be PV integrated to application in VIPV and BIPV.
- **Application Site:** refers specifically to the attributes given at the place of installation when there is a not given surface area defined, so the Available Dimensions must be collected according to the implementation morphology.
- **Geolocation:** takes into account all external conditions to the PV modules operation. It involves the study of the source of light from the sun in the form of Radiation and its dependence on the Atmosphere regarding to Environmental Interactions of the application site. Python™/ library *pvlb* is used to know solar resource for PV systems (Holmgren et al., 2015).
- **Working Conditions:** includes gravitational interactions related to the mass of the PV surface itself, (i.e., Dead Loads) and, if it is moving, how Accelerations affect the structural integrity of the PV system.

END is found twice along the diagram and occurs when it is not possible to guarantee the radius of curvature and reliability of solar cell according to the application, in second instance it occurs when the entire diagram is completed. Source of external information, allows grouping the Constraints and Parameters, which are the decision variables of the problem and data that will not vary, respectively, and will be introduced along the problem in the different Phases which are explained below. Particularly, for the phases: Cell's Flexibility and Mechanical and Energetic Validation, information related to the properties materials that constitute the PV module must be defined, which are shown below:

- **Encapsulation Properties Materials:** consists of the inclusion of the properties of the encapsulation materials in terms of their *Mechanical*, *Optical* and *Thermal* behavior. Some of these are extracted from laboratory tests (as detailed in Appendix A).
- **Solar Cell Properties:** establishes the maximum flexibility given by the solar cell through the mechanical analysis. In addition, it includes the *Energetic* characteristics of solar cell in terms of electrical parameters (some of these properties are shown in Appendix A).

Guiding questions allows to make decisions according to the circumstances given with the problem. Source of external information (in terms of Constraints and Parameters) enters throughout the procedural approach, which allow analyze how information is processed, transformed and transferred within each Analysis Steps or Phases. The complete diagram is shown in Fig 4.3

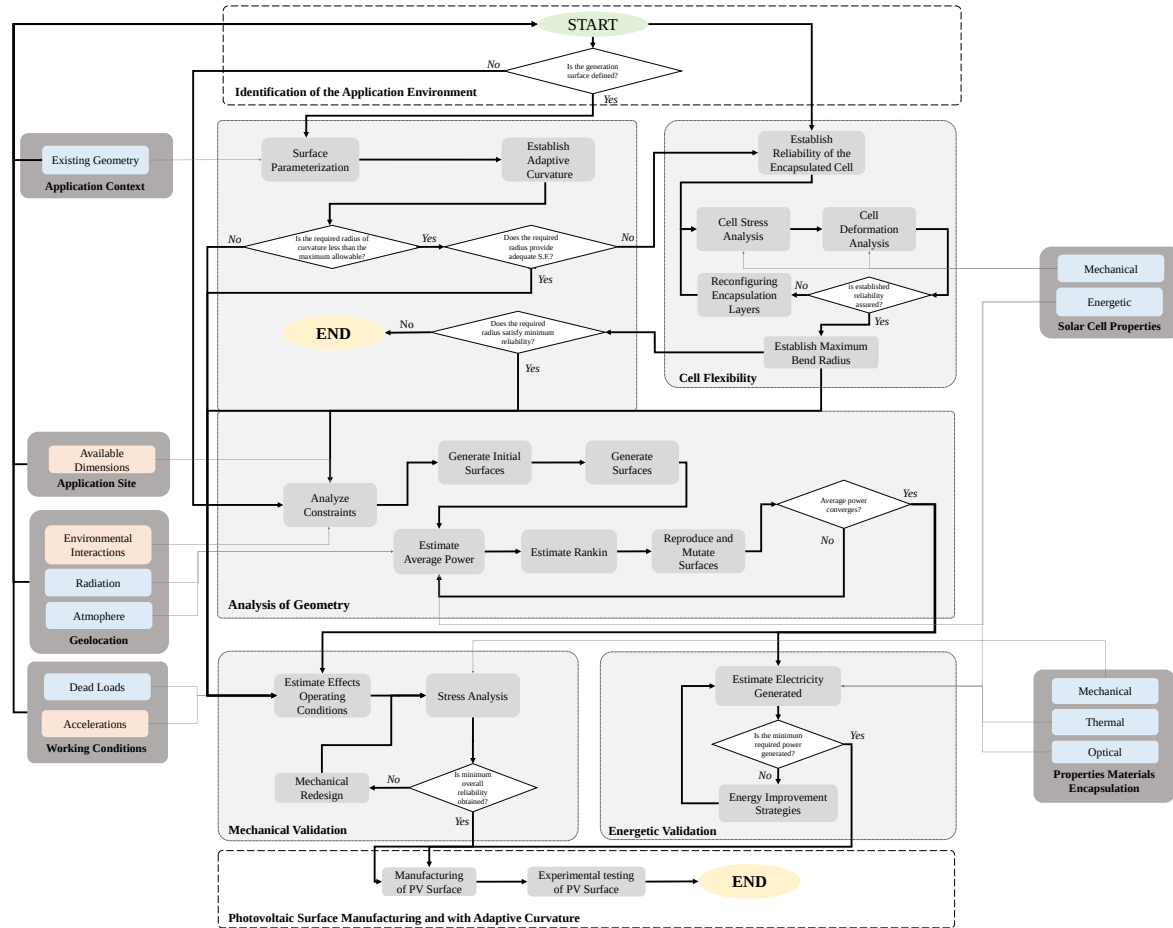


Figure 4.3: Procedural approach

Each of these Phases are presented in the above procedural approach and will be explained with more detail below. It should be noted that the black boxes correspond to steps in other related analyses and allow the logical connection between the Phases which are explained below.

4.2.1 Phase 1: Identification of the Application Environment.

Is the first step of the whole analysis. At this point, the operational environment in which the application will work is analyzed. This includes information related to the Application Context, Application Site, Geolocation and Working Conditions, as it can be seen in Fig 4.4.

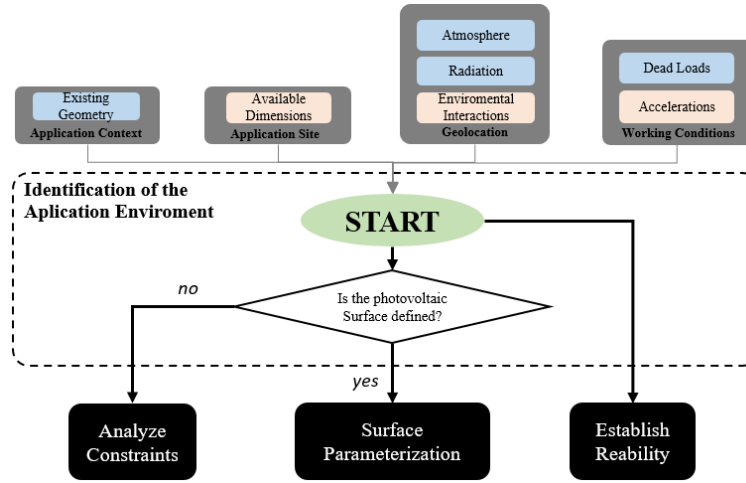


Figure 4.4: Identification of the Application Environment

After having this information, mechanical reliability of overall system must be defined according to the Working Conditions, then it is questioned if the generation surface exists, if the answer is *yes*, then it goes to the Available Geometry (Phase 2), if the answer is *no*, then it goes to the Surface Generation (Phase 4). Taking into account that this procedural approach is given for integration of PV technology in building and transportation sectors, it is explained the requirements and interactions depending on the application and its place.

- **Static Loads:** to correspond to loads due to its own weight that are included without any additional interaction.
- **Dynamic Loads:** refers to loads due to acceleration or deceleration in mobile PV system.
- **Impact Loads:** they are related to impacts due to external objects.
- **Weathering:** it refers to environmental variables in general, including sunlight, humidity, rain, dust and volumetric expansion and contraction.

- **Various Weathering:** considers the change of local conditions, i.e., the variation of all the above variables according to different climates.

In this way, *environmental* and *operating condition* must be analyzed in order to design and manufacture it, maximizing reliability and durability. In addition, the given geometric shapes usually satisfy other previous functions within the prosumer system, therefore electricity generation becomes an additional and usually secondary function.

4.2.2 Phase 2: Cell Flexibility

Cell flexibility analysis begins with establishing the maximum reliability of the cell by first depending on the radius of curvature in which the PV module will operate. Then, a stress and strain analysis is performed based on the mechanical properties of the cell. From these results, if the defined reliability is achieved, the maximum radius of curvature is then established, if it is not achieved, it is necessary to reconfigure the encapsulation layers and perform a new structural analysis until the desired safety factor is met. This procedure is described in Fig 4.5.

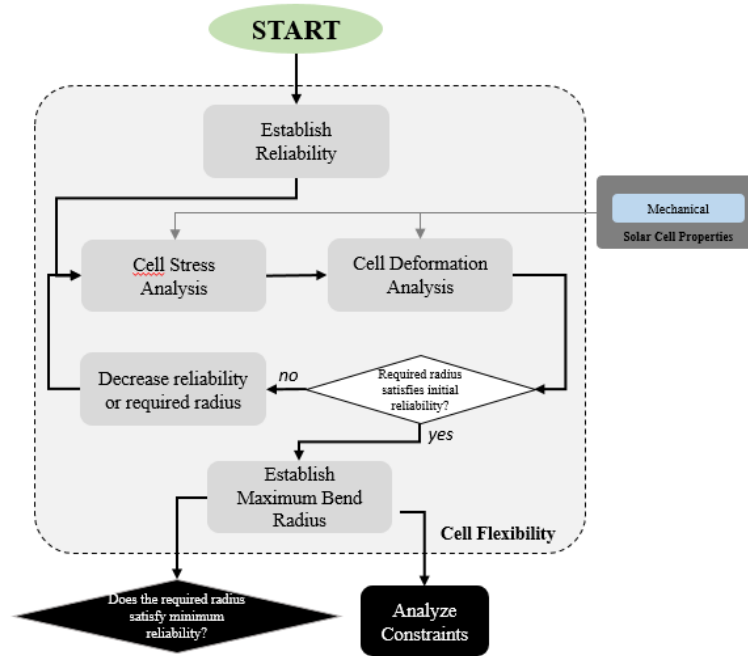


Figure 4.5: Cell Flexibility flow chart

4.2.3 Phase 3: Analysis of Geometry

This phase considers the design conditions of the contour of the geometric shape of the space where the PV surface will be installed. Based on the above, in an application it is possible that the geometry

where the PV surface will be implemented already defined, i.e., there is already a volume or space established for its occupation. On the contrary, it is possible that the user has an available space with solar resource, which he wants to take advantage of and generate electricity, however, it may not have an established geometric shape. This fact is posed as the initial question of this phase, whose scheme is shown in Fig 4.6.

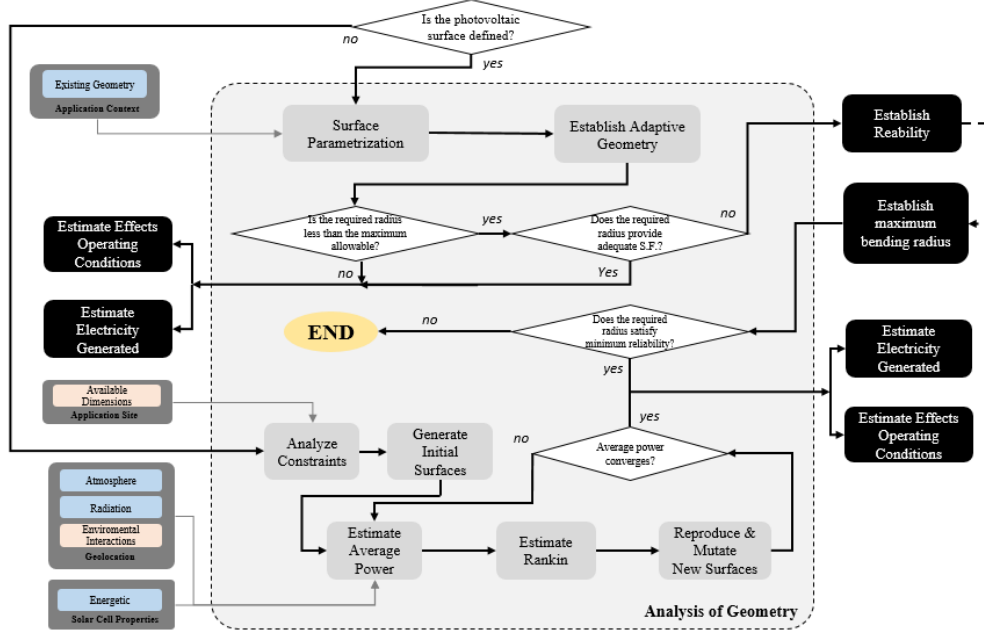


Figure 4.6: Analysis of Geometry

From the analysis of Phase 1 of the procedural approach, it is possible to answer this question, considering the initial requirements given by the stakeholders of the application. In this way, there are only 2 possible answer options: when the answer is *yes*, an analysis will be made from Available Geometry, while, if the answer is *no*, an analysis will be made from Surface Generation. A more detailed analysis of each of these circumstances will follow.

4.2.3.1 Available Geometry

This stage of the analysis arises from the first question, which suggests that the surface attributes, where a PV module will be installed, has been defined. Based on the above, a parametrization of geometry's surface is performed through CAD modeling and, finally, an adapted surface with curvature is obtained. At this point, it is considered whether the radius of the surface is less than the permissible limit. If *not*, the effects of operating conditions and electricity generated are analyzed. If the answer is *yes*, the Safety Factor (SF) must be examined to enable a smaller radius of curvature. This can be achieved redefining the reliability for the cell established by designer (regarding to the application) to

allow a smaller radius of curvature (see Fig. 3.34) and therefore, allowing an adequate SF. If this new SF satisfies the considerations of the designer, then the effects of operating conditions and electricity generation must be analyzed again, continuing with the following Phases. Finally, if the new SF is less than the required, the analysis is discarded in **"END"** and the application cannot be manufactured because it does not meet minimum reliability criteria. Specifically, in this Phase, the geometry of the surface exposed to radiation is given by design requirements (as aesthetic and structural safety) and it defines the attributes and engineering characteristics that the integrated PV module must have. This is the case that will be detailed in Chapter 5 about a VIPV application.

4.2.3.2 Surface Generation

When there is no defined shape or does not exist, i.e., when the answer to the first question of this phase is *no*, this step takes place in order to generate an optimal geometry of a PV according to an area or volume available for its implementation. This fact allows to think about the definition of precise conditions, according to the location of the PV module, in order to find the best surface geometry, through the use of a genetic algorithm (GA), establishing the power setting as the variable to be optimized, this is the case that will be detailed in Chapter 6 about a BIPV application. Therefore, it is necessary to analyze the given constraints, in terms of available space and location of PV systems, which are analyzed below.

Problem Modeling: In order to understand the performance of a PV module in terms of geometric shape and its relationship with the radiation captured, it is necessary to develop mathematical models that allow to accurately describe the physical phenomena in PV surface. Based on the above, the definition of curvature is used in order to define the attributes to describe the geometric characteristics of a PV surface. Also, an irradiance analysis is included in order to know the solar resource for a specific location. Finally, a numerical ray tracing analysis is developed to know the relationship between irradiance and the surface's geometric shape. These models will be described below.

Curvature Condition: From the problem definition, a surface with curvature must be generated. To determine the curvature of a surface, it is necessary to calculate orthogonal radius or curvature see subsection 2.4.5, (Schling et al., 2018). Equation 4.1 is the parametric definition for curve surface.

$$\vec{r} = (x, (u, v), y(u, v)); u, v \in R \quad (4.1)$$

From this definition, it is possible to define the geometric nature of any surface, which must be integrated into the irradiance model, shown below.

Average Power Modeling: Irradiance is the power from the sun that is captured by the PV module. It can vary depending on the time of day, month, year and environmental factors such as cloud cover and ambient temperature. To estimate the generation effects on a surface (dS), a vector field condition is assumed, in which the magnitude of the vectors changes throughout the day, being smaller in the mornings and afternoons. Thus, irradiance vector $G(t)$ changes in magnitude and direction $r(t)$ throughout the day. Consequently, the generated surface must have the ability to find a balance point between these factors through its topology in order to maximize the generated power. This situation is presented by means of the following mathematical model:

$$P = \frac{1}{t_f - t_o} \iint [G(t)\vec{r}(t)] d\vec{S}dt \quad (4.2)$$

The above equation states that the mean power generated (P) by PV surface, is the summation of the irradiance $G(t)$ in a specific direction $r(t)$ over a differential surface dS within a time interval dt . This expression will be used in subsequent analyses in order to evaluate different PV surfaces.

Ray Tracing Modeling: Based on the historical irradiance of the selected location for the PV surface, it is necessary to develop a tool to determine the amount of radiation captured by the surface. Taking into account that the analyzed surfaces may have some degree of curvature, it is possible that under certain hours of the day, the same geometric shape of the surface generates a self-shading condition, which is taken into account and minimized by the GA. This is based on the logical condition that if a ray from the same origin impacts on more than one element, there is self-shading.

Genetic Algorithm GA: In order to find the best curved surface, according to the parameters described, it is necessary to propose an Genetic Algorithm (GA) that allows, through iteration, to build an optimal solution topology (Kuri et al., 2002). The GA begins with the discretization of the surface's geometry through meshing. Then, a set of first surfaces with curvature that fit the given volume are proposed, estimating their average power captured by radiation. From this calculation, the surfaces with the highest captured power are chosen, which are then subjected to a reproduction and mutation process to obtain better surfaces. Finally, iterations of this process are carried out until the optimal PV surface that maximizes the captured power is obtained. This is the case for the second BIPV case study that will be detailed in Chapter 6. Each of the steps necessary to obtain optimal PV surfaces through GA will be discussed below.

Analyze Constraints: The selected study site is Medellín, Colombia, which is a city located in the northern hemisphere of the earth. To find an optimal surface it is necessary to know the local level radiation and the movement of the sun in that location. There are no operating loads associated with the surface because the surface is static.

Generation of Initial Population: The first surfaces of the population are generated from known mathematical functions, such as planes, paraboloids and sinusoidal functions with the given radius and area restrictions.

Estimate Average Power and Rankin: Integrating the irradiance model, the ray tracing model and curvature condition in Equation 4.2, it is possible estimates the average power captured (P) by the obtained surfaces throughout the generations developed by the GA. This allows identify and order the best individuals (with highest average poert) for each generation. Through this process it is possible to know the geometric potential of surfaces to capture solar radiation. This fact allows the GA to make decisions based on the nature of the surfaces evaluated in the fitness function, which gradually leads to the convergence of the study.

Reproduce and mutate new surfaces: From the first population, the crossover between them begins to find better individuals and form a second generation of better characteristics. Also, random mutations of some individuals within the population are performed to then re-generate the meshes with the attributes of their parents and the imposed mutations. Then, individuals obtained are evaluated in the fitness function establishing a ranking with the best results. At this point, the best surfaces become part of a second generation while the worst ones are discarded. This process is repeated until the convergence of the study is reached.

Optimal surface: The surfaces arise from the reproduction of the generated individuals, which are progressively evaluated in the fitness function, allowing to gradually create individuals with better characteristics, which in this case, are surfaces with higher radiation capture. Taking into account that the problem has spatial restrictions of area and radius of curvature, the surface must converge to a maximum power value, considering the values of the given restrictions. It is at this point that the optimal PV surface for the given conditions is obtained and must have attributes that allow its fabrication and modeling, therefore, it is necessary to perform an analysis of the curvature

Error Analysis: in this way, the local radius of the smallest along the entire area of the surface is evaluated, validating that it has a value greater than the maximum allowed to ensure the structural integrity of the photovoltaic cells.

4.2.4 Phase 4: Mechanical Analysis

Both for the case in which the geometry is previously defined or when it is generated through the GA, the effects of the operating conditions are evaluated, considering loads due to its own weight and

inertial changes. Then, a new stress analysis is performed, to see if the obtained reliability satisfies the minimum safety requirements, as described in Fig 4.7.

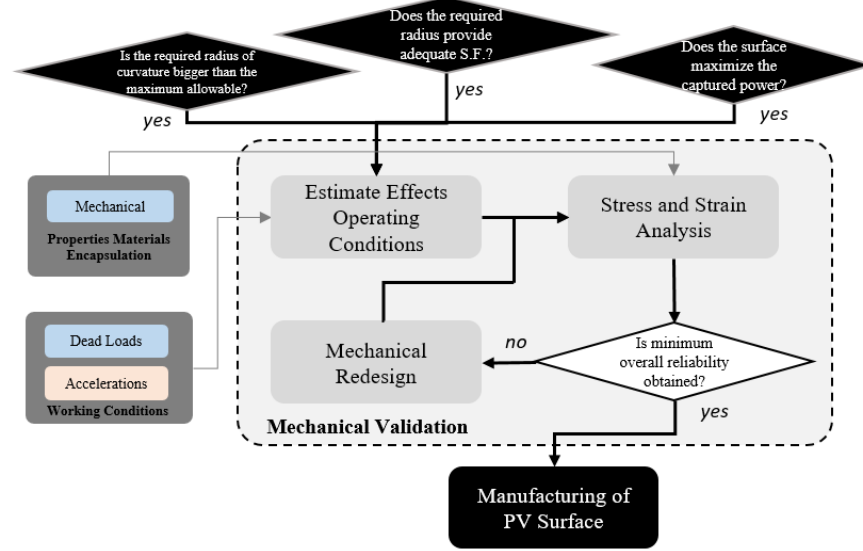


Figure 4.7: Mechanical Analysis flow chart

If the answer is *no*, a mechanical redesign of the PV module reinforcement is required. But, if the answer is *yes*, it is decided, from the mechanical validation point of view, that the PV curved surface can be manufactured.

4.2.5 Phase 5: Energetic Analysis

In parallel to the mechanical analysis, an energy transformation study is also carried out. It is based on the fact that the light energy, entering to the PV module, is transformed into electricity, heat and losses due to optical phenomena. In this way, a multiphysical model is proposed to find the usable electricity inside the PV module, taking into account geometry and its impacts in thermal and optical phenomena over the encapsulation material, including electrical characteristics of the solar cell. This process is shown in Fig 4.8.

If the PV surface does not generate the minimum required energy, it is necessary to consider energy improvement strategies (if possible). In case the answer is *yes* about the minimum required energy, then the manufacturing of the adaptive PV surface can be carried out.

4.2.6 Phase 6: Photovoltaic surface manufacturing and testing

After obtaining an adequate mechanical and energetic behavior for the analyzed surface, the fabrication of the adaptive PV curved surface is carried out. For this purpose, a plastic based manufacturing

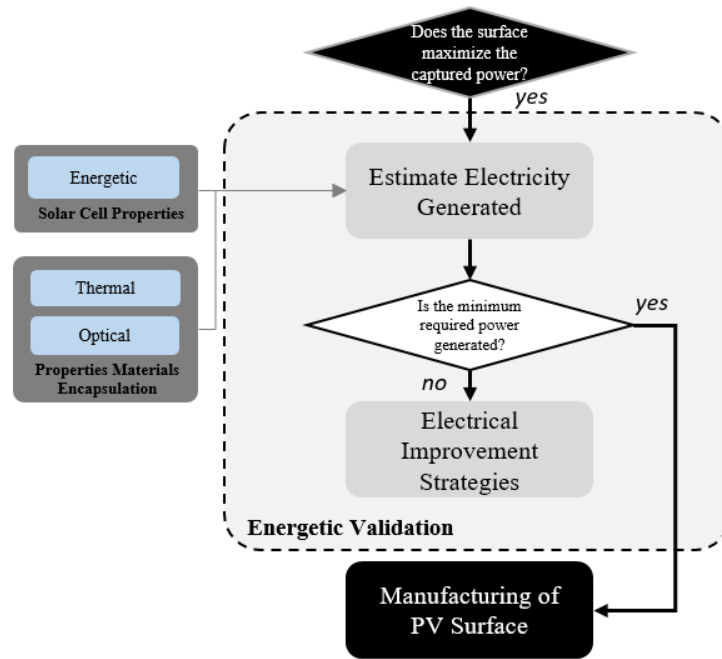


Figure 4.8: Energetic Validation flow chart

process for PV modules is proposed, through the arrangement of different layers of epoxy resin and fibers in order to increase the flexibility of the PV surface, without compromising its general performance. This is described in Fig 4.9.

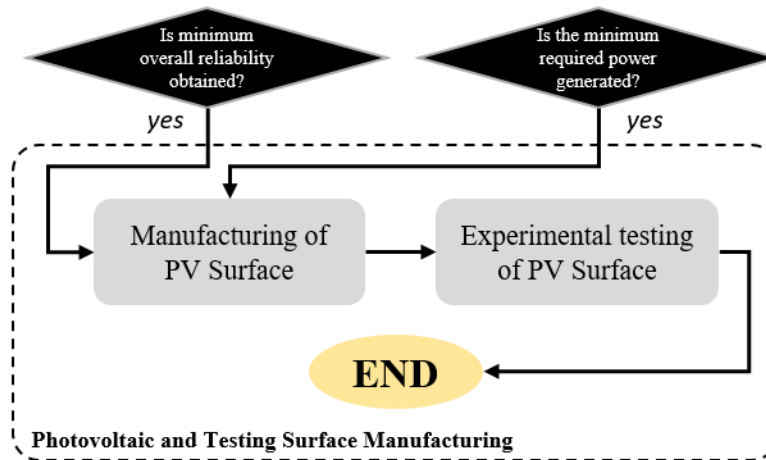


Figure 4.9: Photovoltaic surface manufacturing and testing flow chart

Through the fabrication of the PV surface fabrication presented in the case studies, this analysis step also includes experimental measurements of the real performance of the fabricated PV surfaces, which will be shown in the following chapters.

4.3 Cases of study proposed

Using this procedural approach, it is possible to obtain curved PV surfaces with the ability to be adapted to geometric shapes (given or not given) exposed to solar radiation for any application and location, without compromising the structural integrity of solar cells and maximizing the energy captured by radiation.

For the purposes of this research and taking into account that the applications in prosumer nodes are given in the context of the integration of PV systems to vehicles and buildings (VIPV and BIPV, respectively), an application case for each of these approaches will be developed in depth. Finally, and based on the proposed procedural approach, a first VIPV case study of an electrosolar boat will be carried out, which is explained in depth in Chapter 5. While for the BIPV case study, a problem of the use of surfaces exposed to radiation in terraces of Colombian constructions will be addressed in Chapter 6.

Chapter 5

VIPV Case Study: Electro-solar Boat Roofing

Within the framework of the ENERGETICA 2030, in the Sustainable Mobility Project, the design and implementation of an electro-solar boat for public transportation was proposed. In order to give the boat the character of "electro-solar", it was defined that the roof, in addition to protect the passengers from the sun and rain, needed to have the ability to generate electricity from the available area exposed to radiation. The render of the proposed boat is shown in Fig 5.1



Figure 5.1: *Rendering of the electrosolar boat from ENERGETICA 2030*

According to the proposed approach (described in Chapter 4), the following subsections will describe the detailed design of PV modules with curvature, adapted to the formal design of the electrosolar boat. Also, impacts of associated boat operation loads and how the manufacturing process can meet these requirements were analyzed, as well as the physical phenomena associated with the operation and its influence on the overall performance. Each of the analyses will be approached from the procedural approach and will be analyzed below.

5.1 Phase 1: Identification of the Application Environment

The electro-solar boat has been implemented through a design process between the electro-propulsion, PV array, hydrodynamics and energy storage subsystems. This fact meant that the level of development had to be coupled to the other subsystems in terms of design. Consequently, the objective of this case study is to analyze the conditions of the operating environment and its relationship with the design of the curved PV modules for loads associated with the movement of boat, in order to establish the appropriate dimensions to ensure proper reliability.

The design of the sunroof and its PV modules is based on the available area for protection of users from rain and sun. Similarly, the height is given to ensure the greatest possible comfort when users enter and exit the boat. Likewise, the PV modules are required to have curvature in order to understand aspects related to their performance, reliability and manufacturability. Thus, the geometric shape of the PV modules is defined by the roof design and its integration with the complete boat, based on research criteria on its morphology, aesthetics, usability and aerodynamics. Taking into account that the site, where the boat will operate, is the city of Magangué (Colombia), so, it is necessary to analyze the atmospheric conditions found in that place. Fig. 5.2 shows some relevant information related to the behaviour of the temperature and the wind speed at that location.

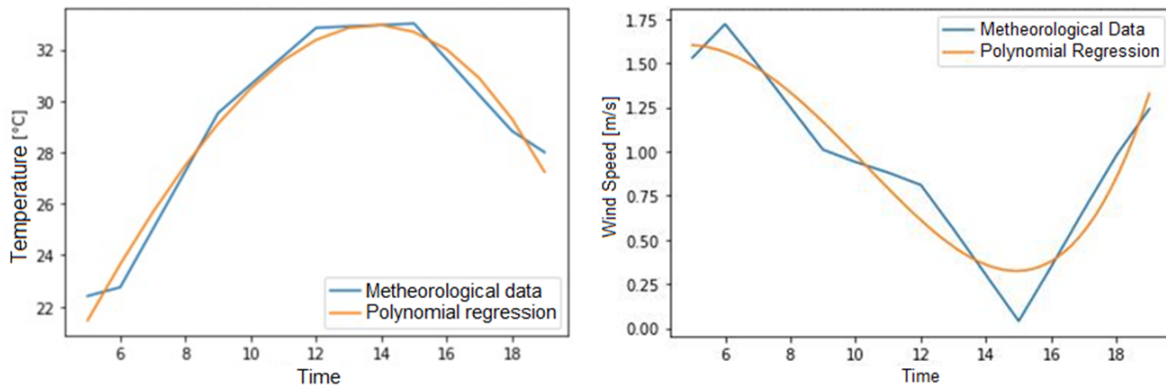


Figure 5.2: Weather conditions in Magangué, Colombia. Mkasi et al. (2018)

The boat was designed to cover the Magangué-Pinillos route, where PV modules will be subjected to operating conditions related to navigation, such as winds, inertial changes and humidity during the journey of about 45km along the Magdalena river. However, the center of operations of the boat will be in Magangué, so the radiation conditions for the subsequent analysis will be given for this location. Based on the above and by means of the PVWatts[®] software, irradiance values for the Magangué's location was determined, as shown in Fig 5.3.

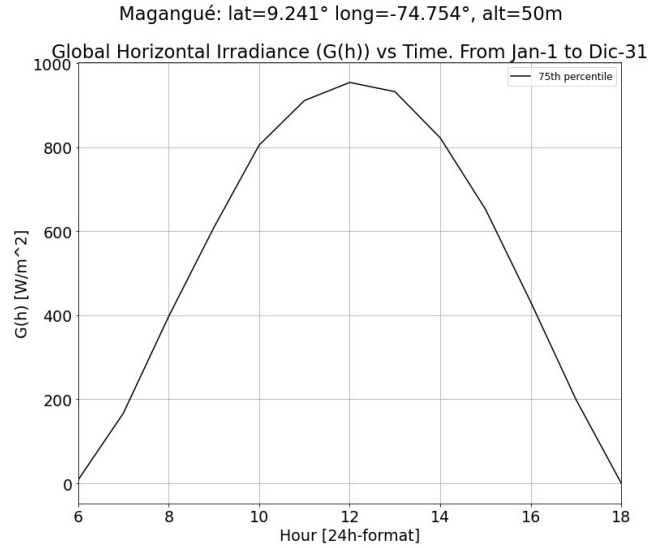


Figure 5.3: Irradiance in Magangué from PVWatts ®.

A complete day was determined. The aim is to evaluate the influence of the sun on the curved and flat panels, irradiance reach a maximum values at noon on $940\text{W}/\text{m}^2$ in Magangué, Colombia.

5.2 Phase 2: Cell Flexibility

Maximum curvature radius in PV module will be based on the ability of the solar cell to bend and take the shape to installate it in the available space. Assembling this type of PV modules, it is necessary to preload the cell so that it adjusts to the shape of the reinforcement. This is necessary to estimate the maximum deformation that cell can suffer, allowing an adequate safety range. For the solar cell, Silicon isotropic mechanical properties will be used Ashby (2008). Layout of selected solar cell is shown in Fig 5.4

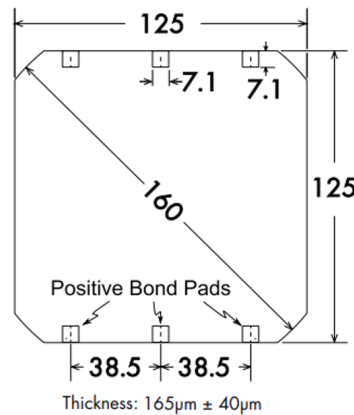


Figure 5.4: Dimensions of SunPower® C60 Solar cell

In addition to the stresses in the cell by the preload, it is important to analyze the boat operation which brings additional loads, being critical in the PV array as it compromises the reliability. This safety factor (SF) must be high enough to ensure low probability of failure. To estimate this condition, a maximum allowable stress of 10MPa is proposed, in order to avoid entering the failure zone of c-Si cells in worst case (Sander et al., 2013), defining a SF of approximately 8, due to the approximation of the cell and the possible unknown associated operating loads. In this way, a static structural analysis is carried out in ANSYSTM to analyze the effects caused by a load in the center of the cell, assigning fixed supports on cell edges. The deformations obtained will allow to find the maximum allowable bending radius, taking into account an allowable stress of 10MPa , for a reliability of 95% (see section 3.3.1). The results are shown in Fig. 5.5.

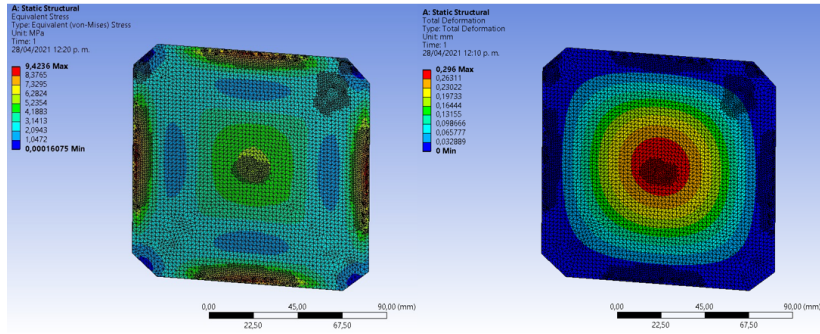


Figure 5.5: Stress and Deformation in SunPower® C60 solar cell

A maximum stress of 9.4MPa is obtained, which is less than the proposed allowable stress and presents a SF of 15 that adequately responds to the functional and structural requirements of the solar cell. Likewise, a maximum deflection of 0.29mm is obtained, which allows assembling the reinforcement and the cells within a radius of curvature of 6.51m , this value is obtained from geometrical estimations. Comparing with the minimal radius measured in the roof structure of $9,2\text{m}$, it is needed less curvature with respect the minimal radius found. Therefore, it is concluded that the cells will have the capacity to support the loads related to the bending.

5.3 Phase 3: Analysis of Geometry

As previously stated, the geometric shape of the boat's roof was defined based on research, aesthetic and usability criteria. Based on the above, conceptual exploration of most common geometric shapes in boat roofs was carried out, as well as the inclusion of some of our own concepts. From this brainstorming, 3 concepts were pre-selected according to the criteria of the project team, these shapes are shown in Fig 5.6

After this conceptual exploration and through a research group voting, sketch number 1 was

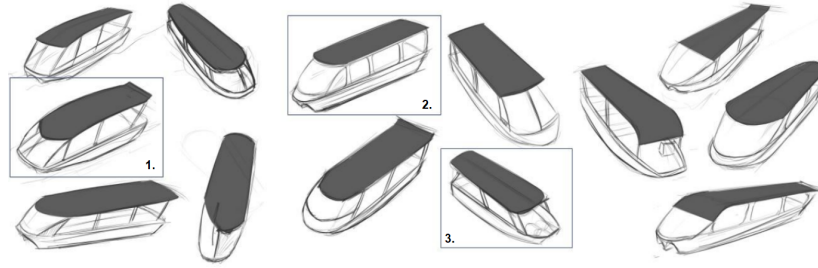


Figure 5.6: Brainstorming geometric shapes for integrated sunroofs

chosen as the final shape. This way, a geometry with a double curvature of longitudinal radius of $15m$ and transverse radius of $9m$ was obtained, with an area of $12.6m^2$. In order to facilitate the manufacturing and assembly of integrated PV array, it was decided to divide the entire roof into 14 equal areas, distributed in 7 rows and 2 columns, which have the same geometrical attributes, as shown in Fig 5.7.



Figure 5.7: Integrated PV roof subsystem, composed by PV modules

Finally, a total area was divided in 14 PV modules with double curvature with same geometry are set as final design, offering important advantages in terms of installation, manufacturing and assembly since they are easily replaceable and exchangeable. Taking into account that the surfaces have a certain degree of curvature and that, in addition, electricity generation was the variable to be maximized, the look for solar cells on the market was carried out, in order find a type of cell with the highest degree of flexibility, minimizing interconnection times while maximizing efficiency, deciding to use SunPower® C60 cells. Fig 5.8 shows the geometry obtained for the PV module with the previously selected c-Si cells.

Based on the proposed geometry and its final area, a total of 48 selected solar cells can be accommodated, allowing a space of approximately $1mm$ between the cells and nearly $5cm$ at the edges of the solar panel for passing connections and the attachment mechanism to the roof structure. Different analyses are then carried out, in order to find the desired thicknesses to withstand the

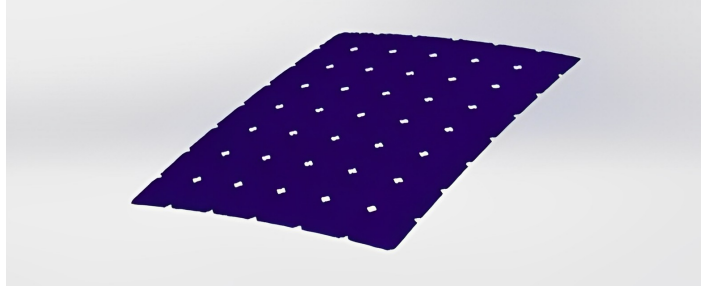


Figure 5.8: Roof-integrated PV module dimensions

conditions to which the system is exposed.

5.4 Phase 4: Mechanical Analysis

Regarding to the use of these PV surfaces within the boat, an analysis of working conditions is carried out. This is based on the behavior of the mechanical phenomena presented in electrosolar boat operation, and the influence of properties materials. Fig 5.9 shows the arrangement of materials for materialization of the curved PV modules.

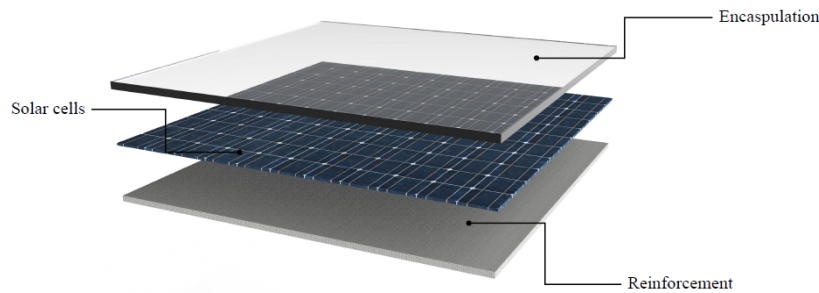


Figure 5.9: Arrangement of layers in PV module

The analysis between the internal operation of a PV module and its external conditions (associated with operation of the boat), allows to define technical characteristics that system must have for adequate operation. The layout of the curved PV module must ensure the strength of solar cells and facilitate the manufacturing. Therefore the most suitable materials to meet these requirements are also analyzed.

Materials Selection: It is observed that solar cells are assembled and encapsulated within 2 elements: the encapsulation material and the reinforcement, which guarantee adhesion with the cell, characteristics and functions of these materials will be explained below.

- **Encapsulation Material:** must ensure that the light passes adequately through the medium,

in order to be captured by the solar cells. For this purpose, a search for materials with attributes of transparency and translucency was carried out at CES Edupack™, which allowed defining epoxy resins as the most suitable family of materials for their manufacture (Bernal del Río et al., 2021). However, there are different types of epoxy resins in the market, so it was necessary to analyze optical properties through a spectrometer (see Appendix A). It was obtained that Ecopoxy resin has the lowest absorbency, which allowed defining this material for the manufacture of the encapsulation.

- **Reinforcement Material:** an adequate adhesion to the Encapsulation must be guaranteed, so composite materials based on fiber fabrics are an excellent option. They are conformed of a fiber material (fabrics) and a matrix that in most engineering applications use resins, which guarantees a chemical affinity to the selected material for the Encapsulation. Also, the Reinforcement of a PV module must ensure the structural integrity of the solar cells and allow the assembly with the encapsulation material.

In (Espitia-Mesa et al., 2022) is observed that the loads perpendicular to the surface have the most negative effects on the solar panels. Therefore, a material that has adequate resistance to bending and that also allows electrical insulation, to avoid short circuits in the system, is sought. After performing bending tests for different types of composite materials, it is obtained that the best material, in terms of cost-benefit and that satisfies the structural requirements, is the fiberglass for Reinforcement and Ecopoxy resin for encapsulation. The measured properties in this study are found in Appendix A.

Based on the above, a mechanical and structural analysis of some critical loading conditions is proposed, using the properties found in the laboratory tests in order to obtain values closer to reality, taking into account the high reliability of 95% that must be guaranteed.

5.4.1 Working Loads Analysis

Using the geometry defined in Fig 5.8, and taking into account that main function of reinforcement is to guarantee the integrity of solar cells, a mechanical study of the PV curved module is carried out, considering critical operating conditions. From several iterations, a thickness of $6mm$ was defined for the glass fiber in the Reinforcement, and a thickness of $2mm$ for Ecopoxy resin for Encapsulation. Considering these materials and thicknesses, a structural analysis is made according to critical conditions that could occur during the operation of the electro-solar boat and fixed supports on the edges of PV modules, which are presented below.

5.4.1.1 Critical Static Case

A scenario is considered in which the electro-solar boat is parked without movement, so it must support the force of its own weight, which is approximately $12.86kg$ for each PV module. In order to analyze the behavior of these materials and take it to a more demanding condition, a critical scenario is assumed in which PV module must withstand conditions of maintenance and installation work on the roof, which involves supporting of load due to the weight of an operator and possible tooling, therefore a load of $1000N$ in perpendicular direction of the surface of the PV module is added to the study. Fig 5.10 shows the stress distribution for solar cells given for this configuration.

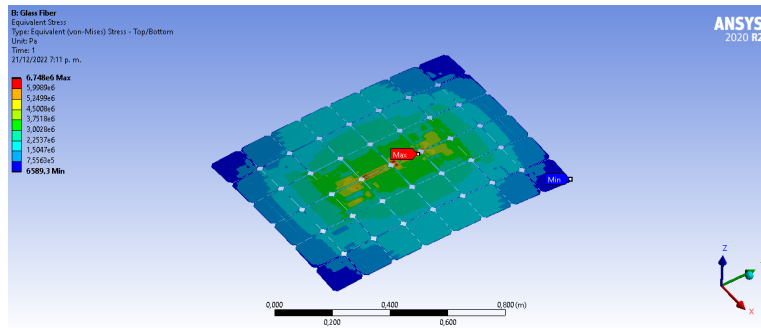


Figure 5.10: Solar cell stresses in critical static case

It is obtained that the highest stress is obtained in a central part of the PV module, near the edge of the cell, with a magnitude of approximately $6.7MPa$, which is a very small value compared to the fracture stresses of $80MPa$ given in Fig. 3.34, so that reliability conditions are satisfied. Likewise, a deformation analysis for solar cells is performed, which is shown in Fig 5.11

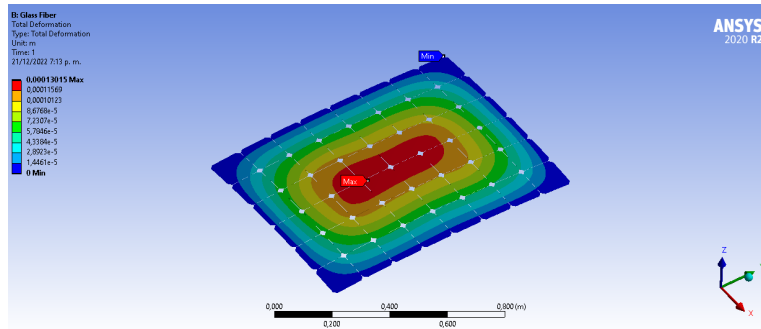


Figure 5.11: Solar cell deformations in critical static case

It is then observed that the maximum deformation is approximately $0,1mm$ in the center of PV module, which is a negligible value, compared to the surface area of the solar panel. In addition, compliance with this condition is very important because PV modules have critical conditions sus-

ceptible to damage when subjected to bending moments, thus ensuring adequate behavior under this condition. This analysis was performed with shell-type elements and reached convergence at 35228 nodes and 32814 elements, with an element size of $26mm$.

5.4.1.2 Sudden Braking Case

During the operation of the boat, it is possible that inertial changes due to deceleration have structural implications on the PV module. Therefore, a sudden braking analysis is performed, in which the vehicle has a maximum speed of $60km/h$, stopping in a time of $5s$. From this, a braking force parallel to the movement is assumed, considering the mass of PV module and the sudden deceleration condition, which gives a magnitude of $2.6kN$. The stress analysis for this condition in solar cells is shown in Fig 5.12

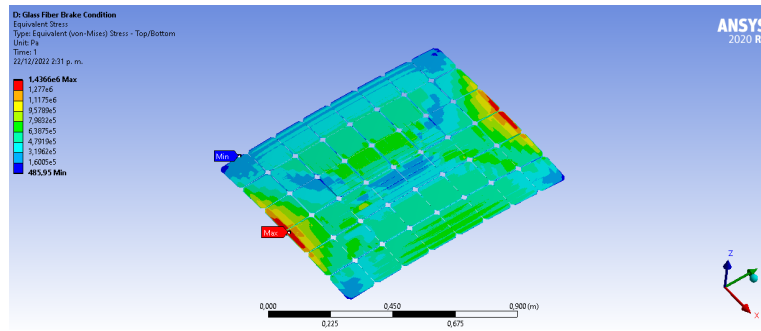


Figure 5.12: Solar cell stresses in sudden braking

A stress distribution, different from the previous condition is observed, in which the maximum stress value decreases to $1.4MPa$, which is to be expected because inertial loads parallel to the surface do not generate bending moments. The maximum stress value is found at the edges lateral to the direction of the braking load, due to the pinning condition at the outer edges of the PV module. In Fig 5.13, the deformation analysis of the simulated condition is shown.

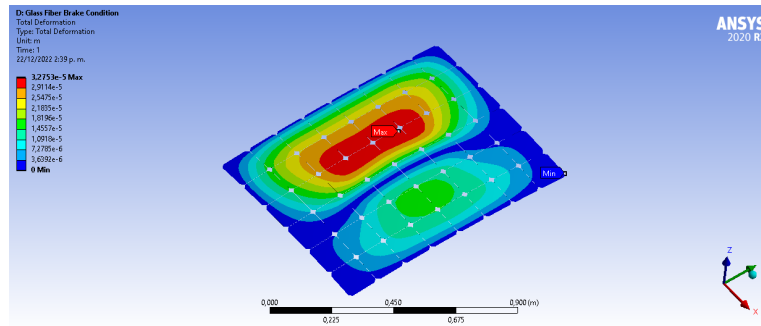


Figure 5.13: Solar cell deformation in sudden braking

The deformation distribution has an interesting pattern, in which, it presents a maximum value of

0,03mm near the center of mass in the direction of load application, while in the remaining half, the presented deformation is smaller. This obtained value is negligible compared to the external measurements of the PV surface. The convergence of this study was achieved in the 43256 elements and 39057 nodes, also, an element size of 19mm was used.

5.5 Phase 5: Energetic Analysis

Based on the selected materials and the curved shape of the PV modules in the boat, an energetic analysis is performed. Optical analysis is developed using the ray tracing software TracePro, in order to evaluate the generation potential of the surface depending on the direct irradiance conditions. For thermal study, a Finite Element Analysis (FEM) is implemented in ANSYSTM and finally, for an Electrical Analysis was used Simulink of Matlab[®]. These analysis will be explained below.

5.5.1 Optical analysis

In order to analyze the impact of the PV modules geometry, a study is carried out in TracePro[®] software to evaluate the radiation collection capacity of the double curvature solar panel, which is oriented to the south. Fig 5.14 shows the irradiance obtained in each hour throughout the morning, assuming that the values obtained for the afternoon are equivalent.

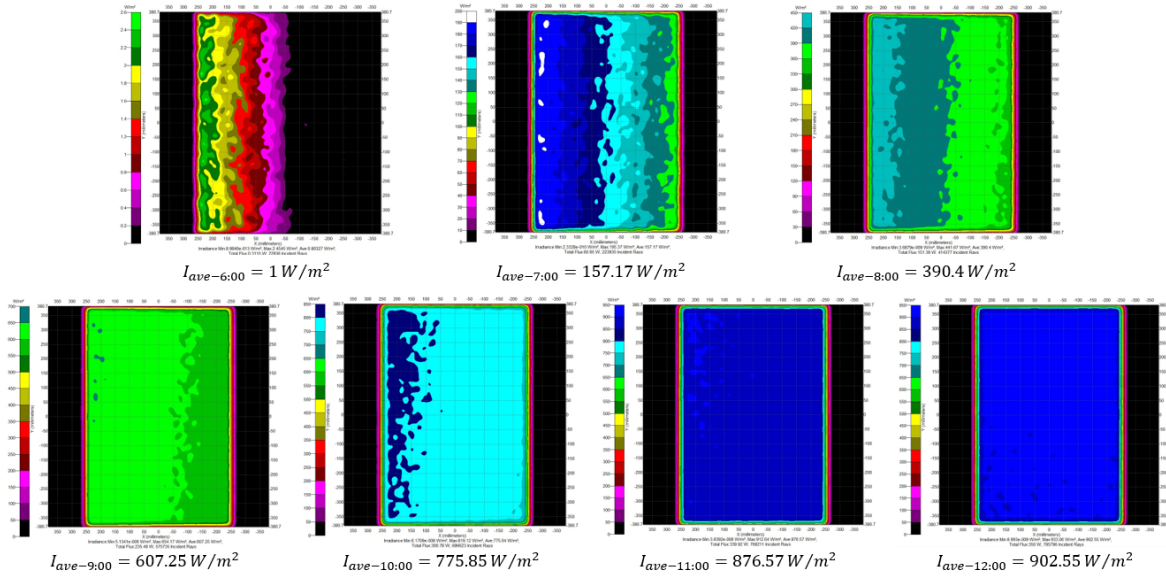


Figure 5.14: Study of captured radiation

The average captured irradiance increases over time until noon and being almost zero in the early morning hours. At 6am it is observed that, due to the curvature, half of the PV module does not receive radiation, so the average irradiance is very low. This is reaffirmed in the electrical analysis because in cells connected in series, electricity generation must fall completely. Between 7am and 8am, a similar pattern is observed in which the magnitude of the average irradiance is divided in half of the panel, however, it is only until the second half of the morning that there is a significant radiation, so this phenomenon is not very influential in the overall performance. At 9am and 10am, the average irradiance is well distributed over the surface, due to the fact that the sun's elevation angle allows rays to impact throughout the area. At 11am and 12m, the maximum average radiation is captured, which reaffirms the uniform distribution over the entire area, so it is the time when most electricity generation occurs. Therefore, geometric shape of PV module has an important influence on the irradiance captured and finally in the power generated, as it can be seen in Fig 5.15.

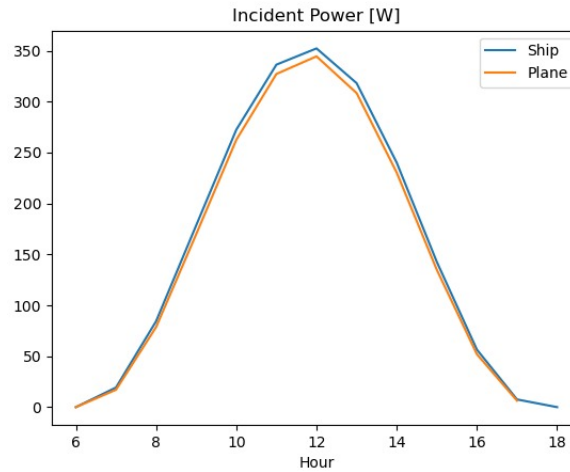


Figure 5.15: Power captured from a flat vs. curved PV modules

In this way, the power captured by a PV module on the roof of the electrosolar boat was analyzed with respect to a flat geometry with the same capture area. In essence, for outdoor hours, it is obtained that the curved surface has a total absorbed power of 2387W, which it has advantages in terms of angle of exposure to the sun throughout the day, so a slightly higher collection power of 3,97% is observed throughout the day and finally, more energy is generated with respect to the flat geometry with total power absorbed of 1931W. This fact is very important and promising, because it is possible to think that some geometries with curvature could present better performance than conventional flat shapes. The above simulation was developed with a total of 4.000.000 rays, non-polarised light with an average wavelength of 546.1nm during the winter solstice day of 23th September.

5.5.2 Thermal Analysis

Taking into account that most of the energy losses of a PV module are given by the generated heat, it is necessary to perform a thermal analysis, starting from the different mechanisms of heat transfer, which are shown in Fig. 5.16.

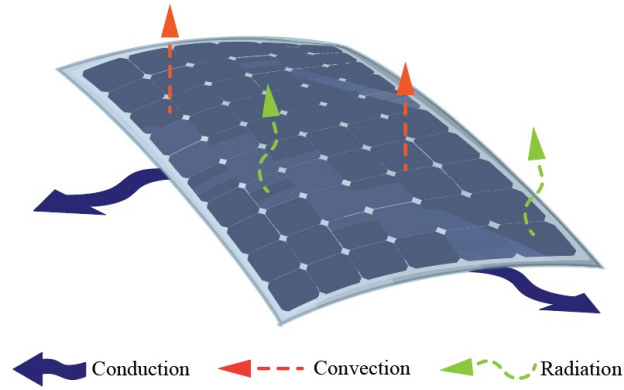


Figure 5.16: Heat transfer phenomena in a PV Module.

When the boat is stationary, the PV module is dissipating heat by natural convection. This analysis is performed by means of FEM and is shown in Fig 5.17. Thus, a simulation is established for the components of complete solar panel, whose temperature distribution is as follows.

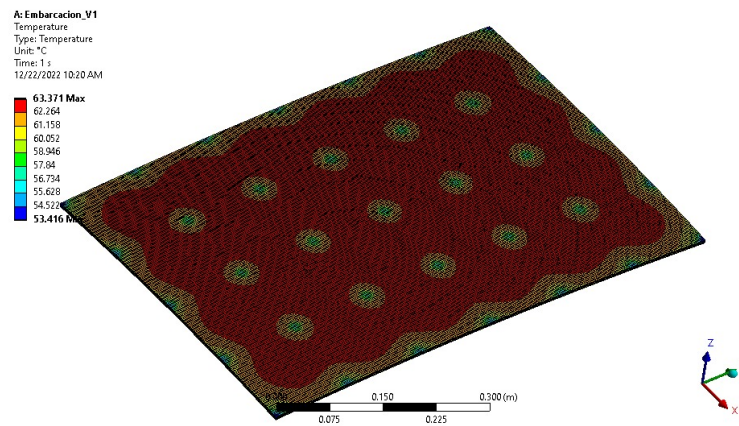


Figure 5.17: Temperature distribution in the integrated PV module

It is observed that the temperature tends to be concentrated in the center of PV module, with the edges being the coldest places. The spaces in the center of the panel that has lower temperature corresponds to the spaces between cells, which are filled with encapsulating material. A view of the behavior of the solar cells is shown Fig 5.18

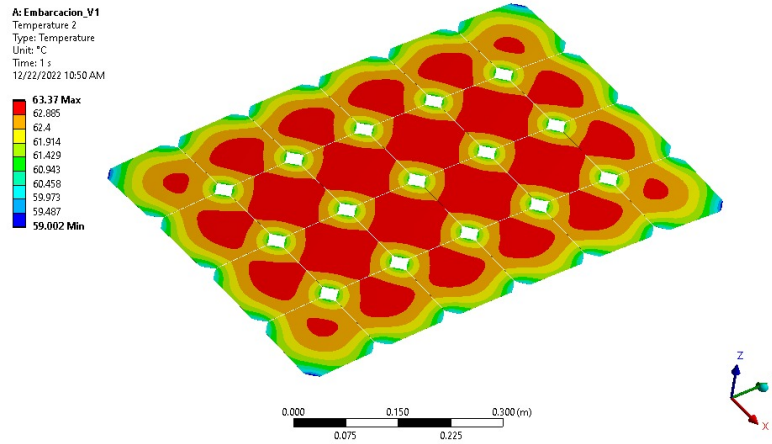


Figure 5.18: Temperature distribution in solar cells

The cells closest to the center are the hottest (up to 63°C), while the cells at the edges have a considerably lower temperature along their surface (only 59°C). It should be noted that the temperature distribution in these cells does not have a uniform behavior. It is also necessary to analyze the heat flow in the direction normal to the surface, as shown in Fig 5.19

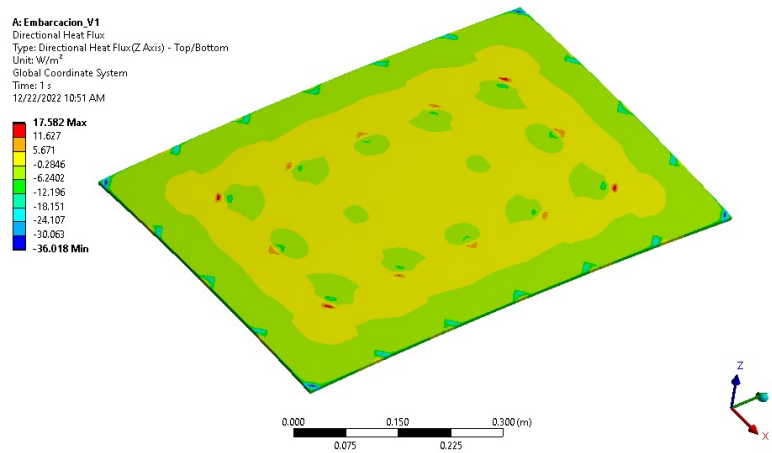


Figure 5.19: Heat flow in the Z direction

It is observed that the heat flow through the reinforcement is $17,58W/m^2$, which is a very low value with respect to the energy captured by the surface and suggests that the temperature in the solar cells does not depend significantly on the thickness of the reinforcement. This study was developed with next boundary conditions: convection on top face with $h_{conv} = 5W/m^2°C$, encapsulation heat flux of $q_{enc} = 13,38W/m^2$ and solar cell heat flux of $q_{cell} = 725,86W/m^2$. The convergence of this simulation was reached for 130640 nodes and 127979 elements for an element size of $3mm$.

5.5.3 Electrical Analysis

Previously, in Section 5.2, it was defined the chosen cell for materialization of the PV modules of the electrosolar boat. The SunPower® C60, was the chosen reference due to its cost-benefit ratio and flexibility capacity, being a c-Si. For electrical analysis, it is necessary to take into account the energetic properties of this cell in Standard Typical Conditions (STC), which are shown in Fig. 5.20

Electrical Characteristics of Typical Cell at Standard Test Conditions (STC)					
STC: 1000W/m ² , AM 1.5g and cell temp 25°C					
P _{mpp} (Wp)	Eff. (%)	V _{mpp} (V)	I _{mpp} (A)	V _{oc} (V)	I _{sc} (A)
3.34	21.8	0.574	5.83	0.682	6.24
Unlaminated Cell Temperature Coefficients					
Voltage: -1.8 mV / °C			Power: -0.32% / °C		

Figure 5.20: Energy properties of the SunPower® C60

Based on these electric characteristics and its voltage drop coefficient and power per temperature, it is necessary to estimate the generation of the integrated PV array on the roof of the boat. Modules are connected in series in order to obtain sufficient voltage to power the vehicle's battery. In Fig 5.21, a simulation environment in Simulink® of PV modules is shown.

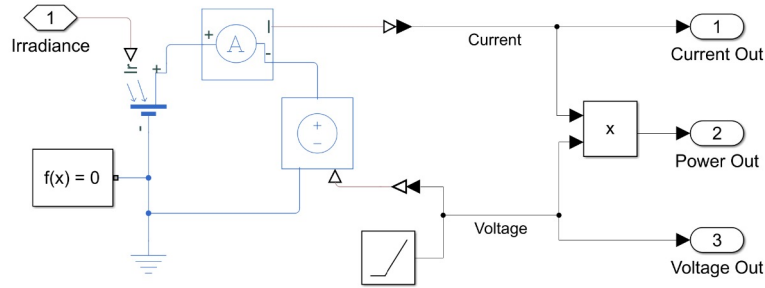


Figure 5.21: PV array in Simulink-Simscape®.

In this scheme there are blocks of variables that are related to each other to estimate the characteristic curves of the PV system, between the Simscape and Simulink environment. There is a product, which calculates the power from the voltage and current, an irradiance variable, a current and a voltage controlled source. The voltage is introduced from a ramp that supplies 50V in 60s, in addition to a configuration block and a ground reference. From the above and using the electrical characteristics of solar cell, the VI and PV curves of the PV module are generated, which are shown in Fig 5.22 below.

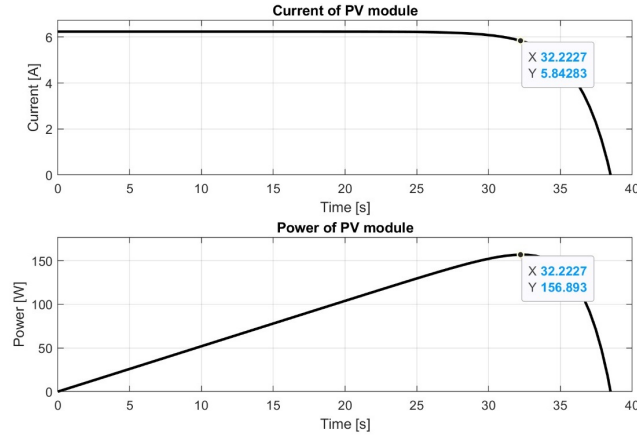


Figure 5.22: VI and PV curves of the PV module

In the "solar cell block", the variations of irradiance and temperature are included by a function of the sun's resource and the ambient temperature of Magangué, respectively. Thus, it is found that the Maximal Power Point (MPP) has a current of 5.84A and a power of 156W are obtained for the individual PV module. This result is shown in Fig 5.23.

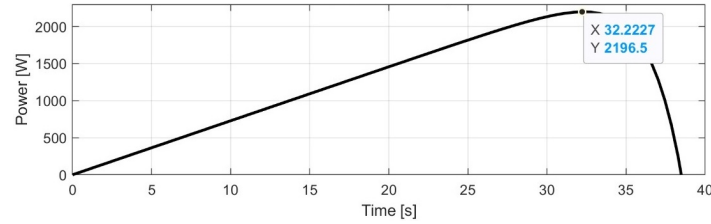


Figure 5.23: PV curve of PV array

Finally, the maximum power for the PV array on the roof of the electrosolar boat is 2.2kW. It should be noted that these values relate to a maximum generation potential, because these estimates consider direct irradiance and a static position of the boat.

5.6 Phase 6: Photovoltaic surface manufacturing and testing

Final dimensions and materials used in the PV modules was defined on the basis of the physical analyses in the previous Phase (see Section 5.5). Based on the geometry given by the formal design, a double curvature PV surface with given radius must be manufactured, which allows the solar cell to flex in order to adapt the contour of the solar panel and also withstand the loads due to the movement of the boat. Finally, encapsulation process is proposed that includes the aforementioned characteristics and maximizes the reliability of the encapsulated solar cells and the complete system. The general steps for the fabrication of the PV modules of the solar boat roof are shown in Fig 5.24.

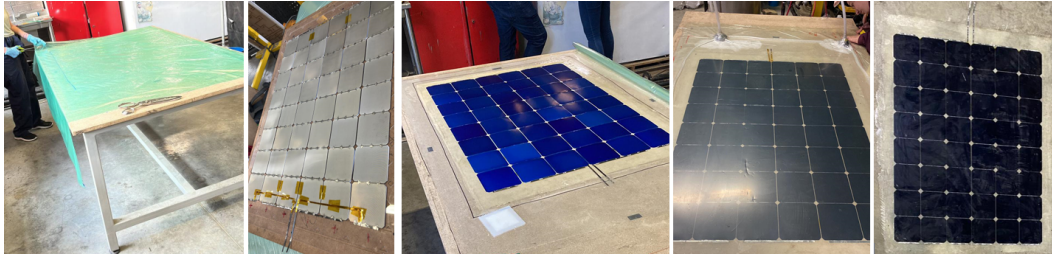


Figure 5.24: PV module lamination process

Considering that PV modules will be manufactured from laminated composite materials, it is necessary to prepare the surface by applying at least 5 coats of release wax. Then, the vacuum bag is cut to size to provide pressure at the time of lamination. At the same time, the cells are connected and then, on the previously prepared surface, the fiberglass fabrics impregnated with epoxy resin are placed on the lamination surface. On top of the glass fiber, the interconnected cells are positioned and Ecopoxy resin is spilled over the cells. The PV module is sealed with the vacuum bag and pressure is applied with the vacuum pump at least for 24h until the resins have completely cured, reaching an impregnation close to 53%. Finally, the PV module is carefully demolded to avoid cracking of the PV cells. These PV modules are assembled on the tubular roof structure and connected to the battery, as it shown in Fig 5.25 where the complete roof with PV array can be observed.



Figure 5.25: Materialization of PV array of electrosolar boat

After the manufacturing of the 14 curved PV modules, some performance tests are carried out in a controlled environment, which will be described below.

Operating performance After installation of the complete PV array, some performance tests were carried out. During on of the testing trips, some performance variables were measured at 12m, as it can be seen in Fig. 5.26.



Figure 5.26: Irradiance and current measured in boat operating site

During the test, the solar roof had an irradiance of $1151\text{W}/\text{m}^2$ and a current of 6.83A , as well as a measurement of 277V , which allows to obtain a maximum power of 1.9kW . This measure is 13.6% less than the theoretical estimation made in subsection 5.5.3, and it might be due to the cracking of some cells during the handling of the roof while transport and unloading the boat, decreasing the voltage, and consequently dropping the electricity generated.

Chapter 6

BIPV Case Study: PV application in a Rooftop Area

The case study here described, makes emphasis on Building Integrated Photovoltaics (BIPV) particularly in the generation of optimal geometric shapes, to which a solar panel can be integrated, based on spatial, structural, architectural and manufacturing constraints. This is achieved from a geolocation and radiation study that allows knowing the energy generation potential of a specific site, considering the effects associated with the atmosphere on a geometric surface by means of a ray tracing study. For this case, there is a flat area exposed to radiation on the terrace of a building. In the Colombian context, terraces are very common elements in homes; they are a cement slab that in most cases serves as a roof, the terrace is usually unoccupied, so it is a potential area for photovoltaic (PV) use, Fig 6.1 show some terraces.



Figure 6.1: Terraces in popular neighborhood's in Medellín, Colombia.

For this case study, there is no defined geometry or loads associated with movement. This fact allows to generalize the problem of PV surfaces morphology, because, in addition to the manufacturing of PV modules with adaptive capacity and their energy estimation, it is necessary to generate the geometric shape of the surfaces in question, taking into account the problem constraints. At this point, it is assumed that among infinite generating surfaces for a given available planar area, flat PV modules may not be the optimal generating geometry, therefore, a comparative analysis between the curved PV surface obtained with respect to the conventional plane geometry will also be included. For the development of this study, the methodology proposed in Section, was followed 4.1

6.1 Phase 1: Identification of the Application Environment

Similar to the VIPV case study presented in Chapter 5, it is necessary to collect information regarding the application context: geolocation and working conditions. However, BIPV applications do not have associated inertial loads related to movement and only dead loads will be taken into account. It is important to remark that, depending on the location of the PV module, the electricity in function of average irradiance may vary depending on the available hours of sunshine per day and throughout the year. For this reason, it is important to clarify the characteristics of a particular site, in order to evaluate the electricity generated by a PV module based on its location. In order to implement this approach to the case study (see Fig. 6.2), it is required to analyze the solar resource available, sun's movement and irradiance location, which is obtained for 52 sample days in Medellín, Colombia.

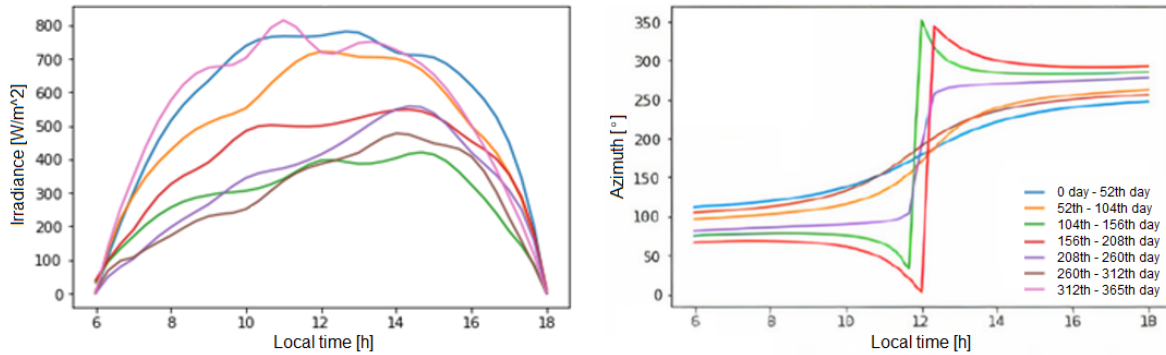


Figure 6.2: Solar resource 26 sample days throughout the year in Medellín, Colombia Mkasi et al. (2018).

Through this information, it is possible to know the available irradiance and the azimuth angle at the application site, which will be important as initial conditions of the problem. Additionally, it should be noted that for this case study, the geometry of the PV module is not pre-defined (as rooftops are flat) and will be generated in the following sections.

6.2 Phase 2: Cell Flexibility

The cell flexibility problem was addressed for the electrosolar boat in Section 5.2, analyzing an individual SunPower® C60 cell from its deformation and stresses. Taking into account the methodology proposed in Section 1.6 for development of the case studies. An analytical estimation of cell flexibility is presented, taking into account the encapsulation materials and their mechanical properties. In this way, it is needed to find the optimum thicknesses to minimize the stresses in the cell, maximizing curvature achieved by the cell. Fig 6.3 shows the flexibility analysis schematic for an encapsulated solar cell.

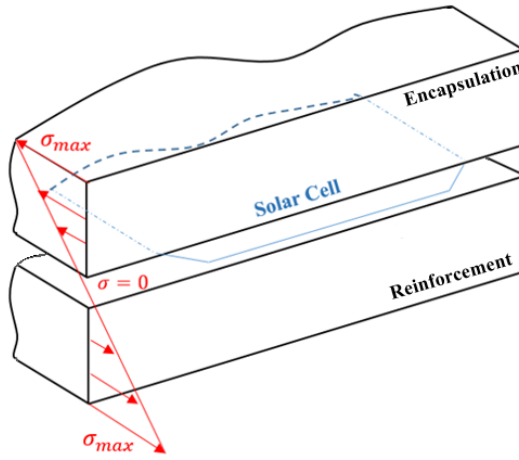


Figure 6.3: PV modules bending stress diagram

Flexibility of PV modules is given by the cell's capacity to withstand bending moments. It must be ensured that the stresses in the cell tend to zero, so its location with respect to the encapsulation materials is very important. As we already know, on top of the cell is the encapsulation material, which must have good transparency properties while the reinforcement is made of composite materials and its function is to provide structural integrity to the cell. Thus, the position of the solar cell with respect to the encapsulation and the reinforcement is critical, and the mechanical properties of these materials have a very important influence, as it is detailed in Appendix A. To estimate the best cell position for the analyzed configuration, the set Reinforcement-Solar Cell-Encapsulation is assumed to be a composite beam, where Equation 6.1 shows the positioning of the neutral axis ($\bar{y}_i$), which should be sought to coincide with the cell, while Equations 6.2, 6.3 show the stress in the cell (σ_i) and the radius of curvature (r), respectively.

$$\bar{y} = \frac{\sum E_i A_i \bar{y}_i}{\sum E_i A_i} \quad , \quad (6.1)$$

$$\sigma_i = -\frac{M \cdot (\bar{y}_i - \bar{y}) \cdot E_i}{\sum_i E_i I_i} \quad , \quad (6.2)$$

$$\rho = \frac{\sum_i E_i I_i}{M} \quad . \quad (6.3)$$

Where:

- $\bar{y}_i$ [m]: is the distance to the measurement axis.
- E_i [GPa]: is the Young's modulus of the layer material.
- M [N.m]: represents the applied moment.
- A_i [m²]: is the cross-sectional area of the layer
- σ_i [MPa]: is the bending stress in the layer.
- I_i [m⁴]: is the moment of inertia of the layer.
- r [m]: is the radius of curvature obtained.

From the development of these equations, the expressions for the stress according to the layer σ_i in Equation 6.4 and Safety Factor SF_i in Equation 6.5, for the analyzed position, are obtained as shown below.

$$\sigma_i = -\frac{(\bar{y}_i - \bar{y}) E_i}{r} \quad . \quad (6.4)$$

$$SF_i = \left| \frac{\sigma_{yield,i}}{\sigma_i} \right| = \frac{r}{|\bar{y}_i - \bar{y}| \cdot E_i} \quad . \quad (6.5)$$

From the analysis of the above equations, an analysis is carried out about the stress due to the application of curvature condition as a function of the location of the thicknesses of the layers of the materials and their properties. A clockwise moment of $M = 1N.m$ and a homogeneous rectangular cross-section for the layers of cell width and complete adhesion between layers were assumed. The reinforcement material was glass fiber, and for the encapsulations Ecopoxy Resin was selected which is a Epoxy Resin type for transparency applications. Some mechanical and optical properties of these materials are presented in Appendix A, and the results are shown in Fig 6.4.

A stress diagram is obtained, as a function of layer thickness. In the interaction between the encapsulation and the cell, it is assumed a maximum stress of approximately $56MPa$. This value does not exceed the fracture stress of $80MPa$ for c-Si cells under perpendicular loads, considering a failure probability of 5% without effect loads due to inertial changes. This defines a minimal SF of approximately 1,43 because it has no additional loads, as described in Section 3.3.1. Compressive stresses occur between the cell and the reinforcement, which increase to a maximum value of $13MPa$

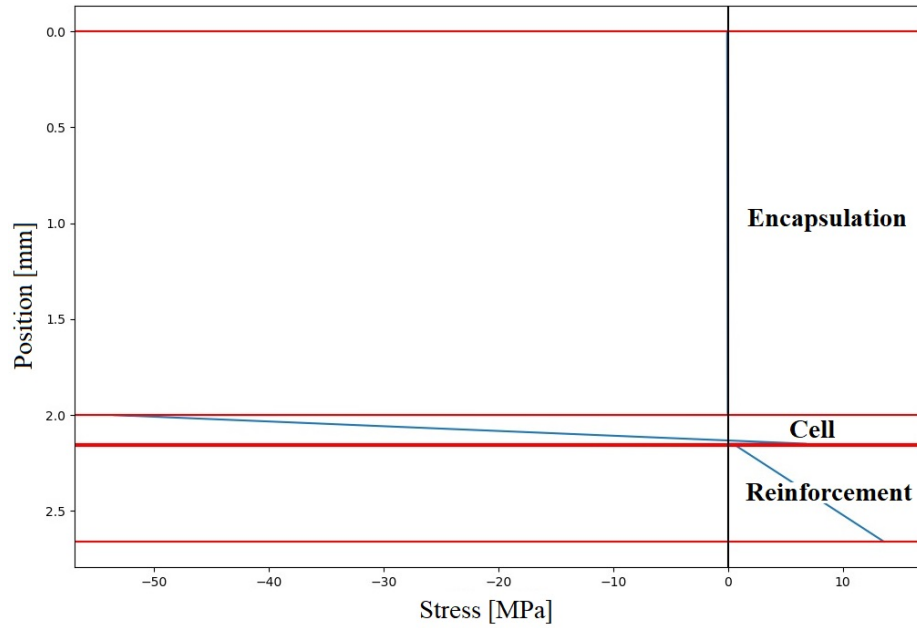


Figure 6.4: Stresses by layers.

at the end of the reinforcement, for given conditions. This fact allows to relate the Safety Factor (SF) and the radius of curvature (r), in terms of the established reliability of 95%, as is shown in Fig 6.5.

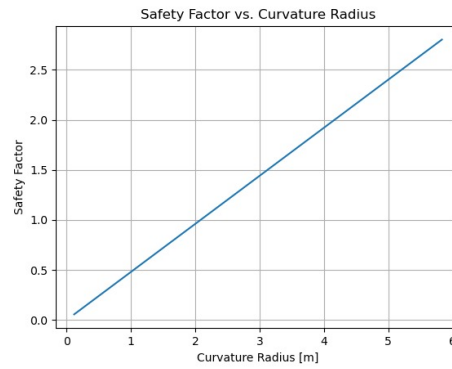


Figure 6.5: Safety Factor (SF) vs Radius of curvature (r).

From the above analysis, it is obtained that for the given material configuration, a curvature radius of $3.12m$ will be selected, for the assumed $SF = 1.5$, taking into account that BIPV applications does not have inertial operating loads. In addition the probability of failure consideration of 5% is maintained. With respect to the VIPV case study described in Chapter 5, the maximum allowable radius decreased a total of $3.2m$, which allows establishing a surface with greater curvature for this study (Modes et al., 2011).

6.3 Phase 3: Analysis of Geometry

In order to generate a solar collection surface, for a specific location, it was necessary to use an algorithm as explained in Subsection 4.2.3.2, in order to obtain optimal geometric shapes. It starts with the space occupied by a conventional flat PV module in an area delimited by the aligned points $ABCD$. Considering that increasing the surface area, it increases the radiation collection area, and so is why the surface is allowed to have a height of $1m$, in order to offer freedom to the analysis and increase the search horizon. Furthermore, the radius of curvature found in Section 6.2 is considered. The approach to this problem is shown in Fig 6.6.

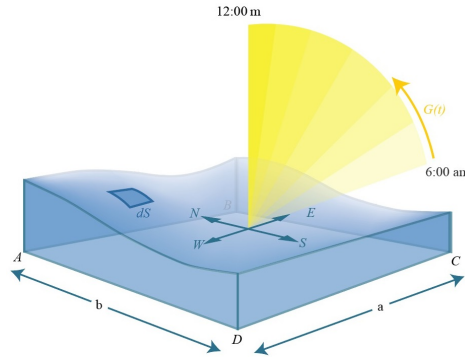


Figure 6.6: Optimal surface problem definition.

Additionally, the unit to be analyzed will use values of $1m$ from the edges a and b , and the surface dS can vary their geometry, according to the maximum radius of curvature r that the cells can take. The aim is to seek other geometric shapes to maximize the the power captured and finally the energy harvested. It is known, solar cells do not have a large deformation range, due to their fragile nature, so a maximum radius of curvature needs to be established.

6.3.1 Problem Modeling

In order to find a PV surface that maximizes the capture power and also considers the given spatial and radius constraints, it is necessary to couple the curvature condition with the irradiance condition in order to know the energy captured by each geometry. Additionally, the ray tracing tool allows to know deeply the direction and magnitude of the radiation on the surface. The implementation of each of these is explained below.

6.3.1.1 Curvature Condition

Curvature condition responds to the ability of solar cells to form curved surfaces. For this purpose, the maximum radius condition of $3, 12m$ (see Section 6.2). From the above, it is expected that PV module

can be adapted to an optimal morphology obtained. A Gaussian radius of $400m$ is assumed, therefore surface is developable (there is no stretching in the PV module), which is accord to Egregium's theorem in order to allow minimizing membrane stresses (Vaziri, 2009).

6.3.1.2 Average Power Modeling

In order to model the pattern of the sun in the sky, a PythonTM program is implemented with the help of the open source library *pplib* to obtaining the variable $G(t)$ and $r(t)$ in Equation 4.2. Similarly, to model the behavior of on-site weather conditions, *TMYdata* were extracted from the open source *pvgis* database, with PV surface orientation to the south. By coupling the solar resource information with respect to the nature of the curvature expressed in Equation 4.1, it is possible to estimate incident radiation on the surface. However, this condition is not sufficient to know how the rays incide on the surface, so it is necessary to include a ray tracing model, which is explained below.

6.3.1.3 Ray Tracing Modeling

To evaluate the way in which the rays incident on the surface, it is necessary to discretize the area obtained. This is possible through of a mesh, it made from Delaunay triangulation in which the vertices are connected forming as many triangles as possible, maximizing the angles and minimizing the length of the sides (TELLO, 2013). From the generation of this triangular mesh, the barycenter of each of these triangles is determined, which will be the origin of the rays, while its direction will be given by the position vector of the sun. Based on the above, the Muller Trumbore algorithm (Möller and Trumbore, 2005) is implemented to determine the amount of rays captured by the surface.

6.3.2 Genetic Algorithm GA

The implementation of the GA brings together all the information described so far. It is necessary to analyze the initial conditions of the problem on a set of first surfaces, which are evaluated according to their amount of radiation collection. Then, these surfaces reproduce and mutate to form new individuals, which are again evaluated in order to form new generations. This process is repeated until an individual is obtained, which maximizes the average collection power. The steps to obtain such an optimal surface are shown below.

6.3.2.1 Analyze Constraints

One of the main constraints of this case study is related to the PV surface occupancy space, which is shown in Fig 6.6. Regarding the operating conditions, only loads due to its own weight are considered, because the PV surface is stationary. Additionally, it is necessary to take into account the solar resource of the application site, which is shown in Fig 6.7.

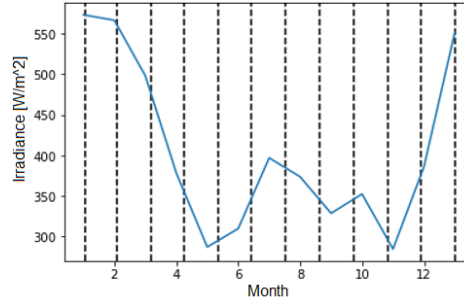


Figure 6.7: Average monthly irradiance in Medellín, Colombia.

Above, it is shown the average irradiance throughout the year for Medellín, Colombia. Large variation can be seen in the monthly average irradiance values throughout the year, which is due to weather conditions and rainy season in territory. Starting from the initial conditions of the problem, it is necessary to set up some first surfaces, which are shown below.

6.3.2.2 Generation of Initial Surfaces

From the given spatial and curvature constraints, and taking into account that the surfaces are functions of 2 variables, the first individuals based on known mathematical functions are presented. These surfaces and their respective functions are shown in Fig 6.8

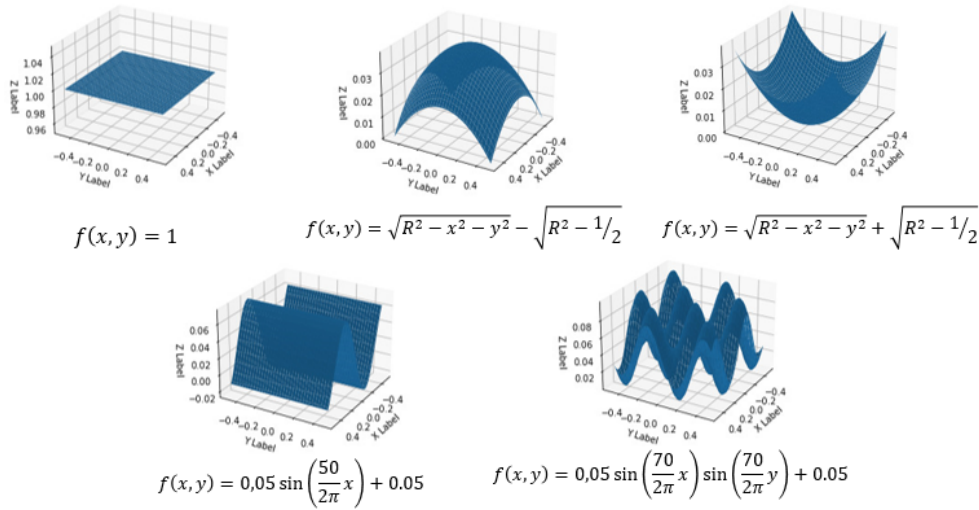


Figure 6.8: first surfaces from known mathematical functions

Considering this first population, new individuals are generated from the combination of different surfaces. This is achieved by averaging the Z coordinates to generate a new point, which defines the height for a new surface. This process is repeated over the entire (x, y) plane, which makes it possible to create new individuals with parental characteristics.

6.3.2.3 Estimate average power and ranking

The evaluation of the first surfaces and their descendants is done through the fitness function, which allows knowing the radiation power capture potential, according to the geometrical attributes presented in the individuals. It should be noted that the fitness function is given by Equation 4.2, which relates all the characteristics of the modeling of the problem: curvature definition, average power estimation and ray tracing. From the results obtained, a **Ranking** is made according to the scores obtained from each of the surfaces, in which the best ones are reproduced among themselves to create new individuals, which is explained below.

6.3.2.4 Reproduce and mutate new surfaces

In first generation, a total of 23 surfaces are generated, which, after evaluating their average power, are ordered from the highest to the lowest energy captured. In this way, first 8 individuals are reproduced among themselves, in order to obtain another 23 new individuals for next generation. The mutation is given by the addition or subtraction of a value on the Z coordinate axis and it is a function of 2 parameters: *mutation weight* and *mutation probability*. Both are given by a uniform distribution that when normalized, allows to obtain additional values of Z that subtract or add at each point of the surfaces, this allows to mutate the geometry obtained after a reproduction.

6.3.2.5 Optimal surface found

A total of 200 generations with 23 individuals each one were evaluated in 19.4h. Fig. 6.9 shows the elite surfaces generated in each generation with their respective power generated and surface area.

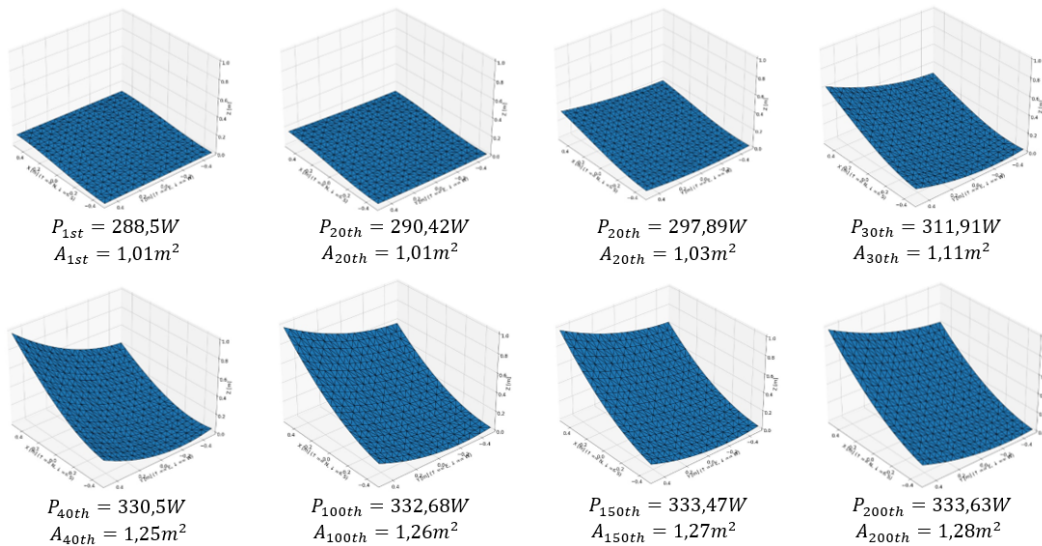


Figure 6.9: Optimal PV surface development

In Fig. 6.10 can be observed that during the first 40 generations, the geometrical changes of the surface occur at an accelerated rate. In the first generation, a PV surface with almost completely flat geometry is observed, in which the value of the surface area is quite close to given by the spatial constraints of the problem. From then on, the surface begins to occupy the space in height given in the problem, whose maximum value is $1m$. This fact makes both, the surface area and the average power, begin to grow, the latter presenting a more accelerated growth. After generation 40, there is no significant increase in the area, so the convergence of the study begins to occur, which is carried out until generation 200.

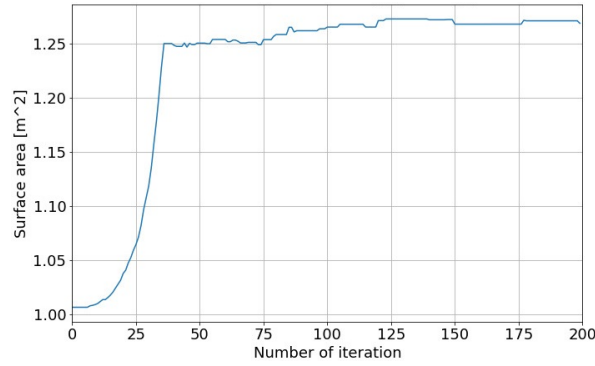


Figure 6.10: Convergence of surface area

The surface area reaches convergence at generation 200 with $1.28m^2$. This fact allows reaffirming the higher power generation that the optimal surface has, due to its larger incidence area. Regarding to the average power generated, it can be said that a similar behavior, as it can be seen in Fig 6.11.

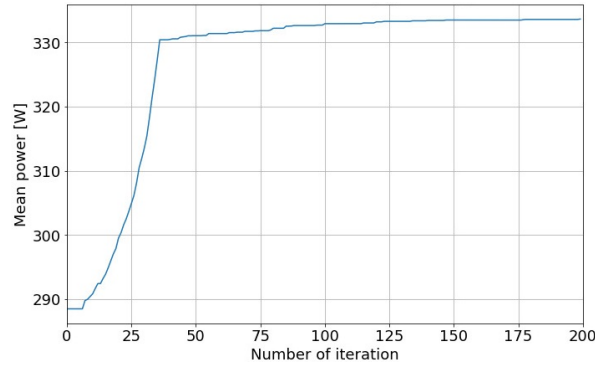


Figure 6.11: Convergence of mean power

At the beginning of the study, there is a mean power, close to $288.5W$, which corresponds to the almost flat PV surface. At generation 40, the important growth value corresponding to $330.5W$ is reached. Then, GA runs until generation 200, where the average power growth is not significant, reaching a value of $333.63W$. An optimal PV surface is obtained, which maximizes radiation capture

for the specific location, considering historical climatic and atmospheric conditions throughout the year. Spatial and morphological restrictions of the place of installation of PV module and the maximum flexibility is considered. This fact rethinks the occupation of integrated PV systems in areas with limited conditions, particularly in BIPV systems, which allows obtaining a higher energy generation with respect to the implementation of conventional flat PV systems in this type of applications.

6.3.2.6 Error Analysis

The quality of found values is studied, depending on the curvature characteristics of the surface obtained. Thus, an analysis of the Gaussian radius is performed, in order to know the behavior of the curvature of the surface, along the catchment area, which is shown in Fig 6.12.

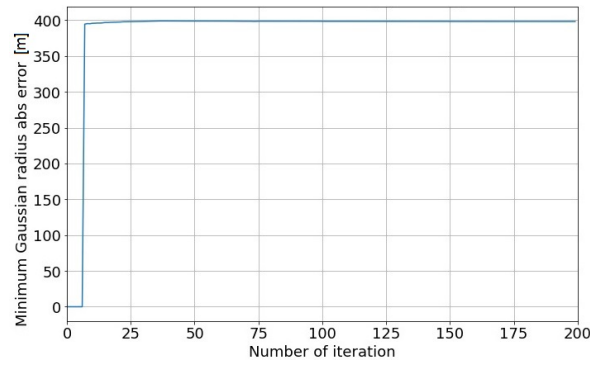


Figure 6.12: Gaussian curvature error

It is observed that from the first generations, a Gaussian radius of zero is presented. This is due to the fact that iterations start with a flat surface. In generation 9, this value increases to 400m, which is the assumed Gaussian radius and this is maintained throughout the study. Considering the above, in Fig 6.13, the Gaussian curvature map along the optimal surface of generation 200 is shown.

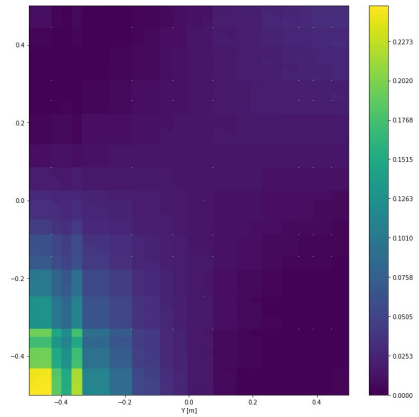


Figure 6.13: Gaussian curvature at optimum PV surface

A curvature heat map is shown from a top view. It is evident that the Gaussian curvature is very small in almost all area. This reaffirms the cells ability to adapt to the obtained contour, while in the lower left part is shown the maximum value of Gaussian curvature. It corresponds to $0.2273m^{-2}$, which due to its location and magnitude, does not represent a risk of fracture for the solar cells. Regarding convergence, Fig 6.14 shows an analysis of its behavior.

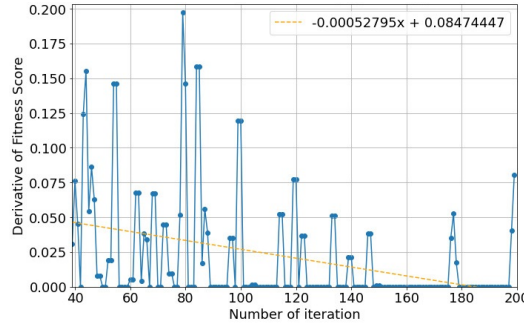


Figure 6.14: Sensitivity analysis of convergence

Convergence graph begins to stabilize after iteration 40. It is necessary to analyze whether the area and mean power values are really stable. Therefore, the fitness function is analyzed with each new generation, for which a trend line with negative slope is generated, indicating that the change obtained of values tends to zero as the iterations increase, indicating that the convergence is finally obtained.

6.4 Phase 4: Mechanical analysis

With respect to the mechanical performance of the optimal PV surface a study with FEM is carried out to determine the inherent structural response of the geometry obtained with respect to the assumed operating loads mentioned in Subsection 5.4.1.1 which $1000N$ is applied perpendicular to the surface, with fixed support on the edges of the PV modules. Fig 6.15 shows the stress analysis for solar cells obtained for the assumed condition.

A stress distribution that is not symmetrical, due to the geometry of the surface, is then observed. Additionally, a maximum stress of $5.9MPa$ is found in the upper left part of the surface, where the Gaussian curvature is higher. This surface has a better mechanical behavior than flat panel, mainly due to the significant moment of inertia and the position of the force with respect to the geometry obtained, which decreases the perpendicular load components on the surface.

Based on the geometrical shape obtained by the optimization algorithm and the arrangement of the PV cells along the area, the mechanical behavior of the flat PV module is analyzed and compared with the structural performance of the optimal surface shown in previous subsection 6.5.2. Note that

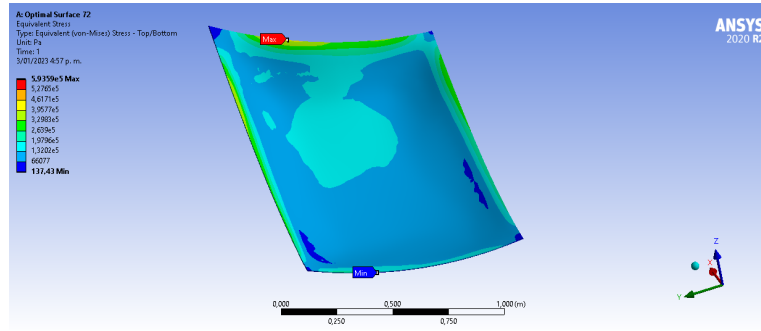


Figure 6.15: Solar cell stress distribution in optimal PV surface

flat PV module must be leaned at an angle of $6,5^\circ$ to maximize the generation, according to the latitude angle presented in Medellín, Colombia. For the given space of $1m \times 1m$ in flat area, a flat PV module of $1m \times 1.05m$ can be accommodated because it occupies this same space on the ground, due to its slope. Thus, an analysis is performed for both cases, where, in addition to the weight of the PV modules, a $1000N$ load is added, assuming the maintenance condition presented in Subsection 5.4.1.1. As mentioned above and for the selected materials and thicknesses of the layers, Fig 6.16 shows the stress distribution obtained in the inclined flat PV module under the additional load of $1000N$.

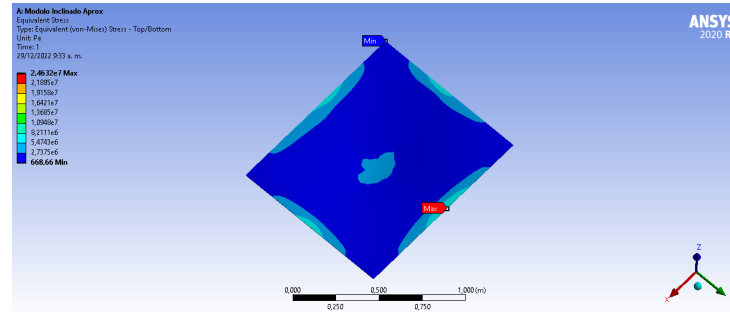


Figure 6.16: Stress distribution in flat PV module with inclination

A maximum stress of $24.6MPa$ is observed near the fixed support, which gradually decreases towards the center of the module, where a stress close to $5MPa$ reappears, which it is a low value with respect fracture stresses of c-Si solar cells. The convergence of this study was reached at 449189 nodes, 455994 elements and an average element size $5mm$.

6.5 Phase 5: Energetic Analysis

Energy analysis is performed to know the performance of PV module adapted to the optimal surface geometry, taking into account the geometrical effects on the amount of captured radiation that is finally converted into electricity. Energy output in PV module is affected by some aspects which are

heat, optical losses and electricity, where the estimation of two of them, enables to know the other one. The following subsections will show the physical and numerical simulation models that will be addressed to understand the energy transformation problem within the PV module with the optimal geometry found. For the BIPV case study, the optimal surface has the capacity to hold 72 cells, while the flat module only accommodates 64. This analysis will be carried out using the proposed manufacturing process detailed in Section 6.6.

6.5.1 Thermal-Optical Analysis

As previously shown in Fig 3.50, the area under the curve of the $1.5AM$ spectrum is the overall energy of the light spectrum that is transformed into different energy loss phenomena and electricity. This approach make possible to describe the energy transformation of PV modules. Based on the knowledge of the material properties, described in Appendix A, the optical phenomena (described in Section 2.4.1) and thermal phenomena (described in Section 2.4.2) are analyzed for the manufacturing configuration. Fig 6.17 shows the loss energy patterns (optical and thermal) occurring inside the solar panel. These are needed to understand the energetic behavior of the optimal PV surfaced.

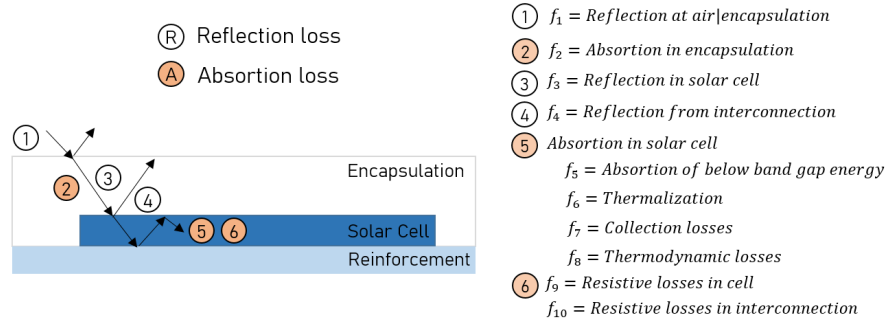


Figure 6.17: Optical and thermal losses in the proposed PV module configuration

Thus, to find each of the losses associated with the cell and the interconnection (see Fig 3.48), the first model proposed by (Krauter and Hanitsch, 1996) is implemented as it is widely used in the literature (Shen et al., 2020), (Siddiqui et al., 2022), (Abdolzadeh and Zarei, 2017), (Hanifi et al., 2018). This allows obtaining an area for each of the energy losses on the spectrum for a given day (January 28th in 7am, 10am, 1pm hours) for the BIPV case, and the result is shown in Fig 6.18.

Considering symmetrical irradiance between morning and afternoon and analyzing time of 7am, 9am and 1pm it is obtained a very similar behaviour. Reflection losses are higher at the beginning of the day in the flat PV module compared to the optimal PV surface. This gradually decreases and operation stabilizes. For both, highest energy losses are given by thermalization with about 27% , followed by thermodynamic losses with approximately 20.5% and finally below band gap energy absorption with 18%. This results suggests geometrical shape of PV module reduce the amount of

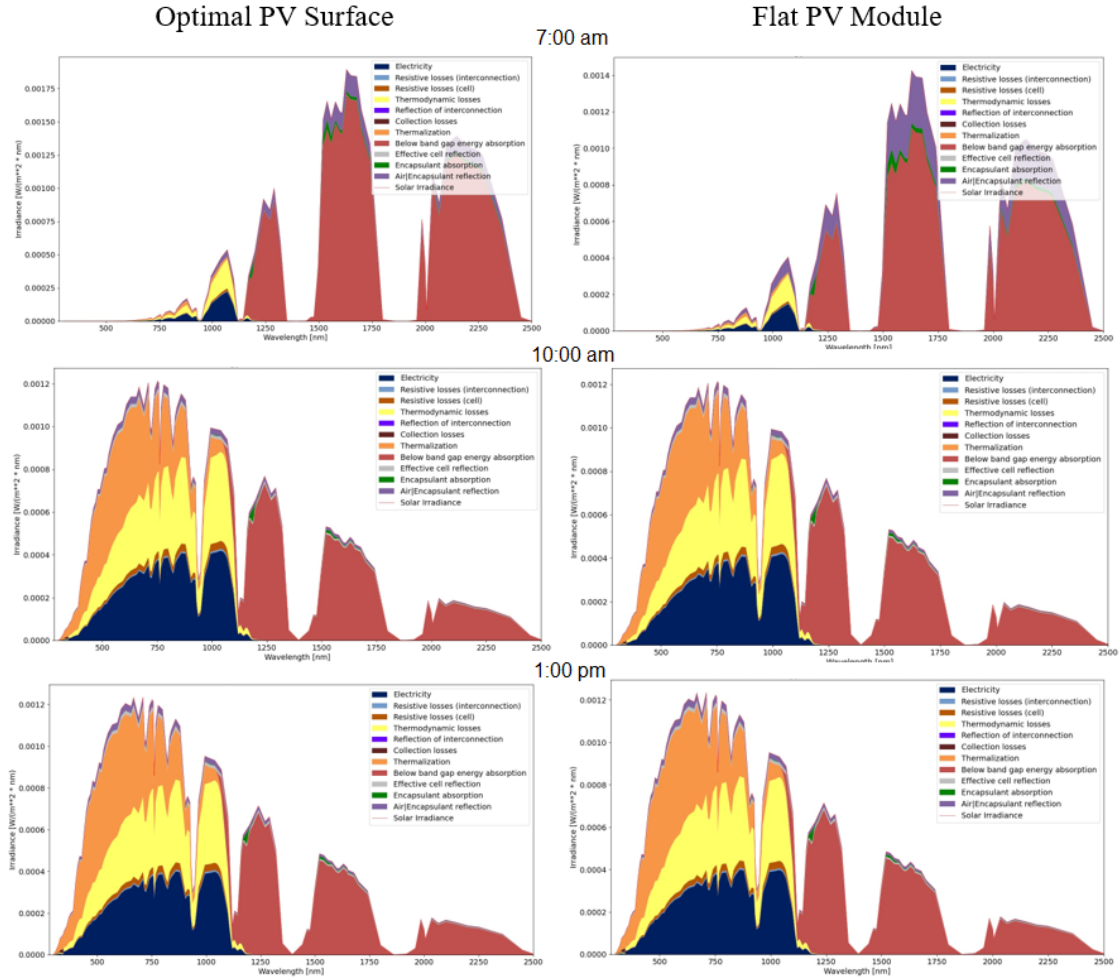


Figure 6.18: Energy phenomena in flat PV Module vs Optimal PV surface

Astronomical event	Energy Captured [Wh]			Reflection Losses [Wh]		
	Flat panel	Optimal surface	Gain	Flat panel	Optimal surface	Gain
<i>Spring equinox</i>	1971.8	2479.8	25.76%	370.36	310.91	15.95%
<i>Summer solstice</i>	2412.2	3555.8	47.41%	785.88	243.7	68.99%
<i>Autum equinox</i>	5076.9	6826.2	34.52%	1196.4	640.7	46.55%
<i>Winter solstice</i>	2258.9	2435.5	7.8%	974.9	394.4	59.54%

Table 6.1: Energy captured and reflection losses

optical losses, this is an important feature that makes Optimal PV Surface generate more power.

6.5.2 Optical Analysis

The objective of the optical-mechanical analysis is to understand the relationship among the optimal PV surface, the stresses generated in the cells to achieve that geometry and their radiation capture capacity. Based on the optimal geometry, a ray tracing simulation is performed in the Tracepro™ software under conditions of the solstice and equinox days, which have an interesting sun position. Fig 6.19 shows the results of this study.

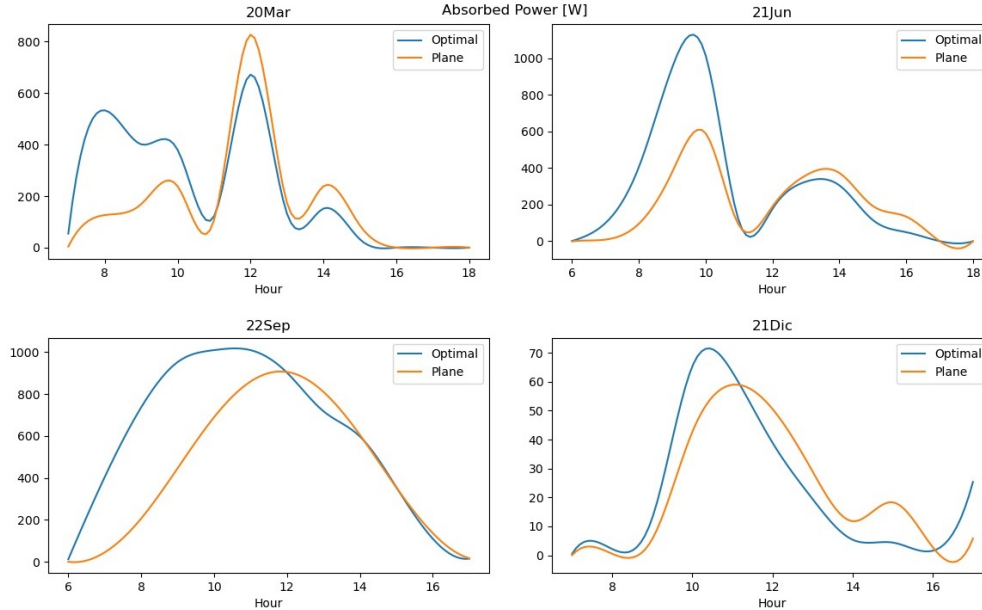


Figure 6.19: Power captured by radiation on optimum surface and flat panel.

In general, it can be seen that the optimal surface performs very well in the morning, while in the afternoon, the flat geometry tends to be better, in most cases. However, the higher irradiance uptakes in the mornings result in higher amounts of energy being produced, as shown in Table 6.1.

For all given astronomical events, the optimal surface captures more energy by radiation than the flat panel. Also, the optical losses are lower on the optimal surface, suggesting that there is a very important relationship between the geometrical shape of the PV modules and the associated reflection losses. Since the geometric shape allows for greater radiation capture, in theory, more electricity could be generated. This fact will be analyzed below.

6.5.3 Electrical Analysis

The electrical analysis for this case study was carried out experimentally. For this purpose, a circuit was designed for the analysis of power data and electrical characteristics of the PV modules. Tests of the circuit design and the role of geometry in PV modules are exposed in Appendix B. Similarly, in order to carry out the electrical modeling of the optimal surface, 2 PV modules will be fabricated. The first one will be a PV module of $1m \times 1m$ $1m^2$, consisting of 64 SunPower® solar cells, which will serve as a point of comparison to evaluate the performance of the optimal PV surface (obtained in Subsection 6.3.2.5). The second PV module manufactured will be $1.125m^2$, consisting of 72 cells, which will be coupled to the geometry of the optimal surface, which are shown in Fig. 6.20.



Figure 6.20: Test of fabricated PV modules with flat geometry

Using data acquisition circuit, a test is carried out on January 26th of 2023. In this case the VI and PV curve are measured and are shown in Fig 6.21. This test was in midday under the same environmental and irradiance conditions.

Flat PV module used for the optimal surface (72 cells) presents $20W$ more at noon than the flat PV module of $1m^2$ (64 cells). This result is related to the additional solar cells used and it will be the point of reference to comparing the behavior among optimal PV surface and the flat PV module. PV module of 72 cells is assembled into the optimal PV surface of $1.28m^2$, which corresponds to an inevitable reduction in area of 12.1%. It is worth remembering that both modules share the same effective occupancy area of $1m^2$. The VI and PV curves generated at 3 times of the day, these are shown below in Fig 6.22

The performance of optimal PV surface in the mornings, is better than the PV module, while

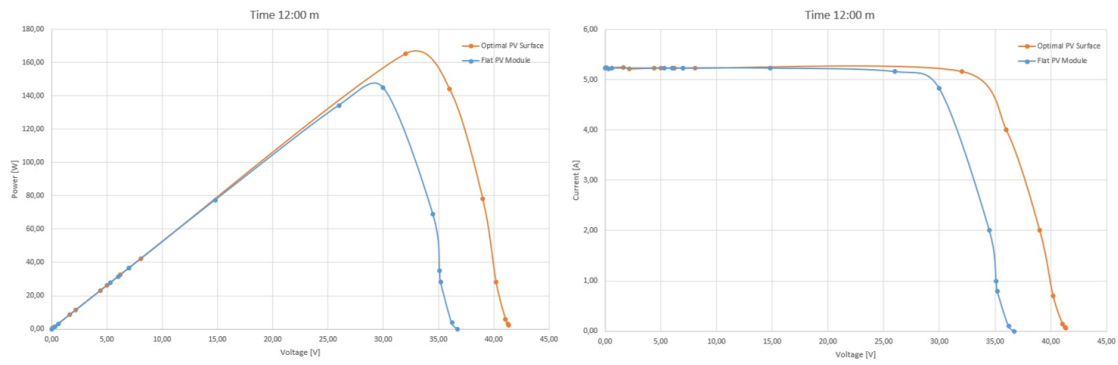


Figure 6.21: VI and PV curves for fabricated optimal and flat PV modules

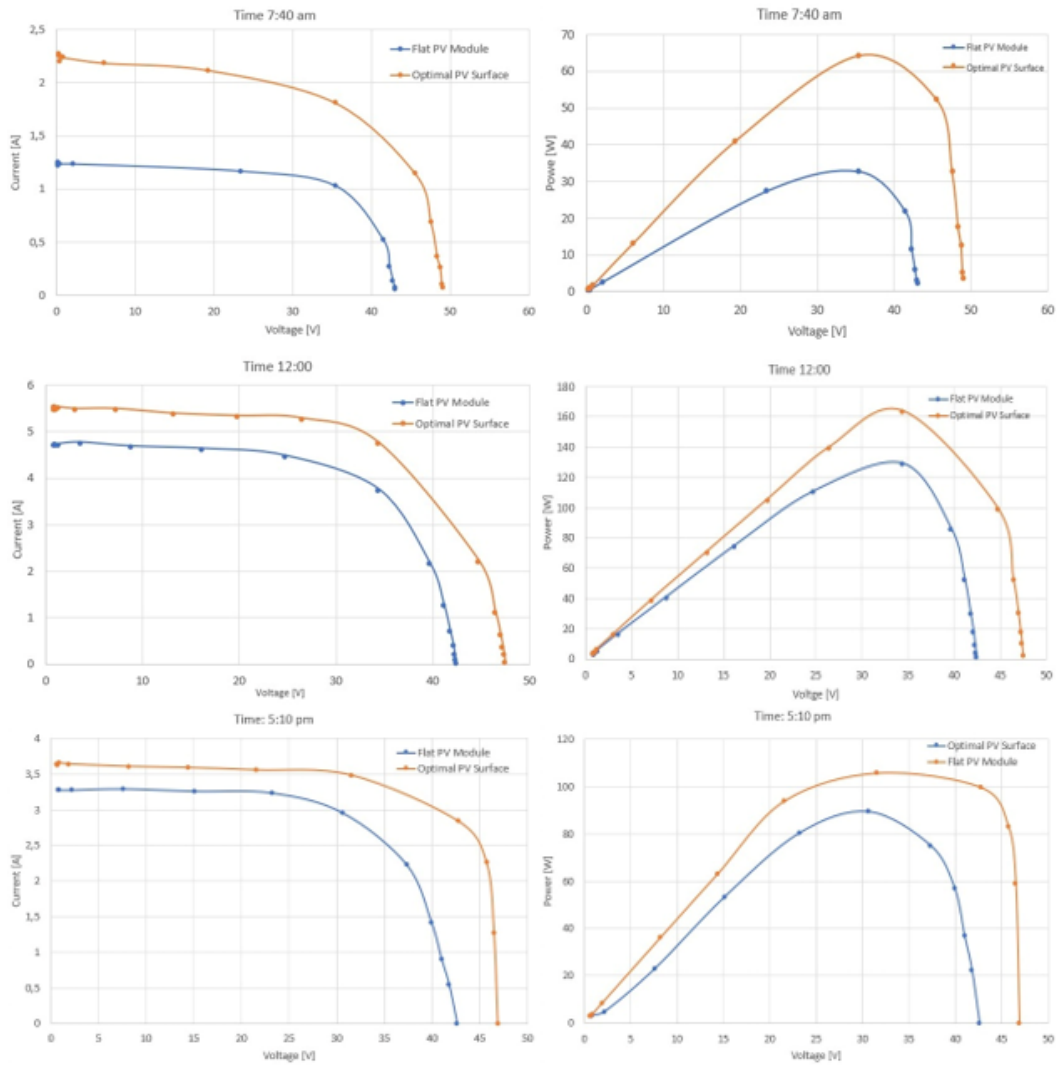


Figure 6.22: VI and PV curves at moments of the day

at midday and in the afternoon they are somewhat similar, although the optimal PV surface is still better. In order to understand the performance of the optimal PV surface and the flat PV module, performance tests are carried out in controlled operating environments, which are shown below.

6.6 Phase 6: Photovoltaic surface manufacturing and testing

Considering that in this case there is no established geometry of the PV systems, a manufacturing process that offers the highest degree of flexibility possible in order to adapt to the generated surface without compromising the structural integrity of the solar cells must be used. Similar to commercial solar panels, a layered arrangement using the materials described in with thicknesses close to 1mm for reinforcement and encapsulation is used to minimize the mechanical stresses on the solar cell due to bending. Fig 6.23 shows the optimal surface fabricated from serial planes with a flat PV module adapted with a total of 72 cells, whose baseline is the flat PV module of 1m^2 conformed by 64 cells.



Figure 6.23: Optimal and flat PV modules manufactured

From the temperature measurement, it is possible to know the status of the PV modules and their performance. For this reason, thermographic camera measurements of the PV modules are carried out. In order to analyze the performance of both PV modules, Fig 6.24 shows the temperature distribution for both PV modules at 12m.

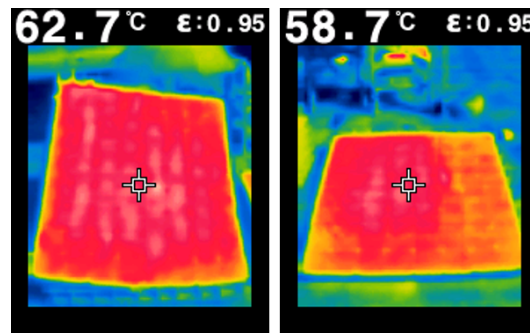


Figure 6.24: Temperatures for fabricated curved PV modules

Temperature difference in this condition is about among the PV modules is 4°C . Although the difference between power is not so large, the PV surface is hotter, therefore it must be receiving more perpendicular irradiance, but decreased electricity generation, which suggest differences in irradiance between cells. From the above, the maximum power points of each of the measurements made throughout the day for both PV modules (on July 29, 2023) are plotted in Fig 6.25.

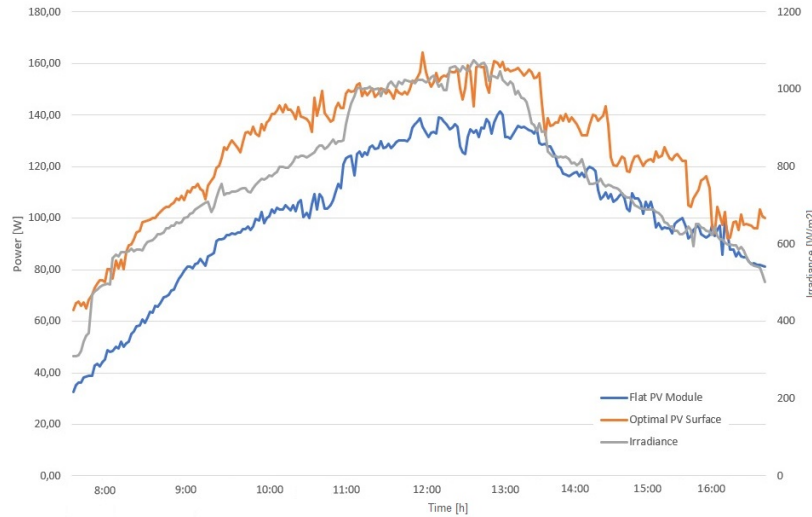


Figure 6.25: MPP of the flat PV module and PV surface throughout the day

Thus, it is observed that the optimal PV surface has a larger area under the curve than the flat PV module, which allows concluding that the optimal PV surface generates an additional 20,2% of energy than the flat one for the given geometrical conditions. When comparing this value with the generation of the modules in flat geometry, the difference in that instance was of 11,2% so it is found that the energy obtained from the optimal PV surface is greater than flat PV module. Therefore, it can be concluded that geometric shape of the PV modules could has a beneficial effect on the radiation capture and finally on the electricity generation in PV surfaces. Fig. 6.26 shows the integration of the optimal PV surface to the terrace of a building.

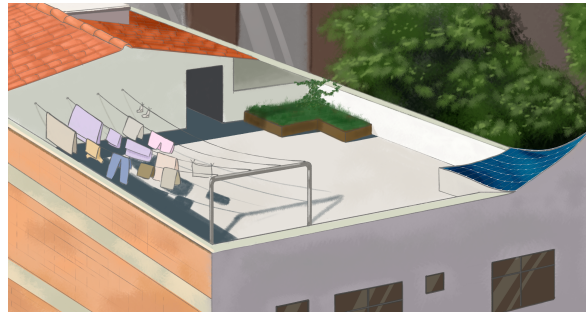


Figure 6.26: Integration of the optimal PV surface to the terrace of a building

From the sustainable construction and architectural development of the building, an area is defined as available for the implementation of this type of applications that maximize the generation of electricity to help meet the energy consumption demands of its inhabitants. This fact, raises a new panorama of use of spaces and surfaces exposed to radiation in the construction of housing, depending on the space available and its solar resource.

Chapter 7

Conclusions

The exploration of applications and uses of PV surfaces with curvature, has allowed developing models to know the energy behavior of PV modules taking into account their geometry, and also to generate tools that allow generating optimal geometries of surfaces exposed to solar radiation according to spatial restrictions and solar resource depending on the application site. The above, framed in a development of manufacturing processes, allowed the manufacture of semi-flexible PV modules with monocrystalline silicon solar cells and performance tests in real operating environments. These models are applied to a first case study based on Vehicle Integrated Photovoltaics (VIPV), and a second case study framed in Building Integrated Photovoltaics (BIPV). Next, the conclusions of this work will be presented, based on a global approach, which allows responding to the objectives set at the beginning of this research.

- After review of the state of the art, it is found that almost **67% of the PV modules presented in VIPV applications are non-flat geometries, while for BIPV applications only 20% have geometries with curvature.** With respect to the solar cells used, only 15.8% of the papers used silicon cells in curved PV surface applications due to their limited flexibility, likewise, only 1 of the papers manufactured their own PV modules with plastic based processes, the rest used commercial PV modules. The solution approach presented in the papers is usually accompanied with at least two tools among which are: numerical models (based on analytical models), simulation (based on software packages) and experimental models, among which, about 84.2% of the papers present numerical solutions, 47.3% experimental models and 36.8% simulations. With respect to future works, only 21.05% performed irradiance analysis as a function of geometric shape. This conclusion fulfills the Specific Objective 1.
- The mechanical strength and durability of solar cells depends on the combination of the materials used for the fabrication of the reinforcement and their mechanical properties. In this

case, the adaptation of semi-flexible PV modules to contours with curvature generates bending stresses that affect the structural integrity of the solar cell which generates micro-cracks decreasing the electricity, so a reliability of 95% is considered for both cases of study. **For the electro-solar boat, the individual flexibility of the cell was estimated, obtaining a bending radius of $6.51m$ based on the adaptability condition. For the second case study, cell flexibility was prioritized and the effect of reinforcement and encapsulation was included, obtaining a radius of $3.2m$ for adaptation to curved developable contours or with Gaussian curvature tending to zero.** From the above, it is possible to fabricate semi-flexible PV modules with curvature according to the given constraints, which allows the exploration of curved morphologies according to the application requirements.

- Through the addressed case studies, the design and fabrication of semi-flexible PV modules is developed based on the operating environment, the properties of the materials used in the fabrication and given functional requirements. A VIPV module is subjected to loads due to inertial changes, while in BIPV applications it should only withstand dead loads (including wind, water and snow) and have flexibility capability in case it has to be adapted to curved contours. From the above, it is recommended to use fiberglass as reinforcement material due to its high flexural modulus; the encapsulation is manufactured with epoxy resin of the best possible optical quality (UVPoxy). Thus, **for high mechanical stress applications it is suggested to have a reinforcement thickness of at least $6mm$ thick and $2mm$ of encapsulation, while if flexibility in the PV modulus is desired to adapt it to established curved morphologies, $0.5mm$ layers are recommended for both reinforcement and encapsulation.** This analysis was performed using mechanical and optical properties measured in laboratory tests, which provides an in-depth description of the actual physical behavior of the fabricated PV modules. This conclusion fulfills the Specific Objective 4.
- The areas exposed to radiation in vehicles and buildings can have defined geometric shapes as is the case of the roof of the electro-solar boat. However, if there is a space free of shadows in which a solar panel can be installed and there is no defined morphology, it is possible to think of generating a geometric surface to adapt PV modules that maximizes the solar energy captured, producing electricity due to the solar resource available in that space. From the use of a genetic algorithm (GA), an optimal PV surface is found that maximizes the surface area and the average power captured, taking into account a maximum curvature radius of $3,2m$. **After 200 iterations and $19.4h$, an optimal PV surface for Medellín, Colombia, was obtained with an average annual power capture of $333.63W$ and an area of $1.28m^2$.** This means it was possible to improve about 20.2% additional power and 28%

additional area, compared to a flat PV module of $1m^2$ with a slope of $6,5^\circ$. This conclusion fulfills the Specific Objective 3 and 4.

- The generation of electricity through PV modules involves an energy problem that allows understanding the losses associated with the physical phenomena involved. From the developed multiphysical analysis, an understanding of the energy implications of the geometric shape of curved PV surfaces in the overall energy performance of the system is achieved. The influence of the manufacturing process and materials in the thermal and optical energy losses is also determined. **For the optimal PV surface found, a better radiation capture is observed, decreasing reflection losses up to 59,54% in the winter solstice with respect to a flat PV module.** This suggests that the optimal surface found is better oriented towards the sun in terms of its movement and angular position of the rays with respect to the surface. This conclusion fulfills the Specific Objective 2.
- The optimal PV surface of the BIPV case study, generates more power than the flat PV module, especially in the mornings, while at midday and in the afternoon, the PV module shortens this difference. In order to corroborate this behavior, two semi-flexible PV modules with 72 cells and 64 SunPower® C60 cells, respectively, were fabricated. One of them is used for the adaptation of the optimal surface found and the remaining one corresponds to the flat PV module, established as a point of comparison. These were subjected to radiation for several days of measurement to set a starting point for analyzing the data obtained. When comparing the generation in flat condition without slope of both PV modules under the same conditions, there is an additional 12.5% of energy under the same conditions for the 72-cell PV module with respect to the 64-cell PV module within a given period of time. However, **when comparing the 72-cell flat PV module adapted to the optimal surface contour with respect to the flat one with a 6.5° , the additional energy generation is 22.5%, which reaffirms the better performance of the PV surface with curved geometry with respect to conventional flat PV modules.** This conclusion fulfills the Specific Objective 4.

7.1 Further Research

The development of adaptive optimal PV surfaces provides a range of possibilities in the integration of PV systems to areas and contours with available solar resources. Most of these systems are integrated into buildings and vehicles, which adds an interesting level of customization to each product, in relation to the functions performed by the PV modules integrated into the devices. Within VIPV, since the mass of the PV modules has an energy consumption that affects the overall efficiency, it is ideal to think of strategies to further decrease the weight of the PV modules, so **it would be useful to**

analyze the possibility of implementing topological optimization to the reinforcements of the PV modules and explore low density materials for the same. Taking into account that the encapsulation is the material that first receives solar radiation, **it is necessary to think of optical strategies that allow reflecting UV rays, which affect the chemical bonding of the epoxy resin, thus reducing its useful life, likewise, the use of filters to reflect the infrared part of the solar spectrum allows passively cooling the PV module.**

The fabrication of PV surfaces with curvature is made possible by the controlled bending of the encapsulated monocrystalline silicon solar cells. For the curvature radii presented in this study there are adequate safety factors, however, **there is still no formal estimation in the literature that relates the current and voltage generation capacity as a function of the micro-cracks generated by mechanical stresses** in the cell due to the adaptation to curved contours, which can have an important impact on the development of optimal PV surfaces of larger size and curvature.

From thermographic camera measurements, it is observed that **the angle of incidence of the radiation on the surface can bring positive effects on the generation** because the irradiance increases locally, which generates more power. However, this also causes a higher thermalization causing negative effects on the voltage, so **it is necessary for future work to estimate this relationship and its implication in the overall performance** of the optimal PV surface. This fact is related to the differences in local irradiance on the surface due to the geometric shape with curvature, which can generate current drops because some cells are subjected to greater irradiance than others. It is possible that **this behavior can be improved by establishing interconnection strategies** based on the geometry obtained to reduce the negative effects of these differences in current or mismatch between cells.

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Appendix A

Characterization of PV module manufacturing materials

The development of this work allowed the integration of manufacturing solutions to engineering application problems, relating to the transportation and construction sectors through VIPV and BIPV, respectively. Manufacturing processes based on composite materials and resins do not require sophisticated tooling for their implementation, however, to obtain quality results it is necessary to develop a practical skill in the cutting, separation, arrangement, impregnation and adhesion of the fabrics to minimize the number of defects in the final part. For this it is necessary to define the best materials according to their performance, taking into account terms of availability, accessibility and cost.

A.1 Materials Selection

Previously, we proposed the manufacture of PV modules from the vacuum bag lamination of interconnected solar cells. In the lower part of the cell there is the reinforcement, in charge of maintaining the geometric shape of the module and guaranteeing the structural integrity of the solar cells. For the encapsulation, the highest possible transmittance is required to reduce optical losses, and it also has a structural role, so it is desirable that it is a material with good mechanical properties. For the reinforcement-encapsulation assembly, high thermal conductivity is required to facilitate the evacuation of the solar cells and low electrical conductivity for short-circuit protection, which directly affects the reliability of the PV system.

A.1.1 Reinforcement Material

The reinforcement of a PV module must have the capacity to keep the stresses in the solar cells low in the face of loads due to its own weight or inertial changes. Normally, PV modules are supported at their ends, so all the weight of the module falls on the central part of the panel, generating bending stresses, so a material with good mechanical behavior is required. Based on the above, a search for composite materials with better

mechanical behavior is carried out, among which are: glass fiber (GF), aramid fiber (Kevlar) and carbon fiber (CF). The mechanical behavior of the layers for a load of 1000N is shown in Fig A.1.

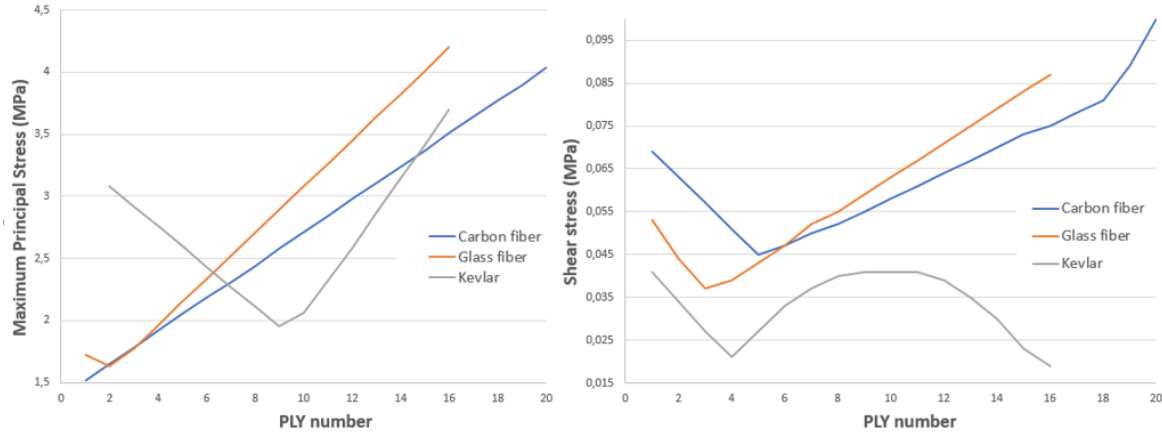


Figure A.1: Stresses in reinforcement plies *Espitia-Mesa et al. (2021)*

A very similar behavior is observed between CF and GF. The layers in contact with the cell receive a lower stress that increases according to the layer order. In contrast, Kevlar offers the lowest stresses in the intermediate layers of the reinforcement, while the outermost layers reach the maximum values. Likewise, the Shear Stresses generated by the joint between the fabrics, which is an important factor in the failure of solar panels due to delamination which causes 10% of the failures of solar panels Chowdhury et al. (2020). Shear stresses between layers have very low values. However, it can be seen that Kevlar is the material that behaves best under these conditions, maintaining lower stress values than the other materials throughout each of the layers. It can be seen that there are materials that behave better depending on the type of load they are supporting, however, the basic function of the reinforcement is to maintain the structural shape, i.e. bending stiffness. For this reason, a flexural test is performed under *ASTMD790 – 03*, used in the determination of flexural properties of reinforced plastics and electrical insulation materials. This standard establishes two types of procedure, one for relatively brittle materials, i.e., that break quickly, and procedure B for materials that are ductile to bending, this is used in this case. Fig A.2 shows the setup performed for this test.

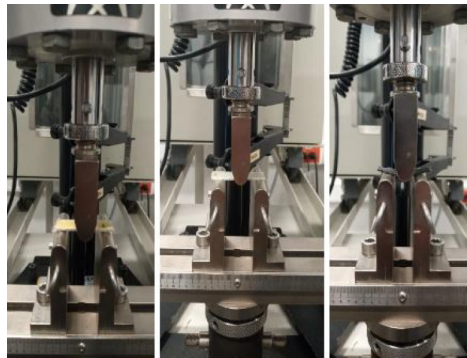


Figure A.2: Flexure test set-up in kevlar, GF and CF, respectively *Espitia-Mesa et al. (2022)*

These tests were performed using the *ASTMD790* standard on a Instron universal machine, model 3366. A total of 15 rectangular specimens (5 each material with Rygid Epoxy Resin and impregnation close to 54%) were tested for plains of kevlar, CF, and GFr with a surface density of $\sigma_K = 296g/m^2$, $\sigma_{FC} = 198g/m^2$ and $\sigma_{GF} = 145g/m^2$ respectively. From the bending test we obtained a flexural modulus of elasticity of $E_K = 1,52GPa$, $E_{CF} = 7.42GPa$ and $E_{GF} = 7.14GPa$, with an impregnation percentage close to 50% using rigid epoxy resin. The flexure stress vs. strain curves for each of the specimens are shown in Fig A.3

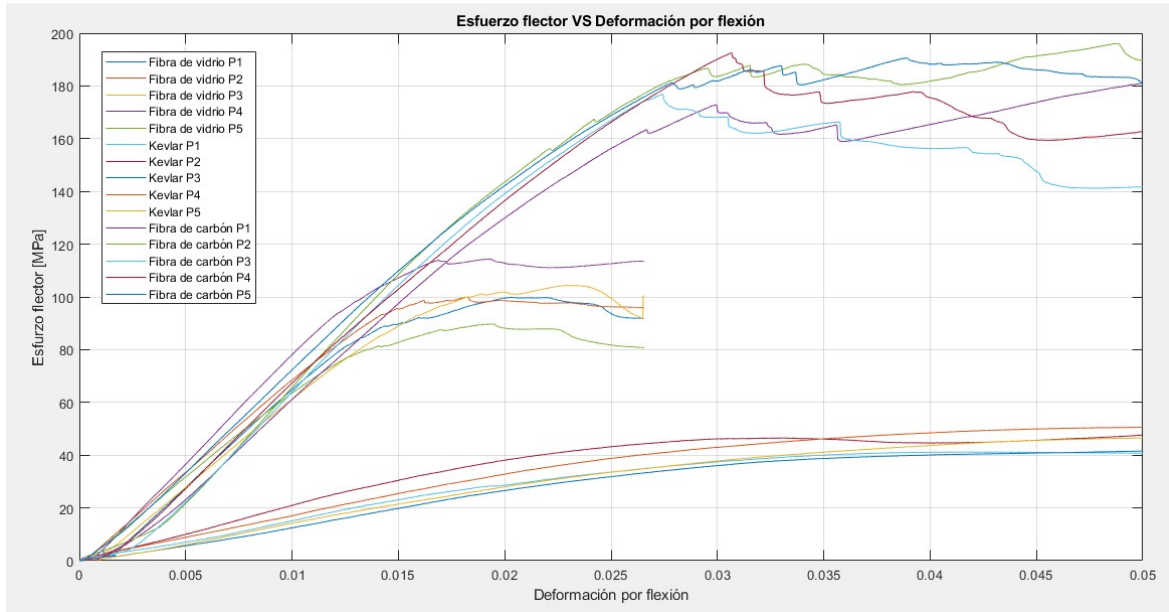


Figure A.3: Flexure test results in kevlar, GF and CF Espitia-Mesa et al. (2022)

It is observed that the flexural rigidity of CF and GF are superior to those of Kevlar, which presents high ductility. However, the fracture toughness of the fibers is higher in CF than in GF, making it the best reinforcement material from the mechanical properties.

A.1.2 Encapsulation Material

Encapsulation materials must have good optical properties should be used in order to increase the efficiency of electrical power generation. For the selection of encapsulation materials, CES Edupack software was used taking into account some parameters. Unlike the reinforcement, the encapsulating material should be as transparent as possible, in order to increase transmittance values by decreasing absorption, and it should also have the ability to adhere to the GF reinforcement. In order to find this material, a search is made in CES EduPack taking into account the following aspects:

- **Refractive index between 1.134 and 1.520:** this range takes as reference the refractive index of glass (1.520) which is the most commonly used encapsulation material in conventional PV modules.
- **Operating temperature between 60°C and 80°C:** PV cells are usually heated to around 65°C, so this range is proposed because the temperature in the PV module depends on external factors.

- **Translucent and transparent material:** this fact orients the search for materials that easily allow light to pass through.
- **Resistance to water and UV radiation:** due to its exposure to the environment, this material has the ability to resist the effects of water and sun for a prolonged period of time.

Fig A.4 shows the application of these filters.

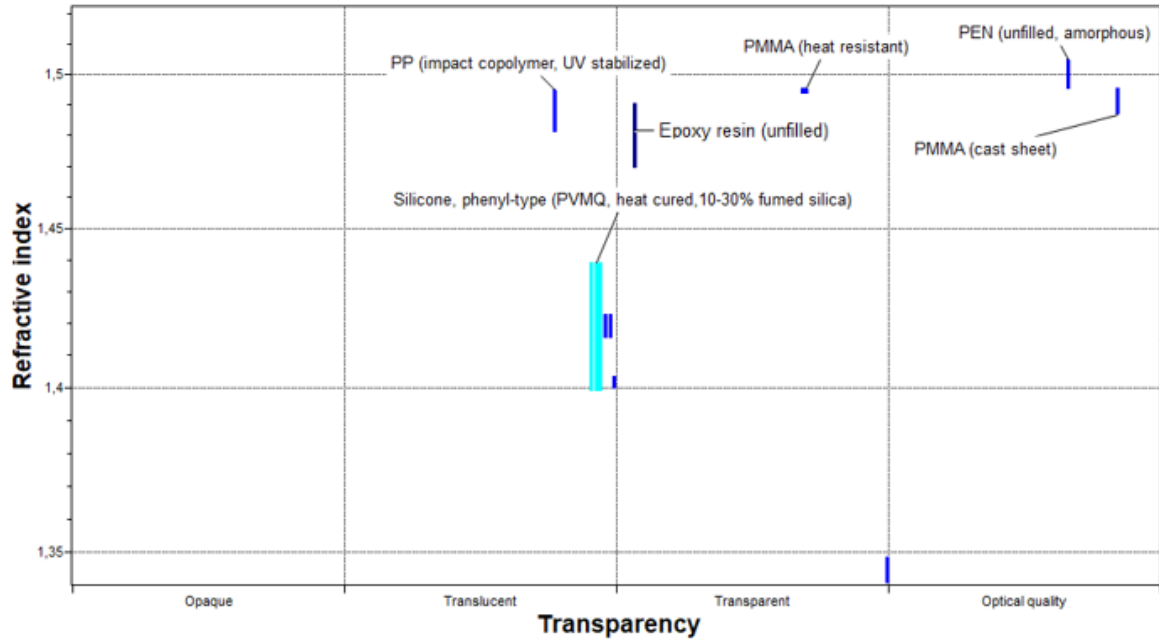


Figure A.4: Results of encapsulation materials selection in CES Edupack

The families of candidate materials are observed once these filters are applied, most of them are polymers such as PP and PMMA commonly used in the manufacture of containers and 3D printing. Silicones also appear, which are excellent optical materials but do not have chemical adhesion with glass fiber, because the matrix material used for the reinforcement are usually epoxy or polyester resins, so it was decided to use the family of epoxy resins for the manufacture of the encapsulation, since there is a great variety and availability, its use is simple and does not require sophisticated tooling for handling.

A.2 Mechanical Properties

Defining the materials for encapsulation and reinforcement, a search is made in the bibliography of the mechanical properties for these materials, in order to know the structural capacity they have to perform mechanical resistance models. The material properties found and the tests related to used materials will be shown below.

A.2.1 Tensile test

ASTMD368 establishes a test method for the determination of the tensile properties of reinforced and unreinforced plastics by means of standard samples. The fabrication of these samples was carried out in a metal mold, which was rigorously cleaned and waxed before casting the resin in order to avoid adhesion with the mold. Fig A.5, shows the tensile test for epoxy resins: Flexible, CCR and UV Poxxy epoxy.

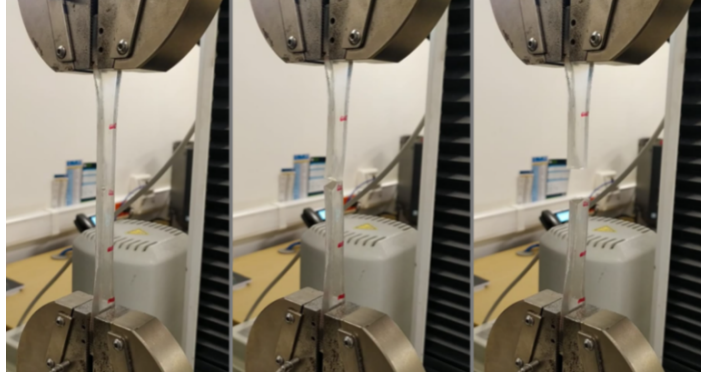


Figure A.5: Tensile test

A.2.1.1 Flexible Resin

For the determination of the Young's modulus, 2 samples were taken in the universal machine, positioning the two respective strain gauges, then, they were subjected to traction until a load equivalent to $50kN$ was applied obtaining an average Young's modulus of $4,61MPa$. Fig. A.6 shows the results of subjecting 5 samples to traction until rupture. It is possible to observe that their behavior is clearly linear, which makes this material fracture before presenting a plastic deformation. The average experimental tensile strength for this composite is $2,67MPa$.

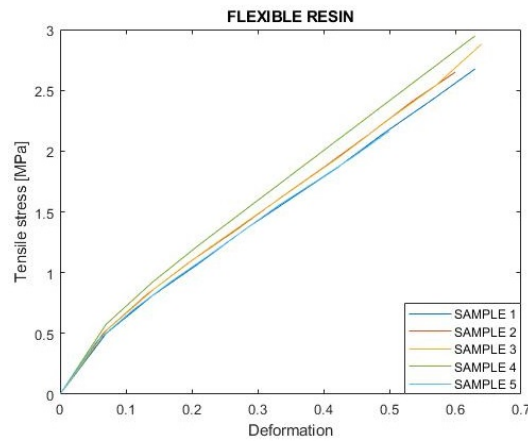


Figure A.6: Tensile test for Flexible Resin

A.2.1.2 Rigid Resin

In the same way as for the flexible resin specimens, 2 samples of rigid resin were taken in the universal machine, positioning the strain gauges, then, they were subjected to traction until a load equivalent to $300kN$ was applied, corresponding to a value below the plastic deformation of the resin to extract Young's Module, which has a value of $307,20MPa$. On the other hand, 5 samples were taken and subjected to a tensile test until they reached their rupture, which, on average, reaching a yield stress of $15.05MPa$ which is shown in Fig A.7

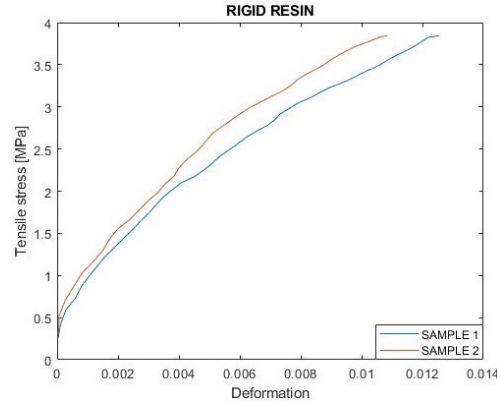


Figure A.7: Tensile test for Rigid Resin

A.2.1.3 UV Poxy Resin

Analogously to the case of the two resins mentioned above, 2 samples were taken in the universal machine, positioning two strain gauges, and were subsequently subjected to traction until a load equivalent to $200kN$ was applied, a value below the plastic deformation of the resin obtaining an average Young's modulus of $91,74MPa$. Similarly, 4 samples were taken and subjected to a tensile test until rupture was reached in relation to an ultimate stress of $2,67MPa$, this tensile test is shown in Fig A.8

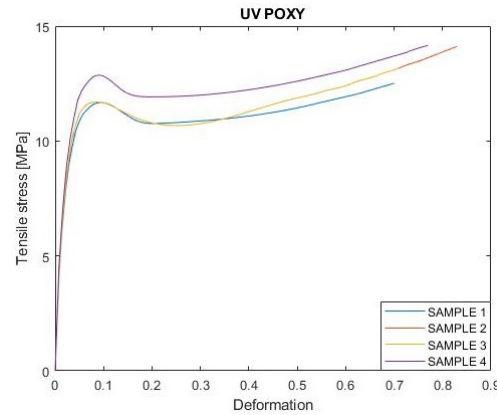


Figure A.8: Tensile test for UV Poxy Resin

A.2.1.4 CCR Resin

For the case of the CCR epoxy resin, sample failure was occurred when about $150kN$ had been applied, showing a predominantly linear behavior during all its deformation, being this a clearly elastic deformation. Subsequently, 5 samples were subjected to the tensile test until a load of $50kN$ obtaining an averaged Young's Modulus of $4,95MPa$. Once the strain gauges were removed, all the specimens were taken to failure, obtaining the results shown in Fig. A.9. From these 5 samples, the ultimate fracture stress was taken and averaged, obtaining as a result at experimental fracture stress for CCR resin of $2,11MPa$.

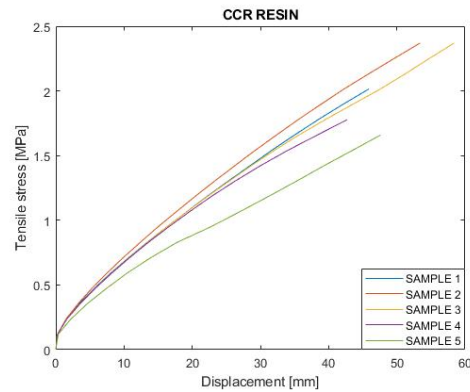


Figure A.9: Tensile test for CCR Resin

Finally, it is obtained that the resin with the best mechanical behavior is the rigid resin with a yield strength of $15,05MPa$, followed by UV Poxy with $2,67MPa$.

A.2.2 Hardness test

Taking into account the nature of the resins, a *ShoreD* test was performed to measure the hardness of the resins, in order to know their capacity to withstand erosion and scratching. Fig A.10 shows a diagram of the test performed.



Figure A.10: ShoreD test

A total of 10 samples per resin were measured and their values were averaged, obtaining that the Rigid resin is the hardest with $67,4\text{ShoreD}$, followed by the UV Poxxy with 62ShoreD . In third place is the CCR resin with 45ShoreD and in last place is the flexible resin with 38ShoreD . This fact reaffirms the hardest resins as the best candidates to be the potting material.

A.3 Optical Properties

In order to know the optical potential of the resins tested so far, a measurement of the incident power and transmittance was performed on a total of 5 samples for each material. In this case, the rigid one is discarded since it is mainly used in fiber reinforcement casting.

Spectrometer test In order to know the light transmitting capacity of each type of resin, it is necessary to carry out laboratory tests using spectrometer to measure the transmittance of the resins along the light spectrum. A Xenon lamp, whose spectrum is one of the closest to that of the sun, is used for this purpose. The setup is shown in Fig A.11.

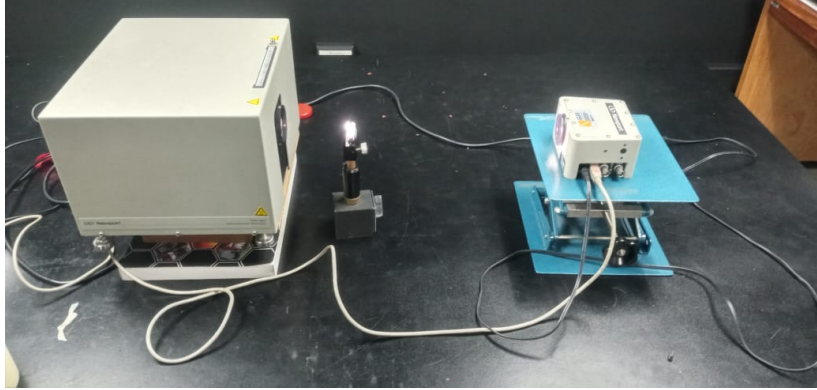


Figure A.11: Set up spectrometer test

It can be seen on the left side the xenon lamp, on the right side the spectrometer and between these, a sample held by tweezers receiving the xenon light. Transmittance is the ratio of the amount of transmitted light that reaches a detector once it has passed through a sample, I_t , to the amount of light that impinged on it I_o Díaz et al. (2000). This is given by A.1

$$T = I_t/I_o \times 100 \quad (\text{A.1})$$

Using the set up shown, 5 samples of each resin with dimensions of $2 \times 2 \times 0.2\text{cm}$ were tested. In experiment, xenon lamp was positioned in front of a spectrometer approximately 30cm apart and the amount of photons for a given wavelength. These data were taken as reference I_o and the same measurement was made for each of the test specimens in order to obtain I_t , placing them one by one between the xenon lamp and the spectrometer. In Fig A.12 is shown the results of the averaged transmittance by each resin.

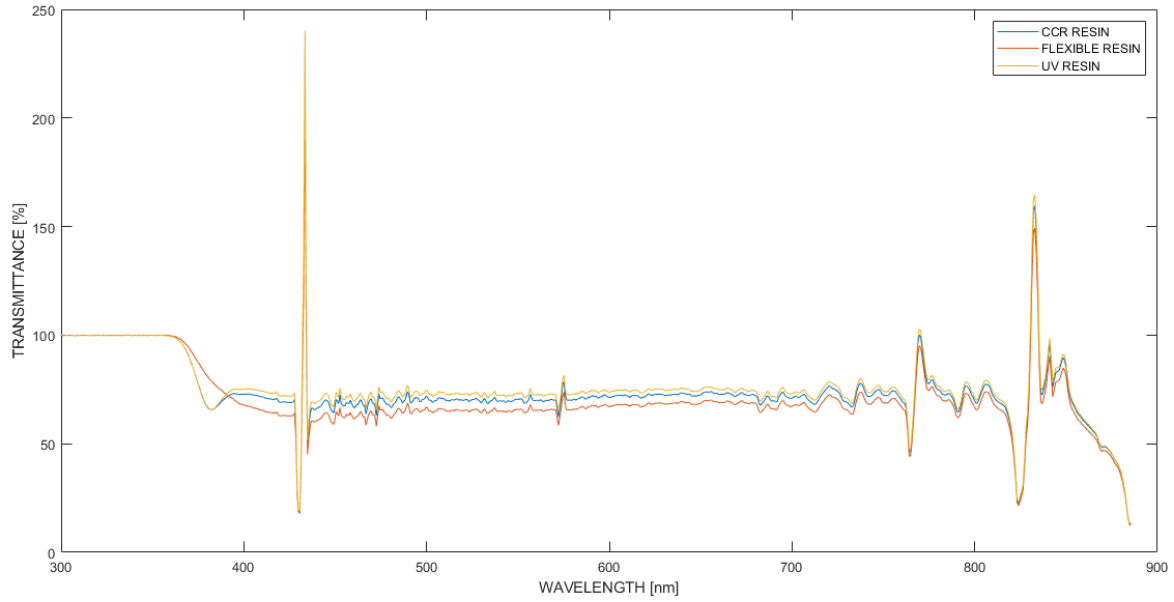


Figure A.12: Transmittance of resins used

UV Poxxy resin is the one with the highest transmittance along the spectrum, which means that it has the lowest absorption losses when light enters the medium. This is followed by the CCR and finally the flexible resin. These results lead to the conclusion that the resin with the best optical performance is the UV Poxxy resin, which was selected for the manufacturing tests presented in this study.

Appendix B

Performance and experimental testing of curved PV surfaces.

In order to corroborate the performance results of the optimal PV surface developed in 6 , an experimental exploration is performed in order to understand the role played by the geometrical shape of the PV modules in irradiance collection and, therefore, in electricity generation. Within this analysis, it is necessary to develop a test protocol that allows defining PV module geometric configurations to evaluate their performance under real irradiance conditions. Likewise, it is necessary to implement a tool that allows taking measurements in real time in order to know the performance characteristics of the PV modules with the same solar resource. Each of the aspects addressed in this experimental exploration will be discussed below.

B.1 Data acquisition circuit design

The solar resource together with the atmospheric conditions are unpredictable, which contributes to the stochasticity of the problem. PV modules work in radiation conditions that can change suddenly, varying the performance of this type of system. This fact means that in order to compare the performance of 2 or more solar panels, it is necessary to measure them under the same climatic and radiation conditions, this is only possible if the measurements are made at the same time. Additionally, the variable that is expected to be known is the maximum power delivered by the PV module, because during a given time, a delivered power is energy, which allows to easily compare the performance of the solar panels with each other. The operation of the circuit will be explained below.

B.1.1 Electronic circuit

We propose the design of an electronic circuit to measure current, voltage and maximum power of PV modules and then these data can be stored reliably. For this purpose, an Arduino Nano CH340 was selected, which is the main microcontroller of the system. Also, there is an ADS1115 analog-to-digital converter that converts the

voltage and current measurements from the PV modules to a signal that the microcontroller can understand, process and store. To convert the digital signals sent by the microcontroller to analog signals, the MCP4725 digital-to-analog converter is used, which converts the signals and sends them to the MOSFET's (IRFP250) to enable current flow. Fig B.1 shows a schematic of the circuits used for testing.

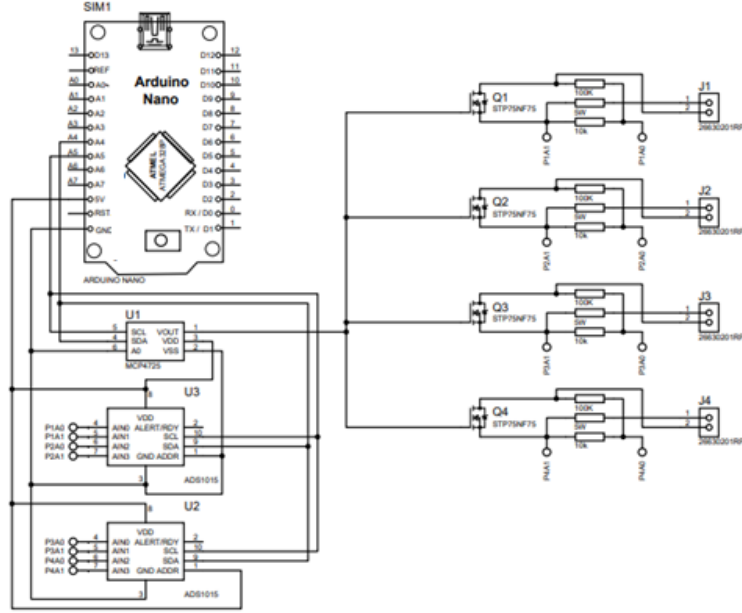


Figure B.1: Acquisition circuits diagrams

In order to generate VI curves, the voltage step is gradually opened from open circuit to short circuit through a signal that the Arduino nano sends to the DAC within a defined time interval of $20ms$, which allows to generate the VI and PV curves for a given time instant. This measurement is performed every $10s$ to avoid excessive heating of the MOSFET's during the measurement day. Data acquisition was performed by means of a serial connection between the microcontroller and Microsoft Excel, through the Data Streamer add-in, which allows data acquisition in tables in real time. Fig B.2 shows the circuit implemented.

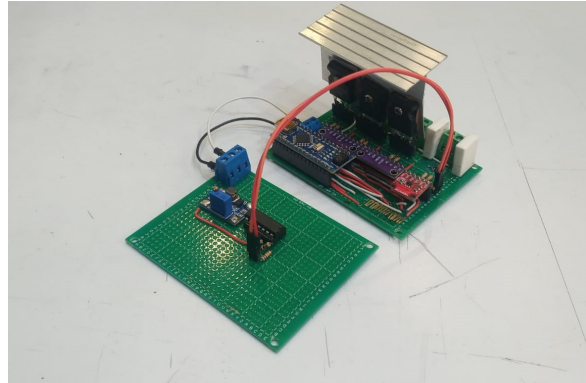


Figure B.2: Circuit fabricated

B.1.2 Calibration

In order to have certainty of the acquired data, it is necessary to perform the calibration of the elements that integrate the circuit. To do this, we work with open circuit and vary the voltage values with a variable source. In this way, a voltage reading is made from the source and from the controller, for different values in order to generate the calibration function, which in this case is a straight line. With respect to the current, the same exercise is performed in short circuit, varying the current passing from the variable source, which also generates a straight line. This exercise allows obtaining reliable data for the resolution of the instruments used.

B.2 Experimental performance of PV modules.

The objective of this test is to generate simple curvature configurations for flexible PV modules in order to understand the geometrical effect on the generated power. Each of the tests performed and their respective purpose are described below.

B.2.1 Test 1: Commercial PV modules with planar geometry

Taking into account that these PV modules may not behave exactly the same, in addition to the noise generated during data acquisition, an initial configuration test of 4 PV modules in planar geometry under the same atmospheric conditions shown in Fig B.3 is performed.



Figure B.3: Initial test of 3 PV commercial flat modules

In this way, the connection of the 3 inputs of the circuit is tested. In this way, on January 24th, a measurement was made from 7 : 40am to 4 : 30pm, the available time of solar resource of the place of development of these operation tests. For the midday conditions, a measurement of the *VI* and *PV* curves was made for this test, obtaining the results shown in Fig B.4.

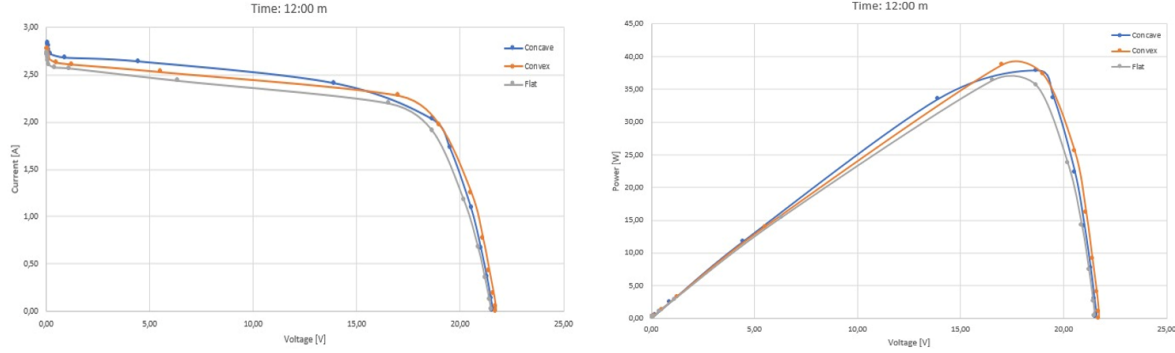


Figure B.4: VI and PV curves for commercial flat PV modules

With respect to the lowest generation PV module corresponding to flat, there are variations in the maximum power found for 12 noon of 39.14W, 38.1W and 37.3W, this results are based in a irradiance of $1148W/m^2$. Fig B.5 shows the temperatures in PV modules of 12m.

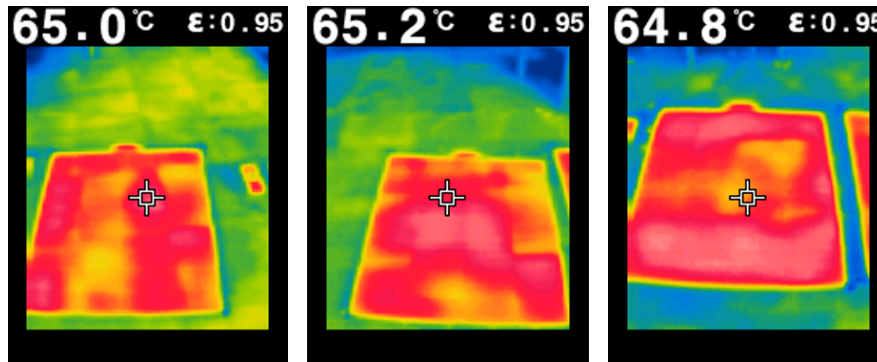


Figure B.5: Temperatures for commercial flat PV modules

Temperature of the 3 PV modules is close to $65^{\circ}C$, with only a difference of $0.2^{\circ}C$ between them, so it can be concluded that the modules behave practically the same. Based on the above, if in the following test, higher powers than these ranges are generated for the same conditions, it means that the geometry of the PV modules has an implication in the electricity generated due to the fact that they are the same reference of panels, because the difference between the lowest power PV modules with respect to the others is 2.1% and 4.9%, respectively.

B.2.2 Test 2: Commercial PV modules with curved geometry

The flexible PV modules used allow to adapt to established curvature contours, so a test involving a fully concave and convex with a radius of curvature of 1m, these are compared with flat PV module, in order to analyze the generated power and its influence with module geometry. The test setup with numbered modules is as follows is shown in Fig B.6.



Figure B.6: Test of commercial PV modules with curved geometry

As in the previous test, a measurement is made using the circuit designed with 3 flexible PV modules during the hours presented, taking as reference the PV module in plane geometry. For 12 noon on January 25th with an irradiance of $1098W/m^2$, the VI and PV curves shown in Fig B.7 were obtained.

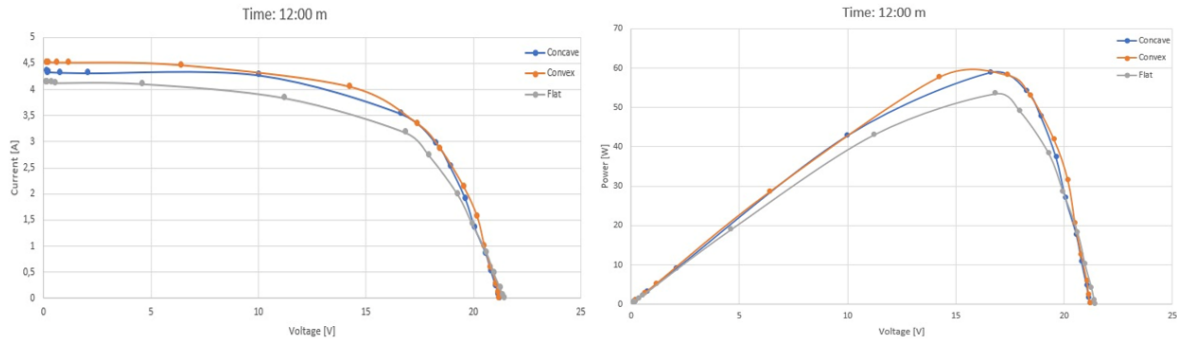


Figure B.7: VI and PV curves for commercial curved PV modules

It is then obtained that the geometry with the best performance is the convex geometry with a maximum power of 59,6W for noon, followed by the concave geometry with 58,1W and finally the flat geometry with 54,2W. With respect to temperatures, Fig B.8 shows the distribution of temperatures in PV modules.

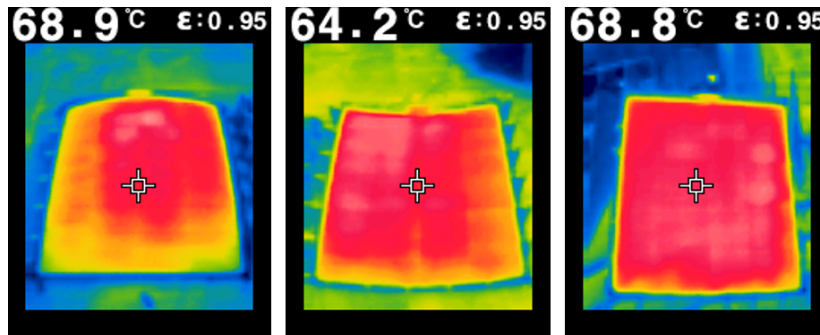


Figure B.8: Temperatures for commercial curved PV modules

It can be seen that the convex PV module has a lower temperature of $64.2^{\circ}C$, being the one that delivered the highest power. With respect to the flat and convex modules, higher temperatures are observed of $68.8^{\circ}C$ and $68.9^{\circ}C$, respectively, which suggests a drop in power. Also, a temperature pattern associated to the

incident radiation is observed, in the PV module, this temperature distribution is constant, however in the curved modules there are certain areas with higher temperature where apparently the irradiance increases. In comparison with the flat surface, the convex geometry presents an additional 9,96% of power, while the concave has an 7,2%. Taking into account that these variation values are higher than those shown in the above test of all flat PV modules, it can be concluded that the curvature may offer better power output due to better orientation to the sun.