MODELLING AN INNOVATIVE SHADING SYSTEM INTEGRATING PV

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Abstract

The use of PV system as an alternative for electricity generation purposes has increased during the past years, as well as its inclusion into the architectural design based on BIPV concepts. Therefore, forecasting power produced by those kind of PV plants is fundamental for the reliability, safety and stability of the grid, and for the optimization of the design and of the control strategy of such systems. For these reasons, in this project it has been developed a model which represents the dynamic performance of an innovative external shading device, that allows PV integration.

First, a suitable model to determinate the incident irradiance over a tilted surface for any day of the year was set, starting from the general solar radiation theory, considering the second order effects provoked by the angular losses and the spectral shift. Consequently, from such irradiance, it has been designed a suitable PV model characterized by a five-parameter model, which is able to forecast the power generated with a good accuracy level.

Such PV model was extended in order to consider shading effects, i.e. non-uniform irradiance over different cells, since the aim was to develop a model able to represent the behavior of a PV array integrated on an external shading device. Furthermore, a suitable optical model was developed to predict the performance of the shading device, with a curved geometry and the possibility to use any combination of surface material. Subsequently, as the idea of the project is to forecast output power for any geometry, it has been designed a case study following a special geometry, which is based on an innovative external shading device designed by the architect Pietro Franchi and the engineer Stefano Rui.

An experimental apparatus was set up in order to study the impact of shades on the cells under different configurations of the shading device and validate the PV model. Therefore, a prototype of a generic lamella system, which might emulate some geometric configuration and features of the innovative external shading device, was mounted on the roof of the Energy Department of the Politecnico di Milano. The prototype corresponds of two lamellas, in two separate levels, over each lamella is placed a flexible monocrystalline PV panel. Thus, by evaluating the PV production under different conditions, such as the position and inclination of the lamellas, the PV model was validated against measurements.

Finally, a control strategy has been proposed to regulate the external shading device to maintain a sufficient daylight level in the room containing overheating risk and exploiting PV
generation. Such analysis allowed to quantify the performances of the innovative BIPV system in terms of hours of daylight exploitation, PV production and effective shading capability to ensure solar control.
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In recent years, one of the greatest priorities at global scale is the development of alternative sources of energy generation, especially the ones related to renewable energy sources (RES), which produce a low-environmental impact with respect to the conventional ones. In addition, the constant growing of energy demand generated by the increasing of the population and the industry, making in the long term that the conventional fossil fuels (oil, coal, natural gas) would not be enough for covering the whole electrical demand. Therefore, options such as wind power, solar, renewable biomass and energy storage devices (fuel cells) would play a main role, producing changes on the paradigm of the global energetic system.

According to the REN21 (Renewable Energy Police Network for the 21st Century) reports, the contribution of RES to the worldwide energy production was 19.3 %, as it can be seen in the Figure 1. From all the RES existent, the modern renewables ones are starting to overcome the traditional biomass, which traditionally was implemented for heating applications, contributing with 10.2 % [1]. Besides, studies developed by the IEA (International Energy Agency) have shown that energy consumption would grow up more than 50 % from 2009 (4.8x10²⁶ kJ) to 2030 (7.3x10²⁶ kJ). Hence, RES should increase at the same rate, under the sense that by 2050, more than the half of global energy needs must be satisfied by such resources [2].

Consequently, in the Figure 2 is shown the growth of the global renewable energy compared to total final energy consumption for the years 2004-2014, where the predictions given by IEA are proved. Thus, modern renewables have started to increase at a higher rate, mostly due to the implementation of incentives such as FIP (Feed-in-Premium), FIT (Feed-in-Tarif) or QO (Quota Obligation). Such incentives have been developed to fulfill the IEA scenarios, in order to limit up to 2-4 °C the average global temperature increase [3].
INTRODUCTION

On the other hand, the deployment of established technologies as hydro, along with newer technologies such as wind and solar photovoltaic, has ascended quickly, causing an increment on the confidence in those technologies, reducing their costs and opening new opportunities. By analyzing a report done by IRENA (International Renewable Energy Agency), is evaluated the diminution of LCOE (Levelized Cost of Energy) of different RES technologies between 2010 and 2014 with respect to the fossil fuels, making some of them competitive nowadays [4]. Such information is summarized in the Figure 3.

Thereby, based on such growth levels on the energy producing capacity, together with the low LCOE values for RES, it is expected for the future the active and important participation of solar photovoltaic in the global energy market. By focusing on the conversion process form solar energy to electricity, the direct conversion through solar cells is one of the
most efficient. For this reason, this kind of RES has received a major attention by specialized researcher centers worldwide.

Figure 3. LCOE from utility-scale renewable technologies, 2010 and 2014. Source: [4]

The generation of electrical energy by using the photovoltaic conversion of the solar irradiance is quite important due to the following aspects:

- The basic source of energy is limitless and is available all over the earth
- There is no environmental pollution (no greenhouse gases generated), also is almost maintenance-free.
- It has the capability of converting diffuse irradiance with the same conversion efficiency as direct irradiance.
- Its versatility allows the construction of systems with a very low power (mW) till several (MW) by using the same technology.

However, from an economic point of view, photovoltaic generation (PV) has some limitations regarding to the cost of the kWh, basically such energy cost is more expensive with respect to the one generated by a conventional energy source. Nevertheless, as it has been already said, currently there are some strategies which guarantee at the mid-term that the PV energy cost might be equal or lower than the conventional one. Among these strategies are included government subsidies, new regulatory framework based on the large inclusion of RES into the electrical system.
Nonetheless, the change of the conception between states and economies (considering the benefits of the scale-economies) open the possibility of installing lower size generation power plants. These plants are placed close to the consumption centers, which takes importance again, because they consider the newest technological developments regarding to environmental concerns, working together with the backup given by the network. Thus, the implementation of more flexible systems, called distributed systems, appear as an alternative of higher penetration into the general electrical system framework.

The diffusion of distributed generation through photovoltaic systems brings important challenges for the planning, operating, investment, and regulation of the traditional electrical systems. Under that sense, the big group of generation of electrical energy would count with more players, which can be aggregated power plants (MV) or distributed power plants related to any final customer (LV). Concerning the interconnected systems, this kind of generation implies a change on the regular paradigm. The final customer can deliver electrical energy to the system in low voltage (medium voltage as well), which contributes, among some things, in solving grid capacity support, nodal hosting capacity of the grid, and reducing the dependency of the centralized system.

By covering all the ideas previously exposed, an optimal alternative for the final customer to generate electrical energy through PV systems is the one related to the integration of such systems into the building, this solution is known as BIPV (Building Integrated PV). The BIPV is the implementation of solar photovoltaic power as a multifunctional building component i.e., besides the power generated by the panels, the building can use an extra energy by means of implementing additional technologies. Simultaneously to the energy produced, BIPV also protects the building from exterior elements by acting as a standard material enveloping the building.

First of all, as it is mentioned previously there are two major benefits by applying BIPV. The first one consists of taking advantage of the energy generated by the PV system, which is also working together with the grid under the concept of PVGCB (Photovoltaic Grid Connected Building), as it is shown in the Figure 4. The second, is to reduce the operational energy (OE) for building heating, cooling, and lighting. Thus, the final customer would supply energy to its load by means of the PV generator and the local grid, where can exist the case in which, according to the conditions of the day, some energy can be also delivered to the grid. In addition, the solar panels can be installed as a façade for the building, operating as a shading device decrease the solar heat gain of a building by 80% to 90% [5], increasing at the same time the social welfare of the people inside the building.
1.1 Building Integrated Photovoltaic (BIPV)

On these days, it is well known that the building sector is one of the major energy consumer with an overall consumption close to 32% worldwide [6]. Besides, in Europe, all the new buildings must comply the requirements asked by the Energy Performance of Buildings Directive (2010/31/EU) of the European Parliament and Council [7], even more, by 31st December 2020 all new buildings in Europe should be nearly zero-energy consumption building (NZEB), i.e. the building energy consumption and production – by means of renewable sources – needs to be balanced.

Thus, the concept of NZEB brings into consideration the notion of the Building Integrated Photovoltaic system (BIPV), which is a special PV application, in which the PV generators are installed either on the façade or on the roof of a building, but with the addition of being implemented as an integral part of the building structure, replacing some components of the building. In this way, it is being provided an efficient way of reducing energy consumption, delivering electricity at a lower cost than the grid electricity to end users, particularly during certain peak demand times.

The concept of BIPV can be adopted depending on the climate, built environment, electricity industry structure, government policies, local product offerings, market stimulation mechanisms, consumer demand, existing industrial capabilities and the forms of tariff arrangement for grid-connected PV power generation [8, 9]. Also, the modularity allowed by this system it is translated into short installation times, also the lack of moving parts reduces the need for maintenance [10].

The sizing and design of a BIPV system is based mainly on the load profile of the building, as well on the PV output. In addition, it should consider all the building design constraints and its location. There are also regulatory requirements concerning on the
buildings that must be met, for instance the local building codes and product certification requirements will stipulate specific standards for BIPV mounting, fixing, and fire resistance [11]. For this purpose, a product certification is required, usually carried out in an independent testing laboratory after passing satisfactorily a prescribed set of testing procedures (e.g. cycling of humidity, freeze/thaw, temperature, rain) [12].

1.1.1 BIPV features

As it is mentioned already, BIPV replaces some conventional building materials, making profit by saving the purchase and installation of such materials, and at the same time it is implemented as part of the weather protective building envelope [13].

First, it should be mentioned that BIPV system output depends on:

- The availability of the solar radiation on the accessible building surfaces, which is determined by climate, inclination, latitude, orientation and the urban setting.
- The PV efficiency and its degradation with time.
- Partial over shading, accumulation of dirt, dust or snow on modules.
- Coupling to the electrical network, electrical wiring resistance and voltage drop in diodes.

Above all, BIPV brings the advantage of avoiding the increment in the thermal load of the building, by creating a gap between the PV and the building element (such as brick, slab, etc.), placed behind the PV. On this gap, there is an air ambient circulating, which remove the produced heat. During wintertime, this air is directed into the building to cover part of the building load; during summer, such air is send back to ambient at a higher temperature. BIPV can serve as a shading device for a window, a semi-transparent glass facade, a building exterior cladding panel, a skylight, parapet unit or roofing system.

Moreover, PV can be integrated on almost every structure from small buildings (household level) to high rise buildings (skyscraper). As the BIPV modules are fabricated directly onto building materials, in theory it can, in high-volume production, lead to lower distribution and installation costs [14]. Moreover, since most of PV power would be used in the building facilities, the demand energy from the power grid is reduced, also the reliability of supplied power to the building is improved, because in case of network failure, the BIPV would work as a back-up system. With the new storage technologies, the low-cost storage of BIPV systems could become a reliable, distributed power source, which would be immune to widespread disruptions [15].

From architectural point of view, the BIPV brings the following features:

- reduction of initial investment costs by replacing façade roof/shading elements.
- can be architecturally friendly (esthetically appealing).
• since building surfaces are used there is no necessity for additional land area.
• can act as a shading device
• can form semi-transparent elements of fenestration
• BIPV can form part of a grid-failsafe antennae system for cellular communications

From the electrical point of view, the following features are considered:
• when grid-connected, avoids the costs of batteries possible system oversizing.
• the electricity is generated directly at the point of use, reducing thus the losses associated with transmission and distribution processes.
• can be designed to generate electricity at peak time, thus for commercial building for example the peak electricity grid demand is reduced

1.1.2 BIPV typologies

BIPV can be implemented for: 1) roofing materials, 2) wall and windows materials and 3) flexible PV modules. The BIPV can be integrated either on the roof of new buildings or where a major roof replacement is undertaken. The methods of integration include interchangeable PV panels (see Figure 5), prefabricated and insulated [16]. Fully integrated BIPV roofing systems must perform the function of a standard roof and provide, drainage, insulation and water tightness.

The roofs suggest an attractive place for BIPV due to:
• unshaded solar access.
• the cost is offset partially by the displacement of roofing materials by BIPV modules
• flat roofs generally enable more optimal solar cell placement and orientation,
• when a pitched roof is near optimally inclined, the necessity of a support frame is eliminated.

Figure 5. Structure of exchangeable PV shingle. Source: [17]
Many roof-integrated BIPV are module-based roof tiles, slates (used on flat roofs), shingles or standing seam (for tilted roofs) units. The design of a PV tile or shingle conforms usually to regional or local roofing methods and building codes. Nowadays, some solar manufacturing companies are designing PV modules visually pleasant. In the Figure 6 is seen a photography of a BIPV installed in the Bejar market retrofit project in Spain, in which were used three types of PV glasses with different colors and structures [16].

![Figure 6. Bejar Food Market PV skylight. Source: [16]](image)

By integrating different thickness, sizes, transparencies and colors on the PV module, is easier to be integrated as an artistic building element, therefore, more structures would start to be built using those kinds of technologies. In addition, the overall electrical efficiency of the system is not seen affected, for the specific Bejar project, the developer states that the “Kromatix” glass shields would negligibly reduce the module efficiency [16]. Moreover, the integration of PV components depends also on its industrialization grade. An industrialized product should be affordable and certified by the electric and constructive point of views (i.e. thermal mechanical and optical datasheets).

For the architectural integration, shape and size flexibility of the PV modules offer the option to substitute tiles or shingles [18], whose characteristics are far from the traditional ones. Not only the modules are important, but the complete PV system as well. It must be used mounting and interface products for roofs, façades and shading.
systems, nowadays many of the integration requirements lead to the use of custom products, so that the cost of the system rises.

Another fact to consider is the color of the PV material. Generally, construction elements are often light and warm (plasters, stones, bricks etc.), while the PV cells are very different (dark, blue, green, purple). With these set of available colors (usually with lower efficiency) and transparency (thanks to different thicknesses), the architects have a wide range of possibilities to integrate them into the building. Nevertheless, the need for electrical contact manufacturing requires a geometrical configuration of cells, at least in one direction [19] (often is more practical to have square configurations). The contacts also influence the texture of the cell, providing another variability grade. Sometimes those junctions represent an issue to be considered, because it is not provided in cases such as frameless modules, encapsulated framings etc. [20].

Furthermore, nowadays the manufacturers provide a range of BIPV products that varies from the PV technology until the constructive application, including both crystalline modules and thin film cells in different colors and shapes [20], some of the products are:

- as roof/façade modules substituting traditional elements (m-Si).
- as roof shingles (m-Si, p-Si, a-Si).
- as roof tiles (m-Si, p-Si, a-Si).
- as external movable solar shades (m-Si, p-Si).
- as window shutters (p-Si).
- as curved and industrial roofs (a-Si).
- as ventilated claddings (a-Si).
- as curtain walls (a-Si).
- as glasses (a-Si, CIS).
- as ventilated roofs (a-Si).
- in spherical micro-cells (a-Si).
- as architectural elements in façades (a-Si).
- as curtains (a-Si).

This list is just representative of the manufactured products and it does not aim to be complete.

1.1.3 Movable external shading devices in façades

Shading devices for buildings are generally designed to control intense direct sunlight and to ensure comfort in any workspace. When blocking solar heat gain is a main issue, external shadings are particularly suited. Furthermore, they can act as an architectural element to make smooth façades more beautiful to see.
In the northern hemisphere, this kind of systems are particularly important for south façades, but if it is possible, they should be applied for east and, especially, west façades, reminding that each exposition requires different solutions. For instance, for south façades horizontal devices, such as awnings and overhangs, are more appropriate while for east/west façades vertical devices, such as vertical fins, are usually more valuable.

Another goal of the external shading devices to be noticed, they reduce glare when the sky is too bright. The color of the system influences its performances, so it is important to choose it wisely. An example could be an external shading device with light colors, which enhance diffuse light transmission whereas with the dark colors it tends to reduce heat gains as maximum as possible.

External shading devices can be either fixed or movable, where the fixed devices are cheaper in terms of both capital and maintenance costs, while the movable ones achieve the best results in terms of energy savings. In fact, they are more effective in blocking undesired heat gains because the interior devices block the light inside the building. However, a combination of both systems is an optimal solution giving the building visual homogeneity from the external observer point of view, simultaneously the occupants have the possibility to regulate themselves the light level. As an example, a light colored exterior device can be used to reduce solar heat gains and allow high diffuse light transmission, while in the interior a dark color, with a manually adjustable device such as a blind, can allow a supplemental shading capacity.

The high cost of automated movable external shading devices can be recovered by a reduced expenditure in cooling loads and equipment, and they are more reliable than the interior manually regulated systems. In fact, the behavior of the occupants may be not correct making vane the expenditure for manual systems. Moreover, a comfort issue, such as excessive solar light, can turn into an economic issue, which workers can feel uncomfortable, spending time in adjusting shadings, bring energy consuming fans and reducing the thermostat setting. Another advantage of exterior devices, and of venetian blinds, is that they not only reduce glare by shielding the sky view, but also, they redistribute the light indoor reaching deeper distances and allowing further electrical lights load savings.

On the other hand, it is important to remember that direct sunlight has an important role in buildings, because it allows the growth of plants, strong local illumination, gives sense of daily variation providing a visual and emotional link to the outdoor, warms the spaces in winter.

To summarize, the optimal shading device should be external adjustable, preferably automated. It should be a system with the possibility of high regulation, which allows the inclusion into the building of high amounts of light when is needed, but also, it presents the characteristic of very low solar heat gains to reduce the energy needs of the building.
1.1.4 An innovative external shading device

As proceeding of a previous Master Thesis in Politecnico di Milano, the work presented in [21] is a pioneering lamella shading device, which has a design characterized by longer distances between the elements and more flexibility in its regulation. By having more distant lamellas it is implied less mutual shadows, in addition, higher flexibility implies more convenient tilting for the PV modules if they are used in the structure. By analyzing this application, it is seen the potential to combine an advanced technological solution for the buildings shading in south façades with a high-quality integration of PV modules in buildings. According to that, one of the aim of the project is to model such BIPV device and evaluate its performance.

The innovative design, firstly studied by Dama and Franchi [22], then patented by Franchi and Rui [21], is meant to allow a high degree of solar control and an adequate daylight illumination of the interior of the building with a single system.

Compared to an adjustable and not extensible shading device, which is able to offer the same beam radiation blocking capability, the extensible lamellas allow a higher penetration of diffuse radiation. Therefore, there is a higher daylighting fraction and a higher solar gain when is needed. The main difference between the existing and the new devices, is the higher inter-distance between the lamellas, given by the extensible device. In the Figure 7 there is a comparison between both lamellas, showing how such lamellas work seasonally for summer and winter.

Figure 7. Comparison between lamellas, application during summer and winter. Source: [23]
Furthermore, in the Figure 8 is shown how the innovative lamella operates. Showing how it is possible either to change the distance between lamellas, or extend the size of each lamella, depending on the currently necessity. At the same time, by analyzing the Figure 7 the study done in [22] shows that during heating season, when the sun is low in the sky, that double distance is responsible of a transmission increase up to 25 % for diffuse radiation and up to 30 % for direct radiation. On the other hand, in the summer season, when cooling is needed and the sun is high in the sky, the beam sun rays are completely blocked whereas up to 25 % more diffuse radiation can pass.

The lamella geometry selected is a lenticular section composed by two separated curved plates that can slide on a lenticular central body in opposite directions. Moreover, the central body can rotate on its own axis, allowing the maximum flexibility in regulation. The rounded shape and the option to use different materials make the device very interesting and full of possibility in the architectural field. Thus, the regulation flexibility and the increased distance between the lamellas left an open space for photovoltaic integration which is the field of exploration of this project.

1.2 Objectives

To develop and validate a model of an innovative external shading device onto the building, which integrates photovoltaics systems as an alternative of energy saving for the building, based on the BIPV concepts. Moreover, to build a prototype placed on the roof of the Politecnico di Milano Energy Department building, which would be used for evaluating the respective developed model.
1.3 Methodology

Regarding with the exposed above, the development of this project aims to serve as a starting point to generate a space in which is possible to study the impact of PV generators in function, not only on the electrical point of view, but also on the architectural point of view. For that reason, are proposed several PV models that work at pair with an innovative façade model, evaluating the overall energy produced under different scenarios and analyzing the impact and benefits of installing external shading devices as PV technology.

Basically, the idea is to implement a lamella in front of the building façade. Such lamella would be constructed with solar panels, i.e., on the building would have installed a shading device based on a clean, high-grade solar energy source for the operational energy. To do that, the following steps should be considered:

- To evaluate the solar energy that reaches a generic oriented surface together with the Sun position at any time, estimating the amount of solar energy that is accessible to the PV cells depending on the light incidence angle, the light spectrum and the PV technology.
- To design the device to make the PV integration worthwhile and consequently being able to calculate the shadows that the modules can suffer.
- To simulate several PV models, thus is possible to select one reliable PV model to calculate the energy production of the modules, likewise, modeling the effect of the heterogeneous shadows on PV modules power production.
- To characterize the innovative device optical performance and evaluate the benefits of its application into buildings.
- To develop a control strategy for the innovative device to obtain the optimal position of the lamella on the façade, considering all the results of the previous steps.

After all is necessary to implement a validation task for all the steps through the comparison with experimental data and/or authoritative sources, giving as a result a solid model and a scientifically reliable quantification of the performance of the device.

The simulated PV models are developed in the mathematical software tool MATLAB®. Based on all the models and information existent in the literature, the respective simulated models are made. For each simulated model, real meteorological data given by the “Solar Tech Lab” of the Politecnico di Milano is taken, also in the cases in which is required, a pre-step is applied for adjusting some data into the model.

The geometry of the lamella to be installed on the building façade must be analyzed in detail. Due to the lamella might have different position (open, close, mid-point), such position implies the constant existence of shadows over the solar panel for a given period.
Thus, is determined a priori the size and duration of the shadow over the solar panel, making more accurate the simulated model.

With the purpose of determining the real impact of the lamella over the solar cells, an innovative prototype is developed. The idea is to build and install such prototype on the roof of the Energy Department building, together with all the facilities belonging to the “Solar Tech Lab”. By using the prototype different scenarios can be executed for evaluating its performance in the simulated model.

Finally, as it is mentioned previously, the idea is to generate electrical energy ensuring, at the same time, sufficient daylight, when available, and providing solar control, when needed, in order to reduce heating, cooling, and lighting for the interior of the building. Hence, is developed a control strategy for obtaining the optimal position of the lamella, which benefits both electrical and operational energy point of view. For that reason, is implemented a software tool called EnergyPlus, which would be communicated with the simulated models done in MATLAB. After numerous simulations and scenarios is determined the optimal position of the lamella.

At the end, all the data taken by the simulated models is compared with real information, for testing the veracity of the respective models and its repercussion into the building OE factors. Firstly, starting from the basic model, all the data given by the “Solar Tech Lab” is considered. Secondly, for evaluating the shadows generated by the lamella, real data given by the prototype installed at the roof are considered.

In accordance with the foregoing, the development of this system might be considered as a researching tool, which opens academic spaces within the university. Such spaces would be available for the students to contribute with future investigations related to this topic. In general, this project together with the goals of the energy department would allow the Politecnico di Milano to benefit with an addendum to the existent “Solar Tech Lab”, in which can be evaluated in detail the newest concepts of BIPV at low or high scale. Above all, this can be considered as a starting point for the creation of interdisciplinary processes between professors and students, thus allowing the active participation within sundry approaches close to electrical engineering, as a main goal of creating a sustainable campus framework for the whole university.

1.3.1 Structure of the thesis

This work is structured in eight main chapters, which describe the methodology developed. In addition is included four appendixes.

In the first chapter is presented the introduction of the document, where is exposed the problematic and necessity of why is important to implement this project, together with the reference of the BIPV concept, as a crucial part of the development of this project. Likewise,
is enlisted the objectives of the project and the methodology, where is explained the analysis, development and respective results of the remaining chapters.

In the chapter 2 is shown the main concepts of solar radiation theory, considering all the parameters and equations to develop a suitable model able to determinate the incident irradiance over a tilted surface for any day of the year. Besides, such model is validated with respect to real measurement data given by solar tech lab, proving its legitimacy for future computations.

In the chapter 3 is exhibited the concept of the PV system and how it can be integrated into the network by using PV-grid connected system. Then, are described all the formulas existent in the literature, necessary to simulated the PV cell showing a suitable way to extract all the meaningful parameters. Finally, it is done the validation of the chosen model with respect to measured real power data given by the solar tech lab of the Politecnico di Milano.

In the chapter 4 is exposed the optical model developed in this project. Staring from the calculation methods is established the respective model, considering key factors such as view factors, viewed and undisturbed fractions, bidirectional transmission, and so on. After that, the model is validated with respect to the software tool Window. Nevertheless, there are some innovative scenarios to be considered, hence, it has been designed an innovative optical model based on a special geometry to be implemented in the lamella. At the end, it is validated this new optical model.

In the chapter 5 is studied the prototype built for the project, identifying the necessity of designing and installing this prototype on the roof of the Energy Department building, describing the experimental device and all the elements implemented to build such prototype. Moreover, is evaluated the shadow impact generated by the geometric way of the prototype.

In the chapter 6 is explained the PV model considering shading effect, for that reason is explicated which is the shading effect over the solar PV cells, bearing in mind new key points such as hot-spot problem and the inclusion of by-pass diode. Also, is presented the Simulink model developed to evaluate the addition of the by-pass diode into the regular PV model, simulating several scenarios, depending on the geometry presented in the previous chapter. Lastly, the model is validated with respect to real data collected by the prototype installed in the roof of the Energy Department building.

In the chapter 7 is manifested the control strategy followed by the project. To do such control strategy, it has been implemented the software tool EnergyPlus, in which is simulated a standard building integrated with external shading device based on PV panels. The idea with the strategy is to maintain always an acceptable daylight inside the room, capable of solar control and PV energy production. It is showed results for specific scenarios such as a winter, summer and spring day, showing for each one of them the daylight factors and the PV energy produced.
Finally, in the chapter 8 is gathered all the conclusions obtained by developing this project.
In any solar system, it is crucial to determine precisely the amount of solar radiation that is reaching the collecting surface at any time in order to size the components, predict the production of energy, choose the proper design and determine the feasibility of the project.

Depending on the nature of the technology involved and the aim of the project itself, the degree of precision required is different from case to case, thus it is not only important the energy received by solar radiation at a given time, but also the angle of incidence of the direct beam component, the amount of diffuse radiation and the spectrum of the radiation. Differently from many commercial PV application, whose sizing can, nowadays, follow some simple rules to be cost effective, when it is being considering a BIPV shading device system, the threshold is subtle, due to some intrinsic problems such as close shadows, tilt and/or azimuth angles variation along the day, heterogeneous temperature variation on the modules which makes either the PV cells work in bad conditions or the energy production difficult to predict.

Therefore, the model developed in this project requires a quite fine time scale, then a sample time of 10 minutes is implemented. Also, a high degree of precision is needed for determining the solar position, as well as a solid distinction among the radiation components. By doing that, the model is reliable in those above mentioned fast-changing conditions.

In the literature, for many hourly solar applications, or even daily ones, the time scale is well-detailed to consider accurate solar radiation calculations. Due to the unpredictability of the weather, in the solar engineering is meaningless to work on a finest time scale. As solar calculations are performed since many years ago and their use is widely diffuse, it is easy to find many models to do those hourly computations. A good example is the work of Duffie and Beckman [24], which has become an international standard on such field and so during this
project is used the same nomenclature to explain the principles of the solar radiation calculation. Posteriorly, two different methods to be used to get 10 minutes time step calculations are obtained. Finally, the method proposed is validated with the experimental data.

Finally, during the developed of this chapter, not only would be calculated the incident irradiance, but it would also be considered second order effects that would influence the effective energy collected by the PV modules.

2.1. Main Concepts

It is well known that almost all the energy on the Earth is delivered by the Sun. From such energy source, the solar radiative power which reaches the planet is about 170000 TW. Such power is enough to move the water cycle, to make the winds blow and biomasses to grow and so on. Thus, solar energy is by far the biggest renewable energy resource. This is possible, because inside the sun core, the hydrogen fuses into helium, releasing power around 3.85X10^26 W at a temperature close to 15X10^6 degrees [24]. However, the convection zone of the Sun reaches a temperature of 5777 K approximately. In fact, that is the temperature of a black body emitter, which is the best approximation to the Sun spectrum measured outside the Earth atmosphere.

The black body spectrum can be calculated following the Planck’s law, expressed by the Eq. (2.1). Moreover, in the Figure 9 is shown the graph of such spectrum.

\[
E_{λ, b}(λ, T) = \frac{2hc_0^2}{λ^5 \left[ \exp\left(\frac{hc_0}{λkT}\right) - 1 \right]}
\]

Eq. (2.1)

Where,

\[ h = \text{Plank constant} = 6.62607004 \times 10^{-34} [m^2kg/s] \]
\[ k = \text{Boltzmann constant} = 1.381 \times 10^{-23}[J/K] \]
\[ 2hc_0^2 = C_1 = 3,7405 \times 10^{-16} [m^2W] \]
\[ \frac{hc_0}{k} = C_2 = 0,0143879 mK \]
By integrating the Plank’s law on the whole spectrum, from zero to infinity, the Eq. (2.2) is obtained.

\[ E_b = \sigma T^4 \]  
Eq. (2.2)

Thus, a temperature of 5777 K leads to a flux of \( 6.315 \times 10^7 \) W/m\(^2\) emitted by the convective zone surface, at a radius of 6.95\( \times 10^8 \) m. It is assumed that the radiation does not interact with vacuum, thus the mean Sun-Earth distance of 1.495\( \times 10^{11} \) m the Solar Constant is obtained, represented by the Eq. (2.3).

\[ G_{sc} = E_b \frac{R_{\text{Sun}}^2}{R_{\text{Sun-Earth}}^2} = 1367 \text{ W/m}^2 \]  
Eq. (2.3)

Where,

\[ R_{\text{Sun}} = \text{sun radius [m]} \]
\[ R_{\text{Sun-Earth}} = \text{mean Sun Earth distance [m]} \]
\[ E_b = \text{Spectrum [W/m}^2\text{]} \]

However, the solar radiation reaching the Earth surface is not constant, due to the variation of the Sun-Earth distance and the solar activity. In fact, the Earth orbit has an eccentricity of around 1.7 %, with the minimum distance occurring at perihelion [24]. Therefore, the radiation outside the atmosphere for a certain year day can be determined by Eq. (2.4).
\[ G_{on} = G_{sc} \left( 1 + 0.33 \cos \left( \frac{360n}{365} \right) \right) \left[ \frac{W}{m^2} \right] \]

Eq. (2.4)

Where \( n \) is the day number of the year, in years where February 29th is present (leap years), the \( n \) value is treated like February 28th. Solar cycles last for roughly 11 years and involve a variation of about 0.02% respect to what is mentioned above, i.e., such variation is commonly neglected, as it has been done in this project.

In the Figure 10 is found the yearly behavior of the irradiance, which is implemented to determine the radiation outside the atmosphere. Furthermore, in the Figure 11 the different components of the extraterrestrial irradiance and how they arrive to the Earth surface is shown.

Figure 10. Maximum irradiance along the year. Source: [25]

Figure 11. Different components of the extraterrestrial solar radiation. Source: [25]
It must be noticed that not all the energy which reaches the atmosphere is available on the surface. This is mainly due to the interaction between the atmosphere and the radiation, which is characterized by scattering and absorption singularities that cause its attenuation. Thus, the three-typology observed of scattering includes [24]:

- Rayleigh scattering;
- Mie scattering;
- Non-selective scattering.

Rayleigh scattering occurs if the particle size is much smaller than the incident radiation wavelength. This phenomenon turns the sky blue when the radiation crosses a small thickness of atmosphere and it turns it red when the sun rays are low on the horizon during sunrise and sunset. That is because the blue radiation, of shorter wavelength, is four times more scattered than the red light, so the red scattering is not perceptible for high Sun positions, when the atmosphere crossed is the less.

Instead of Rayleigh, if the dimension of the particles is bigger than the wavelength Mie scattering occurs, and the reflected light will have the color of the affected particle. For that reason, the clouds are seen in bright white when there is much light.

On the other hand, the non-selective scattering is responsible for the grey color of low clouds and fogs, and does not depend on the incident radiation wavelength. Finally, in the Figure 12 is displayed a map graph in which is found the solar radiation incident all over the world and how much resource is available.

![Figure 12. Solar radiation availability on the globe. Source: [25]](image-url)
A useful parameter that allows to model the sky scattering behavior is the air mass. Air Mass $AM$ indicates the length traveled by the radiation in the atmosphere in relation to the atmosphere thickness. Such expression is represented by Eq. (2.5).

$$AM = 1/\cos\theta_Z$$

Eq. (2.5)

Where,

$$\theta_Z = \text{Zenith angle of the sun [degrees]}$$

As a result of the scattering, caused mainly by: water vapor, carbon dioxide and ozone, on the Earth is received solar radiation in two forms: beam radiation and diffuse radiation.

As it is mentioned above, the scattering depends on which and how many particles the sun rays get in touch with during their journey. It is well known that in different parts of the world there are different weathers along the year, so that not only the amount of radiation varies, but also its spectrum. Therefore, the solar radiation distribution not only depends on the latitude, but it is far more uneven because different wavelengths are absorbed by different particles. Such particles may be present unevenly across the atmosphere. Thus, the short-wave radiation is completely absorbed by oxygen, ozone and nitrogen; the visible radiation can be absorbed and scattered by dust, aerosols and pollutants; whereas the long-wave radiation can be absorbed up to 20% by water vapor and carbon dioxide.

### 2.2. The position of the Sun

The Sun position in the sky is important for solar systems application and it can be always expressed, referred to an observation point, by a pair of angles: the zenith angle (or its complementary solar altitude angle) and the azimuth angle. The zenith angle ($\theta_Z$) has values either from 0°, when it is exactly on the zenith, to 90°, at the horizon height. The azimuth angle ($\gamma_S$) has values from -180° to 180°, with the zero value on the South and increasing from East to West [24].

The method to calculate these two angles depend on the latitude of the location ($\Phi$), the declination angle ($\delta$) and the hour angle ($\omega$). The declination angle is the angle between the terrestrial spin axis and the circle of illumination of the Earth, that varies seasonally (in fact this is the cause of the seasons) following the Eq. (2.6).

$$\delta = 23,45 \sin \left[ \frac{360(n + 284)}{365} \right] \ [deg]$$

Eq. (2.6)

While the hour angle is the angle between the sun and the local meridian, expressed by Eq. (2.7).
\[ \omega = 15(ST - 12) - (L_L - L_R) \ [\text{deg}] \]

Eq. (2.7)

Where \( ST \) is the solar time, and this angle is corrected by the difference between local longitude and reference longitude of the time meridian. Note that \( \omega \) is zero at solar noon, negative in the morning and positive in the afternoon.

The solar time is different from the standard time due to some disturbances in Earth rotation as predicted by Kepler’s laws. In fact, “The radius vector joining the planet to the Sun covers equal areas in equal times”. The solar time, presented by Eq. (2.10), will be equal to the local time plus the following correction factor shown in Eq. (2.8). The respective time equation correction is shown in the Figure 13.

\[
E = 229.2(7.5 \times 10^{-5} + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B \ [\text{minutes}] 
\]

Eq. (2.8)

\[
B = (n - 1) \frac{360}{365} 
\]

Eq. (2.9)

\[
ST = \text{Local time} + \frac{\text{reference longitude} - \text{local longitude}}{15} + \frac{E}{60} \ [\text{hours}] 
\]

Eq. (2.10)

![Figure 13. Time equation correction expressed in minutes. Source: [25]](image)

After all, zenith and azimuth angles can be calculated by follows Eq. (2.11), Eq. (2.12) and Eq. (2.13).

\[
\cos \theta_z = \sin \delta \sin \Phi + \cos \delta \cos \Phi \cos \omega 
\]

Eq. (2.11)
\[
\gamma_S = C_1 C_2 \gamma_S' + C_3 \left(1 - \frac{C_1 C_2}{2}\right) 180 \text{ [deg]}
\]

Eq. (2.12)

\[
tan \gamma_S' = \frac{\sin \omega}{\sin \delta \cos \omega - \cos \Phi \tan \delta}
\]

Eq. (2.13)

\(C_1, C_2\) and \(C_3\) are constants that can assume the value of +1 or -1 depending on \(\omega, \delta\) and \(\Phi\) in order to force the solar azimuth angle to stay in the proper quadrant. It assumes values between -180° and +180° just like the hour angle does.

In the Figure 14 is shown a summary schematic diagram, which represents the tilted position of the surface with respect to the incident solar radiation. By analyzing the scheme is observed the characteristics solar angles explained above.

\[\text{Figure 14. Solar coordinates. Source: Own}\]

2.2.1. Alternative solar position methods

For high precision applications, such as high-concentration solar thermal applications, the degree of precision in calculating the solar coordinates of the presented model is not satisfactory, so a variety of different models have been created. Muriel et al. [26] have checked different models, proposed the PSA algorithm that slightly improves the previously revised ones. Moreover, in their work, they fully described it and demonstrated its easiness to use. Due to that, in this project it is followed a test methodology similar to that one, along with the classical model, to understand if this application is worthwhile to expend some computational effort for this task.
2.3. Solar radiation on tilted surfaces

In order to know the energy reaching in a given moment on a tilted surface ($\beta$), oriented at $\gamma$ degrees from south, first it is necessary to know the angle of incidence of the beam light on the surface. A usual simplification is to assume that the declination angle is constant over a day, so that one variable in the calculation can be neglected. At a given instant the solar incidence angle is given by Eq. (2.14), Eq. (2.15), Eq. (2.16) and Eq. (2.17).

$$\cos \theta(t) = T + U \ast \cos \omega(t) + V \ast \sin \omega(t)$$  \hspace{1cm} \text{Eq. (2.14)}

$$T = \sin \delta \ast (\sin \Phi \cos \beta - \cos \Phi \sin \beta \cos \gamma)$$  \hspace{1cm} \text{Eq. (2.15)}

$$U = \cos \delta (\cos \Phi \cos \beta + \sin \Phi \sin \beta \cos \gamma)$$  \hspace{1cm} \text{Eq. (2.16)}

$$V = \cos \delta (\sin \beta \sin \gamma)$$  \hspace{1cm} \text{Eq. (2.17)}

Secondly, it is necessary to get some weather data to understand which is the amount of radiation reaching the location in that time. Solar radiation can be divided in a beam, directional component coming directly from the Sun and in a diffuse component resulting from atmospheric scattering, but once all this radiation reaches the ground it is not completely absorbed. This partial reflection, called albedo, can illuminate tilted surfaces and depends on the reflectivity of the ground. On a horizontal surface, whose sky view is not obstructed, there are only two components, the beam and the diffuse.

The simplest instrument to measure the solar radiation is the pyranometer, that measure the total radiation flux ($I_h$). A more sophisticated instrument is the pyrheliometer, which is able to measure the beam component ($I_{b,h}$) separately thanks to its very narrow vision angle, but it needs a very accurate tracking system. The most common solution implemented consists in measuring the total irradiance with a pyranometer and the diffuse irradiance ($I_{d,h}$) by shading with a band another pyranometer. By doing that, the daily sun path is obstructed, so the only component that is registered is diffuse. The direct component can be calculate as the difference between the two measurements. This is the strategy applied in the experimental set-up of this project, in the Test Facility of the Solar Tech Lab, which will be described in the following chapters.

Once measured the radiation on the horizontal, the model of the sky behavior is required to understand which irradiance is reaching a surface that is exposed differently. As reported by Soga et al. [27] and by Noorian et al. [28], there are many studies that show how to calculate the diffuse component on a tilted surface on hourly basis. The hypothesis that this
component is completely isotropic proved to be unsatisfactory when it is compared with measurements: in fact, it is possible to estimate, starting from the horizontal data, different sub-components of the diffuse radiation fraction. Some of these models, such as Hay, Reindl and Skartveit ones, use the clearness index as parameter to do it.

The clearness index is defined as the ratio between hourly energy on the horizontal and the hourly energy on the horizontal just outside the atmosphere. This latter can be calculated by Eq. (2.18) and Eq. (2.19).

\[
H_0 = \frac{86400}{\pi} G_{on} \left( \cos \Phi \cos \delta \sin \omega_S + \frac{\pi \omega_S}{180} \sin \Phi \sin \delta \right) \left[ \frac{J}{m^2} \right]
\]

Eq. (2.18)

Where the sunset hour angle can be calculated as:

\[
\omega_S = \arccos(-\tan \Phi \tan \delta) \ \ [deg]
\]

Eq. (2.19)

Eq. (2.18) comes from the hourly integration of the product of the maximum irradiance and the incidence angle between the sun and the horizontal, that is the solar zenith angle.

On the other hand, a different, but very closely related topic, is the separation of the diffuse irradiance, that is on instantaneous values. There are some statistical correlations useful to pass from hourly energy to power, and then distinguish the instantaneous sub-components. Conceptually, once the instantaneous beam and diffuse irradiances are obtained, the methodology to follow is:

1. To divide the diffuse radiation in sub-components depending on the sky conditions.
2. To apply geometrical view factors to each component and sub-component of the solar radiation (beam, reflected, different types of diffuse) separately.
3. To sum all the different components obtained together.

The development of this project uses irradiances values registered for 10 minutes time steps. Due to that, it is acceptable to suppose that the radiation is nearly constant during such time interval and it is equal to its average value. Thus, the correlations made for irradiances can be extended to the project’s intervals, making the proper changes in the integrations.

Regarding the first step, there are different options to evaluate. Above all, the main include: isotropic model; circumsolar radiation anisotropy, circumsolar radiation and horizon brightening anisotropies.

The isotropic model implies a homogeneous distribution of the radiation from every sky direction. This is the simplest model and it does not need any parameter. Nevertheless, this is the less accurate model.
The circumsolar anisotropy model, also known as Hay and Davis model, distinguishes between the isotropic part and a brighter part that comes from solid angles close to the Sun position in the sky. It requires the use of two parameters: the beam ratio and the beam index. The beam ratio is the geometrical view factor of the beam radiation and it will be discussed later on, while the beam index ($A_i$) is very similar to the clearness index, but it is in terms of irradiance and involves the beam part of the radiation. The circumsolar part is higher if the direct component is bigger, and so if the sky is clearer.

$$A_i = \frac{G_{bh}}{G_0}$$

Eq. (2.20)

The third option is called HDKR model and includes a further brighter zone in the sky in correspondence to the horizon. Additionally, it requires a third parameter to quantify the horizon brightening. When the horizon is not clear of obstacles such as hills, mountains and buildings, it is not easy to understand if such model is possible to be applied. Therefore, in this project is applied the Hay and Davis model (such model is one of the most used due to its simplicity).

As it has been mentioned before, to calculate the beam and the circumsolar diffuse radiation on a tilted surface, it is needed a geometrical factor that distributes the radiation received by a horizontal surface on another one with a different incidence angle. Instantaneously the beam ration is defined by Eq. (2.21).

$$R_b = \frac{\cos \theta}{\cos \theta_z}$$

Eq. (2.21)

However, even with relatively small-time steps, it is not possible to simplify the ratio of Eq. (2.21) with the ratio of the average values. That can lead to huge errors, especially when the angles involved are small (for instance, during sunrise or sunset this ratio can tend to infinity). For a given time interval, characterized by an initial hour angle $\omega'$ and a final hour angle $\omega''$ it is obtained the expression of Eq. (2.22).

$$\overline{R_b} = \frac{T(\omega'-\omega') + U_h (\sin \omega'' - \sin \omega') - V (\cos \omega' - \cos \omega')}{T_h (\omega'-\omega') + U_h (\sin \omega'' - \sin \omega')}$$

Eq. (2.22)

$$T_h = \sin \delta \sin \Phi$$

Eq. (2.23)

$$U_h = \cos \delta \cos \Phi$$

Eq. (2.24)
The isotropic diffuse component on the horizontal is fully viewed by a horizontal surface, but a tilted one has a view factor of the sky calculated by Eq. (2.25).

\[
F_D = \frac{1 + \cos \beta}{2}
\]

Eq. (2.25)

The albedo component is supposed to be isotropic and its intensity is equal to the product of the total irradiance on the horizontal multiplied by the reflectivity of the ground. The view factor of a surface to the ground is given by Eq. (2.26).

\[
F_R = \frac{1 - \cos \beta}{2}
\]

Eq. (2.26)

As a conclusion, the average total irradiance reaching a tilted surface, that in the project case is representative of the average irradiance over ten minutes is expressed by Eq. (2.27).

\[
\bar{G} = \bar{G}_{b,h} + \bar{G}_{d,h}A_g \frac{1 + \cos \beta}{2} + \bar{G}_{d,h}(1 - A_g) \frac{1 - \cos \beta}{2} + \bar{G}_{R,g} \frac{1 - \cos \beta}{2}
\]

\[
\text{[W/m}^2]\]

Eq. (2.27)

In the Figure 15 is shown how the different radiation components reach a tilted surface, considering the HDKR sky model.

Figure 15. Solar radiation incident over a tilted surface. Source: [24]

2.4. Angular losses

Not all the radiation that reaches the surfaces of the PV modules is transmitted to the cells, some part of that is reflected by its cover, that is usually an in-glass material. The amount of reflected radiation depends at first instance on the angle of incidence, but also, it
depends on the soiling. If the modules are not cleaned periodically, some dust is deposited on it, especially in dry locations.

For this reason, the real performance of the cells would not be the same if the surface of the cover is clean and the light comes perpendicularly. This kind of losses are often neglected, but they can lead to overestimation of the energy produced during a long time. Hence, Martin and Ruiz [29] developed an analytical model whose parameters are fitted thanks to an experimental campaign. According to their model, the angular losses for any incidence angle can be expressed by Eq. (2.28).

\[
AL = 1 - \left( 1 - \exp \left( -\frac{\cos \theta}{ar} \right) \right) \left( 1 - \exp \left( -\frac{1}{ar} \right) \right) 
\]

Eq. (2.28)

Where, parameter \( ar \) is the angular losses coefficient, which depends on the encapsulation configuration and on the degree of soiling. It may vary from 0.13 for clean low reflecting encapsulation with Indium Tin Oxide (ITO) layers on amorphous silicon, up to 0.27 for very dirty surfaces. For clean materials, it is possible that a good angular response coincides with poor transmittance at normal incidence as it is the case for glass-ITO configurations. In the Figure 16 is shown the behavior of the coefficient \( ar \) with respect to different incident angles.

The total reflection of a light ray is always calculated as the normal reflectivity worsening due to the dust \( R_{0,dusted}/R_{0, clean} \), which varies from 1 to 0.9, multiplied by the angular losses. It is convenient to assess, for a directional irradiance an effective irradiance that is corrected in the light of the reflection losses, as it expressed by Eq. (2.29).

\[
G_{dir, eff} = \frac{R_{0,dusted}}{R_{0, clean}} G_{dir}(1 - AL(\theta))
\]

Eq. (2.29)

![Figure 16. Angular losses coefficient effect on angular losses Source: Own](image)
The same reduction factor can be applied for both beam and circumsolar diffuse radiation. On the contrary, for isotropic diffuse and albedo components, there is not just one direction, but the angular losses correlation must be integrated on the solid angle hemisphere. To do that the Eq. (2.30) is used.

\[
ALD = \frac{\int_0^{2\pi} d\varphi \int_0^{\pi/2} AL(\theta) \cos \theta \sin \theta d\theta}{\int_0^{2\pi} d\varphi \int_0^{\pi/2} \cos \theta \sin \theta d\theta} = \frac{2\pi \int_0^{\pi/2} AL(\theta) \cos \theta \sin \theta d\theta}{2\pi \left[ \sin^2 \theta \right]_0^{\pi/2}}
\]

\[
ALD = \sum_{i=1}^{N} 2AL(\theta_i) \cos \theta_i \sin \theta_i \Delta \theta_i = \sum_{i=1}^{N} AL(\theta_i) \sin 2\theta_i \Delta \theta_i
\]

Eq. (2.30)

Where the solid half-hemisphere is divided into \( N \) portions following on the incidence angle \( \theta \), each one counting for an angle range \( \Delta \theta \).

Such distributed angular losses coefficient can vary between 3 % and 11 % depending on the soiling. The isotropic type effective irradiances will be calculated as follows by Eq. (2.31).

\[
G_{iso,eff} = \frac{R_{\text{adjusted}}}{R_{\text{clean}}} \cdot G_{iso}(1 - ALD)
\]

Eq. (2.31)

### 2.5. Spectral shift effect

PV cells are spectrally selective, that means they are able to catch a different fraction of light depending on its wavelength. Under Standard Test Conditions (STC), the light has a spectrum corresponding to \( AM=1.5 \), so in general under real condition the efficiency of the modules will be different from the nominal one. In the Figure 17 is represented the spectral responsivity of a silicon cell, for different types such as monocrystalline, polycrystalline and amorphous.

Furthermore, in [30] is proposed a method for the characterization of the spectral influence on PV modules based on the clearness index and a modified air mass parameter, both measurable on-site. The modified air mass considers the atmospheric pressure, but as the Weather Station of Solar Tech Lab does not measure it, for the development of the project such factor has been ignored. Instead of it, it has been used the correction of the air mass for high zenith angle, that is \( \theta_Z > 60^\circ \). The behavior is represented by Eq. (2.32).

\[
AM = \frac{1}{\cos \theta_Z + 0.15(93,885 - \theta_Z)^{-1.253}}
\]

Eq. (2.32)
Moreover, such work presents an easy way to use a parametric formula of the spectral responsivity, which is applicable either to monocrystalline, polycrystalline or amorphous silicon cells. Such formula is represented by Eq. (2.33).

\[ S = cS_{STC} \exp\left(a(K_T - 0.74) + b(AM - 1.5)\right) \]

Eq. (2.33)

Where, \( S_{STC} \) is the spectral responsivity in standard conditions and it depends on the technology. The parameters \( a, b \) and \( c \) depend on the technology and on the type of radiation component (beam, diffuse, albedo). For cloudy days no clear correlation emerged, so they registered directly the values of the effective responsivity for the diffuse and albedo component. Notice that in this case, the circumsolar diffuse radiation must be treated as an isotropic diffuse because it has the same spectrum. For each of the three radiation components, the corrected irradiance that considers the spectral shift is then obtained by Eq. (2.34).

\[ G_{SS} = G_{eff} \frac{S}{S_{STC}} \]

Eq. (2.34)

In the Table 1 and Table 2 re gathered the values for all the parameters involved in the Eq. (2.33) and Eq. (2.34).

<table>
<thead>
<tr>
<th>Table 1. Spectral responsivity: standard and cloudy conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m\text{-Si} )</td>
</tr>
<tr>
<td>( S_{STC} )</td>
</tr>
</tbody>
</table>
Moreover, in the Figure 18 it is showed the behavior of the spectral responsivity ratio with increasing versus the clearness index for m-Si. That graph is not representing a real behavior, as the constant part on the left is representing the responsivity ratio in “cloudy” conditions, that means a lack of beam radiation: this situation happens for \( A_i=0 \), independently from the \( K_T \) value. It is represented in this way because the tested conditions in [30] never went below \( K_T=0.5 \) for sunny days.

![Spectrum shift on mono due to \( K_T \)](image)

Figure 18. Clearness index dependence of spectral responsivity ratio for m-Si. Source: Own
2.6. Validation of the model

The objective of this part of the work is to understand if the method described for the calculation of irradiance is good enough to be used in the BIPV energy production model. To do so, it is compared the measured data of global irradiation on a 30° tilted pyranometer with the calculations done in the project based on horizontal data. The instruments used for this scope, are the ones existent on the Weather Station of the Solar Tech Lab, located on the roof of the Energy Department of the Politecnico di Milano [31].

To understand the quality of the results, four weeks have been analyzed in the four seasons of the year 2016. For each week, it two errors are calculated, both expressed in percentage: the weighted mean absolute error and the normalized root mean square error, following the Eq. (2.35) and Eq. (2.36).

\[
WMAE = \frac{\sum_{i=1}^{N} |G_{mes,i} - G_{est,i}|}{\sum_{i=1}^{N} G_{mes,i}} \times 100 \text{ [%]}
\]

Eq. (2.35)

\[
nRMSE = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^{N} (G_{mes,i} - G_{est,i})^2}}{\max(G_{mes})} \times 100 \text{ [%]}
\]

Eq. (2.36)

The implementation of the solar radiation estimation method, with both solar position calculation methods, demonstrated to be in good agreement with the measured data as shown in Table 3.

<table>
<thead>
<tr>
<th>Solar coordinates model</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duffie &amp; Beckman</td>
<td>8,78</td>
<td>7,59</td>
<td>9,73</td>
<td>15,67</td>
</tr>
<tr>
<td>Muriel</td>
<td>8,80</td>
<td>7,42</td>
<td>9,77</td>
<td>15,54</td>
</tr>
</tbody>
</table>

Table 3. Radiation calculation errors

Considering that the three pyranometers used for the measurements have a tolerance between 2,5 % and 5 %, depending on the product, the errors that can be addressed to the method with high confidence are very few, except for the autumn week. To have an idea of the impact of such errors, in the Figure 19 and Figure 20 are reported the best and the worst weekly performances of the model.
Figure 19. Muriel version model for the spring week. Source: Own

Figure 20. Duffie & Beckman version of the model for the autumn week. Source: Own

From such results, it is discovered that the method to calculate the radiation on tilted surfaces is accurate. Even if there is no evidence with this test that one solar position calculation method is better than the other one, for the development of the project is implemented the PSA algorithm, mainly because it is supposed to be more precise. Such method could make the difference in the moment of calculating the shadows that are casted on the PV cells.
3. CHAPTER 3
PV MODEL SIMULATION

On this chapter is described the concept of the photovoltaic system and how its respective photovoltaic effect operates applied to electrical engineering environment. Along with this, it is explained which are the photovoltaic applications existent nowadays, focusing specially in the PV-grid connected system, which is the one currently developed by the project. Then, is exposed how the photovoltaic cell is simulated, clearing up in detail all the formulas to be implemented and each one of the existent models in the literature, showing a suitable way to extract all the meaningful parameters. Finally, it is done the validation of the chosen model with respect to measured real power data given by the solar tech lab of the Politecnico di Milano.

3.1. PV Systems

PV modules are solid-state devices that convert sunlight directly into electricity without any intervening heat engine or rotating equipment (conventional techniques). It generates electricity without producing emissions of greenhouse or any other gases, and its operation is nearly silent. PV systems can be built in any size, from milliwatt (mW) to megawatt (MW), because the system might be modular, thus by adding solar panels the respective output power is increased.

In addition, the system can be based either on crystalline technologies such as monocristalline and polycristalline, or on thin films of materials, such as amorphous silicon alloys, cadmium telluride, or copper indium diselenide. All those materials are interesting for working with, because they are suitable to do mass production techniques and the amounts of active materials required are small.
Another aspect to consider is the easiness to install the systems in remote areas without any access to the grid. For such areas, even if the PV system can result expensive, at the end of the day it is cost-effective, especially because either there is no power from conventional sources or having power from conventional sources there is impractical and costly. On the other hand, for grid connected distributed systems, the actual value of photovoltaic electricity can be high because this electricity is produced during periods of peak demand, thereby reducing the need for costly extra conventional capacity to cover the peak demand. Additionally, PV electricity is close to the sites where it is consumed, thereby reducing transmission and distribution losses and thus increasing system reliability.

Finally, a PV cell consists of a P–N junction fabricated on a thin layer of a semiconductor, which is a material consider as a good conductor of electricity. The materials most commonly used are silicon (Si) and compounds of cadmium sulphide (CdS), cuprous sulphide (Cu2S), and gallium arsenide (GaAs).

Likewise, as long as the PV cell is being exposed to the sunlight, electrical current is generated on the outlets terminals of it. Such electrical output, taking from a single cell is generally small, thus multiple cells are connected and encapsulated (usually glass covered) to form a module (also called a panel) which produces a greater voltage, and as a consequence greater energy values to use. Finally, PV panel is the main building block of a PV system, and any number of panels can be connected to give the desired electrical output.

**PV Effect**

The photovoltaic conversion is a process to change the electromagnetic radiation into electrical power. When the photons with energy larger than the band-gap energy of the semiconductor are absorbed, create some electron–hole pairs proportional to the incident radiation. Under the effect of the internal retarding electric fields of the p–n junction, these carriers are swept apart and create a photocurrent which is directly proportional to solar irradiance [32].

![Figure 21. Photovoltaic effect. Source: Own](image-url)
On the contrary, if the photon energy is smaller than energy band gap, the electron will not have sufficient energy to jump into the conduction band, and the excess is converted into kinetic energy of the electrons, which leads to increased temperature. This is the reason for the low efficiency of the photovoltaic cells. That operation is represented in the Figure 21.

**Solar cells principles and manufacturing nobs**

A PV cell basically consists in an absorber and selective contact [33]. There are many different materials and geometry to build them, but all of them share the same current-voltage characteristic, since they are based on the same semiconductor diode behavior.

Inside the absorber, the light generates electron-hole pairs due to the excitation of electrons to higher energy electronic states and the consequent creation of a positive charge, with low energy, in the hole it left behind. While the light continues exciting electrons this phenomenon continues, but in the meanwhile recombination increases leading to a steady condition. This condition is characterized by a splitting of the quasi-Fermi energy of the absorber into a high value for electrons and a low value for holes.

If the absorber is faced with materials with a different quasi-Fermi level (i.e. if between the materials there is an electrochemical potential difference), it is created a driving force to transport electrons and holes towards them. If the facing material has higher energy, the electron will tend to flow to them through the conduction band, while holes to low-energy contacts through the valence band. Anyway, to make current to flow in only one direction (i.e. with no chance for electron and holes to pass through both contacts at the same time), the contact must be selective, i.e., a Hole Transporting Layer (HTL) and an Electron Transport Layer (ETL) are required.

If the cell is leaved under illumination and left in open circuit, the electrochemical potential of the electrodes will align with the electron/holes quasi-Fermi level due to the selective contacts. For this reason, it is registered an open circuit voltage in solar PV cells. If some voltage is applied in the opposite direction, i.e. imposing a voltage lower than the open circuit one, the current can flow and thus PV power is obtained.

In Figure 22 the working principle of any solar cell is explained. Electron (showed as red) and holes (showed as blue) energy levels are represented on the vertical axis. On the right side, the ETL has a high energy channel in red while on the left side, in blue, the channel of HTL is represented. It is important to notice that electrodes properties are not important in determining the cell characteristics when good selective contacts are achieved.
P-N junction are absolutely the most studied selective contact for solar cells, as it is the base for crystalline silicon working and it theory is diffused worldwide [34]. However, different doping of semiconductors is not the only way to fabricate selective contacts. For instance, it is possible to use metal-semiconductor interfaces or heterojunction structures. The secret behind the silicon solar cells relies mostly not on the P-N junction itself, but on the excellent absorbing characteristics of crystalline silicon (p-type often). In fact, it is possible to have high performance of solar cells even without the P-N junction.

It is important to note that maximum efficiency of solar cells can be achieved only if both HTL and ETL are present. Furthermore, P-N junction HTL performance can be enhanced by the addition of N-N+(HTL) and P-P+(ETL) junctions that make the contacts even more selective, making “passivated” cells to be more efficient than the traditional ones.

The p-type absorber /P-N junction technology is well suited for ordered crystalline cells, where the electrons can diffuse through the absorber easily and reach the contacts. For disordered materials, such as amorphous silicon, the ability of the minority carriers to diffuse is dramatically reduced, so that the use of selective contacts alone is not sufficient to make a cell work. For that kind, it is necessary to build an electric field in the absorber layer to make carriers drift towards the selective contacts. This influences the cell model as it will be explained later.

To make the crystalline cells collecting as much photons as possible, their external surface is textured before the phosphorous deposition in order to decrease reflection losses. For the same reason, an antireflection coating is added on top of it. After that, the metal (silver) contacts are added to collect electrons and connect the cell to the electrical circuit.
**PV Systems Applications**

A solar cell is an electronic device which transforms solar radiation into electrical energy [35]. Due to the voltage drop on each cell is around 0.5 volts, the total amount of electrical applications is directly associated with the number and configuration used of such cells, which builds a solar module and further a PV generator. The output power produced depends linearly, on a first approach, on the modules surface [36].

Under a general point of view, a PV system is built by a gathering of modules and a set of elements which adapts the electrical energy produced by the generator for multiple applications such as: outside lighting, complete electrification and selling energy into the grid [37]. PV systems can be classified into two main groups: stand-alone and grid-connected [37]. In the Figure 23 is shown a block diagram for the classifications previously mentioned.

![Figure 23. Block Diagram (a) Stand-Alone (b) Grid-Connected](image)

The first group is required to ensure the electrical availability in cases in either the generation is lower than demand or when there is not sunlight. For that reason, is indispensable to store the energy produced during such periods. On the other hand, for the second group there is no safety requirements in the energy supply, so that the criteria for electing the generator power is more ambiguous. In this case, the network is an electrical energy infinite source. This kind of systems allow to exchange electrical energy with the grid, when the generation exceeds the user energy needs, and will withdraw energy from the grid when the demand is higher than the energy generated by the PV. For the development of this project is selected the last group, because the BIPV would be connected to the grid without the necessity of a battery group, making energy exchange between the building and the electrical network every day (when is required).
**PV Grid Connected**

A PV system grid-connected consists in an array of elements, in which are including the solar panels and the inverters. As it is already explained, the objective of PV system is to generate electrical energy from the solar primary radiation through the photovoltaic effect. If such systems should be connected in facilities in which the grid voltage is from nature alternate, is necessary to implement an inverter which allows to inject electricity into the power system from the PV generator [38].

On the Figure 24 is shown a specific block diagram for a Photovoltaic Grid Connected Building (PVGCB), in which is found each one of the components used by the system, which also can be applied in distributed generation DG. As a first instance, it is found the PV generator, which is formed by PV modules and its correspondent support structure. Then is found the inverter, which is the responsible to adequate the power parameters produced by the DC generator to variable voltage, which is the one required by the low voltage electrical network. In addition, there is the point of common coupling (PCC), in which is located the protection elements used for PVGCB safety. Along with the previous elements, it is installed a bidirectional meter, which object is to register the energy consumed by the grid plus the energy delivered to the system in a specific instant of time. Finally, there is the load, which is made by all the elements (linear and no-linear) which demand electrical energy for its functioning, and the electrical network.

![Figure 24. PV System Grid-Connected. Source: Own](image-url)
Its functionality with the electrical network consists on the transformation of the DC energy produced by the PV generator into AC energy. That energy must guarantee the same parameters of the network, so the PV generator can connect automatically with the grid. The inverter is the device in charge of that process, providing a stable voltage output and a variable current in function of the irradiance. The alternate current generated by the inverter is synchronized with the grid frequency (50 – 60 Hz), after that, it passes through the meter and is injected to the network.

### 3.2. PV cell characteristics

As it was explained above, a PV generator is a gathering of solar cells, connections, shielding parts, and supports. The semiconductors with which the panels are made, are treated in a specific way to form an electric field with positive on one side (backside) and negative on the other side, facing the sun. If electrical conductors are attached to the positive and negative sides, an electrical circuit is created and the electrons flowing are captured in the form of electric current, called photocurrent ($I_{pv}$). Thereby, during darkness the solar cell is not enabled and works as a regular diode, i.e., a p-n junction that does not produce any current or voltage. Nevertheless, if such terminals are connected to an external, large voltage supply, a current is generated, such current is called the diode current or dark current ($I_D$).

The equivalent circuit is denoted in the Figure 25, it is characterized by an electrical equivalent one-diode model. Nonetheless, through this document are presented all the possible existent models implemented for this project. This circuit can be used for either an individual cell, or a module consisting of some number of cells, or an array consisting of several modules connected each other.

![Figure 25. Single solar cell model. Source: Own](image)

As it can be seen in the Figure 25, the model consists on a current source $I_{pv}$, a diode, and a series resistance $Rs$, together with a shunt resistance $Rp$. Both resistances represent the inherent losses of the solar cell, where $Rs$ represents connection losses, bulk resistance of the semiconductor, whilst $Rp$ is the resistance related to the diode and represents the losses.
PV MODEL SIMULATION

due to recombination of electrons, also it represents the non-ideality and impurity in the materials. From developing Kirchhoff’s current law, the net current is given by the Eq. (3.1).

\[
I = I_{pv} - I_D = I_{pv} - I_o \left\{ e^{\frac{q(V+I*Rs)}{k*T_c}} - 1 \right\} - \frac{V + I * Rs}{R_p}
\]

Eq. (3.1)

Where,

\[ k = \text{Boltzmann’s gas constant} = 1.381 \times 10^{-23} \text{ [J/K]} \]
\[ q = \text{Electron charge} = 1.602 \times 10^{-19} \text{ [J/V]} \]
\[ T_c = \text{Absolute temperature of the cell [K]} \]
\[ V = \text{Voltage drop across the cell [V]} \]
\[ I_o = \text{Dark saturation current[A]; Strongly dependent on the temperature} \]

By analyzing the behavior of the solar cell, its current-voltage characteristic curve can be plotted for a certain irradiance at a fixed cell temperature and represents range of combinations of current and voltage [39]; an example of such behavior is shown in the Figure 26, for irradiance and temperature standard values. When the cell is short-circuited, the current is at maximum (short circuit current, \( I_{SC} \)) and the voltage across the cell is zero (point A). When the PV cell circuit is open, with the leads are not making a circuit, the voltage is at its maximum value (open circuit voltage, Voc), thus the current is null (point B).

![Figure 26. Representative current-voltage curve for PV cells. Source: Own](image)

As it can be appreciated in the figure above, when the cell’s terminals are connected to a variable load (resistive at the best scenario), the operating point is determined by the intersection of the I-V solar cell curve and the load I-V characteristic curve (point C). As the load is variable, its I-V characteristic curve can work at any point of the graph. If the load resistance is small, the cell operates in a region of the curve which behavior is similar as a
constant current source, almost equal to the short-circuit current. On the other hand, if the load resistance is large, the cell operates in a region of the curve, where the cell behaves more as a constant voltage source, almost equal to the open circuit voltage.

The power output can be calculated by the product of the current and voltage. Thereby, by applying such mathematical expression the power-voltage curve can be plotted, that curve is represented in the Figure 27. If a comparison between both graphs (Figure 26 and Figure 27) is done, for any case, either open circuit or short circuit, the power is zero. On the contrary, between open circuit and short circuit, the power output is greater than zero. Furthermore, the maximum power should be the one in which the load resistance is optimum (point C on the Figure 26, called maximum power point). When the maximum power point is analyzed, the operating points of the current (Imp), voltage (Vmp) and power (Pmp) are found, basically because when the cell is operating on such point the output power is maximized.

![Figure 27. Representative power-voltage curve for PV cells. Source: Own](image)

In addition, other fundamental parameters that can be obtained from Figure 26 are the short-circuit current and the open circuit voltage. The $I_{SC}$ is the higher value of the current generated by the cell and is obtained under short-circuit conditions, i.e., $V = 0$, and $I_{pv}$ is equal to $I_{SC}$. The open circuit voltage corresponds to the voltage drop across the diode when it is traversed by the photocurrent, $I_{PV}$, which is equal to $I_{o}$, when the generated current is $I = 0$ [40].

From Eq. (3.1) the value of $Voc$ can be obtained, evaluating the condition of $I=0$. Thus, the value of $Voc$ is expressed in the Eq. (3.3) Such voltage is the operating voltage of the cell during nighttime.
\begin{equation}
0 = I_{pv} - I_o \left( e^{\frac{qV}{kT_C}} - 1 \right)
\end{equation}
Eq. (3.2)

\begin{equation}
V_{oc} = \ln \left( \frac{I_{pv}}{I_o} + 1 \right) * V_T
\end{equation}
Eq. (3.3)

Where, \( V_T \) is the thermal voltage, which is given by:

\begin{equation}
V_T = \frac{k * T_C}{q}
\end{equation}
Eq. (3.4)

Furthermore, if Eq. (3.1) is analyzed in detail, it can be noticed that shunt resistance is usually bigger than load resistance, whereas the series resistance is smaller than the load resistance, thus, few power is dissipated within the cell. Hence, those two resistances can be neglected and the new expression for the current is given in the Eq. (3.5).

\begin{equation}
I = I_{pv} - I_o \left( e^{\frac{qV}{kT_C}} - 1 \right)
\end{equation}
Eq. (3.5)

For obtaining the maximum operational values the output power of the solar cell is analyzed. The expression is given by Eq. (3.6).

\begin{equation}
P = V \times I
\end{equation}
Eq. (3.6)

By replacing Eq. (3.5) into Eq. (3.6) it gives:

\begin{equation}
P = V \times \left( I_{pv} - I_o \left( e^{\frac{qV}{kT_C}} - 1 \right) \right)
\end{equation}
Eq. (3.7)

The Eq. (3.7) can be differentiated with respect to \( V \). When that value is set equal to zero, the maximum external voltage (Vmp) which gives the maximum power point is obtained. Notice that the result is an explicit equation of the voltage \( Vmp \) in terms of \( Ipv, I_o, T_C \) therefore if these data are known \( Vmp \) can be found by trial and error implementing the expression of the Eq. (3.8)

\begin{equation}
\left( e^{\frac{qV_{mp}}{kT_C}} \right) \times \left( 1 + \frac{q * V_{mp}}{k * T_C} \right) = 1 + \frac{I_{sc}}{I_o}
\end{equation}
Eq. (3.8)

For the case of the load current which maximizes the output power (Imp) the Eq. (3.8) is replaced into Eq. (3.5), thus:
\[ I_{mp} = I_{SC} - I_O \left\{ \frac{1 + \frac{I_{SC}}{I_O}}{1 + \frac{q \cdot V_{mp}}{k \cdot T_C}} - 1 \right\} \]

Eq. (3.9)

By solving the algebraic expression:

\[ I_{mp} = \frac{q \cdot V_{mp}}{k \cdot T_C + q \cdot V_{mp}} \cdot (I_{SC} + I_O) \]

Eq. (3.10)

Finally, as it is already explained, the output power is given by the product between current and voltage, now for evaluating the maximum operating point is simply enough with replace the respective values with their maximum values.

\[ P_{mp} = V_{mp} \cdot I_{mp} = \frac{q \cdot V_{mp}^2}{k \cdot T_C + q \cdot V_{mp}} \cdot (I_{SC} + I_O) \]

Eq. (3.11)

Till now, it only has been treated the solar cell behavior under standard conditions, such as irradiance = 1000 W/m² and temperature = 25 °C. Nevertheless, for the real operation, those values are variable and they have a big influence on the cells behavior, as it can be seen in the Figure 28.

From the figure above is seen that the open circuit voltage increases logarithmically by the increasing of irradiance, whilst the short-circuit current increases linearly. With respect to the influence of the cell temperature on the cell characteristics, is appreciated that the main effect is on the open circuit voltage, which decreases linearly causing the cell efficiency drops, also the short-circuit current increases slightly with the increase of the cell temperature.

![Figure 28. Influence of irradiation and cell temperature on PV cell characteristics. (a) Effect of increased irradiation. (b) Effect of increased cell temperature. Source: Own](image-url)
As it has been mentioned along this document, the solar cell can be operated as modules, i.e., for any desired output power, solar cells can be connected in series or parallel. In the Figure 29 is shown how the I-V characteristic curve is modified in the case where two identical cells are connected either in parallel or in series. When two identical cells are connected in parallel, the voltage remains the same but the current is summed, whereas when the cells are connected in series, the current remains the same but the voltage is summed. For both cases, it is followed the criteria of Kirchhoff's laws.

**PV panels and arrays**

PV modules are designed for outdoor use in environments such as marine, tropic, arctic, and desert. For the developing of the PV process, both the composition of the material and its atomic structure have significance. Usually the material includes silicon, gallium arsenide, copper indium diselenide, cadmium telluride, indium phosphide, and many others [41]. The atomic structure of a PV cell can be single crystal, polycrystalline, or amorphous. The most commonly produced PV material is crystalline silicon, either single crystal or polycrystalline.

Normally, the output power of a PV cell is less than 2 W at 0.5 V output voltage making it unusable for many applications. [42]. Hence, PV cells are connected in an array of series and parallel configuration in order to generate the required current and voltage. The solar cells are normally grouped into modules, which are encapsulated with various materials to protect the cells and the electrical connectors from the environment [43]. Basically, the solar panel consist of parallel branches $N_{pp}$, and for each branch there are cell series connected $N_{ss}$, as it can be seen on the Figure 30. These strings of cells are encapsulated with a polymer, a front glass cover, and a back material. Also, a junction box is attached at the back
of the module either for the wiring to other modules or connection to other electrical equipment.

![Diagram of serial and parallel array for a Solar PV model. Source: Own](image)

Based on the figure above, Eq. (3.12) can be derived, in which the current and voltage of the cell array becomes as follows [42, 44, 45].

$$I = N_{pp} \left( I_{pv} - I_0 \left[ e^{\left( \frac{V+I \times R_s \times \left( \frac{N_{ss}}{N_{pp}} \right)}{V \times R_s} \right)} - 1 \right] \right) - \left( \frac{V + I \times R_s \times \left( \frac{N_{ss}}{N_{pp}} \right)}{R_p \times \left( \frac{N_{ss}}{N_{pp}} \right)} \right)$$

Eq. (3.12)

The variables $I_{pv}$, $I_0$, $R_p$, $R_s$ are the initial parameters to be considered on a singular PV panel. When an array with multiple series and parallel branches is evaluated, the values of $N_{pp}$ and $N_{ss}$ must be considered as well. In this way, the simulation’s model will be able to represent any possible combination ($N_{ss} \times N_{pp}$) that could exist in the facility.

### 3.3. Models of PV systems

For modelling any PV module its electrical behavior should be considered, hence the non-linear I-V characteristic curve must be estimated [39]. In addition, some researchers have utilized circuit topologies to model the characteristics of the module when is subjected to environmental variations such as changes in irradiance and temperature [41, 46, 47].

Subsequently, several PV cell equivalent circuits have been reported in the literature [47, 48, 49, 50, 51]. These models are done specifying the numbers of parameters required to characterize them. Such models are characterized by three parameters [32, 51], four and five parameters [47, 48, 52], six parameters [53] and seven parameters [54, 55, 56, 57]. The unknown parameters along with the respective circuit model are listed in the Table 4.
Table 4. Different models and its respective parameters

<table>
<thead>
<tr>
<th>Group</th>
<th>Model</th>
<th>Parameters</th>
<th>Equivalent Circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Diode</td>
<td>Electrical Models</td>
<td>Three parameters</td>
<td><img src="image1" alt="Single Diode Equivalent Circuit" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$I_{PV}, a, I_{D1}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Four parameters</td>
<td>$I_{PV}, a, I_{D1}, R_S$</td>
<td><img src="image2" alt="Four Parameters Equivalent Circuit" /></td>
</tr>
<tr>
<td></td>
<td>Five parameters</td>
<td>$I_{PV}, a, I_{D1}, R_S, R_P$</td>
<td><img src="image3" alt="Five Parameters Equivalent Circuit" /></td>
</tr>
<tr>
<td></td>
<td>Six parameters</td>
<td>$I_{PV}, a_1, a_2, I_{D1}, I_{D2}, R_S$</td>
<td><img src="image4" alt="Six Parameters Equivalent Circuit" /></td>
</tr>
<tr>
<td>Two Diodes</td>
<td>Electrical Models</td>
<td>Four parameters</td>
<td><img src="image5" alt="Two Diodes Equivalent Circuit" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$I_{PV}, a_1, a_2, I_{D1}, I_{D2}, R_S, R_P$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electrical models with</td>
<td>Seven parameters</td>
<td><img src="image6" alt="Electrical Models with" /></td>
</tr>
<tr>
<td></td>
<td>recombination current</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>in the intrinsic layer</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Single Diode</td>
<td>$I_{PV}, a_1, a_2, I_{D1}, R_S, R_P, \mu_T$</td>
<td><img src="image7" alt="Single Diode Equivalent Circuit" /></td>
</tr>
</tbody>
</table>
The three parameters model is also known as “Single Diode Model”, which by far is the simplest approach to simulate the behavior of the panel, assuming that the cell behaves as an ideal diode [58, 59, 60]. Subsequently, an improved version for the previous model was developed, where is inserted one series resistance (Rs) to the circuit [61, 62], characterized thus by a four parameters model.

However, although that model is still relatively simple, it exhibits serious insufficiencies related to high temperature variations, because it does not consider the open circuit voltage coefficient ($k_v$) [63]. For the previous reason, numerous authors [64, 65, 66, 67] have suggested the inclusion of an additional shunt resistance $R_p$, which increase the accuracy of the model [66]. Such circuit is represented by a five parameters model.

Besides, recently other models have been presented, which consider the recombination current in the intrinsic layer [68, 69, 70, 71]. These models have been developed especially for amorphous and HIT (Heterojunction with Intrinsic) panels representation.

On the other hand, for the implementation of a single diode model, it has been assumed that the recombination loss in the depletion region is absent. In a real solar cell, the recombination represents a substantial loss, which cannot be adequately modeled using a single diode. Considering this loss, was born a necessity for a more precise model, known as the “Two-Diode Model” [72], whose circuit is represented by a seven parameters model. Furthermore, this model presents a good behavior when is used at low voltage [39], low irradiance [54], and when is used considering the space charge recombination current [73].

### 3.4.1. Extraction of model parameters

One of the aims of this project is to define a method to extract the parameters related to the model for the solar module evaluated. These parameters allow to establish a model based on experimental values, which are obtained under standard test conditions (STC). Unfortunately, PV generators always work far from the STC condition. Hence, PV manufacturers usually only list limited technical values, such as short circuit current ($I_{SC}$), open circuit voltage ($V_{OC}$), current at maximum power point ($I_{MPP}$) and voltage at maximum power point ($V_{MPP}$). The values above-mentioned are used for developing the electrical model of the PV panel to represent the I-V behavior.
In order to simulate the cell behavior in MATLAB, it is necessary to recognize all the respective dominant parameters of each model (see Table 4 above). Such parameters are: *photo generated current generated* \((I_{PV})\), *reverse saturation current* \((I_o)\), *series resistance* \((R_s)\), *shunt resistance* \((R_P)\) and *diode ideality factor* \((a)\). To calculate them, some boundary conditions such as \(I_{SC}, V_{OC}, V_{mp}, I_{mp}, k_v, k_i, \) and \(N_s\) are required. Those variables are extracted from the solar cell I-V curve. Those boundary conditions, as it was mentioned before, can be obtained either from the manufacturer’s datasheet or by testing the solar cell.

Thereby, starting from the available data, the following representative points must be found. First, during short circuit condition, \(V = 0, I = I_{SC}\). Second, during open circuit condition, \(V = V_{OC}, I = 0\). Finally, during maximum power condition, \(V = V_{MPP}, I = I_{MPP}\). For all the above point, the temperature effect should also be considered. Moreover, the shunt resistor \(R_P\) (in some literature also known as \(R_{SH}\)), represents the current leakage through the high conductivity derivation across the P-N junction, and is added in parallel with the source and the diode. The other resistance \(R_s\), is connected in series and represents the losses in solder bonds, interconnection, junction box, etc. \([74]\). The resultant expression is already expressed in the Eq. (3.1).

Moreover, the saturation current \(I_o\) is the small current that flows when the P-N junction is reverse influenced \([75]\). The ideal factor for the diode \((a)\), is a significant parameter used to describe if the P-N junction is working close to the ideal case for a semiconductor \([75]\). Some reports such as \([76]\), have concluded that \(a\) and \(R_s\) make such a big impact on the I-V curve shape, especially when it reaches the maximum power point. However, the value \(R_P\) determines the I-V curve slope when it is near to the \(I_{SC}\) point. Some authors have investigated about the ideal factor of the diode, in especial its influence over a PV technology \([41, 74, 77]\) the results are gathered in the Table 5.

<table>
<thead>
<tr>
<th>Technology</th>
<th>(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-mono</td>
<td>1.2</td>
</tr>
<tr>
<td>Si-poly</td>
<td>1.3</td>
</tr>
<tr>
<td>a-Si:H</td>
<td>1.8</td>
</tr>
<tr>
<td>a-Si:H tandem</td>
<td>3.3</td>
</tr>
<tr>
<td>a-Si:H triple</td>
<td>5</td>
</tr>
<tr>
<td>CdTe</td>
<td>1.5</td>
</tr>
<tr>
<td>CIS</td>
<td>1.5</td>
</tr>
<tr>
<td>AsGa</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Source: \([41]\)
**Temperature influence, determination of thermal model**

Modeling the electrical behavior of the cell is the easiest part of the model, but instead when the temperature behavior is tried to be simulated results are always intermittent, therefore it is necessary to evaluate this phenomena with higher detail. To do that, first is implemented two separate temperature coefficients either given by the manufacturers or measured during outdoor tests in actual operating conditions (STC). The definitions for the two parameters are shown below:

- $\alpha_{Isc} \rightarrow$ Normalized temperature coefficient for $I_{SC} [A/^\circ C]$. The term “normalized” means the division between current and temperature, measured for a standard solar spectrum and irradiance level by the module short-circuit current at the standard reference (STC) $I_{SC}$. By implementing this units ($A/^\circ C$) is guaranteed the possibility of applying such parameter for both individual and parallel strings of modules. In the literature, it is also known as “$k_i$”.

- $\beta_{Voc} \rightarrow$ Temperature coefficient for $V_{OC} [V/^\circ C]$. This operates in function on the effective irradiance. Usually, the irradiance dependence can be neglected and $\beta_{Voc}$ is assumed to be a constant value. In the literature, it is also known as “$k_v$”.

With respect to the thermal model, there are two different model that can be implemented, both start its measurement from the ambient temperature. The easiest one is bases on the NOCT (Normal Operating Cell Temperature), which is the cell operating temperature at given conditions such as $G_{NOCT} = 800$ W/m², $T_{amb @ NOCT} = 20 ^\circ C$ and wind speed = 1 m/s. the computation of the actual cell temperature ($T_c$) is reported in the Eq. (3.13).

$$T_c = T_{amb} + NOCT - T_{amb @ NOCT} * G$$  \hspace{1cm} \text{Eq. (3.13)}$$

Whilst the second one is known as SANDIA module temperature model, as it was developed by Sandia Laboratories [78]. This is a more complex model based on experimental measurements, in which are being considered module installation/configuration and wind cooling effect [31]. Such equation is shown below, and specifies the respective back-surface module temperature ($T_m$).

$$T_m = T_{Amb} + G * e^{a+b*WS}$$  \hspace{1cm} \text{Eq. (3.14)}$$

Where $WS$ stands for wind speed (m/s) at a standard altitude of 10 m, $a$ is an experimental coefficient correspondent to the module temperature with high irradiance and no wind, while $b$ indicates the impact of the wind over the cell temperature.
However, cell temperature and back-surface module temperature might be particularly different in some cases. Therefore, through a simple relationship can be related both \( T_c \) and \( T_m \). The cell temperature inside the module is thus calculated using \( T_m \) and a predetermined temperature difference coefficient between the back surface and the cell (\( \Delta T \)). Such expression is listed in Eq. (3.15).

\[
T_c = T_m + \frac{G}{G_{STC}} \times \Delta T
\]

Eq. (3.15)

The respective values for \( a \), \( b \) and \( \Delta T \) are gathered in the Table 6, and each one of them is related for a specific module with its type and configuration.

### Table 6. \( a \) and \( b \) coefficients for different modules and installations

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Mount</th>
<th>( a )</th>
<th>( b )</th>
<th>( \Delta T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass/cell/glass</td>
<td>Open rack</td>
<td>-3.47</td>
<td>-0.0594</td>
<td>3</td>
</tr>
<tr>
<td>Glass/cell/glass</td>
<td>Close roof mount</td>
<td>-2.98</td>
<td>-0.0471</td>
<td>1</td>
</tr>
<tr>
<td>Glass/cell/polymer</td>
<td>Open rack</td>
<td>-3.56</td>
<td>-0.0750</td>
<td>3</td>
</tr>
<tr>
<td>Glass/cell/polymer</td>
<td>Insulated back</td>
<td>-2.81</td>
<td>-0.0455</td>
<td>0</td>
</tr>
<tr>
<td>Polymer/thin-film/steel</td>
<td>Open rack</td>
<td>-3.58</td>
<td>-0.113</td>
<td>3</td>
</tr>
<tr>
<td>22X Linear Concentrator</td>
<td>Tracker</td>
<td>-3.23</td>
<td>-0.130</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Source: [31]

In the Figure 31 is plotted a comparison of the cell temperature during two different days by implementing both temperature models (NOCT and SANDIA). It is seen that SANDIA model is lower than NOCT, and operates in the conditions close to the standard with temperatures values around 50-60 °C, which several researchers have said is the operational temperature for the cells. In fact, SANDIA model has an accuracy of 95%, which corresponds to an error on the energy production prediction of 3% [31]. Due to that, for the developing of this project has been selected SANDIA model with the parameters correspondent to “insulated back”.

![Figure 31. Cell Temperature comparison. Source: Own](image-url)
**Determination of I_{PV}**

The equation for the PV current, which is described as a function of temperature and irradiance, is summarized in the Eq. (3.16).

\[
I_{PV} = (I_{SC,STC} + K_i \Delta T) \frac{G}{G_{STC}} \quad [A]
\]

Eq. (3.16)

Where,

- \( I_{SC,STC} = \text{Short circuit current at STC} \) [A]
- \( \Delta T = T_c - T_{STC}, \text{where } T_{STC} = 25^\circ C \) [K]
- \( G \triangleq \text{Surface irradiance of the cell} \) [W/m\(^2\)]
- \( G_{STC} = 1000 \text{ W/m}\(^2\) \)
- \( K_i = \text{Short circuit current coefficient} \) [A/K]

Due to the PV effect, the light generated current \( I_{PV} \) flows in an opposite direction than the forward dark current. Even if the PV module works as a short circuit operation mode, \( I_{PV} \) continues to flow and is measured such as short-circuit current \( I_{SC} \) [67].

**Determination of I_o and diode ideality factor**

First, the equation that represents the behavior of a single-diode model must be considered including the effect of the temperature variation [79], which is described by the Eq. (3.17).

\[
I_o = \frac{I_{SC,STC} + K_i \Delta T}{V_{OC,STC} + k_v \Delta T} = I_{o, \text{ref}} 
\]

e\left( \frac{V_{OC,STC} + k_v \Delta T}{k_v(\frac{T_c}{T_{ref}})} \right)

Eq. (3.17)

Where,

- \( k_v \triangleq \text{Open circuit voltage coefficient} \) [V/K]
- \( V_{OC,STC} = \text{Open circuit voltage at STC} \) [V]

Moreover, \( I_o \) can be modified in order to consider the material band gap referent to the physical diode behavior. The new expression of the saturation current is given by Eq. (3.18).

\[
I_o = I_{o, \text{ref}} \left( \frac{T_c}{T_{ref}} \right)^2 \left( 1 + \frac{E_g}{k_v \left( \frac{T_c}{T_{ref}} \right) T_c} \right)
\]

Eq. (3.18)

Where \( T_c \) is cell temperature, \( k \) is Boltzmann constant and \( E_g \) is the material band gap. Usually \( E_{g, \text{ref}} \) is 1.121 eV for silicon cells, however, the intention of the model is to cover all
the possible panel outcomes, the following expressions are introduced to find the values of \( E_g, \text{ref} \) and \( E_g \) regular.

\[
E_g = 1.17 - 4.73 \times 10^{-4} \times \frac{T_c^2}{T_c + 636}
\]  
Eq. (3.19)

\[
E_g,\text{ref} = \frac{E_g}{1 - 0.0002677 \times (T_c - T_{ref})}
\]  
Eq. (3.20)

Special considerations must be implemented when is developed “Two-Diode Model”. Although a greater accuracy can be achieved using this model (if it is compared to the single diode model), it requires the computation of seven parameters, including the introduction of a new term \( I_{o2} \), which compensate the recombination loss in the depletion region [72].

For the two-diode model some authors have estimated the values for \( I_{o1} \) and \( I_{o2} \) doing an iterative process. Nevertheless, that iterative process can require a huge computational time, which also, can be increased by the selection of a non-suitable initial guess variable [80]. For that reason, under the developing of this project, the estimation of the reverse saturation current is found by applying the estimation done by [55], in which a new analytical expression for \( I_{o1} \) and \( I_{o2} \) is shown in the Eq. (3.21).

\[
I_{o1} = I_{o2} = I_0 = \frac{I_{SC,STC} + k_i \Delta T}{V_{OC,STC} + k_i \Delta T} \times e^{\left(\frac{V}{n_i}\right) \times V_T} - 1
\]  
Eq. (3.21)

Therefore, by applying Eq. (3.21), it is saved all the computational time, because there is no need to implement an iterative process to obtain the values of \( I_{o1} \) and \( I_{o2} \); instead, this solution can be found analytically starting from the diffusion theory postulated by Shockley, where the value of \( a_i \) can be assumed to be one [72]. Even so, the value of \( a_z \) cannot be the unity as well, on the contrary, it can be flexible.

Based on the results obtained on [56], the value of \( a_z \) must be higher or equal than 1.2, because within this range was obtained the maximum relationship between the theoretical and the experimental I-V curve. Since \((a_1+a_z)/p=1\) and \(a_1=1\), then \(p\) must be higher or equal than 2.2. With this assumption, Eq. (3.1) can be re arranged as it shown in Eq. (3.22).

\[
I = I_{PV} - I_0 \left[ e^{\frac{V+I \times R_S}{V_T}} + e^{\frac{V+I \times R_S}{(p-1) R_T}} - 2 \right] - \left( \frac{V + I \times R_S}{R_p} \right)
\]  
Eq. (3.22)

As it can be seen above, now the “Two-Diode model”, which originally had seven parameters, turns out to be a new “Two-Diode model” which only requires the computation of five parameters. Thereby, the computational time is reduced from the original estimation.


**Determination of Rs and Rp values**

Along this document has been shown two expressions able to obtain the value of the current of the PV generator considering the effect of the one single diode or two diodes (Eq. (3.1) and Eq. (3.22) respectively). Now is necessary to obtain an expression for $R_p$ at the maximum power point (Mpp) of the PV generator. Hence, from Eq. (3.22) can be derived this expression, represented by Eq. (3.23).

$$
R_p = \frac{V_{mp} + I_{mp}R_s}{I_{PV} - I_0 \left[ e^{\frac{V_{mp} + I_{mp}R_p}{V_T}} + e^{\frac{I_{PV} - I_{mp}}{V_T}} - 2 \right] - \frac{P_{max,E}}{V_{mp}}} \tag{3.23}
$$

It is seen, if the value of $R_s$ change, $R_p$ would change respectively. In addition, Eq. (3.23) has the advantage to be a linear algebraic expression. Under the previous facts, is possible to implement an iteration tool for obtaining the corresponding $R_s$ and $R_p$ values, just by increasing the value of $R_s$ continuously [81]. The concept associated consists on equalize the calculated peak power ($P_{mp, C}$) with the experimental peak power ($P_{mp, E}$), which is given by the manufacturer.

The iterative method selected to be followed is the Newton-Raphson because easily is obtained an advantage of a very quick, quadratic convergence for initial values near to the root [81]. The method is applied to Eq. (3.1) as follows in the Eq. (3.24).

$$
I = I - \frac{f(V, I)}{f'(V, I)}
$$

$$
I = I - \frac{I_{PV} - I - I_{01} \left[ e^{\frac{V + I R_s}{a_1 V_T N_s}} - 1 \right] - I_{02} \left[ e^{\frac{V + I R_s}{a_2 V_T N_s}} - 1 \right] - \frac{V + I R_s}{R_p}}{\frac{R_s}{R_p} \left[ I_{01} R_s \left[ e^{\frac{V + I R_s}{a_1 V_T N_s}} - 1 \right] - I_{02} R_s \left[ e^{\frac{V + I R_s}{a_2 V_T N_s}} - 1 \right] \right]} - 1
$$

Eq. (3.24)

In concordance with Newton-Raphson method, is necessary to select a suitable initial guess values good enough to find a convergence region (typically low values) [31]. Thus, the initial value for $R_s$ is considered zero whilst the initial value for $R_p$ is obtained thanks to the Eq. (3.25).

$$
R_{p0} = \left( \frac{V_{mp}}{I_{SC,STC} - I_{mp}} \right) - \left( \frac{V_{OC,STC} - V_{mp}}{I_{mp}} \right)
$$

Eq. (3.25)
Furthermore, the first term in bracket of Eq. (3.25) is the slope of the line segment between the short circuit current and its maximum point, whereas the second one shows the slope of line segment between the open circuit voltage and its maximum point [56].

![Flow chart](image)

**Figure 32. Algorithm to determine Rs and Rp. Source: Own**

Is valid to say that for a typical PV module, difference between the nominal values of $V_{OC}$ and $V_{mp}$ is not large; thus, the second term value will be lower. Likewise, the first term will also be a lower value compared to the actual value of $R_P$. Consequently, both values would give good initial guess for the iterative process.

In the Figure 32 is shown the flow chart where is represented the algorithm implemented to find the values of $R_P$ and $R_S$, starting from the initial guess values along with the output variables $I$ and $V$. 
Finally, some authors have shown that $R_p$ has a slightly dependence with respect to the incident irradiance [82]. Through experimental data is possible to determinate a relationship between the shunt resistance and the absorbed radiation, such behavior is represented by Eq. (3.26).

$$R_{sh} = R_{sh,ref} \cdot \frac{G_{STC}}{G}$$

Eq. (3.26)

**Extraction of a four parameters model**

Nowadays, five parameters model represents the reference in PV engineering as it seems to be a compromise between precision and computational effort. However, for basic PV applications, uncertainties the solar radiation collection or the cell temperature make elusive the importance of a detailed model for conditions far from the optimal ones, when the energy production is low.

For this reason, Lorenzo [83] proposed a simplified model based on the five parameters model, but with some hypothesis that are very well satisfied in many circumstances:

1. The effect of parallel resistances is negligible
2. The photo generated current and the short-circuit current are equal
3. $\exp\left(\frac{V + IR_S}{V_t}\right) \gg 1$

The effect of parallel resistance, that is due to leakage currents caused by p-n junction non-ideality and impurities near the junction, is not negligible, especially at low irradiances, but it is said to be compensated by the particular way the series resistance is calculated here: it assures the model to work at nominal conditions with just the series losses. Nevertheless, when the conditions are far from that one, due to temperature or irradiance, there might be some difference.

The second hypothesis is true when the series resistance is very small. For c-Si, especially for monocrystalline, the bulk resistance of the semiconductor material is very low, and a proper manufacturing can set the resistances of the contacts, the connectors and the terminals at very low levels.

The last simplification is allowed for high cell voltages, that is fine for the usual maximum power points.

Under the considerations explained above, the four-parameter model proposed should work quite well when the cell is operating under conditions close to the nominal ones, and probably with errors lower than other steps needed to calculate the PV energy production. Still, this model will be compared with the above described (more complex) ones such as the five and six parameters models.
Firstly, it is needed to calculate the thermal voltage at STC, by the reference one, that usually for semiconductors is given at a 300 K temperature, expressed by Eq. (3.27).

\[
V_t(\text{STC}) = V_t(300K) \frac{T_c(\text{STC}) + 273.15}{300} \quad [V]
\]

Eq. (3.27)

In order to find the value of the series resistance, an empirical expression has been proposed by Green [84], based on the following formulas. This procedure of series resistance calculation does not require any iteration, and considers all the losses that occur in nominal conditions. Whenever the conditions change this model inevitably lead to some mistake, and with the validation it would be seen if it is acceptable or not.

First, is defined the normalized voltage as it is expressed by Eq. (3.28)

\[
v_{oc} = \frac{V_{oc}(\text{STC})}{V_t(\text{STC})}
\]

Eq. (3.28)

Then, the normalized resistance is given by Eq. (3.29).

\[
r_s = \frac{R_sI_{SC}(\text{STC})}{V_{oc}(\text{STC})}
\]

Eq. (3.29)

The modified fill factor at nominal conditions should be given by Eq. (3.30)

\[
FF = \frac{P_{MPP}}{V_{oc}I_{sc}} = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1} (1 - r_s) = FF_0 (1 - r_s)
\]

Eq. (3.30)

\[
r_s = 1 - \left( \frac{V_M(\text{STC})I_M(\text{STC})}{V_{oc}(\text{STC})I_{SC}(\text{STC})FF_0} \right)
\]

Finally, the series resistance of the cell is represented by Eq. (3.31).

\[
R_s = r_s \frac{V_{oc}(\text{STC})}{I_{SC}(\text{STC})} \quad [\Omega]
\]

Eq. (3.31)

Due to the above cited simplifications, and with the calculated values of the thermal voltage and series resistance, the following formula is obtained for the current.

\[
I = I_{sc} - I_o \exp\left( \frac{V + IR_s}{V_t} \right)
\]

Eq. (3.32)

By solving the equation for $I=0$, the equation of Eq. (3.33) is considered.
\[ I_0 = I_{SC} \exp\left(-\frac{V_{OC}}{V_T}\right) \]

Eq. (3.33)

Then, by substituting Eq. (3.33) into Eq. (3.32), a new equation that allows to get the I-V curve for any environmental condition with only commercial catalogue information is obtained, represented by Eq. (3.34).

\[ I = I_{SC} \left[ 1 - \exp\left(\frac{V - V_{OC} + I R_S}{V_T}\right)\right] \]

Eq. (3.34)

Where \( R_s \) is a constant and \( I_{SC}, V_{OC} \) and \( V_T \) depend on irradiance and cell temperature.

**Modified model for a-Si:H cells**

Amorphous silicon cells are fabricated with a p-i-n junction structure instead of the crystalline silicon p-n junction. It means the between the two doped silicon layers there is a layer of intrinsic silicon that is the place where the electric field is extended. Thus, the driving force for the collection of the photo generated carriers is the drift, and not the diffusion as in p-n junctions.

This is due the fact that in amorphous material the diffusion length is about 20 times shorter than the drift length due to its disordered structure, so the latter mechanism gives much more probability for the carriers to be collected during their lifetime.

Quantitatively, by following Merten et al. [85], it is possible to define, for a small forward voltage, a carrier collection efficiency as it is expressed by Eq. (3.35).

\[ X(V) = 1 - \frac{d}{\mu \tau_{eff}} \frac{V_{bi} - V}{d} \]

Eq. (3.35)

Where \( d \) is the thickness of the intrinsic layer, \( \mu \tau_{eff} \) is the effective drift length and \( V_{bi} \) is the built-in voltage between the p doped and the n doped layers.

Therefore, it is possible to calculate a recombination current that is responsible of further losses respect to p-n junction technologies given by Eq. (3.36).

\[ I_{rec} = I_{ph} \frac{d^2}{\mu \tau_{eff} (V_{bi} - (V - I R_s))} \]

Eq. (3.36)

The authors report that the built-in voltage has commonly a value of 0,9 V, and in [86] they say that in the PV-Syst software this equation is used with a \( d^2/\mu \tau_{eff} \) value of 1,4 V, even if it depends on material and can vary a little from case to case.
Following the five-parameter model, the modified form of the current-voltage equation appears in Eq. (3.37).

\[ I = I_{ph} - I_{rec} - I_0 \left( \exp \left( \frac{V - IR_s}{V_t} \right) - 1 \right) - \frac{V - IR_s}{R_p} \]

Eq. (3.37)

In this work, these analytical model is neither tested nor implemented, but it could be interesting for future work, as second-generation modules, they have a potential for BIPV applications, as mentioned in the BIPV applications section.

### 3.1. Validation of the PV Model

From the PV model simulated in MATLAB it can be obtained electrical parameters such as output power, current and voltage. To determine how accurate the model is working, it must be done a comparison between the simulation data and real data. To take all the real data is used the Solar Tech Laboratory, which is placed at the roof of the Energy Department of the Politecnico di Milano (latitude 45.502941 °N and longitude 9.156577 °E) [87]. The laboratory provides a database of real power, current and voltage values, which can be used to control the results of the model.

The methodology proposed to verify the simulated model is the following:

1. Take all the meteorological data necessary to develop the model, i.e., from the Solar Tech Lab is taken the information regard to incident Irradiance, ambient temperature and wind speed measured. Also, it is identified which solar modules should be considered, and with those, their datasheet values are gathered consequently (see Table 7).
2. Define an error definition to implement on the comparison between the simulated data from the MATLAB development and the reference values given by the solar tech lab.
3. Implement all the equations described till now to develop the model (equations correspondent to chapter two and chapter three of this project). By doing this a suitable model with output values is ready to be evaluated.
4. Take all the real electrical parameters measured by the Solar Tech Lab, arrange the data in such a way that a suitable comparison between simulated and real data can be effectuated.
5. Present a set of graphs in which are compared the real and simulated power data.
3.5.1. Input data of the model

As it is explained above, from the solar tech lab are taken climatic data such as ambient temperature, wind speed and incident irradiance. To develop the comparison simulation six days were proposed to be evaluated: June 19th, June 26th, June 30th, July 03rd, July 09th, and July 11th, all those corresponds to the year 2016. In the Figure 33 is summarized all the climatic data for the six days.

![Figure 33. Climatic data (a) June 19th, (b) June 26th, (c) June 30th, (d) July 03rd, (e) July 09th, (f) July 11th. Source: Own](image)

The idea is to simulate a model which can operates either for monocrystalline or polycrystalline technology. Hence, it is considered two different solar panels existent on the laboratory, one with monocrystalline technology, and the other one with polycrystalline technology. The specifications of the modules are summarized in the Table 7.

From the table above is seen two different input data either for monocrystalline or polycrystalline modules. This is due to the ease given by the laboratory to measure the real data of the modules, thus a confront between manufacturer data and real data can be implemented, avoiding as much as possible any external error originated by the manufacturer.
Table 7. STC specifications for the modules used in the simulation

<table>
<thead>
<tr>
<th>Input Data</th>
<th>Monocrystalline</th>
<th>Polycrystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Datasheet values</td>
<td>Measured Values</td>
</tr>
<tr>
<td>Pmpp (Wp)</td>
<td>245.392</td>
<td>238.336</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>0.141881</td>
<td>13.7802</td>
</tr>
<tr>
<td>Ns</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>NOCT (°C)</td>
<td>47</td>
<td>47</td>
</tr>
<tr>
<td>Isc (A)</td>
<td>8.48</td>
<td>8.37</td>
</tr>
<tr>
<td>Voc (V)</td>
<td>37.1</td>
<td>37.15</td>
</tr>
<tr>
<td>Vmpp (V)</td>
<td>7.84</td>
<td>7.84</td>
</tr>
<tr>
<td>Impp (A)</td>
<td>31.3</td>
<td>30.4</td>
</tr>
<tr>
<td>ki (A/°C)</td>
<td>0.002544</td>
<td>0.002544</td>
</tr>
<tr>
<td>kv (V/°C)</td>
<td>-0.12631</td>
<td>-0.12631</td>
</tr>
</tbody>
</table>

Source: [87]

3.5.2. Error definition

The objective of this project is to develop a model with a high accuracy level in terms of PV energy production. To determine such level of accuracy, it is necessary to define the error to be adopted. In the literature, there are a lot of error definitions that can be implemented on this project. Among all the errors, it is considered will be those which implement an hourly error, such as Normalized mean absolute error NMAE, weighted mean absolute error WMAE, and Normalized root mean square error nRMSE. In the previous chapter has been explained the WMAE and nRMSE error, hence in this chapter is only define the normalized error represented by Eq. (3.38).

- NMAE, based on net capacity of the plant $C_N$

$$NMAE \% = \frac{1}{N} \sum_{h=1}^{N} \frac{|P_{m,h} - P_{p,h}|}{C_N} \times 100$$

Eq. (3.38)

Where,

- $C_N = net \ capacity \ of \ the \ plant$
- $N = number \ of \ daylight \ hours$
- $P_{m,h} = Average \ power \ produced \ (measured) \ in \ the \ hour$
- $P_{p,h} = Power \ simulated \ in \ the \ hour$
With respect to WMAE and nRMSE errors, the equation found in the chapter two are slightly modified to work with power values instead of irradiance values. Those equations are found below.

- **WMAE**, based on total energy production

\[
WMAE \% = \frac{\sum_{h=1}^{N} |P_{m,h} - P_{p,h}|}{\sum_{h=1}^{N} P_{m,h}} \times 100
\]

Eq. (3.39)

- **nRMSE**, based on the maximum produced power (Pm, h)

\[
\text{nRMSE} \% = \sqrt{\frac{\sum_{h=1}^{N} (P_{m,h} - P_{p,h})^2}{\text{max}(P_{m,h})}} \times 100
\]

Eq. (3.40)

### 3.5.3. Results of simulation

By going through this chapter there are several PV models identified, the idea is to evaluate all of them and determine which is the best model, whose results would have a high accuracy level with respect to the real data measured by the solar tech lab. To do that different scenarios were proposed, depending on the number of parameters (four, five or six parameters), the cell temperature model chosen (NOCT or SANDIA) and the evolution of the model equations by changing some values (Io and Rp), and by adding new ones (spectral shift). In the Table 8 are gathered all the scenarios proposed.

<table>
<thead>
<tr>
<th>Model</th>
<th>Temperature Chosen</th>
<th>Rp and Io</th>
<th>Spectral Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>4a</td>
<td>NOCT</td>
<td>N. A</td>
<td>No</td>
</tr>
<tr>
<td>5a</td>
<td>NOCT</td>
<td>Fix</td>
<td>No</td>
</tr>
<tr>
<td>6a</td>
<td>NOCT</td>
<td>Fix</td>
<td>No</td>
</tr>
<tr>
<td>4b</td>
<td>SANDIA</td>
<td>N. A</td>
<td>No</td>
</tr>
<tr>
<td>5b</td>
<td>SANDIA</td>
<td>Fix</td>
<td>No</td>
</tr>
<tr>
<td>6b</td>
<td>SANDIA</td>
<td>Fix</td>
<td>No</td>
</tr>
<tr>
<td>5c</td>
<td>SANDIA</td>
<td>Variable</td>
<td>No</td>
</tr>
<tr>
<td>6c</td>
<td>SANDIA</td>
<td>Variable</td>
<td>No</td>
</tr>
<tr>
<td>5d</td>
<td>SANDIA</td>
<td>Variable</td>
<td>Yes</td>
</tr>
<tr>
<td>6d</td>
<td>SANDIA</td>
<td>Variable</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Source: Own
On the other hand, by analyzing in detail the climatic data shown in the Figure 33, it is decided to make the comparison with the meteorological data of the June 26th and June 30th, because during such days is seen two different conditions, one with a sunny day irradiance (June 30th), whilst the other presents variable irradiance along the day, most likely due to a cloudy day (June 26th). By doing that, it can be proved that the proposed PV model is able to work in all the existent conditions, from a perfect sunny day till a variable cloudy day.

In order to effectuate the comparison of all the models (four, five and six parameters), the scenarios proposed above in the Table 8 must be considered, both for monocrystalline and polycrystalline. To make the respective comparison among all the models it is necessary to have a reference point, which in this case is the real power measurement made by the solar tech lab.

For each one of the models it has been made an error analysis, based on the error definition previously explained. In the Figure 34 and Figure 35, it is shown the summarize for all the errors for both catalog and measured values of the monocrystalline and polycrystalline modules.

On the contrary, the following comparison are projected to determine which is the most accurate model in a graphical way.

- With data measured make a comparison among 4a, 5a & 6a.
- With data measured make a comparison among 4b, 5b & 6b.
- With data measured make a comparison among 5c & 6c.
- With data measured make a comparison among 5d & 6d.
- With data given by the manufacturer make a comparison among 4a, 4b, 5c, 5d, 6c & 6d.
**Errors June 26th**

![Graph showing errors for June 26th]

*Figure 34. Summary errors June 26th. Source: Own*

**Errors June 30th**

![Graph showing errors for June 30th]

*Figure 35. Summary errors June 30th. Source: Own*
Graphical comparison

Figure 36. Comparison of the models by considering measured values as inputs June 26\textsuperscript{th}. Source: Own

By compared both graphs in the Figure 36, which are related to a cloudy day, it is seen that for all the models the output power seems to be similar to the real data, that statement can be proved if the Figure 34 is analyzed as well. For that day, most of the errors percentage are lower than 5 \%, except by 5d and 6d, this is mainly due to the inclusion of the spectral
shift. On the other hand, when the same approach is done for a sunny day, in the case of polycrystalline solar panel (also a little in monocrystalline), four parameters model is more inaccurate, in fact by analyzing Figure 35 the errors of such model are around the double than the six parameters model and much more than with respect to five parameters.

Based on those results, a further comparison is made only for five and six parameters models in the sunny day (June 30th). That comparison is found in the Figure 38. It is seen that for the peak irradiance values (around the hours 12 to 14), the six parameters model is higher than the reference power values. By analyze Figure 35, for instance the NMAE value for five parameters is around 1.5 %, whilst for six parameters the same error is around 3.5 %.

Consequently, the most suitable model to choose and keep working in the further chapters is the 5c. In the Table 9 are gathered all the errors related to such model, besides from the table can be examined that all errors values are never higher than 4 %, proving a high accuracy level for the model selected.

<table>
<thead>
<tr>
<th>Error</th>
<th>Monocrystalline</th>
<th>Polycrystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>June 26th</td>
<td>June 30th</td>
</tr>
<tr>
<td>NMAE</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>WMAE</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>nRMSE</td>
<td>2.3</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Source: Own
An interesting aspect to evaluate is the one correspondent to the input data coming from the manufacturer, which are the ones taken from the datasheet. Till now, all the evaluation has been done by considering as input data the measured values from the panels, thanks to the implementation of sensors through an additional labor made by the solar tech lab. On the first evaluation, the errors obtained are lower, proving than the model work successfully. However, when the datasheet values are considered, the expected errors are higher than the previous case. This behavior can be observed in the Figure 39.

The simulated model tends to get worse on the polycrystalline module. As a matter of fact, by implement a comparison between the Table 9 and Table 10, it is seen how is increased the percentage error, especially during the sunny day. Graphically it can be seen first on the Figure 39, in which the power produced by the model 5c is higher than the reference one. Also, in Figure 35 can be seen the same behavior with the higher errors of catalog values in comparison to the measured values.

Table 10. Errors of model 5c by considering datasheet data

<table>
<thead>
<tr>
<th>Error (%)</th>
<th>Monocrystalline</th>
<th>Polycrystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>June 26th</td>
<td>June 30th</td>
</tr>
<tr>
<td>NMAE</td>
<td>0.5</td>
<td>2.2</td>
</tr>
<tr>
<td>WMAE</td>
<td>3.4</td>
<td>5.3</td>
</tr>
<tr>
<td>nRMSE</td>
<td>2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Source: Own
NOTE: in the appendix A, it is found the segregation in detail of all the errors, if a clearer explanation is needed. With respect to the graphical comparison in terms of power, all the graphs for the two days evaluated are placed in the appendix 1.
The aim is to characterize the optical performance of a complex geometry system with the possibility to use any combination of material. Due to the unusual configuration implemented, conventional software is not suitable, hence, is decided to develop an own model, flexible to study the optical performance of the façade shading system.

Under that condition, a MATLAB code has been written. Such code can be used for few geometrical and material inputs, turning back a bidirectional front transmissivity and back reflectivity characterization of devices integrated in a glazing system. To validate this code, the results has been compared with the software Window [88].

4.1. Calculation method

For the development of the project, is fundamental to obtain a result comparable with trusted references, with the idea of describing completely the optical behavior of the device, and use it as input for the control strategy analysis. During the development of this analysis it has been looking for Bidirectional Transmittance Distribution Functions (BTDF) and Bidirectional Reflectance Distribution Functions (BRDF) respectively. Such functions assign for any input/output direction pairs a specific transmittance/reflectance information. They are the most complete characterization, being able to be used in both Window and EnergyPlus software. By producing BTDFs the code can be validated using EnergyPlus software as a daylighting simulator to develop the control strategy analysis. Fortunately, they were developed to work together, so they use the same matrix basis and the same conventions, as they will be discussed in detail further on.
Moreover, this study is limited on the visible light interaction, nevertheless, it could be done, as Window does, with the infra-red light, to develop a thermal model of the building with complex solar gains: it can be developed as a further improvement for future works.

The Complex Fenestration System (CFS) is composed by a diffusing part, the lamellas, and a specular part, the glasses. The procedure used to perform the calculations is similar to the one presented by Carli [89]. Thus, the contributions to the transmission through the CFS “layer” is divided in a direct part, which does not take part to reflections among the lamellas, and a diffuse part, which activates a mutual reflection cascade. As follows, the method is explained from the transmissivity point of view, but it can be applied to reflection with few changes.

4.1.1. Model inputs

Geometry definition

Firstly, it is necessary to describe the geometry of the system. In a shading device, the dominant behavior is due to cross sectional response, therefore, in the model is simplified the 3D object to its cross section. As the behavior in each inter-lamella space is identical for symmetry, the cross section is reduced to a section that involves just one lower lamella, one upper lamella and the glazing behind them. To avoid complicacies, it is assumed as a hypothesis no gap between the lamellas and the glazing material, even if it is not true. The elimination of this simplification can be a further step to a more realistic and flexible model. Then, the lamellas curved surface is approximated to a few small segments dependent on its curvature. Thus, each segment can be treated separately, with its own properties and view factors. The final object that will be used to study the mutual reflections is a polygon formed by the lamellas segments and two vertical segments that unite their extremes: they represent the sky and the glazing surface.

Materials properties

The slat materials are considered as opaque, even if it possible to use semi-transparent materials. They can be only characterized by their reflectivity, which has been considered isotropic. They behave as a diffuse Lambertian emitters, where the radiation received, independently from its directional or diffuse nature, is reflected homogeneously throughout all the facing hemisphere. The intensity of the radiation measured from any direction depends only on the incidence angle between the direction and the surface, and its represented by Eq. (4.1).
\[ E_S(\theta) = \rho I_s \cos(\theta) \, d\Omega \quad [W/\text{sr}] \]

Eq. (4.1)

Where,

- \( E_S \) = radiation emitted per unit of solid angle and emission
- \( \rho \) = surface reflectivity
- \( I_s \) = total received radiation per unit area
- \( \theta \) = incidence angle related to solid angle considered
- \( \Omega \) = solid angle

The glass is almost merely a specular reflector. It is characterized by an angular reflectance that depends on the incidence angle that is by far predominant. Furthermore, it conserves a Lambertian behavior that is limited by its typically very low diffuse reflectivity, that is calculated by integrating the angular reflectance over a hemisphere. In this way, it can reflect the beam rays hitting its surface and take part to the mutual reflections of the diffuse radiation. Also, its transmittance depends on the incidence angle.

Moreover, the sky is considered as a primary source of directional radiation, while the rest of the surfaces that are illuminated are considered as secondary diffuse light sources. To the sky is addressed a null reflectivity, thus it behaves as a radiation sink during the diffuse light reflection calculations.

**Angle coordinates and matrixes basis**

To univocally indicate the radiation directions, it is necessary to set a number of solid angles that divide the hemispheres rounding the CFS “layer” facing the sky and the inner ambient. To have a direct comparison with Window and to facilitate the integration in EnergyPlus, is decided to use the same angle coordinates as well as the same solid angles division. In the Figure 40 is shown a frontal view of the hemisphere, with a reduced number of directions to avoid confusion. Also, is presented the coordinates in \( \phi \) and \( \theta \) terms, where \( \phi \) is the angle between \( x \) axis and \( xoy \) projection of the direction of interest, while latitude angle \( \theta \) is the angle between \( z \) axis and the direction of interest. Thus, it can be evaluated their value in ranges between 0° and 360°, and between 0° and 90° respectively. Each direction can alternatively be referred in terms of profile angle and relative azimuth.
The profile angle is a very important angle in shading analysis because it identifies the projection of any direction on the cross-sectional plane, that is a plane of symmetry assumed. In fact, for non-specular elements it can be treated rays with the same profile angle in the same way, simplifying a lot the calculations. For specular elements instead, is always use the incidence angle. In solar calculations, the profile angle can be defined by Eq. (4.2) [24].

$$\alpha_p = \tan^{-1} \left( \frac{\tan \alpha_s}{\cos(y_s - y)} \right) \ [\text{deg}]$$

Eq. (4.2)

In the case of implementing different coordinates, it is convenient to calculate with a different Greek letter, to understand the different application and stay coherent with the nomenclature use by Carli. This is calculated by Eq. (4.3).

$$\psi = \pm \tan^{-1} (\sin \varphi \cdot \tan \theta) \ [\text{deg}]$$

Eq. (4.3)

Where the sign is positive for the hemisphere facing the sky and negative for the other one. Likewise, each bidirectional calculation can be ordered in a 145x145 matrix, where each element in the columns and rows identify an incoming and outgoing direction identified by a $\varphi/\theta$ angles pair. For seeking convenience in the project, it is always referred to incoming directions with $i$ and to outgoing directions with $j$. The reflecting elements will instead define...
by $c$ when they are treated as receivers and by $q$ when they are treated as emitters. Each direction is related to a solid angle portion, which weight can be determined by:

$$
\Lambda = \frac{1}{2} (\sin^2 \theta_h - \sin^2 \theta_l) \Delta \varphi
$$

Eq. (4.4)

Where,

$h_i = \text{higher limit of the solid angle}$

$l_o = \text{lower emit of the solid angle}$

Both in terms of latitude angle.

### 4.1.2. View Factors

In order to perform the calculations, is necessary to know the view factors between any segments pair of polygon analyzed. Whenever the distance between the segments is great enough respect to the segment dimension, the view factor can be approximated in 2D [90] with the formula represented by Eq. (4.5).

$$
F_{qp} = \frac{\cos \alpha_1 - \cos \alpha_2}{2} \frac{L_p}{L_q}
$$

Eq. (4.5)

As showed in Figure 41, $\alpha_1$ and $\alpha_2$ are the angles formed keeping the center of segment $q$ as vertex and the two extremes of segment $p$ as directions, measured counterclockwise. If some part of segment $p$ is not viewed, the angles and length are limited to the segment $q$ horizons. This approach works very well for almost all the situations, but when the lamellas have convex sections some errors appear for adjacent or very close segments.

Figure 41. View factor schematic representation. Source: [90]
4.1.3. Viewed Fractions

When the lamellas are not flat, light rays coming from certain direction can be thwarted by protruding segments, thus not all the “activated” segments are fully illuminated. It is necessary to calculate, for each incoming/outgoing direction, and for each receiving/emitting segment, the visible fraction. This has been done by calculating all the possible intersections that the directional rays have with the lamellas and by reducing the received/emitted radiation by a factor between 0 and 1. When referring to incoming radiation it would be treated as $Ill (i, p)$, while for outgoing radiation it would be $Vis (j, q)$.

4.1.4. Undisturbed transmission

Whenever a directional light ray hits the glazing surface, there is a part of the radiation that passes directly through it, without any reflection, as it is represented in Figure 42. This contribute, for incoming directions that involve it, is dominating the overall transmissivity, because it is far less sensible to dispersion. It is proportional to the fraction of glazing that can be seen from the sky in the incoming direction and it propagates only in the direction it came from and it can be calculated by Eq. (4.6).

$$
\tau_{dir-dir}(i, i) = \frac{a(\psi(i))}{d}
$$

Eq. (4.6)

Figure 42. Undisturbed light transmission representation. Source: [89]
### 4.1.5. Bidirectional transmission

Each segment that is struck by a directional ray, becomes a Lambertian source of radiation, according to its own reflectivity and the incidence angle of the ray. The directional rays can come directly either from the sky segment or from the glazing, where they have been reflected secularly. The incidence angle in the two cases can be respectively calculated by Eq. (4.7) and Eq. (4.8).

\[
\theta_p(i, p) = \cos(\alpha(i)) \cdot \cos(\beta(p)) + \sin(\beta(p)) \cdot \cos(\alpha(i)) \cdot \cos(\gamma(i))
\]

Eq. (4.7)

\[
\theta_p2(i, p) = \cos(\alpha(i)) \cdot \cos(\beta(p)) + \sin(\beta(p)) \cdot \cos(\alpha(i)) \cdot \cos(-\gamma_2(i))
\]

Eq. (4.8)

In the same way, it is defined the incidence angle for the radiation that leaves the segments and goes towards the inner ambient by Eq. (4.9).

\[
\theta_q(j, q) = \cos(-\alpha(j)) \cdot \cos(\beta(q)) + \sin(\beta(q)) \cdot \cos(-\alpha(j)) \cdot \cos(-\gamma_2(j))
\]

Eq. (4.9)

Due to these two sources of beam radiation, the total radiation received by any segment from an incoming direction is calculated by:

\[
E_p(i, p) = \frac{I_{ll}(i, p) \cos(\theta_p(i, p))}{\cos(\theta(i))} + \frac{I_{ll2}(i, p) \cos(\theta_p2(i, p)) \rho_{glaz}(\theta(i))}{\cos(\theta(i))}
\]

Eq. (4.10)

Then, every activated segment becomes a source of diffuse radiation, emitting a total radiation due to one single incoming direction calculated by Eq. (4.11).

\[
J_p(i, p) = E_p(i, p) \rho_p
\]

Eq. (4.11)

As demonstrated by Dama and Lastaria [91], in a grey and diffuse enclosure, such as the one under analysis, it is possible to calculate the radiation reaching the segments \( q \) due to all the multiple reflections caused by the activation of a certain segment \( p \) from part of directional light rays coming from the \( i \) direction as its represented by Eq. (4.12).

\[
E_{pq}(i, p, q) = M_{(q,p)} \cdot J_p(i, p)
\]

Eq. (4.12)

Where \( M_{(q,p)} \) is the element of row \( q \) and column \( p \) of the matrix \( M \) that is represented by Eq. (4.13).
\[ M = (I - RF)^{-1} \]  
Eq. (4.13)

Where,

\[ I = \text{identical matrix} \]
\[ R = \text{diagonal matrix containing the reflectivity} \]
\[ F = \text{square containing the view factors from element } p \text{ to element } q \]

The total radiation reaching q due to a directional bundle of rays, is the summation of the contribution of all the activated segments, as it can be seen by Eq. (4.14).

\[ E_q(i, q) = \sum_{p=1}^{N} E_{pq}(i, p, q) \]  
Eq. (4.14)

Similar to what is have been done so far, the radiation emitted by a segment q in a direction j will be represented by Eq. (4.15).

\[ I_q(i, q, j) = \frac{E_q(i, q) \rho(q)}{\pi} \text{Vis}(j, q) \frac{L_q \cos \theta_q(j, p)}{d \cos \theta(j)} \]  
Eq. (4.15)

The first term indicates the intensity emitted by the element, which is equal to the radiosity divided by \( \pi \), whilst the second term is the visible fraction. Then the intensity is scaled following the Lambert law and distributed on the glazing with the two remaining terms.

Finally, we can obtain the bidirectional transmittance summing all the contributions of the segments q as it can be seen by Eq. (4.16).

\[ \tau_{\text{bidir}}(i, j) = \sum_{q=1}^{N} I_q(i, q, j) \]  
Eq. (4.16)

Summarizing, all the steps are found in a single matrix equation represented by Eq. (4.17). Likewise, in the Figure 43. is shown the schematic representation of bidirectional transmission.

\[ \tau_{\text{bidir}}^{ij} = (M_p,q^T(E_p R_p)^T)^T R_q^q C_i^q \]  
Eq. (4.17)

Where,

\[ E_p = \text{matrix containing all the } E_p(i, p) \text{ elements} \]
\[ R = \text{reflectivity matrix} \]
\[ C = \text{matrix containing all the elements of } \frac{I_q(i, q, j)}{E_q(i, q)} \]

**Figure 43.** Bidirectional light transmission through mutual reflections scheme. Source [89]

### 4.1.6. Overall Bidirectional transmission

With \( \tau_{\text{bid}} \) it is obtained information about how the lamellas distribute the incoming radiation in the hemisphere and with \( \tau_{\text{dir-dir}} \) it is known the amount of undisturbed light passing between them (that is non-zero only for \( i=j \)), but it still must cross the glass (the reflection has already been counted) through the application of its transmittance. Furthermore, it is applied the weight of each outgoing direction related to each unit radiative power, which is entering the system distributed across all the outgoing hemisphere. Such terms can be found by Eq. (4.18).

\[
\tau_{\text{tot}}(i, j) = \left( \tau_{\text{bid}}(i, j) \ast \tau_{\text{gl}}(\theta(j))A(j) + \tau_{\text{dir-dir}}(i, j)\tau_{\text{gl}}(\theta(j)) \right)
\]

Eq. (4.18)

Where the two components have been kept separated to highlight the difference between them as it would be seen below.
4.1.7. Directional-to-hemispherical and hemispherical-to-hemispherical transmission

With the aim to know the total transmissivity for a directional beam radiation, it is sufficient to sum all the total bidirectional transmittances over the outgoing hemisphere as it is represented by Eq. (4.19).

\[ \tau_{\text{dir-hem}}(i) = \sum_{j=1}^{N} \tau_{\text{tot}}(i, j) \]

Eq. (4.19)

When this is applied to solar calculations, \( \tau_{\text{dir-hem}} \) coincides with the beam radiation transmissivity, while the beam-to-beam and beam-to-diffuse transmissivity can be deduced by its decomposition shown by Eq. (4.20) and Eq. (4.21).

\[ \tau_{\text{beam-beam}}(i) = \tau_{\text{dir-dir}}(i, i) \tau_{\text{glaz}}(\theta(i)) \]

Eq. (4.20)

\[ \tau_{\text{beam-diffuse}}(i) = \sum_{j=1}^{N} \tau_{\text{bidir}}(i, j) \tau_{\text{glaz}}(\theta(j)) A(j) \]

Eq. (4.21)

Similarly, the hemispherical-to-hemispherical transmissivity, that coincide with the diffuse-to-diffuse transmissivity, can be calculated by Eq. (4.22).

\[ \tau_{\text{hemi-hemi}} = \tau_{\text{diffuse-diffuse}} = \sum_{i=1}^{N} \frac{\tau_{\text{dir-hem}}(i) A(i)}{\pi} \]

Eq. (4.22)

Where, the intensity in each radiation is the unit divided by \( \pi \) and then at each direction is applied its own weight, as it is seen above.

4.2. Validation of the code

The code used to calculate the optical properties of the CFS is conceptually very similar to what is used in Window, but at the same time is more flexible and used a couple of different mathematical formulations regarding to the view factors and multiple reflections calculation in cavity. As Window is recognized as an international standard, the idea is to test this method by comparing the results for some geometries replicable with the existing software. The subject to confront are:

1. Flat horizontal slats, with unitary and triple inter-distance between the slats (vertical spacing/lamellas depth).
2. Symmetrically curved horizontal slats, with unitary and triple inter-distance between the slats.

3. Symmetrically curved tilted slats, with unitary and triple inter-distance between the slats.

For the project characterization is used materials taken from the Window library, such as clear glass and an opaque slat material. Also, in Window is selected the same geometry and the same segment subdivision of the lamellas, imposing a gap as close as possible to zero between them and the glass.

It is calculated the $\tau_\text{hemi-hemi}$ absolute errors, the absolute for each direct-to-hemispherical transmissivity and the weighted error for each direct-to-hemispherical transmissivity, that considers the relative importance of each incoming direction. The absolute errors are calculated as $|\tau_{\text{calculated}} - \tau_{\text{Window}}|$, while the weighted absolute errors as $|\tau_{\text{calculated}} - \tau_{\text{Window}}| \Lambda$.

- The hemispherical-to-hemispherical transmissivity absolute error stays in the range $0.17 \div 1.26\%$
- The direct-to-hemispherical transmissivity absolute error normally stays below $5\%$, with some peak up to $15\%$.
- The direct-to-hemispherical transmissivity absolute weighted error normally stays below $0.3\%$, with some peak up to $0.8\%$.

It can be seen graphically in Figure 44 and Figure 45 that the peak errors are concentrated in the high-profile angle absolute value directions, that are the one with the lower transmissivity.

Figure 44.Hemispheric transmittance vs. profile angle for horizontal flat slats. Source: Own
In the light of this comparison, it is considered the code validated and it can be used to characterize the external shading device.

4.3. Back reflection calculation

To characterize the external shading device from the visible light point of view, information about front-transmissivity and back-reflectivity are considered as the minimum requirements. To calculate these, is necessary to apply some modifications to the method described previously. This is because the idea is to estimate the amount of light coming from, whereas in the previous calculations, it was the “outgoing” hemisphere that come back again towards the same hemisphere. Conceptually, the steps are the same, but with some difference gathered below:

- The light passes two times across the glass, one before the cavity calculation and one after.
- There is no second source of primary directional radiation as on the “bottom” of the cavity there is the sky. It behaves as light as well.
- There is no undisturbed part because the radiation that crosses the lamellas gap is lost.
- The incidence angles of the incoming radiation coincide with the incidence angle of the outgoing radiation.
- In the case of non-symmetrical glazing, such as compositions of different glasses with selective coatings, it is important to distinguish between front and back properties.
4.4. Characterization of the innovative design

4.4.1. Description

A special geometry is selected to study, which represents the hypothetic prototype of the shading device to be produced. Thus, it is defined a lenticular body with a depth of 29,86 cm, with a curvature ray of 0,9 m and an arch length of 30 cm. The inter-distance between the lamellas has been set equal to two times their depth, that is 59,72 cm. The tilt angle can vary between 0° and 70°, with 10° steps and the curved plates can slide up to 50 % of their length (15 cm each). The lamella surface is doubled in five steps, in the end there are 48 possible geometries. In Figure 46 it is seen the cross section of the lamella when it is 70° tilted and fully extended. By consider these proportions, it is possible to cover almost completely the façade.

![Lamella cross section](image)

Figure 46. Lamella cross section for a case of 70° tilted angle and fully expanded. Source: Own
The upper plate is supposed to be a PV material. By considering the explained in the Chapter 2, section 5, it is decided to use a reflectivity of 0.19, calculated with a normal reflectance of 0.16 and an angular losses coefficient of 0.16. With respect to the lower plate and the lenticular body, it is supposed to have a reflectivity of 0.6, that is quite conservative.

Behind the shading device, it is supposed to be a double low-E glass, composed by a 4-mm thick clear glass, a vacuum gap of 0.1 mm, and a 4-mm thick clear class coated with a low-E 270 layer. It is characterized by a center of glass transmittance of 0.69, a hemispherical front reflectivity of 0.21. The angular properties as reported in the Table 11.

<table>
<thead>
<tr>
<th>Θ</th>
<th>τ</th>
<th>ρ</th>
<th>_</th>
<th>ρ_b</th>
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<tr>
<td>0°</td>
<td>0.6900</td>
<td>0.1177</td>
<td>0.1326</td>
<td></td>
</tr>
<tr>
<td>10°</td>
<td>0.6863</td>
<td>0.1165</td>
<td>0.1340</td>
<td></td>
</tr>
<tr>
<td>20°</td>
<td>0.6768</td>
<td>0.1155</td>
<td>0.1350</td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td>0.6644</td>
<td>0.1197</td>
<td>0.1400</td>
<td></td>
</tr>
<tr>
<td>40°</td>
<td>0.6473</td>
<td>0.1337</td>
<td>0.1532</td>
<td></td>
</tr>
<tr>
<td>50°</td>
<td>0.6129</td>
<td>0.1633</td>
<td>0.1778</td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td>0.5359</td>
<td>0.2275</td>
<td>0.2248</td>
<td></td>
</tr>
<tr>
<td>70°</td>
<td>0.3889</td>
<td>0.3729</td>
<td>0.3295</td>
<td></td>
</tr>
<tr>
<td>82.5°</td>
<td>0.1276</td>
<td>0.7249</td>
<td>0.6413</td>
<td></td>
</tr>
</tbody>
</table>

Source: Own

4.4.2. Analysis of the performance

Because of the case study simulation, the CFS can be characterized with 48 BTDF/BRDF matrix pairs to be used in any daylight simulation. The hemispherical-to-hemispherical transmissivity and back reflectivity is reported in Figure 47 and Figure 48, as functions of the tilt and sliding steps.

Also, the peculiarity of the shading device gives a very wide range of CFS diffuse transmissivity, from 12.7 % to 62.9 % (that for the shading device only represents roughly a range between 18 % and 91 %). What is particularly important, is the possibility to choose a variety of regulations that allows the light to enter in different ways. To show that, it is compared the project system with a traditional not-extensible system, with a clear glass only behind it, to better highlight the behavior of the lamellas.

In the Figure 49 it is shown that during the “maximum transmission” mode, which happens with the horizontal and reclosed lamellas, the innovative design allows more undisturbed light to pass through. For high profile angles, it lets pass even more light after the multiple reflections, as it can be appreciated by looking to the diffuse component.
Figure 47. Hemispherical-to-hemispherical transmissivity. Source: Own

Figure 48. Hemispherical-to-hemispherical reflectivity. Source: Own
On the other hand, in the Figure 50 and Figure 51, it is appreciated that at 45° tilted position, if the plates are reclosed the light passing is bigger than the traditional system. When the lamellas are extended at their maximum size, the behavior is very similar among them (the innovative system is blocking even a little lighter due to its shape), guarantying the same type of solar control.

**Figure 49.** Visible transmittance vs. incoming profile angle for horizontal and reclosed lamellas. Source: Own

**Figure 50.** Visible transmittance vs. incoming profile angle for 45° and reclosed lamellas. A is the traditional device while B is the innovative device. Source: Own
Figure 51. Visible transmittance vs. incoming profile angle for 45° and fully extended lamellas. A is the traditional device while B is the innovative device. Source: Own

To better understand which is the power of the innovative flexibility, it is analyzed which is the impact on the direct-to-hemispherical transmittance of three main parameters of the geometry: the tilt angle, the lamellas extension, and the inter-distance among the lamellas.

In Figure 52 is evaluated the reclosed lamellas at double inter-distance (as in the case study) with variable tilt angle. The peak in transmittance is shifted towards negative values as the tilt angle increase, but weakly reducing the overall diffuse transmissivity, that is represented by the integral of the curve. For positive profile angles, that can be occupied by the sun, the reduction is very strong, which means that the sun rays are increasingly blocked.

Subsequently, in the Figure 53 it is possible to notice that for a 40° tilted lamella with double inter-distance, the extension of the plates entails a decrease of the overall transmission due to its reduction for positive profile angles, but it keeps the peak of transmissivity at the same negative values. It represents an alternative to block the sun rays by tilting, allowing thus to maintain a certain PV slope and simultaneously regulate the transmissivity, blocking beam light at the designers wishes.
Finally, in the Figure 54 is appreciated how changing the inter-distance between $40^\circ$ tilted, the fully extended lamellas change dramatically the overall transmissivity. Depending on the need of solar control for the ambient, it can be chosen the appropriate inter-distance. With a double value, the shading device can shade completely the façade does not matter.
which season of the year. As an extra test, the lamellas can be spaced even more, giving more space to the PV modules to work without shadows and with optimal angles.

Figure 54. Evaluation of the transmittance varying the inter-distance among the lamellas. Source: Own
5. CHAPTER 5

THE EXPERIMENTAL SET UP

This chapter is divided in three big groups: introduction of the Solar tech lab facility, description of the experimental device, and explanation of the shadow impact under the geometrical parameters of the prototype. After a brief presentation of the instrumentation used for the experimental activity, it is explained why is needed to design a prototype used as a study case. For that reason, it is gathered a photographic record as well as some schematic diagrams to show the prototype installed on the roof of the Energy Department, together with all the elements used on the prototype. Then, it is explained how the prototype works, presenting diagrams and scenarios of testing. Finally, it is evaluated the shadow impact generated by the geometric way of the prototype. Therefore, it is shown the geometrical forms to followed in order to estimate the shadow cast over the PV modules.

5.1. The laboratory facility

The laboratory, whose geographical coordinates are latitude 45.502941° N and the longitude 9.156567° E, counts with a total of 29 photovoltaic modules, within which it comprises ten monocrystalline, eleven polycrystalline (from three different manufactures) and five hybrids (photovoltaic and thermal, PVT).

The rated power of the module ranges from 75 to 300 Wp. All modules are oriented as the structure with γ equal to -6°30’. The connection to the grid is carried out by micro inverters, one for each module. The operating parameters of each micro inverter are transferred in real time, using wireless connection, to a PC to store them. Such measurement of both energy and power are useful for optimizing the modules operation while a special device, whose electrical circuit scheme is represented in Figure 55, is able to track the I-V and P-V curves for researching purposes.
The energy flows between the PV system and the electrical grid are measured by an energy meter whose accuracy class is 0.5 for the active power [87]. Also, the environmental conditions are monitored with a meteorological station equipped with a solar irradiance sensor, temperature-humidity sensors, wind speed/direction sensor and rain collector.

Furthermore, the facility is equipped with infrared cameras and thermocouples to analyze the thermal behavior of the modules for any condition of the day. In the Figure 56 is presented a photograph of the Solar Tech Lab, where it can be seen the solar panels placed in the roof of the Energy Department, together with the meteorological station, which can be seen in the middle of the image.
5.2. Description of the experimental device

In recent years the implementation of BIPV has increased because it can be used as a full constituent of the building envelope. As well as its easiness to combine the building functions of the envelope with the electricity generation. The following are some examples which include those functions [92]:

- External shading devices containing PV cells.
- Roofing tiles, directly replacing traditional pitched-roof materials. Those, can be also placed on low-sloped roofs in some climates.
- Rainscreen cladding and curtain walling, where PV is used as the external cladding element.

Moreover, when a PV module is completely integrated in the building framework, its electrical and thermal behavior would change in comparison to its conventional installation. Hence, when a BIPV project is developed both electrical and thermal parameters, as well as such behavior should be considered. As a result, the main parameters which affects the performance are: the degree and nature of ventilation [93], the mounting structure, the inclination/orientation and, generally the presence of shadows [94].

For the development of this project, the idea is to consider a BIPV, which applies the PV cells to operate as an external shading for the building envelope, as it can be seen in the Figure 57.

![PV external shading device in zero energy building of Singapore. Source: [95]](image)

Figure 57. PV external shading device in zero energy building of Singapore. Source: [95]

To follow the mentioned above, the prototype is based on a new mechanical device designed to improve the seasonal flexibility of permanent external shading systems based on lamellas, varying both the tilt angle and the lamella extension [22]. As a target of simulation and performance evaluation, it has been designed a prototype system placed on the roof of
the Energy Department building of the Politecnico di Milano, next to the Solar Tech Lab, as it can be seen in the Figure 58.

![Prototype designed. Source: Own](image)

**Figure 58.** Prototype designed. Source: Own

In order to install the prototype, it has been implemented a special framework, which provides support for all the solar panels implemented together with the wood supports placed at the lateral of the framework simulates the lateral structure needed in a real building façade application (that part is noted as <<A>> on the Figure 58). In addition, there are two side supports in charge of setting the tilting angle of the surface (solar panels) according to the tested scenario, those supports are found as <<B>> in the Figure 58. Also, the prototype is comprised by two sets of PV modules denoted in the Figure 58 as <<C>>, together with a micro inverter referred to each one of the sets and all the wire connection placed in the back part of the wood where the solar panels are placed.

### 5.2.1. Design of the experimental device

The original device designed presented in [21] considers a depth of the lamellas of few less than 30 cm width and an unspecified length. To design the prototype, it has been started thinking about the constraints existent. The idea is to work with PV modules suitable for this kind of integration, with voltage and current characteristics in agreement with the requirements of the instrumentation of the laboratory (i.e. the inverters).

In the lamellas, the PV modules can be either a structural part of the framework, or a covering layer. In the case of the project, the structure of each lamella consists in the lenticular body on which the top plate and the bottom plate can slide. Hence, the framework
should not support mechanical stresses, but on the contrary the module shall be the sustained element and it must be as light as possible.

Therefore, it is decided to use a flexible, lightweight monocrystalline silicon PV module originally designed for transport and portable applications. The manufacturer could provide with several dimensions and configuration; thus, it has been selected the most appropriate model for project scope.

In addition, the most limiting factor for connecting the PV modules to an inverter, most of the time is the voltage. The inverters used in the Solar Tech Lab have a minimum voltage requirement of 12 V, the idea is to use two inverters, one for the unshaded field and another for the shaded one. In order to record the current-voltage point, as well when the back row of cells of each module of the lower array is shaded that is why is implemented two different inverters, when the weather is hot and the PV voltage decrease, the total voltage reached the minimum value.

Due to the information previously explained, it has been selected the GSC 85 modules [96] because each cell produces around of 0,58 V, thus, is considered three shaded GSC 85 modules to produce 15,66 V, that means leaving a 30% margin on the minimum 12 V. As the modules consists in two rows of cell, the lamellas are 36 cm deep.

Another interesting geometry could have been to work with just one row, making the lamellas thinner, but it would require more long structures, making impossible to study the shadow effect. It is important to study this latter because is preferable to have always two rows with longer inter-lamellas distances that smaller and closer lamellas. If the lamellas are close each other and shadow is casted on just the first cell due to lateral shadows, PV production might be lost. On the other hand, if the lamellas are far from each other and the PV cells are disposed in two parallel rows, it is more likely to lose one half of the PV production, but with the other half keeping producing energy at its maximum level. It is for this asymmetrical shading of the back and front rows of the shaded array that it has been asked to the manufacturer for customize the modules, looking for connecting each nine cells PV string separately with by-pass diodes.

As the module is just a covering layer, it is not necessary to cover the whole lamella with PV cells, therefore, a blank space is left between the PV module and the lateral support, thus, it would be generated power during longer periods of time at a day. By leaving 26 cm to each side, there is more time in early morning and late afternoon to produce power, this is especially important during summer season, when the sun crosses the south faster that during winter season.

5.2.2. Elements of the prototype

In general terms, the prototype designed has the following main components:
EXPERIMENTAL SET UP

- PV panels
- By-pass diodes and junction box
- Tilted mechanism
- Framework
- Grid-Tie Inverter

With respect to the solar panels installed, the prototype takes three single PV panels connected in series for each level, as it can be appreciated in the schematic graph presented in Figure 59. Likewise, in the Table 12 are gathered all the electrical and physical specifications related to a single PV module.

![Schematic diagram](source: Own)

Figure 59. Schematic diagram. Source: Own

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technology</strong></td>
<td>Monocrystalline</td>
</tr>
<tr>
<td>Vmp (V)</td>
<td>10.44</td>
</tr>
<tr>
<td>Imp (A)</td>
<td>8.16</td>
</tr>
<tr>
<td>Pmax (Wp)</td>
<td>85.19</td>
</tr>
<tr>
<td>Voc (V)</td>
<td>11.7</td>
</tr>
<tr>
<td>Isc (A)</td>
<td>8.45</td>
</tr>
<tr>
<td>Efficiency</td>
<td>15.91</td>
</tr>
<tr>
<td>kv (%/°C)</td>
<td>-0.33</td>
</tr>
<tr>
<td>ki (%/°C)</td>
<td>0.036</td>
</tr>
<tr>
<td>NOCT (°C)</td>
<td>42</td>
</tr>
<tr>
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<td>H (mm)</td>
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</tr>
<tr>
<td>L (mm)</td>
<td>360</td>
</tr>
<tr>
<td>W (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Source: [96]
As it can be seen in the Figure 58 and Figure 59, the prototype consists of two levels, one on the top of the other, in which are placed flexible monocrystalline solar panels, connected in series, to have as a nominal electrical values a voltage around 35 V without considering its respective losses, giving a maximum output power of 255 Wp. It must be noticed that flexible panels have some positive outcomes for this kind of projects, but they are strongly affected by shaded effect.

For each nine cells of the solar panel it is installed in parallel a by-pass diode, which is implemented to offset the existent shadow effect (in the following chapter such effect would be explained in detail). Those by-pass diodes are installed inside a junction box located on the back part of the panels, linked directly with the wood in which the panels are placed. In the Figure 60 it is shown the junction box with its respective by-pass diodes. Those diodes are noted by the yellow circles, in the same graph can be appreciated as well the MC4 connectors implemented for solar PV applications.

The idea of the prototype is to work under different topologies, which consists of changing the tilted angle of the lamella, thus the incidence irradiance can/cannot be used, including natural light for the building interior. To do such movement, the prototype counts with a special device, noted as <<*>> in the Figure 61. As it can be seen in the same figure, the current position of the panel is 45°, and the device has been zoom in to see it in detail.

Figure 60. Junction box and by-pass diodes. Source: Own
Finally, the idea of installing the prototype on the roof of the building is to take advantage of all the possible benefits given by the Solar Tech Lab of the Politecnico. Among such benefits, the main one consists on using the existing grid-tie micro inverters. By using those inverters, all the electrical parameters are transferred in real time, using wireless connection, to a PC to store them. Also, the energy flows between the PV system and the electrical grid are measured by an energy meter whose accuracy class is 0,5 for the active power [31].

5.2.3. System operation

The main function of the BIPV designed is to generate electrical energy by using solar panel installed over lamellas, which are installed as an external shading device, offering help to increasing the thermal and comfort factors of the building. To understand in detail how the BIPV deigned would work onto the building, it has been done a study case by installing a prototype of tests. The main functions of the prototype are mainly related to mechanical aspects. There is the possibility of changing the degree of inclination of the lamella, and, it is also possible to change the distance between the two levels.

As it can be seen in the Figure 58 and Figure 62 (a), the prototype is done with two separated levels. Each level can change its tilted position according to a selected scenario. Besides, the distance between level can be modified. For the development of the project, it has been proposed the scenarios described in the Table 13.
Table 13. Scenarios proposed for testing

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Tilted angle</th>
<th>Distance between levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.5 (0.52 cm)</td>
</tr>
<tr>
<td>2</td>
<td>45°</td>
<td>1.5 (0.52 cm)</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>2 (0.69 cm)</td>
</tr>
<tr>
<td>4</td>
<td>45°</td>
<td>2 (0.69 cm)</td>
</tr>
<tr>
<td>5</td>
<td>30°</td>
<td>2 (0.69 cm)</td>
</tr>
</tbody>
</table>

Source: Own

Nevertheless, there is another alternative scenario that might be evaluated, but it has not been evaluated so far. It consists on move the lamella on the horizontal axis, either forward or backward, changing thus the geometrical way of the prototype, modifying the incident irradiance and the shadows generated. Such scenarios open the gap to keep making research activities, evaluating different outcomes that might arise by changing the topology of the lamellas.

The prototype, as it is mentioned above, has an inclination device, which allows to change its tilted angle from 0° till 180°, with steps of 15 °. To do that, there are four screws on the corners to loosen up the device and as a central screw which works a central axis of rotation. Such behavior can be seen in detail in the Figure 62 (b). For the good of the project only the range from 0° to 90° would be used.

Figure 62. (a) levels of the prototype (b) different tilted position. Source: Own
Afterward, another aspect to consider is the tilted angle and how that changes the incident light into the building. As it has been already comment, this BIPV system is designed as an external shading device, wherewith there is the possibility of obstructing the natural light going into the building. Therefore, if it is desired more natural light inside the building, the tilted angle can be modified till being completely open (0°), but the electrical energy produced by the solar panel might be the minimal. On the other hand, if the aim is to generate as much electrical energy as possible, it can be selected a tilted position which obstructs some natural light.

Finally, another aspect to consider is the shadow impact generated by one lamella over the other one (upper lamella over the lower one), as well as the respective shadows generated by the lateral supports of the lamellas. Therefore, it is necessary to evaluate such condition in detail for all the scenarios, as it is explained in the further chapters.

### 5.3. Calculation of the shadows

In order to model the effect of the shadows on the performance of the PV modules, it is necessary to calculate when and how close some obstacles, such as vertical supports and/or upper PV panels, cast shadows on the analyzed lower PV modules row. This was done with the solar position algorithm described by Muriel and validated in the section 2.4, in which the precision of the solar radiation was estimated. Under that sense, the purpose is to trace the main surfaces that rounds the panel on its plane.

The dimension of the module components is simplified as shown in the top view reported in Figure 63. The dimensions of the cells are increased to diminish the number of segments for which calculate the intersections, but as they are scaled in all the directions, the percentage of shadowed area on the real cell is very similar to the percentage of shadowed area on the increased one.

![Figure 63. Dimensions of the module placed in the lamella. Source: Own](image-url)
The problem of the shadows has been divided in two sub-problems whose effects overlap: 1) vertical shadows and 2) lateral shadows.

Vertical shadows are present due to the casting of the profile of the upper row on the lower one. This kind of shadows depend essentially on the profile angle and the tilt angle of the lower modules. It is well known that the vertical distance between the lamellas and their inclination can reduce the problem to its 2D cross section representation, shown in Figure 64. Depending on the intersection between the projection of the upper row extremity and the lower row section, the shadowed percentage of the front and back cells can be calculated.

For the lateral shadows the procedure is similar, but it depends on the relative azimuth angle. This time the 3D situation is simplified with the projection on the horizontal plane of the lower row and of the lateral support, as represented in Figure 65. With the intersections among the segments forming the PV module representation, it is possible to calculate the shadowed areas of each cell.

By overlapping the shadows casted vertically and horizontally, it is obtained the overall shadowed area for each cell. At the end is gotten 18 factors $F_{\text{ill}}$, one for each PV cell, whose values stay between 0 and 1. These factors will be multiplied by both beam and circumsolar diffuse radiations. On the contrary, the isotropic diffuse and albedo components remain
unchanged. The implementation of the shadows on the irradiance calculation for any PV cell is represented by Eq. (5.1).

\[
G_{cell} = G_{albedo} + G_{iso,diffuse} + F_{ill}G_{circum,diffuse} + F_{ill}G_{beam}
\]

Eq. (5.1)

Figure 65. Top view of a slat element. Source: Own
On this chapter is described the effect of partial shading over the photovoltaic systems, showing the main side effect given by the partial shading (hot spot phenomenon) and its respective solution to implement (by-pass diode). In detail is explained how the partial shading becomes a temperature problem, developing hot spots which might damage the whole module. Furthermore, is explained some details and techniques to determine how many cells can be under the effect without getting damage the whole module, which is crucial to know in advance how the BIPV designed would work. On the other hand, it is explicated the concept of the by-pass diode, starting from the equations of the V-I behavior, along with the operation and ways of connection. Then, is shown a Simulink model designed to represent the behavior of a PV cell under the partial shading effect, in which are presented all the blocks implemented and the meaning of each one of them. Finally, it is done the validation of the chosen model with respect to measured real power data given by the prototype installed in the roof of the Energy Department of Politecnico di Milano.

6.1. Shadow effect over the solar cell

Often PV arrays get shadowed fully or partially by factor such as passing clouds, building, poles, trees, etc. In the case of this project, as it has been explained in the previous chapter, there are moments of the day in which due to geometry proposed for the lamella, the PV panels placed in the upper level generates a constant shadow over the lower level ones. Under such partial shading conditions, the operation of PV arrays get more complicated, with more than one power operating peak. For that reason, is important to predict the
characteristics to obtain possible maximum power, because that unavoidable shadow would seriously affect the PV performance and its output power.

Moreover, this partial shading might cause hot spot in the corresponding cells, causing several damages to these. Such damage cannot only affect the output power of solar system, but also can bring security and reliability problems.

However, it is quite expensive and takes much time to get operating output characteristics of PV arrays under non-uniform working conditions. Therefore, it is necessary to have a simulation model to study the effect of partial shading on solar PV arrays working characteristics.

### 6.1.1. Hot spot problem

Till now, all the equations referred in the previous chapters assume that all the PV cells and modules are identical and working with the same operating conditions. Nevertheless, as it has been explained above, that assertion is not always true, some cells has some dispersion in its characteristics.

There are a few reasons for that, first, the manufacturer process might infer in deviate a bit on the cells characteristics. Second, the different operating conditions that can happen simultaneously on the PV generator, i.e., conditions in which some cells receive lesser irradiance than others.

Thus, this dispersion has the following side-effects [97]:

- The maximum output power produced by the PV generator is lower than the summation of the maximum power of the panels that build the generator. This kind of losses are denominated “losses by decoupling”. This is due to the differences in the V-I characteristics for each individual module. One way to reduce these losses consist on sorting out all the modules in different categories based on the $I_{SC}$ value, building thus each branch with modules belonging to a same category.

- For specific circumstances, some cells might become “loads”, dissipating the energy generated by the other cells, forcing to elevate in a remarkable way the temperature. If such temperature value overcome a range between 85 and 100 °C, the materials implemented to encapsulate the module would damage till making them useless. This phenomenon is known as hot spot.

When there are two or more elements series connected, it is flowing the same current whereas the voltage of the array is given by the summation of the voltage drop on every element. Let’s assume two identical PV cells under the same condition, i.e., they are receiving the same irradiance. If the respective V-I characteristic curve is plotted, the $I_{SC}$ present
should be the same for the two cells (series connection), whereas the $V_{OC}$ is the summation of the $V_{OC}$ of each cell.

Now, considering the scenario in which some of the cells connected in series exhibit $I_{SC}$ value lower than the other ones either by a manufacturer problem or by partial shading effect. In this case, the cell less lit provides a current, that might behave as a load, if a reverse voltage is applied, consuming the energy generated by the PV module, even reaching the thermal break point (hot spot phenomenon).

As it can appreciate in the Figure 66, the part of the PV modules that receive uniform irradiance continues operating at optimum efficiency during the partial shading condition. At the same time, the cells are forced to operate with reverse bias voltage to provide the same current as the unshaded cells because the current that flows through every module in a series configuration is constant.

![Figure 66. Curve I-V of PV cells in a reverse bias region. Source: Own](image)

When a load is connected, as an example a resistance $R$ which forces the PV module to operate in the point B, both cells have the same current value, but with two different voltage $V_a$ and $V_b$ respectively. To analyze this phenomenon, is considered the limit case in which the cells are in short circuit ($R=0$). such case is represented in the Figure 67, where is shown a circuit where one of the cells is partial shading whilst the other one is receiving fully irradiance.
Figure 67. Equivalent electrical scheme of two PV cells series connected. Source: Own

For this condition, the current flowing in the circuit is the one correspondent to point A (voltage equal to zero). For this current value, the voltage generated by the shaded cell ($V_c$) is equal in absolute value to $V_b$ (bias voltage).

Thus, if $R=0$

$$V = I \times R = 0$$

Eq. (6.1)

Then, by applying Kirchhoff’s law to Figure 67.

$$V_{\text{light}} + V_{\text{shaded}} = V_R = 0$$

Eq. (6.2)

$$V_{\text{shaded}} = -V_{\text{light}}$$

Then, if instead of two cells connected in series, there would be $n$ cells, the shaded voltage would have a negative value equal to the absolute value of the summation of the voltage generated by the illuminated cells ($n-1$). Therefore, in the shaded cell there is a positive current flowing, but with negative voltage, consequently, there is power absorbed, till a value equal to the power generated by all the lit cells.

In case the load (resistance) would not be null, $V \neq 0$, the voltage in the shaded cell is given by Eq. (6.3).

$$V_{\text{shaded}} = V_R - \sum_{n-1} V_{\text{light}}$$

Eq. (6.3)

In addition, there is a value of $R$ in which $V_{\text{shaded}} = 0$, called as $R_{\text{lim}}$, where the shaded cell does not dissipate energy. In the Figure 66, such value is the point in which is intercepted the V-I curve of the array with the V-I curve of the lit cells (point C). For values of resistance higher than $R_{\text{lim}}$, the shaded cell generates energy to the load, but with values lower than the
cells fully irradiated. On the other hand, for resistances lower than $R_{lim}$, the energy generated by the lit cells is dissipated, either in the load and/or in the shaded cells. Hence, the resulting reverse power polarity consumes the power and reduces the extractable output power of the shaded PV system.

Furthermore, as it has been explained so far, the shaded cell moves the V-I curve to lower current values with respect to the no shaded cells. In the limit case, when the cell is fully shaded, such cell behaves as a diode. In the Figure 68 is represented this comportment, when one of the cells is fully shaded. Also, both cells are assumed to be connected in series to a specific load with a resistive value equal to 0, in which one of them is not receiving any irradiance at all.

![Figure 68. Equivalent electrical scheme, diode behavior or one cell. Source: Own](image)

Again, by applying Kirchhoff’s voltage law:

$$V_R = V_{light} + V_{diode} = 0$$

Eq. (6.4)

The shaded cell behaves as a reversed biased diode, not allowing to pass any current (in fact, there is a small amount of current passing, related to the reverse saturation current). As the current flowing is almost zero, the voltage drop on the illuminated cell as well as on the resistance is null. Therefore, there is not current flowing, making the module to operate in open circuit, generating $V_{OC}$. Thus, the diode is subjected to a negative voltage equal than the generated cell, as it is expressed by Eq. (6.5).

$$V_{diode} = -V_{light} = -V_{OC}$$

Eq. (6.5)

By applying the same concept explained above, if instead of two cells, it is being evaluated a whole module with $n$ cells, where only one cell is shadowed, such cell takes a negative voltage of absolute value equal to the $V_{OC}$ value of the $n-1$ cells illuminated, i.e., a
biased voltage $n-1$ times $V_{OC}$. If such voltage is higher than the reverse break voltage ($V_{\text{break}}$), the cell gets damage, as it can be seen in Eq. (6.7). On the other hand, if the voltage is lower, when the cell is again without shadow, it would operate without any issue. Thus, it can be determined the maximum number of $n$ cells connected in series that can be connected without bursting risk, as it is expressed in the Eq. (6.7).

$$ |V_{\text{break}}| > |n - 1| \cdot V_{OC} $$

Eq. (6.6)

$$ n < \frac{|V_{\text{break}}|}{V_{OC}} + 1 $$

Eq. (6.7)

Summarizing, continuous operation of the shaded cells in excessive reverse bias voltage can result in hot spots and cause an open circuit in the entire PV array. Nevertheless, when a cell is partially shaded (generally illuminated only by the diffuse radiation component), it is still generating voltage but at a lower current value, suffering hot spot problems. This phenomenon is usually solved by inserting a bypass diode into a predefined number of cells in the series circuit [98].

6.1.2. By-pass diode application

Normally, when the PV cell is under partial shading, the achievable power obtained from the PV module is determined by the shaded cell. However, by introducing a new device into the PV connection scheme, it is possible to make a new path of exploiting as much as possible the resource, thereby resulting in reduced losses. Such connection is presented in the Figure 69, with the diode inside the circle

![Figure 69. Insertion of by-pass diode inside the PV connection scheme. Source: Own](image)

Generally, a by-pass diode is used in PV modules to avoid fire caused by hot spot, also to reduce energy losses during shading and mismatching conditions. For that reason, the by-pass diodes are usually placed in the protection box. These diodes are connected in parallel to one of a group of cells in the forward current sense, to bring an alternative current path in case of broken cells or shadowed conditions. For this project, as it was explained before, the by-pass diode implemented is connected into a group of nine cells.
Various studies on bypass diode configurations, are summarized in Table 14. By implementing this device, it has been improved the efficiency of PV system under failure condition induced by partially shading, and/or malfunction of the electrical components [99].

Table 14. Impact of by-pass diode

<table>
<thead>
<tr>
<th>Specific parameter</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconfiguration of PV arrays or cell arrangements</td>
<td>Improve the output in shading and reduce losses</td>
</tr>
<tr>
<td>By-pass diode circuit added MOSFET</td>
<td>Reduce hot spot temperature and power losses</td>
</tr>
<tr>
<td>Impact of partial shading on PV module</td>
<td>Evaluate power losses</td>
</tr>
<tr>
<td>PV model module including shaded cell</td>
<td>Predict output of shading module</td>
</tr>
<tr>
<td>Cell of reverse bias voltage</td>
<td>Comparison of power losses and impact</td>
</tr>
<tr>
<td>MPPT algorithm and DC-DC converter</td>
<td>Reduce power losses in irradiance variation</td>
</tr>
<tr>
<td>Damaged by-pass diode</td>
<td>Analyze damaged diode</td>
</tr>
</tbody>
</table>

Source: Own

**Characterization of by-pass diode**

To define the behavior of the by-pass diode, it can be done through a Schottky barrier diode under a forward bias $V$ [100]. Such expression is given by the relation presented in Eq. (6.8).

$$I = I_s \left\{ e^{\frac{qV}{kT}} - 1 \right\}$$  \hspace{1cm} Eq. (6.8)

$$I_s = A_d \cdot A'^*T^2 e^{-\frac{q\phi_b}{kT}}$$  \hspace{1cm} Eq. (6.9)

Where,

- $A_d = \text{diode area} \ [m^2]$
- $A'^* = \text{effective Richardson constant} = 1201730 \ [A \cdot m^{-2} \cdot K^{-2}]$
- $k = \text{Boltzmann constant}$
- $T = \text{Temperature} \ [K]$
- $q = \text{electron charge}$
- $\phi_b = \text{energy barrier height} \ [eV]$
- $n = \text{ideality factor}$

In the Figure 70 is shown the V-I curve of the by-pass diode. In the curve, it is appreciated how is the behavior of the current in function of the voltage. When the value of voltage is equal or higher than the $V_{OC}$ of the cell (group of cells) connected to the diode, this would be polarized and conducts current. In the graph, such behavior is represented as a high current value. By applying that concept, if there is an abnormal situation on the cell,
either by partial shading or malfunction of the material, the diode would work as an external
current path, i.e., it lets the current to flow when the cell would become a reverse bias diode,
as it has been explained previously.

Figure 70. V-I characteristic curve of a by-pass diode. Source: Own

**Operating mode**

Due to the diode polarity is opposite to the cells, when the cells are reverse biased, the
diode is biased positively. For that reason, the current generated by the PV module finds an
easy path to flow, limiting the maximum power to dissipate by the damaged cell.

Figure 71. Operation of the by-pass diode (a) No shadow present (b) Shadow present. Source: Own
In the Figure 71 is displayed how is the behavior of a PV module with by-pass connected in parallel to each cell. When the module is generating, the current flowing path is indicated by a red line (Figure 71-a). If one of the cell is shaded, such cell behaves as a diode, then the new current path would be the one described by the green line (Figure 71-b). Therefore, as it can be seen in the figure above, the reason of installing diodes for protecting the modules against the shadow impact is because the resistance of the diode is lower than the PV cell reverse biased.

6.2. Simulation of PV shadow effect

Based on the PV equations previously explained (chapters 2, 3 & 4), it has been developed a model of a PV module to analyze the impact of the shading effect over the cells. The model is done using Tag tools in Simulink environment, as well as a code running in MATLAB. The model represents the PV solar panel used in the prototype explained in the chapter 4, whose parameters are gathered in the Table 12.

6.2.1. Simulink model

Above all, it must be clarified that SimElectronics® software works with Simscape™ software and extends the physical modeling capabilities of the Simulink® product family with tools for modeling and simulating electromechanical and electronic systems. It contains blocks that let one model electromechanical and electronic systems at a speed and level of fidelity that is appropriate for system-level analysis. Thus, the main feature of Simulink is the possibility to convert the model's equations in block diagram representation [101].

For the Simulink environment, the effect of the partial shading was included just by varying the incident irradiance over a single cell. The model includes 18 cells series connected, grouped in two groups of nine cells, with its respective by-pass diode in parallel. As a result, a solar PV module is made by the combination of all the cells. The proposed model is shown in Figure 72. As it can be seen, it is necessary at least two cells where one has full incident irradiance while the other one has the effect of shadow, which will reduce the incident irradiance over the cell.

Inside each black box there are all the equations necessary to implement the model. To further details, the whole explanation of the Simulink model implemented is gathered in the appendix 2.
Likewise, a special treatment must be done to the irradiance input values. In the Figure 73 is presented a block called “Inclusion of partial shading”. That block multiplies by the regular incident irradiance times the percentage of the incident irradiance, according to the scenario given by the geometry analysis done in the chapter 5. The block of partial shading is created as a Simulink mask; hence it has several inputs, summarized in the Figure 73. The main components of the mask are the following: start time, duration and factor.

With respect to the start time, that variable describes the time interval in which the shading begins to affect the performance of the power output (also related to its current and voltage). As the idea of this model is to achieve as much accuracy as possible from the real operation, is required a specific time; as it is shown in the graph, it requires the hour, minute and second.
Finally, the last key point of the mask links to a shading factor. As it is mentioned in the all over the document, when it is working with the solar geometry, which represents the position of the sun in the sky, the direction in which beam radiation is incident on surfaces of various orientations, and the shading, two important angles protruded: (1) solar altitude angle ($\alpha_s$) and (2) profile angle ($\gamma_p$). By implementing a good combination of the previous two angles, plus the knowledge of the location of the building in which is installed the solar panel (latitude), is possible to estimate a shading factor for each hour of the day the whole year. That factor (percentage) is the one which must be considered in the mask.

Furthermore, the algorithm implemented to develop the inclusion of the partial shading is presented in the Figure 74. The idea is to work with binary logic ($1 - 0$), where 1 means shadow occurrence, while 0 means not shadow. Basically, if the start time is within the range put in the Figure 73, system understands is under partial shading condition; therefore, it must take the factor of incidence as an output value. Otherwise, if the time is not in the range, the factor given before is considered as null (zero).
6.2.2. Scenarios simulated and output graphs

The characteristics of a PV module for the simulation are described in Table 12. In this simulation, the PV module consists of 18 cells. In addition, the bypass diodes are connected to every nine cells in the reverse direction. Moreover, the idea is to simulate specific shadow scenarios over the cells based on the geometry of the prototype. As it has been explained above, the prototype consists of two level, one on the top of the other, where the upper one level would generate constant shadow over the lower level for specific periods of the day.

In the Figure 75 is shown a diagram of the PV panel to simulate, where is explained graphically which are the cells under the shading effect, depending on the period of the day. What can be said from the graph, basically, there are two main topologies where shadows are expected due to the geometry of the prototype, case a and case b of the Figure 75.

Moreover, in the Table 15 is gathered the shading percentage on each solar cell for specific cases to be simulated. it can be noticed that those cases were explained above in the chapter 5. For explaining the model simulation, it has been selected some of the worst cases, thus the system can be designed, i.e., it can be known beforehand which should be the values of $V_{OC}$ and $I_{SC}$ that the inverter would face when the shading impact is present.

<table>
<thead>
<tr>
<th>CELL</th>
<th>TOPOLOGY</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>70%</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>70%</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>70%</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>70%</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>70%</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>70%</td>
<td>5%</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>70%</td>
<td>70%</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>70%</td>
<td>90%</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>70%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 75. Schematic diagram of partially shaded PV module for topologies a and b. Source: Own
The resultant V-I characteristic curves of the PV module for a specific instant time are shown in the Figure 76, Figure 77 and Figure 78. In the Figure 76 is found the characteristic curve obtained when there is no by-pass diode connected to the PV panel, as well as the optimal V-I curve without partial shading effect, this has been done simulating a scenario in which half of the solar panel is shading affected. On the other hand, in the Figure 77 and Figure 78 is plotted the characteristic I-V curves with the insertion of the by-pass diode for both cases a and b respectively.

Figure 76. V-I curve for a PV panel with and without shadow effect a) 50 % shadow on the cell. b) no shadow on the cell. Source: Own
Figure 77. V-I curve for a PV panel with by-pass diode connected, topology a. Source: Own

Figure 78. V-I curve for a PV panel with by-pass diode connected, topology b. Source: Own
In the Figure 76 it is appreciated the operating conditions, both regular and shading conditions. In normal condition, i.e., when the solar irradiance on the entire PV array is uniform, the P–V curve exhibits only one maximum power point. On the other hand, when the incident irradiance is not uniform on all the cells, if the by-pass is removed, the PV array exhibits only a single peak, but with a significant reduction in the generated power.

Furthermore, during partial shading including by-pass diode (either Figure 77 or Figure 78), there are some cells being less illuminated (in the matter of fact, they are following the pattern given by the Figure 75 and the Table 15). Thus, the difference in irradiance among the cells activates the bypass diode. As a result, four stairs current waveform is created on the I–V curve. Consequently, the corresponding P–V curve is characterized by several local peaks and one global peak, indicated by a red circle on the graph.

By analyzing both graphs, the following can be summarized:

1. When solar PV system is partially shaded, the power output decreases.
2. When the number of shaded cells increases, the number of peaks in power output increases.
3. The Position of the maximum power point is independent on the number of shaded cells.

### 6.3. Validation of the PV model

In the same way that the validation of the model in chapter 3, it has been done a MATLAB code which gives electrical parameters such as generated power, current and voltage. To determine how accurate the model is working, it must be done a comparison between the simulation data and real data.

The real data value is taken from the prototype installed on the roof next to the Solar Tech Lab. All the parameters given by the prototype are saved in the laboratory database, where is extracted real data of power, current and voltage values, which can be used to control the results of the model.

The methodology proposed to verify the simulated model is the following:

1. Establish if the PV module to simulate is under shading effect or not, i.e., to know if it is simulating the PV panels placed on the upper level or the lower level of the prototype.
2. Determining the scenario to simulate, and from that scenario pick up a suitable day to set as a base to simulate.
3. Take all the meteorological data related to the selected days, from the Solar Tech Lab database. The data collected is irradiance, ambient temperature and wind speed measured.
4. Define an error definition to implement on the comparison between the simulated data from the MATLAB development and the reference values given by the solar tech lab.

5. Implement all the equations to develop the model, beginning from the characterization of the solar resource for this specific application (chapter 2 and chapter 4), considering the geometrical shape of the prototype and its respective shadows generated to the panels (chapter 5). By doing this a suitable model with output values is ready to be evaluated.

6. Take all the real electrical parameters measured by the Solar Tech Lab, arrange the data in such a way that a suitable comparison between simulated and real data can be effectuated.

7. Present a set of graphs in which are compared the real and simulated power data

### 6.3.1. Input data of the model

As it is explained above, from the solar tech lab are taken climatological data such as ambient temperature, wind speed and incident irradiance. To develop the comparison to simulate, from the scenarios gathered in Table 13, it has been selected one day for evaluating. The selected days are: July 25th, July 28th, August 1st and August 04th 2017. In the Figure 79 is summarized all the climatic data for the four days.

![Figure 79. Climatic data July 25th, July 29th, August 1st and August 4th. Source: Own](image)
The model would work either for monocrystalline or polycrystalline technology, similar to the model developed in chapter 3. In this case, it has been selected a flexible monocrystalline solar panel, whose parameters are gathered in Table 12.

### 6.3.2. Verification of power output measured

To guarantee a good performance of the experimental set up, explained in chapter 5, it has been done a comparison between the PV panels installed on the upper level and the lower level, as it is depicted in Figure 80 and Figure 81. The idea is to evaluate how is the power condition for two different climatic condition, such as sunny day without clouds and a cloudy day. It is appreciated that, no matter how is the climatic condition of the day, the set of panels placed on the upper level (no shaded effect) were producing less output power than the ones placed in the lower level (shaded affected).

![Figure 80. Measurement power data for a sunny day (August 5th). Source: Own](image1)

![Figure 81. Measurement power data for a cloudy day (August 8th). Source: Own](image2)
By making a comparison among the two pictures above, it is seen that in the center of both power profiles, which corresponds to the hour without shading incidence, there is a power mismatch of approximately of 12.5%, therefore, it implies the existence of some problem within the solar module.

Due to that mismatch issue, it was necessary to characterize the solar panel with data measured in real time. In the Table 16 is collected the results of those measurements, modelling the cell chains of each one of the solar panel, for both levels (up and down).

Table 16. Real data measured over the solar panel

<table>
<thead>
<tr>
<th></th>
<th>Up Level</th>
<th></th>
<th></th>
<th>Down Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>2A</td>
<td>3A</td>
<td>4A</td>
<td>5A</td>
</tr>
<tr>
<td>V_oc [V]</td>
<td>5.36</td>
<td>V_oc [V]</td>
<td>5.33</td>
<td>V_oc [V]</td>
</tr>
<tr>
<td>G [W/m²]</td>
<td>860</td>
<td>G [W/m²]</td>
<td>852</td>
<td>G [W/m²]</td>
</tr>
<tr>
<td>T [°C]</td>
<td>57</td>
<td>T [°C]</td>
<td>57</td>
<td>T [°C]</td>
</tr>
<tr>
<td>V_oc [V]</td>
<td>5.36</td>
<td>V_oc [V]</td>
<td>5.33</td>
<td>V_oc [V]</td>
</tr>
<tr>
<td>G [W/m²]</td>
<td>860</td>
<td>G [W/m²]</td>
<td>852</td>
<td>G [W/m²]</td>
</tr>
<tr>
<td>T [°C]</td>
<td>57</td>
<td>T [°C]</td>
<td>57</td>
<td>T [°C]</td>
</tr>
</tbody>
</table>

Source: Own

By analyzing in detail the results gathered in the Table 16, it is concluded that there is a problem with one of the panels placed in the upper level, more specific, one chain of cells, because the value of the short circuit current measured at that specific time (around 2:45 pm), is lower than the remains solar panels, it is appreciated a change from 7.34 A to 6.58 A, approximately 10.35%. The reduction percentage of current corresponds to the overall power mismatch analyzed previously.
6.3.3. Results of simulation

The idea is to prove the veracity of the model developed, to do that, it has been proposed several days to be evaluated, each one of them is related to a specific scenario proposed in the chapter 5. In addition, the model selected for determining the partial shading effect is the 5c (see Table 8) because, as it has been explained previously, this is the most accurate model, hence it should be the model to keep working. Moreover, due to one of the cells in the upper level seems to be damaged, for evaluating the simulation results, is decided to neglect such panels, i.e., in this section is only evaluated the simulated output power of the panels in the lower level, which are the ones affected by the shadows.

![Power profile July 25th](Figure 82. Power profile July 25th. Source: Own)
Figure 83. Power profile July 28th. Source: Own

Figure 84. Power profile August 1st. Source: Own
In the Figure 82, Figure 83, Figure 84 and Figure 85, are presented the energy profile of each day simulated for the specific scenario proposed. For all the graphs are presented the simulated power, the measured power given by the prototype installed in the roof, in addition, is presented a dotted line (green), which shows the incidence of the shadows during the day. It must be noticed that measured power of Figure 83 has some points on zero, which most likely is due to a technical problem with the inverter and the communication scheme,

On the other hand, the difference on the curves presented in Figure 82 can be explained by an external phenomenon such as an artificial shadow presented at that time (a person, a leaf, etc.), because it is seem a reduction of power similar to the produced by the by-pass diode, but in the simulated line such behavior is not present, mainly because in the forecasted labor done a prior, for such time of the day, there was not a high shadow impact.

Furthermore, by analyzing all the graphs displayed above, it is seen the effect of the shadow on the solar PV panels. The dotted green line represents the shadow incidence on the panels, where at the start and end of the day the effect is maximum (100 %), and it starts to decrease symmetrically till a point of the da in which there is no shadow on the PV modules (0 %). By going through the four scenarios proposed, it is exposed how well the shadow effect is represented by the PV model, showing a matching between both curves.
**Comparison of I-V curve**

Another aspect to consider is the one referent to the characteristic V-I curve of the solar PV panel. Due to the characterization done to the PV panel, it is possible to compare the resultant V-I curve between the real data measured by the solar lab tech facility instrument, and the simulated data. In the Figure 86 is shown the comparison of the characteristic curve, where it can be appreciated that both curves are similar, with a little mismatches points, provoked by the algorithm implemented for obtaining the maximum power. Likewise, by analyzing such graph, it is concluded the veracity of the PV simulated model, which works in concordance with things that have been explained so far.

![Figure 86. Comparison of the characteristic curve of the PV panel between real data measured and simulated data. Source: Own](image)

### 6.3.4. Error definition

The objective of this project is to develop a model with a high accuracy level in terms of PV energy production when a PV panel is under the partial shading effect. To do that, are defined the same error implemented to validate the model previously exposed, i.e., it is selected Normalized mean absolute error NMAE, weighted mean absolute error WMAE, and Normalized root mean square error nRMSE, based on the equations explained before. In the Figure 87 is found a scatter plot with all the errors resulting from the PV simulation.
In addition, to evaluate the accuracy of the model, not only for the whole projected day, but in detail for the timing with and without shading, in the Figure 88 are presented the punctual error for both timings. It must be noticed that some percentage errors are quite high, this is because to the reading of the real data, by issues related to the communication scheme.
To summarize, it has been developed a model to simulate the performance of a PV panel, module or array, when it is under the effect of shadows, especially in cases of constant shadow as the one proposed by the innovative lamella device. For future works, it is necessary to evaluate what would happen if there is different topologies on the lamellas, including the effect explained by [23].
The flexibility of the innovative shading device makes possible a variety of imaginable regulations, thus, to choose among them at any time, the priorities in the functionality of the device must be set, therefore, one or more control strategies can be implemented.

The basic principles in daylighting states that the benefits of daylighting regard both comfort and economics. In fact, the occupants of daylighted spaces enjoy a promotion of healthy circadian rhythm, a reduction of the stress and an improvement of productivity and mood [102]. Furthermore, from the energy savings point of view, the advantage is double, because the highest luminous efficiency of the Sun means less heat per unit of visible light, which leads to smaller and less operated HVAC systems, thanks to that, it is reduced the cooling loads as well as energy, giving money savings. On the other hand, the substitution of electric lights usage with sunlight means a reduced electricity consumption, saving, both money and energy again. Due to these considerations, it has been hypothesized as a main priority to ensure the maximum use of solar light, reducing as much as possible the use of electric lights.

If the comfort point was not strong enough to justify that assumption, it can be noticed that, even if the PV energy production is neglected, the same light ray, which is naturally illuminating the ambient, would never produce enough power hitting PV panels to pass through the module efficiency, thus the electrical plant losses as well as the illuminating device efficiency to light in the ambient. As a conclusion, whatever control strategy to implement, should give as a priority to daylighting up to a certain illumination threshold.

In order to quantify the internal ambient illumination at any time, it is decided to use the EnergyPlus software as a daylighting calculation tool. Previously, as output of the optical model, it was obtained 48 different bidirectional transmittance and reflectance distribution
functions (BTDF and BRDF) pairs, which served as inputs for the CFS object in EnergyPlus input files.

EnergyPlus usually is able to dynamically manage shading devices by actuating the construction state, and varying with time the window objects characteristic, but with the CFS elements this is not possible. After a confrontation with the technical support team of the software, it has been decided to simulate all the possible configurations along one year and to select, for each time step, the configuration which better fits with the criteria of the designed control strategy.

In the following paragraphs, the daylight simulation, the control strategy and the results obtained will be described.

7.1. EnergyPlus simulations

To maintain coherence with other simulations in the project, it is decided to perform the building simulation with a 10 minutes step, which is small enough to ensure a good dynamic response of the shading device, and represents a realistic time step for the real device regulation.

The same geographical coordinates of the Energy Department of the Politecnico di Milano are used together with the weather data of the Milano Malpensa airport taken from the EnergyPlus database.

Besides, it is defined a single-zone building that represents an office of 24 m² floor with a height of 3 m. The walls, the floor and the roof are defined with moderate reflectivity of 0.7 and 0.5 pertaining to plaster and wood respectively.

As it was mentioned before, the window is represented by a CFS element, whose optical characteristic depends on the associated BTDF and BRDF. Regarding the extension of the window surface, which is located on an exterior wall facing south measuring 12 m², exits three possibilities:

A. A vertical window 3 m height and 2 m wide in the center of the wall.
B. A horizontal window 1.5 m height and 4 m wide situated in the higher half of the wall.
C. A full window covering all the south surface, 3 m height and 4 m wide, representing a glass façade.

In Figure 89 the external wall is showed together with the three window shape options.
Figure 89. Front view of the south wall. In light blue window A, vertical, is represented; in dark blue window B, horizontal; in black, coinciding with the wall perimeter, window C, full façade; in red the work plane height is reported. Source: Own

As daylighting controls it has been set two reference points in the office that were measuring the illuminance for each time step:

1. The first reference point located at 3 m from the window and 2 m from the east and the west walls;
2. The second reference point at 5 m from the window and 2 m from the east and the west walls.

Both are situated at the height of the work plane, which is 0,8 m, and will be representing the illuminance of one half of the room. The office top view is represented in Figure 90.

Figure 90. The simulated office and the reference points represented in top view. Source: Own
With these few inputs, and a handful of others, it was possible to run the 48 yearly simulations registering, for each regulation of the device, the illuminance produced along the time on the two reference points \( R_{p1} \) and \( R_{p2} \).

### 7.2. Control strategy

As it was said above, the priority in the regulation of the shading device is to maintain a sufficient daylight level in the room containing overheating risk and exploiting PV generation. The objective is to implement the system in a building with a high level of comfort: as it is well known that occupants appreciate a high illumination level when the light is natural, it is decided to set the threshold higher than the Italian governmental recommendation suggestion for artificial lighting. The minimum illuminance on both reference points must be higher than 800 lux before starting to tilt or extend the lamellas, otherwise they should remain horizontal and reclosed, allowing the maximum light permeability.

As the reference points must represent the illuminance of half of the room, it has been conservatively hypothesized that if the illuminance value registered is lower than 600 lux, the lights of such part of the room will be turned on.

Moreover, if 800 lux are reached in both reference points, it is considered the whole room sufficiently illuminated, then the PV yield would be optimized by tilting the lamellas as close as possible to the optimal tilt angle \( \beta_{opt} \), which is the complement of the profile angle \( \alpha_p \), this is represented in the Eq. (7.1).

\[
\cos \theta = \sin \alpha \cos \beta + \sin \beta \cos \gamma
\]

Eq. (7.1)

As the idea is to minimize the incidence angle, it is maximized its cosines as a function of the tilt angle, as it is seen in Eq. (7.2) and Eq. (7.3).

\[
\frac{d \cos \theta}{d \beta} = 0 = \cos \beta_{opt} \cos \alpha \cos \gamma - \sin \beta_{opt} \sin \alpha
\]

Eq. (7.2)

\[
\beta_{opt} = \arctan \left( \frac{\cos \alpha \cos \gamma}{\sin \alpha} \right) = \arctan \left( \frac{\cos \gamma}{\tan \alpha} \right) = \frac{\pi}{2} - \alpha_p
\]

Eq. (7.3)

Furthermore, it is evaluated the condition to avoid overheating in the building, which might occur when dealing with high window surface exposed to the Sun. To evaluate such condition, it has been hypothesized a critical threshold of irradiance on the window plane based on previous experience in simulation of similar cases. Such threshold should be
evaluated according to the building characteristics through a dynamic simulation. This kind of verification will be implemented in next developments of the work, developments that involve an integrated daylighting-thermal simulation using the optical characterization of the shading device under study. This part is left for future works as so far in EnergyPlus the dynamic control of the CFS properties is not available: therefore we give the work a principally methodological value.

Consequently, it is supposed an incident irradiance on the window higher than 400 W/m$^2$, which represents an excessive thermal gain. This is somehow doubtful, because the real value depends on ambient temperature, occupancy, thermal inertia and so on, but at least it allows to simulate a regulation action. The action, in this case, would be to maintain the optimal tilt angle and extend as much as possible the lamellas, always keeping the illuminance above the requirements.

The control strategy can be summarized in the following points in order of priority:

1) If one of the two reference points registers an illuminance above 600 lux, one half of the light are switched off. The lamellas stay horizontal and reclosed.

2) If both reference points register more than 600 lux, all the lights are switched off. The lamellas stay horizontal and reclosed.

3) If both reference points register more than 800 lux, the external shading device is allowed to stay in a position different than the horizontal to follow the Sun.

   a) If 3 is satisfied, with irradiance on the window below 400 W/m$^2$, the lamellas remain reclosed, whilst the tilt angle should be the closest to the optimal tilt angle.

   b) If 3 is satisfied and the irradiance is higher than 400 W/m$^2$, the regulation extends the lamellas, tilted as in point 3a, in order to block the extra solar gains ensuring at the same time the illuminance on both reference points closest possible to 800 lux.

### 7.3. Analysis of the results

To understand the performance of the regulation of the shading device, three typical days are analyzed, which represent the different situations that may occur during the year, such days are related to a winter day, a spring day and a summer day. For each day the three window types A, B and C were tested with respect to a window without shading. To have an idea of the performance in absolute terms, it is also calculated the Average Daylight Factor for the different configurations.
7.3.1. Winter day

In winter, the intensity of solar radiation is low, but the Sun altitude is lower, so the rays can reach the bottom of the room many times.

As it is showed in Table 17, the lights without shading device with the same window dimension, must stay turned on in a range of 3.58 and 4.7 hours, depending on the window typology. Instead, with the shading device, they stay turned in the range of 3.7 and 5.2 hours. The window type C allows the lower artificial lighting hours, whereas the window type A needs more lighting. It is interesting to notice that there is more electric energy saving with a shaded window C that with unshaded windows A and B. However, the presence of the shading device represents an increment in the electric lights demand between 3 % and 11 %.

The regulation mode follows the point 4 of the strategy, which is to follow the Sun, keeping with high illuminance in the interior, for 3 hours 50 minutes with window A, 4 hours 10 minutes with window B, and 5 hours 10 minutes with window C. The time in each regulation status is reported in Table 18.

Table 17. Daily time with electric lights on in a winter day.

<table>
<thead>
<tr>
<th>Window type</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>With innovative device</td>
<td>4.83 h</td>
<td>5.42 h</td>
<td>6.25 h</td>
</tr>
<tr>
<td>Glass only</td>
<td>5.33 h</td>
<td>5.58 h</td>
<td>6.42 h</td>
</tr>
</tbody>
</table>

Source: Own

Table 18. Daily time in each regulation status for a winter day.

<table>
<thead>
<tr>
<th>Window type</th>
<th>Both lights on</th>
<th>Only light 1 on</th>
<th>Only light 2 on</th>
<th>Daylight without S.T and S.C</th>
<th>Daylight with Sun Tracking</th>
<th>Daylight with Solar Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4.83 h</td>
<td>0 h</td>
<td>0.67 h</td>
<td>0.67 h</td>
<td>3.83 h</td>
<td>0 h</td>
</tr>
<tr>
<td>B</td>
<td>4 h</td>
<td>0 h</td>
<td>1.17 h</td>
<td>0.67 h</td>
<td>4.17 h</td>
<td>0 h</td>
</tr>
<tr>
<td>C</td>
<td>3.5 h</td>
<td>0 h</td>
<td>0.5 h</td>
<td>0.83 h</td>
<td>5.17 h</td>
<td>0 h</td>
</tr>
</tbody>
</table>

Source: Own.

Let’s analyze window A, that is the one characterized by the lower light penetration. In Figure 91 it is seen how the interior illuminance is strongly reduced by the shading device only when there is an excess of light, whilst in the morning and in the evening the reduction is very low.
From Figure 92 it is appreciated how the regulation allows to block beam rays of light by transforming the very high beam-to-beam transmittance into a weak beam-to-diffuse transmissivity. In the green line is shown the transmittance of the glass to beam Sun rays, in red line is presented the overall transmissivity of undisturbed light rays, whilst in purple line there is the transmissivity of diffuse radiation and in yellow the transmissivity of the beam light after the reflections inside the shading device. The same description will be used for and Figure 95 and Figure 97.

Figure 92. Irradiance on the window plane and the transmissivity of the CFS divided by type for a winter day and window A. In light blue, the irradiance on the window plane, in red the beam-to-beam transmissivity, in yellow the beam-to-diffuse transmissivity, in purple the diffuse to diffuse transmissivity, in green the glass transmissivity to beam light. Source: Own
As the priority is the interior illuminance, in Figure 93 it is seen a strong dependence of the transmissivity, especially the beam-to-beam one on it, whilst the influence of the irradiance value on the window is controversial, as transmissivity depends primarily on interior illuminance. When the average between illuminances of \( R_{p1} \) and \( R_{p2} \) overcomes a value around 1100 lux, the light is blocked.

As a comparison, it can be analyzed the same graphics for window type C, which allows in general more light penetration. As we can see from Figure 94, in the same way of window A, the interior illuminance is reduced especially when it is very high, but this time its distribution along time is better as the window has double width.

The performance of the regulation, showed in Figure 95, is the same of above, but protracted longer: it means that we have a higher light permeability together with a higher sun tracking capability.
Figure 94. Illuminance in the reference points and irradiance on the window plane in a winter day and window C. Source: Own

Figure 95. Irradiance on the window plane and the transmissivity of the CFS divided by type for a winter day and window C. In light blue, the irradiance on the window plane, in red the beam-to-beam transmissivity, in yellow the beam-to-diffuse transmissivity, in purple the diffuse to diffuse transmissivity, in green the glass transmissivity to beam light. Source: Own

7.3.2. Spring day

In spring and autumn, the sun is quite strong but not very high in the sky, these are the days with the maximum light penetration. Depending on the window type, the lights are switched on for just 0.7 h to 2 h per day without shading, whilst this time can increase 30 % to 55 % reaching values of 1.2 h to 2.6 h when the shading device is present. The relative increase is very high because the absolute time is very short, as shown in Table 19. The time spent in each regulation status is reported in Table 20.
Table 19. Daily time with electric lights on in a spring day.

<table>
<thead>
<tr>
<th>Window type</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>With innovative device</td>
<td>7.33 h</td>
<td>7.58 h</td>
<td>8.75 h</td>
</tr>
<tr>
<td>Glass only</td>
<td>8 h</td>
<td>8.25 h</td>
<td>9.25 h</td>
</tr>
</tbody>
</table>

Source: Own

Table 20. Daily time in each regulation status for a spring day.

<table>
<thead>
<tr>
<th>Window type</th>
<th>Both lights on</th>
<th>Only light 1 on</th>
<th>Only light 2 on</th>
<th>Daylight without ST and SC</th>
<th>Daylight with Sun Tracking</th>
<th>Daylight with Solar Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.5 h</td>
<td>0 h</td>
<td>0.67 h</td>
<td>0.83 h</td>
<td>0.83 h</td>
<td>5.33 h</td>
</tr>
<tr>
<td>B</td>
<td>2.33 h</td>
<td>0 h</td>
<td>0.83 h</td>
<td>0.67 h</td>
<td>1.17 h</td>
<td>5.33 h</td>
</tr>
<tr>
<td>C</td>
<td>2.27 h</td>
<td>0 h</td>
<td>0.5 h</td>
<td>0.67 h</td>
<td>2.5 h</td>
<td>5.33 h</td>
</tr>
</tbody>
</table>

Source: Own.

As it is possible to appreciate in Figure 96, the behavior response in terms of interior illuminance is exactly the ideal. It is obtained the maximum possible when it is lower than the threshold, then it is approximately constant throughout the day with $R_{P2}$ a bit higher than 800 lux. In fact, the lamellas follow the Sun for just 50 minutes to 2 hours 30 minutes (depending on the window type), whilst their aim is to block the light to avoid overheating for 5 hours 20 minutes. Therefore, the regulation makes the beam-to-beam transmissivity to drop dramatically when the Sun is too strong. For the others shape of windows, the behavior is very similar, the only difference is their bigger width, which allows to save a little of electric lighting and to start to follow the sun a sooner.

Figure 96. Illuminance in the reference points and irradiance on the window plane in a spring day and window A. Source: Own
7.3.3. Summer day

Even if the sun is summer is very strong, its high position in the sky makes it poorly usable by window for daylighting without some special device such as light-shelves. For this reason, the lights in the bottom of the room are often turned on leading to a 1.4 h – 5.8 h of electric lights on, while without shading it was possible to use them for only 0.9 h - 4.5 h (22% - 55% less), as it is showed in Table 21. In fact, with window A and B, it is only possible to have minimum illuminances between 600 lux and 800 lux, thus the lamellas remain horizontal and reclosed all day. On the other hand, with a 12 m2 window it is possible to follow the sun for 3 hours 10 minutes, but it is necessary to block light for other 3 hours 10 minutes. The regulation status along the day is reported in Table 22.

<table>
<thead>
<tr>
<th>Window type</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>With innovative device</td>
<td>5.83 h</td>
<td>4.08 h</td>
<td>1.42 h</td>
</tr>
<tr>
<td>Glass only</td>
<td>4.5 h</td>
<td>3.08 h</td>
<td>0.92 h</td>
</tr>
</tbody>
</table>

Source: Own

<table>
<thead>
<tr>
<th>Window type</th>
<th>Both lights on</th>
<th>Only light 1 on</th>
<th>Only light 2 on</th>
<th>Daylight without ST and SC</th>
<th>Daylight with Sun Tracking</th>
<th>Daylight with Solar Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.67 h</td>
<td>0 h</td>
<td>4.33 h</td>
<td>2.17 h</td>
<td>0 h</td>
<td>0 h</td>
</tr>
</tbody>
</table>
From these results, it is possible to appreciate that the summer season is by far, the more sensitive to the variation of the dimensions of the window, rapidly passing from a barely sufficient illumination for window A, to double its daylight time for window B up to behave as solar tracker/controller for most of the day with a window C.

By observing Figure 98 and Figure 99, the reference point two for window A remains all day very low, so the regulation strategy makes very little to the device. On the other hand, in Figure 100 and Figure 101, it is possible to note that the behaviour is very similar to the spring one, leading to a higher satisfaction of the inmates’ comfort requirements and to a higher PV energy production.

Figure 98. Illuminance in the reference points and irradiance on the window plane in a summer day and window A. Source: Own

Figure 99. Irradiance on the window plane and the transmissivity of the CFS divided by type for a summer day and window A. Source: Own
7.3.4. Daylight Factor

A common instrument to quantify daylighting indoor is the Daylight Factor $DF$. It is defined, for a given point in the illuminated inner ambient, as the illuminance in that point divided by the illuminance outside, where the outside illuminance is due only to diffuse radiation, as it is seen in Eq. (7.4).
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\[ DF = \frac{E_i}{E_o} \]

Eq. (7.4)

This value of course varies from point to point and to calculate it complex calculation is required, which are usually solved by software tools such as EnergyPlus or, more properly, lighting simulation tools. Consequently, in the practice is used a simplified average value of the \( DF \), which does not consider shape and position of the windows, called the Average Daylight Factor \( ADF \). It is calculated for a whole zone with average properties of the inner surfaces, presented by Eq. (7.5).

\[ ADF = \frac{\tau_w A_w F_w}{(1 - \rho_{av}) S} \]

Eq. (7.5)

Where \( \tau_w \) is the average windows diffuse transmission factor (hemispheric-to-hemispheric), \( A_w \) is the windows area, \( F_w \) is the window factor, \( \rho_{av} \) is the average reflection coefficient of the inner surfaces (windows included) and \( S \) is the total surface of the ambient (windows included).

The window factor is the approximate view factor of the window to the sources of diffuse radiation, hypothesizing the sky and the ground to be isotropic emitters it is obtained:

\[ F_w = \frac{1 + \cos(\xi + \zeta)}{2} + \rho_g \frac{1 - \cos(\xi + \zeta)}{2} \]

Eq. (7.6)

Where \( \xi \) is the window tilt, \( \zeta \) is the average elevation (in degrees) of obstacles on the horizon (if any) and \( \rho_g \) is the ground albedo coefficient. In the project case, the horizon is supposed to be clear, the reflectivity of the ground equal to 0.2 and the window is vertical, thus the window factor is 0.6.

The total surface of the office room is constant and equal to 108 m\(^2\), whilst the rest of the parameters depend on the window type and on the regulation of the shading device. In fact, the window area is 6 m\(^2\) in case of windows \( A \) and \( B \), while is 12 m\(^2\) for window \( C \). The transmissivity and the reflectivity of the window depend on the regulation and can vary from 0.12 to 0.63, and from 0.19 to 0.36 respectively. Therefore, depending on the regulation, it is obtained different \( ADF \), which can be additionally divided depending on the window size (its position is not relevant). The performances of window \( A \) and \( B \) are quite similar, even if the bigger width and the high position in the wall make the \( B \) type of window to illuminate more the room in evening and morning, and illuminate more the bottom of the room, which is the critical part.

The Italian technical recommendations state that an \( ADF \) value below to 0.3 % is insufficient, above 0.3 % is sufficient, above 2 % is good and above 4 % is optimum. In the project case, it has two sets of AFD:
CONTROL STRATEGY

- For the A/B type window, the maximum ADF, which is the one with lamellae horizontal and reclosed, is 5.62 %, going down to a minimum of 1.16 % when lamellae are 70° tilted and with the moving parts fully opened.
- For the C type window, the only variation is the window size, thus all the values are doubled leading to a range of ADF, between 2.21 % and 10.45 %.

The complete results of ADF for A/B type windows is reported in Figure 102.

![Figure 102. ADF results for window type A & B. Source: Own](image)

As it can be seen, even in the worst situation, when is blocked as much light as possible, the device ensures a sufficient daylighting. Furthermore, if the device horizontal is kept and reclosed, even with 6 m² windows, it is obtained an optimum daylighting of the room.

To summarize, the device fully demonstrated to provide a very high daylighting capability together with a complete capacity to block excess light avoiding overheating.

### 7.3.5. PV production

To evaluate the benefits of the innovative BIPV system in terms of renewable energy production, it is used the methodology of the previous chapters to estimate the PV energy produced following the described control strategy.

Assuming PV modules with the same characteristics of the one used in the experimental device, with moderate dust deposition on them, it would be possible to install a bit more than four rows and two columns on every office external wall. Therefore, the façade surface of the office can produce, as reported in Table 23, thus:

- In the typical winter day between 1.39 kWh and 1.71 kWh.
In a typical spring day between 3.41 kWh and 3.74 kWh.

In a typical summer day between 2.12 kWh and 2.20 kWh.

Table 23. PV energy production of each PV module for three typical days.

<table>
<thead>
<tr>
<th>Window Type</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Energy in winter</td>
<td>167.8 Wh</td>
<td>177.7 Wh</td>
<td>205.0 Wh</td>
</tr>
<tr>
<td>PV Energy in spring</td>
<td>417.7 Wh</td>
<td>409.6 Wh</td>
<td>448.3 Wh</td>
</tr>
<tr>
<td>PV Energy in summer</td>
<td>263.6 Wh</td>
<td>263.6 Wh</td>
<td>254.0 Wh</td>
</tr>
</tbody>
</table>

Source: Own

As it possible to appreciate, in winter a window that allow a higher light penetration, also allows a production of more PV energy, as to be at the best efficiencies it is required to have high tilt angles. On the other hand, in the spring day, the production dependence on the window type is reduced and its absolute value is by far the highest. At last, in summer the PV production is much lower than in spring, due to both higher air temperatures and less capability of sun tracking, in this day the production dependence on the window type is minimum.

7.3.6. Monthly performance

**Solar Control**

To quantify the solar control capability of the innovative device under study, it is defined the Effective Solar Transmittance Factor that can be calculated as it is shown in Eq. (7.7).

$$STF_{\text{eff}} = \frac{\tau_{\text{sys,eff}}}{\tau_{\text{glz,eff}}}$$

Eq. (7.7)

Where $\tau_{\text{sys,eff}}$ is the effective system transmissivity and $\tau_{\text{glz,eff}}$ is the effective glazing transmissivity. They can be calculated for each month as it is seen in Eq. (7.8) and Eq. (7.9).

$$\tau_{\text{sys,eff}} = \sum_{\text{month}} \frac{\tau_{\text{beam-beam}} \cdot G_{\text{beam}} + \tau_{\text{beam-diff}} \cdot G_{\text{beam}} + \tau_{\text{diff-diff}} \cdot G_{\text{diff}}}{G_{\text{tot}}}$$

Eq. (7.8)
\[
\tau_{\text{glz,eff}} = \sum_{\text{month}} \tau_{\text{glz,beam}} \cdot G_{\text{beam}} + \tau_{\text{glz,diff}} \cdot G_{\text{diff}}
\]

Eq. (7.9)

In this way, it is obtained a quantification of the reduction of transmissivity of the windows due to the innovative shading device installation. The \( STF_{\text{eff}} \) represent the amount of additional daylight blocked by the shading device with respect to the normal glazing. The lower its value, the higher the solar control. For each month and yearly depending on the window type the \( STF_{\text{eff}} \) is reported in Figure 103.

![STF for month or year depending on the window type. Source: Own](image)

The analysis of the \( STF_{\text{eff}} \) reveals that the more permeable to light is the window configuration, the more solar control is necessary and/or available. From one side, it is in fact true that the higher fenestrated surface of window C implies a higher solar heat gain and thus it really need the shading device to block the Sun rays. From the other side, the solar gains for windows A and B are likely to be very similar, but the better illumination of the bottom of the room, such as for window B, allows the shading device to orient better the PV panels and to block more beam radiation when it is needed without affecting the interior illuminance requirements.

**Daylighting**

To quantify the daylighting quality of the device with its regulation, we analysed the time in which is necessary to turn on electric lights in the office with and without the shading device. The performance, studied for a daily schedule from 8h to 18h 7 days per week, is
showed in Figure 104, Figure 105 and Figure 106 and reports a minimum monthly increase of electric lights time of 16.5% in December for window A and a maximum monthly increase of 47.2% in April for window C; the yearly increase in electric lighting time (and expenditure) ranges between 27% and 28%, changing very little with the window type.

Figure 104. Electric lighting time change per month for window A. Source: Own

Figure 105. Electric lighting time change per month for window B. Source: Own
Even if the relative lighting need increase is significant, the overall daylighting performance is good in absolute terms. Complementary, the same result presented in Figure 106, can be plotted in Figure 107, Figure 108 and Figure 109, where the daylight hours are highlighted instead of the lighting hours. It is noticed that the monthly daylight losses are between 1 % and 16 % depending on season and wind shape. In the end, the yearly daylight time worsening results to be 5 % for window C, 9 % for window B and 13 % for window A.
PV energy production

To evaluate how much renewable energy the innovative system can produce it has been simulated the installation of a PV generator with the same geometrical and technical features.
of the one tested in the experimental activity over one year in the Politecnico di Milano location, but facing south. The output was calculated for each module as it was affected by mutual shadows, so reducing its power output according to the results of Chapter 6. In Figure 109 the daily energy production of each module is reported for every month and window type.

![85 Wp module daily energy production](image)

**Figure 110.** Daily PV energy production of each 85 Wp m-Si module per month and window type. Source: Own

To evaluate how the PV panels take advantage of the radiation reaching the façade, t has been introduced a modified façade Performance Ratio for the PV module, based on the vertical irradiation, showing in Eq. (7.10).

\[
P_{RV} = \frac{E_{PV}}{PH_V \times P_p}
\]

**Eq. (7.10)**

Where \(E_{PV}\) is the energy produced by the PV modules, \(PH_V\) is the peak hours value on the vertical façade for the average day of the period under consideration and \(P_p\) is the peak power of the modules. Its value is reported in Figure 111.
It is possible to notice that the modified performance ratio, due how it is formulated, it can assume values higher than one. That means, it is producing more energy with respect to the maximum possible of a vertical module. Moreover, in summer, when the regulation flexibility is the highest and the Sun is high in the sky, the relative performance of the façade is very good.

In terms of energy production per unit surface of the façade, it was possible to pass from the module production to the façade production by multiplying the number of rows and columns of PV module that can occupy one square meter. Due to the geometrical proportion of the device, we can have 0.6945 modules per square meter, that leads to a façade production of about 120 Wh/m²/day, as reported in Figure 111. Anyway, the cost of the system strongly depends on the amount of PV panels installed, so it is interesting to calculate the energy production in terms of PV surface.

As the cost of the system is strongly related to the PV surface applied, it is convenient to analyze the energy production per unit area of PV modules. In Figure 112 it is possible to appreciate that the PV production depends weakly on the window type and presents an average daily value around 395 Wh/m².

In terms of energy production per unit surface of the façade, it was possible to pass from the module production to the façade production by multiplying the number of rows and columns of PV module that can occupy one square meter. Due to the geometrical proportion of the device, it is possible to have 0.6945 modules per square meter, that leads to a façade production of about 120 Wh/m²/day, as reported in Figure 113. However, the cost of the module
system strongly depends on the amount of PV panels installed, thus, it is interesting to calculate the energy production in terms of PV surface.

![Daily energy production per PV surface](image)

**Figure 112.** Daily energy production per PV surface for month and window type. Source: Own

Using Table 24 it is possible to convert the PV modules production data into façade surface production information. It could be interesting to evaluate the performance of the innovative façade system in comparison with other BIPV techniques. The façade monthly energy yield is illustrated in Figure 113.

<table>
<thead>
<tr>
<th>Window type</th>
<th>Active Module Area [m²]</th>
<th>Number of module per façade area [modules/m²]</th>
<th>Active PV surface per façade area [m²_PV/m²]</th>
<th>Yearly average daily production for each module [Wh]</th>
<th>Yearly average daily production per unit PV area [Wh/m²_PV]</th>
<th>Yearly average daily production per unit façade area [Wh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.4325</td>
<td>0.6945</td>
<td>0.3</td>
<td>168</td>
<td>388</td>
<td>117</td>
</tr>
<tr>
<td>B</td>
<td>0.4325</td>
<td>0.6945</td>
<td>0.3</td>
<td>173</td>
<td>400</td>
<td>120</td>
</tr>
<tr>
<td>C</td>
<td>0.4325</td>
<td>0.6945</td>
<td>0.3</td>
<td>176</td>
<td>407</td>
<td>122</td>
</tr>
</tbody>
</table>

Source: Own
Figure 113. Daily PV energy production per square meter of panel installed per month and window type. Source: Own
The purpose of this project was to develop and validate a model of an innovative external shading device onto the building, which integrates photovoltaics systems as an alternative of energy saving for the building, based on the BIPV concepts. Along this document it has been shown all the details related to the development of the model. Below are gathered the main conclusions obtained.

- It has been simulated a method for predicting the power production of existing photovoltaic plants with different PV technologies, in which different PV models are presented to simulate parameters acquisition using MATLAB and Simulink software, predicting the power generated by the solar panel (four, five and six parameters). Among all the models, it has been selected the five-parameter model which provides good accuracy (with percentage error lower than 2 – 3 % according to the evaluated day) with a reasonable computational complexity. The comparison was based on power measured with the inverter installed in the Solar Tech Lab of Politecnico di Milano.

- The developed five-parameters model is based on the one-diode electrical equivalent circuit, followed by one-time calculation of the five parameters \((a, I_o, I_{pv}, R_s \text{ and } R_p)\) at reference conditions, using data provided by manufacturers such as short circuit current \((I_{sc})\), open circuit voltage \((V_{oc})\), and temperature coefficient for both voltage and current \((\alpha \text{ and } \beta)\). In addition, it includes improvements on some parameters such as saturation reverse current and shunt resistance. These values are then used with in the model to calculate the parameters at other operating conditions, making it possible to predict the power output at any operating conditions.
• The model designed for uniform irradiance (i.e. without considering shadow effect) was tested for an effective comparison with the data issued by manufacturers of two different silicon PV modules technologies (monocrystalline and polycrystalline), where its reliability was confirmed against experimental data. Nevertheless, it must be noticed, the accuracy of the model increases when the input data considered are not the ones given by the manufacturer for the standard condition, but the ones derived from the in-situ characterization performed at the Solar Tech Lab. This behavior shows a minimal, but existent, mismatch in the data gathered in the datasheet given by the manufacturer, which at the end, tends to get worse the results of the model. Therefore, the results showed that rather than its complexity, the accuracy of the model depends on (i) the data used for its calibration and (ii) the approach adopted for the calculation of the cell temperature.

• Based on such five-parameter approach the PV array model has been developed with the objective to simulate the production under different – not uniform - irradiance on the cells, due to shading effects.

• The objective of the proposed model is to fit the mathematical I–V equation to the experimental remarkable points of the I–V curve of the practical array. Thus, the model obtained smooth simulated I–V and P–V acquisition characteristics, which allow a continuous estimation of output parameters dynamics. Therefore, the proposed model modularity allows accurately predict the behavior of any unknown or experimental PV cell, module, panel or power system under wide range of operating conditions and physical parameters changes. This model can be used for analyzed the development of a method for the mathematical modeling of PV arrays.

• An experimental set up was built to analyze the impact of shading on the solar PV panel. A prototype, based on the design of an innovative external shading device for BIPV, was installed on the roof of the Energy Department of the Politecnico di Milano (45.502941° N, 9.156567° E). The prototype has the capability of change the inclination of the lamellas surface, allowing to evaluate different scenarios. Such experimental set up has been initially designed to address the issue of solar cells integration in shading devices, where for some configurations the cells might work partially shaded. Afterword, it will allow to propose researches on the design and the features of new BIPV systems, such as testing different PV technologies and studying the thermal effects, in addition, it opens the possibility to implement new typologies on the connection of the by-pass diode, in order to evaluate the effect on the generated power by changing the respective connection of the by-pass diode.

• A simulation methodology for solar cells and PV modules working partially shadowed using MATLAB and Simulink toolbox was established. The proposed
model has been validated by comparison with power measurements at Solar Tech Lab.

- Concerning the irradiance calculation, a critical issue in the implementation of traditional solar calculations for small time steps applications have been analyzed and solved. Sunrise and sunset peculiarity are solved by the integration of the instantaneous formulas and we validate the method by comparing high resolution results with finely measured data.

- A novel optical model for a generic shading device has been developed and validated taking advantage of worldwide trusted software. The feature of the model is the possibility to have a complex geometry and an arbitrary number of different materials. The result was a complete bidirectional characterization of the visible light properties of the innovative shading device under study, and the possibility to extend the characterization to the solar properties in future works.

- The integration of the optical model of the shading device with pre-existing building energy simulation software was carried on successfully. The result is a dynamic regulation capability of the device following a selected control strategy.

- The control strategy implemented for the regulation of the innovative shading device under study was based on the satisfaction of the three basic criteria for the integration of PV on external shading devices: daylighting, solar control and renewable energy production.

- The use of wide fenestration surfaces allows natural light to get deep in the inner ambient thanks to the redirecting capability of the lamellas, that transform part of the beam radiation in diffuse radiation. The use of electric lights due to the unwanted shading effect in low light hours appears to be compensated by the advantages offered by the solar control in warmer conditions. Three different window typologies have been considered. The study showed how horizontal windows allow the light to reach better the inner spaces and so avoiding some lighting expenditure. The device showed an overall transmissivity and a very limited daylighting availability reduction compared to unshaded glazing.

- At the same time, the undesired solar heat gains can be avoided by tilting and extending the lamellas, so that no beam radiation passes through the system when it is not desired to. An effective Solar Transmittance Factor (STF) has been introduced to evaluate the shading capability of the device.

- Finally, the PV energy production has been quantified in order to make the performance of the BIPV system comparable with others of its kind.
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APPENDIX 1

PV MODEL ERRORS

A.1 Errors bar graphs

**Monocrystalline Datasheet Errors**

Fig. A. 1. Normalized errors for all the mono simulated models, datasheet data. Source: Own

Fig. A. 2. Weighted errors for all the mono simulated models, datasheet data. Source: Own
**Monocrystalline Measured Values Errors**

Fig. A. 3. Normalized errors for all the mono simulated models, measured data. Source: Own

Fig. A. 4. Weighted errors for all the mono simulated models, measured data. Source: Own

**Polycrystalline Datasheet Errors**

Fig. A. 5. Normalized errors for all the poly simulated models, datasheet data. Source: Own

Fig. A. 6. Weighted errors for all the poly simulated models, datasheet data. Source: Own
Polycrystalline Measured Values Errors

Fig. A. 7. Normalized errors for all the poly simulated models, measured data. Source: Own

Fig. A. 8. Weighted errors for all the poly simulated models, measured data. Source: Own
APPENDIX 2
PV GRAPHS EXTENDED

A.2 Output power generated comparison

Fig. A. 9. Power output June 26th among models 4a, 5a & 6a, measured values. Source: Own
Fig. A. 10. Power output June 30\textsuperscript{th} among models 4a, 5a & 6a, measured values. Source: Own

Fig. A. 11. Power output June 26\textsuperscript{th} among models 5c & 6c, measured values. Source: Own

Fig. A. 12. Power output June 26\textsuperscript{th} among models 5d & 6d, measured values. Source: Own
Fig. A. 13. Power output June 30th among models 5d & 6d, measured values. Source: Own

Fig. A. 14. Power output June 26th among models 4a, 5a & 6a, measured values. Source: Own
A.3 Set of equations represented by block diagrams

As was mentioned previously throughout the document, it is necessary to represent the behavior of the PV cell by means of following a set of equations, that represents each one of the components of the cell. From the Fig. A. 15 to the Fig. A. 19 are shown these equations.

Fig. A. 15. Temperature Variations. Source: Own
APPENDIX 3
SIMULINK MODEL DEVELOPED

Fig. A. 16. (a) Correction of short circuit current $I_{sc}$ by Temperature (b) Correction of open circuit voltage $V_{oc}$ by Temperature. Source: Own

Fig. A. 17. Determination of Thermal Voltage $V_T$. Source: Own

Fig. A. 18. Determination of the light generated current $IPV$. Source: Own
Fig. A. 19. Determination of the reverse saturation current Io. Source: Own.

Fig. A. 15 and Fig. A. 16 represent the effect of the temperature over the STC values such as \( V_{OC} \) and \( I_{SC} \). Subsequently, on the Fig. A. 17 is represented the Eq. (3.4). Moreover, Fig. A. 18 express the variables of the Eq. (3.16). Finally, Eq. (3.17) is denoted by the Fig. A. 19.

Notice that, is important to clarify that most of the blocks used in the previous figures are the representation of input variables, which are used for solving the respective equations. Hence, before all, is necessary to run those input variables, which basically are obtained by the implementation of any manufacturer’s datasheet. On the case of \( a_1 \) is decided to put \( a_1=1 \), in concordance with the explanation of chapter 3.

**Incident irradiance and ambient temperature**

On the other hand, the input variables related to irradiance and ambient temperature must be considered in a different way. The aim of this simulation model is to perform a dynamical behavior along the time. For that reason, is necessary to create a set of vectors which vary during the simulation time. In the case of both, ambient temperature and incident irradiance, several data are used from meteorological databases, considering sample time of 10 minutes to create the respective vectors.

In the Fig. A. 20 (a) is shown the blocks used for representing the ambient temperature and incident irradiance that are used in the blocks of the Fig. A. 17 and Fig. A. 18. For the seeking of simplicity, a subsystem was created only for containing those curves, as is shown in Fig. A. 20 (b).
APPENDIX 3
SIMULINK MODEL DEVELOPED

Is important to say the simulation is set to run over 86400 steps time, therefore, the "Clock" block is set to that value. The 86400 value means that the module is simulating a whole day (24 hours) but it is running in seconds.

**Electrical circuit model representation**

The overall goal is to simulate the electrical circuit represented by the Figure 25, considering the expression of the Eq. (3.12). To do that, in the Fig. A. 21 is shown the block representation of the circuit model, considering the inclusion of an array configuration for any Nss and Npp cells connected.

The block called Diode 1 is a subsystem which represents the behavior of a regular diode, described by the diode equation. In the Fig. A. 22 is shown such block diagram.
Furthermore, just for making the model representation easier, a last subsystem is created. In this subsystem are only considered the output variables of the PV cell such as current, voltage and power.

Fig. A. 22. Representation of the Diode’s Equation. Source: Own

Fig. A. 23. Global PV cell model. Source: Own
In detail, the Measurements’ displays show three graphs over time of the main output variables (Voltage \([V_{DC}]\), Current \([A]\), Power \([W]\)). Basically, the model is measuring a series current \((I)\) which is flowing on the circuit, whilst for the voltage output \((V)\) is implemented Kirchhoff Voltage Law KVL, where the final output voltage is given by the difference between the diode voltage and the voltage across Series Resistance \(R_S\). Finally, the output power \((P)\) is found by applying Ohm’s Law, simply by multiplying \(I\) with \(V\). The operations explained previously are represented by the Fig. A. 24.

![Diagram of the measurement operations](image)

**Fig. A. 24. Measurement operations. Source: Own**

The last part of the model is related to the load to implement. For the improvement of the cell’s measurements, a variable load was developed. This load has a resistive characteristic, with a given slope and rise. Thereby, the implemented load resembles the behavior of a normal network. In the Fig. A. 25 is shown the block diagram of the variable resistance load.
Fig. A. 25. Block representation of a variable resistance load. Source: Own