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Improvement on the energy harvesting of trapezoidal shaped photovoltaic roof tiles through geometrical analysis and interconnection strategies

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Abstract

(In English) Renewable energies have been consolidated as one of the most important alternatives to achieve a successful energy transition and thus mitigate environmental concerns. Although, they represent a challenge in terms of production costs, it is important to highlight that the implementation of renewable energies contributes to address climate change. In Latin American countries, such as Colombia, there is a great opportunity for the production of renewable energy since there is great potential in sources of energy such as hydraulic, wind, thermal, and photovoltaic (PV). Additionally, main cities offer great potential, as the urban environment offer several surfaces that can be used to collect energy, given their exposure to solar radiation. Consequently, this work will explore the potential of the Building Integrated Photovoltaics (BIPV) concept, which allows to increase renewable energy collection, while merging PV cells with constructive elements; being a complimentary support for the energy transition. In this study, the BIPV concept will be specifically oriented to the application of solar roofs. This approach triggers some opportunities, as planar solar surfaces will not comply the morphological properties of regular roof tiles. A proposed set of geometries will be analyzed in terms of energy collection capabilities. The impact of shadows and electrical reconfiguration will be considered in the simulations. Then, a process to evaluate the power generation potential will be carried out to analyze the feasibility of integrating photovoltaic modules on household roofs by evaluating interconnection strategies for each geometry.

Keywords: Solar Energy, Photovoltaic, Roof Tiles, Irradiance Simulation, Energy Generation, Interconnection Strategies

Resumen

(**En Español**) Las energías renovables se han consolidado como una de las alternativas más importantes para lograr una transición energética exitosa y así mitigar las problemáticas ambientales. Aunque representan un reto en términos de costos de producción, es importante destacar que la implementación de las energías renovables contribuye a contrarrestar el cambio climático. En países latinoamericanos, como Colombia, existe una gran oportunidad para la producción de energía renovable ya que existe un gran potencial en fuentes de energía como la hidráulica, eólica, térmica y fotovoltaica (PV). Adicionalmente, las principales ciudades ofrecen un gran potencial, ya que el entorno urbano ofrece varias superficies que pueden ser utilizadas para recolectar energía, dada su exposición a la radiación solar. En consecuencia, este trabajo explorará el potencial del concepto *Building Integrated Photovoltaics* (BIPV), que permite aumentar la captación de energía renovable, a la vez que junta las celdas fotovoltaicas con elementos constructivos; siendo un apoyo complementario para la transición energética. En este estudio, el concepto BIPV se orientará específicamente a la aplicación de tejados solares. Este enfoque ofrece algunas oportunidades, debido a que las superficies fotovoltaicas planas no cuentan con las propiedades morfológicas de las tejas regulares. Se analizará un conjunto de geometrías propuestas en términos de capacidad de captación de energía. En las simulaciones se tendrá en cuenta el impacto de las sombras y la reconfiguración eléctrica. Luego se llevará a cabo un proceso para evaluar el potencial de generación de energía con el fin de analizar la viabilidad de integrar módulos fotovoltaicos en tejados domésticos mediante la evaluación de estrategias de interconexión para cada geometría.

Palabras Clave: Energía Solar, Fotovoltaica, Tejado, Simulación de Irradiancia, Generación de Energía, Estrategias de Interconexión

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Contents

List of Figures	viii
List of Tables	ix
1 Introduction	1
1.1 Context and background	1
1.2 Objectives	2
1.2.1 General objective	2
1.2.2 Specific objectives	3
1.3 Manuscript organization	3
2 Literature Review	5
2.1 General Overview	5
2.1.1 Photovoltaic Background	5
2.1.2 Principle of Operation	6
2.1.3 BIPV concept and Solar roof tiles application	7
2.2 Photovoltaic Theoretical Framework	7
2.2.1 Incidence of Optical Phenomena	8
2.2.2 Thermal Effects	8
2.2.3 Electrical performance	10
2.3 Partial Shading Effects	13
2.3.1 Mismatch Losses in Photovoltaic (PV) Arrays	13
2.3.2 Techniques to reduce Mismatch Losses	15
3 Proposed Approach	19
3.1 Geometrical Set-Up for Energetic Analysis	19
3.1.1 Main Variables of Trapezoidal Geometries	20
3.1.2 Computational Experiment Design	21

3.2	Radiation Simulation Through Ray Tracing	22
3.2.1	Ray Tracing Simulation Set-Up	22
3.2.2	Ray tracing results	23
3.2.3	Trend analysis	26
3.3	Energy Improvement Through Interconnection Strategies	27
3.3.1	Simulink® Simulations Setup	28
3.3.2	Proposed Interconnection Strategies Based on Fixed Topologies	28
3.3.3	Selection of Geometry and Interconnection Strategy	31
4	Implementation	33
4.1	Manufacturing process	33
4.1.1	Geometry and Reinforcement	33
4.1.2	PV module fabrication	35
4.1.3	Cells Interconnection	36
4.2	Data Collection	37
4.2.1	Devices for data acquisition	37
4.2.2	Experimental Data acquisition	38
4.2.3	Analysis	40
5	Conclusions	41
	References	43
	Acronyms	48
	Appendix A Flux Energy Collection Curves	51
	Appendix B Proposed fixed interconnection topologies	55
B.1	Four Rows Geometries	55
B.2	Five Rows Geometries	58
	Appendix C Power Generation Curves	61

List of Figures

1.1	Residential PV system Cost Benchmark [Ramasamy et al., 2021].	1
1.2	Evolution of global PV accumulative installed capacity [Masson et al., 2013].	2
2.1	Single diode model.	10
2.2	Typical I-V Curve [Surya and Rohman].	11
2.4	I-V and P-V curves for different irradiance levels and cells temperature in series connection.	14
2.5	I-V and P-V curves for different irradiance levels and cells temperature in parallel connection.	15
2.6	Classical interconnection topologies in PV modules.	16
2.3	I-V and P-V curves for different irradiance levels and operation temperatures for a single cell.	18
3.1	Main Diagram.	19
3.2	Traditional trapezoidal roof tile type.	20
3.3	CAD model of the roof morphology.	20
3.4	TracePro® simulation.	23
3.5	Ray tracing simulation results for case A.	24
3.6	Ray tracing simulation results for case B.	25
3.7	Ray tracing simulation results for case A3.	25
3.8	Main effects plots for case A.	27
3.9	Simulink® Simulations Setup.	28
3.10	Power generation per flat area by best fixed interconnection topology and by dynamic reconfiguration implementation for each geometry.	29
3.11	Power Generation by the configurations proposed for A12 geometry.	31
3.12	A12 with Configuration 3.	32
3.13	A12 with Configuration 3.	32

4.1	Wood mold	34
4.2	Reinforcing layer	34
4.3	Cells welded according to alternative A12's surfaces	35
4.4	Vacuum application	35
4.5	Rear view.	36
4.6	Prototype views	36
4.7	V-I curve measuring device	37
4.8	Measuring devices	38
4.9	Experimental irradiance profile on measurement day.	38
4.10	Experimental power generation	39
A.1	Flux Energy Collection for A1 to A4 Geometries.	51
A.2	Flux Energy Collection for A5 to A10 Geometries.	52
A.3	Flux Energy Collection for A11 to A16 Geometries.	53
A.4	Flux Energy Collection for A17 to A21 and Flat Geometries.	54
B.1	Configuration 1 (4 surfaces).	55
B.2	Configuration 2 (4 surfaces).	56
B.3	Configuration 3 (4 surfaces).	56
B.4	Configuration 4 (4 surfaces).	56
B.5	Configuration 5 (4 surfaces).	57
B.6	Configuration 6 (4 surfaces).	57
B.7	Configuration 7 (4 surfaces).	57
B.8	Configuration 1 (5 surfaces).	58
B.9	Configuration 2 (5 surfaces).	58
B.10	Configuration 3 (5 surfaces).	58
B.11	Configuration 4 (5 surfaces).	59
B.12	Configuration 5 (5 surfaces).	59
B.13	Configuration 6 (5 surfaces).	59
C.1	Power Generation Curves for A1 to A4 Geometries.	61
C.2	Power Generation Curves for A5 to A10 Geometries.	62
C.3	Power Generation Curves for A11 to A16 Geometries.	63
C.4	Power Generation Curves for A17 to A21 and Flat Geometries.	64

List of Tables

2.1	Mounting Coefficient Values [Skoplaki et al., 2008].	10
2.2	Framework Variables.	12
3.1	Taguchi L_{18} array [Gutiérrez Pulido et al., 2012]	21
3.2	Factors and levels for cases A and B (units in mm).	21
3.3	Commercial Sunpower PV cell sizes (units in mm).	21
3.4	Models and conditions	22
3.5	Ray tracing simulation results for a complete day (February 13, 2023).	24
3.6	Analysis of Variance. Case A.	26
3.7	Model Summary. Case A.	26
3.8	Coefficients. Case A.	26
3.9	Response Table for Means, Case A.	26
3.10	Response Table for SN Ratios, Case A.	26
3.11	Ray tracing additional simulation results.	27
3.12	Interconnection Strategies Summary	30
4.1	Reported temperatures (measures in °C)	39

Chapter 1

Introduction

1.1 Context and background

The high global demand for energy and its consequent pollution of the planet has become into an environmental problematic with considerable effects [Algarin and Álvarez, 2018]. It is for this reason that renewable energies have been taking an important position in the international framework [Mohtasham, 2015]. Locally, Colombia has a great potential in terms of energy from sources such as hydro, wind, thermal and photovoltaic [Ramirez, 2019]. It is certainly valid to mention that non-conventional renewable energies represent a challenge compared to the affordability of conventional energies. However, they also represent a cost-benefit alternative that is continuously evolving and is becoming one of the best strategies to face climate change and other related adverse problems [Giraldo et al., 2018].

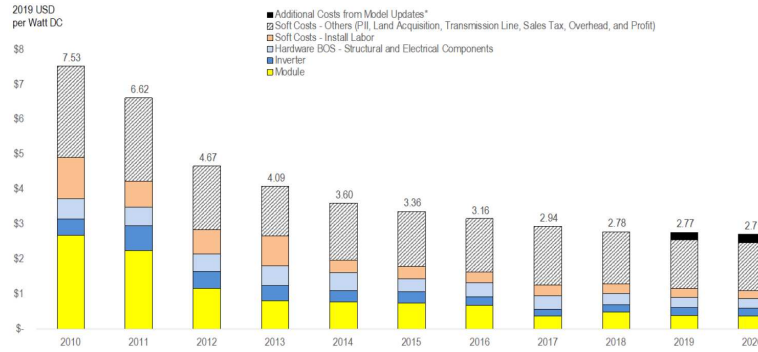


Figure 1.1: Residential PV system Cost Benchmark [Ramasamy et al., 2021].

Figure 1.1 shows a residential PV system cost benchmark. It is shown how costs have been decreasing along the years. On the other hand, Figure 1.2 illustrates the evolution of PV accumulative installed capacity in the world. So it can be seen how PV energy has been growing and its costs have

been falling over the last decades.

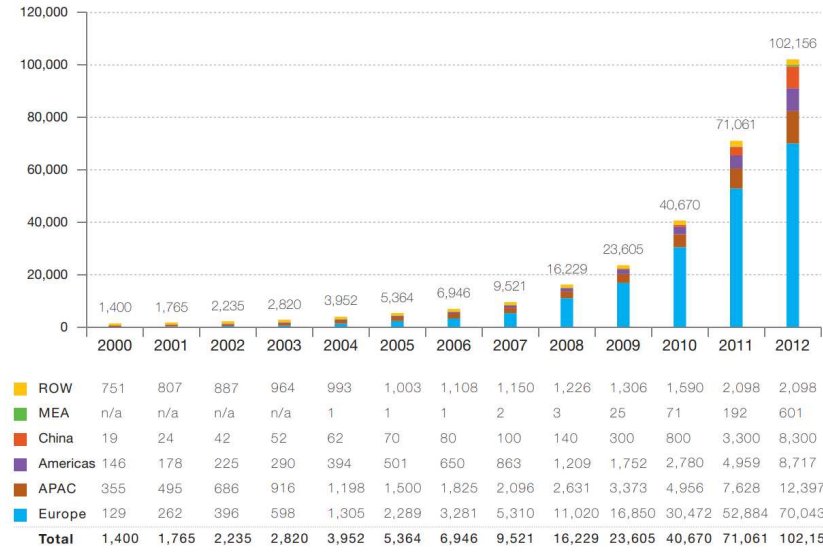


Figure 1.2: Evolution of global PV accumulative installed capacity [Masson et al., 2013].

One initiative that have been developed even at a commercial level to support the energy transition consists in the use of PV modules in buildings; this is known as BIPV. In this concept, the PV modules are not fixed to the building, but are part of it, offering good electrical-thermal supply potential [Biyik et al., 2017]. This work will analyze the concept of BIPV specifically oriented to roofs and the use of this area commonly irradiated by solar rays. Additionally, given the tropical zone in which Colombia is located and the high presence of rainfall, tile roofs have important advantages thermoacoustics, aesthetics, impermeability, flame retardant, and resistance [De Silva and Surangi, 2017].

Next, a state of the art about solar roof tiles, photovoltaic energy, interconnection of PV modules and reconfiguration algorithms will be given. Then, a simulation process will be explained to obtain the results for the analysis. The case study of this work consists of evaluating the technical feasibility of integrating photovoltaic modules in tile-type roofs. For this purpose, the irradiance phenomena will be simulated. Lastly, using a Matlab-Simulink® model, the generation power of the arrays will be estimated to finally compare them and make conclusions.

1.2 Objectives

1.2.1 General objective

The overall objective of this work is “to select the best combination of geometry and interconnection for a BIPV roof, based on a trapezoidal tile type module by using ray-tracing analysis tools, power generation simulations and experimental tests, in order to improve the energy harvesting”.

1.2.2 Specific objectives

- To define a set of feasible geometries by means of a design of experiments to analyze the behavior of ray tracing in relation to the angles and lengths of a trapezoidal profile in order to obtain achievable geometries in terms of the commercial sizes of PV cells.
- To simulate alternatives of fixed interconnections to find the best performance for each geometry.
- To analyze the performance of each geometry with each interconnection topology to select the combination that provides the highest power generation.
- To implement the selected geometry-interconnection alternative and by means of comparisons with respect to a flat panel validate if the behavior trend is similar to that obtained in the simulations.

1.3 Manuscript organization

This document is structured in the following way. After this introductory chapter, there is a review of the state of the art (See Chapter 2) about the subject of PV energy, BIPV and the case study of tile type PV roof. It is followed by the proposed approach (See Chapter 3) and the development of the computational simulations is carried out. Then the implementation of the selected approach (See Chapter 4) is presented to finally conclude (Chapter 5) about the insights and findings that were found during all the work stages.

Chapter 2

Literature Review

This chapter will present a review of the state of the art about the technology to be discussed in this project. Initially, an overview of the photovoltaic energy landscape as a renewable source with growth potential will be presented. Then, a theoretical framework on photovoltaics is introduced. Finally, the main effects of shading on the operation and performance of photovoltaic panels will be explained, and some strategies to reduce them will also be presented.

2.1 General Overview

In this section, a general vision of photovoltaics is presented. First, a review of the photovoltaic landscape is presented. It is followed by an explanation of the principle of operation and the materials used. And finally, the concept of BIPV and its application on rooftops will be introduced.

2.1.1 Photovoltaic Background

Photovoltaic panels or modules are devices that convert solar radiation into electricity. It has become an increasingly popular way to generate electricity as its costs have decreased and its efficiency has increased. The photovoltaic effect was first observed in 1839 by French scientist Edmond Becquerel, who observed that certain materials produced a small electric current when exposed to light [Zaidi, 2018].

In 1954, Bell Labs researchers developed a practical solar cell, the first one in its class. It was made of silicon and had an efficiency of 6% [Goetzberger and Hebling, 2000]. This event led to the development of the first commercial solar cells, which were mainly used for space applications. In the 1970s, the oil crisis renewed interest in renewable energies such as photovoltaics. So the US government started to research and develop programs in order to improve photovoltaic cells and make

them more feasible. During this period, the relation between efficiency and the cost of manufacturing solar cells has increased considerably.

In the 80s decade, remote telecommunications systems and off-grid applications were included in the PV market, this means a big step because there exist in all of the world's homes and rural areas without grid access. In the 90s decade, grid-connected PV systems began to be developed [de Souza et al., 2006], allowing PV users to sell excess electricity generated by their PV system. This event led to the development of net billing policies that motivate homeowners and businesses to install PV systems by allowing them to offset their electricity bills with the electricity they generate.

One of the main advantages of photovoltaic technology is that it generates electricity without emitting greenhouse gases or other pollutants, making it a clean and renewable energy source with low maintenance requirements. However, one of its biggest challenges is cost, which has been reduced considerably in recent years [Bagnall and Boreland, 2008].

And the growth of the PV industry has been accompanied by government measures such as feed-in tariffs and tax incentives, as well as technological advances that have made solar energy increasingly affordable and accessible [Benda and Černá, 2020].

In addition, the efficiency of solar cells is limited by the properties of the semiconductor materials used, which means that significant improvements in efficiency can be difficult to achieve [Abdulrazzaq et al., 2013]. Overall, photovoltaic technology represents a clean, renewable source of electricity that does not emit greenhouse gases or other pollutants and could play an important role in meeting our energy needs in the future.

2.1.2 Principle of Operation

The principle of operation of solar cells is based on the photoelectric effect. This is a phenomenon in which certain materials absorb the light energy incident on them in the form of electromagnetic radiation, which causes the release of electrons and generates a current flow [Marques Lameirinhas et al., 2022]. A photovoltaic cell consists of a thin layer of semiconductor material with a p-n junction. It can be made of materials such as gallium arsenide (GaAs), indium phosphide (InP), synthesized polymers, compounds of copper, indium, gallium, and selenium or better known as multijunction and, most commonly used, silicon (monocrystalline and polycrystalline) [Oyola and Gordillo, 2007].

The p-n junction is created by doping pure metal crystals with impurities to form areas of positive and negative charge. The region near the p-n junction is where the energy conversion takes place. When light strikes the semiconductor material, an excitation of the electrons present in the material occurs, and they are released from their atomic bonds [Hegedus and Luque, 2011]. They are then attracted to the positively charged region of junction, creating an electric current flow, which is the main result of the energy transmitted by the photons of light that have been absorbed [Nelson, 2003].

The total electricity generated is proportional to the intensity of the light incident on the photovoltaic surface, and the efficiency of the cell is determined by its ability to absorb solar irradiation and convert it into electrical energy. Commercially, the energy conversion efficiencies of a photovoltaic cell are in the order of 24.7% for monocrystalline silicon. However, it has been determined that multijunction cells, due to the combination of materials, reach efficiencies of up to 39.3% [Oyola and Gordillo, 2007], although these ones are not yet commercially feasible.

Photovoltaic cells are connected in series and parallel to create photovoltaic modules or solar panels. In turn, photovoltaic modules are connected in different configurations to achieve photovoltaic arrays. Then, the arrays can be connected to an inverter, which converts the direct current (DC) generated by the solar cells into alternating current (AC), which can be used for most of the electrical devices.

2.1.3 BIPV concept and Solar roof tiles application

BIPV is a technology in which photovoltaic modules are integrated directly into the design of buildings, including materials and components [Shukla et al., 2017]. Among its most prominent presentations are roofs, facades, or windows. In this way, BIPV systems can generate electricity from sunlight and, at the same time, act as an active and functional element of the building, so that it can also be used to power the building or the power grid.

In the literature, there are applications of BIPV technology, in the work of Heinsteins et al. [Heinsteins et al., 2013] applications ranging from urban, rural, and even cultural sectors are shown. In addition, mirrors and reflective elements are also used in PV modules [Torres-Madroño et al., 2020]. A solar roof tile is an application of BIPV technology, and in contrast to Building Applied Photovoltaics technology (“BAPV”) it is a roof with integrated photovoltaic modules. These roofs contain arrays of solar cells. Some solar roof tile systems also include a battery storage system, which allows for storage and uses excess electricity generated during the day at night or during periods of high demand. As renewable energies become more popular, BIPV systems will also increase as a common option for architects, builders, and anyone who has the idea of creating sustainable and energy-efficient buildings [Reddy et al., 2020]. As BIPV systems continue to evolve in terms of technology and manufacturing process improvement, they will become more cost-effective and adopted in the construction industry [Sofia et al., 2020].

2.2 Photovoltaic Theoretical Framework

The theoretical framework of photovoltaic technology is based on the fundamental principles of physics, including quantum mechanics and solid-state physics. The behavior of semiconductors materials and

p-n junction physics are key concepts in understanding how solar cells work. The following is a brief review of the behavior and impact of optical, thermal, and electrical phenomena in photovoltaic panels.

2.2.1 Incidence of Optical Phenomena

Optical components are an important aspect of PV systems since they help increase the efficiency of PV arrays by increasing the amount of solar radiation that can be absorbed and converted into electricity. The main optical concepts are the incidence angle and the encapsulation materials. In addition, optical concentrators are also commonly used for increasing the power generation in PV modules [Khamooshi et al., 2014], some of them are used due to its cost-benefit ratio [Bahaidarah et al., 2015].

A fundamental optical variable for understanding the performance of a photovoltaic device is the incidence angle. It consists of the angle at which the sunlight strikes the surface of the PV device with respect to the normal or a perpendicular line to the PV surface. When sunlight strikes a PV device at an oblique angle rather than perpendicular to the surface, then the reflection increases, reducing the amount of light that is absorbed by the PV device [Yadav and Chandel, 2013].

Another effect of the angle of incidence is that the greater the inclination of the incoming solar rays relative to the normal of the surface, the greater the distance that each ray must travel to pass through the encapsulation material and reach the PV surface. In this way, one of the most important characteristics of encapsulation material is its ability to transmit solar rays.

In addition, the encapsulation material also plays a relevant role in protecting the PV cells from the environment. And also allows to assemble the PV array with the reinforcement layer, which provides the structural rigidity to the PV module [Molina-Tamayo et al., 2022]. Two types of materials are commonly used to encapsulate PV cells. The first is glass, which is resistant to solar rays and durable over time. On the other hand, polymer-based materials are also used mainly in thin modules or applications where higher flexibility and lower weight are required.

2.2.2 Thermal Effects

Thermal effects in a photovoltaic array are a key component in electric power generation. From the total energy emitted by the sun and received by a photovoltaic panel, 6.98% corresponds to optical losses, 17.44% to usable electrical energy, and 75.58% to thermal losses, approximately [Hanifi et al., 2018]. Thus, understanding the thermal behavior of a photovoltaic panel makes it possible to simulate it in a more realistic way and thus reduce power losses. The types of heat losses include losses due to the operating temperature of the PV cells, since these operate at a higher temperature than the ambient temperature, heat transfer losses are present.

Thermalization losses also occur when a photon of light is absorbed by a PV cell and transfers its

energy to an electron. This causes it to move and generate an electric current; however, part of the transferred energy is converted into vibrations of the crystalline network of the material, being lost as heat. Another factor is carrier recombination, which occurs when electrons and holes are created in a solar cell [Zhang et al., 2021]. These may recombine and release energy as heat instead of generating electricity. This effect commonly happens at high temperatures.

Moreover, losses also occur due to the in-series resistance of the PV cells, which dissipates energy in the form of heat. Additionally, shading in the PV arrays also causes heat losses since the shaded cells restrict the array current acting as a resistor. The performance of a PV module in relation to its thermal behavior is analyzed by thermal coefficients. These are provided by PV cell manufacturers and indicate proportionally how much voltage, current, and power are reduced per every degree increase on the cell's temperature.

There are different models in the literature for estimating the operating temperature of photovoltaic cells (T_c). One of the best-known is the Nominal Operating Cell Temperature (NOCT) model. This is a standardized concept and its values are included in the technical data sheets of PV modules. The NOCT model allows estimating the temperature of the cells based on values obtained by the manufacturer under controlled conditions Standard Reference Environment (SRE). The NOCT data are taken at 800 W/m^2 , an air mass of 1.5, an ambient temperature (T_{amb}) of 20°C , and a wind speed of 1 m/s . These conditions tend to be closer to reality compared to Standard Test Conditions (STC). The NOCT thermal model equation is shown below in the equation 2.1. In this equation, it can be seen that the NOCT model does not consider the specific wind speed. It also assumes that the changes in cell temperature are proportional to the difference in irradiance levels (G) [Dolara et al., 2015].

$$T_C = T_{amb} + \frac{T_{NOCT} - 20^\circ\text{C}}{800\text{W/m}^2} * G \quad (2.1)$$

There is also an even simpler model. It consists of an empirical formula investigated by Ross [Ross Jr, 1976], which is shown below in the equation 2.2. Where K corresponds to the Ross empirical coefficient, this depends on the type of assembly.

$$T_C = T_{amb} + K * G \quad (2.2)$$

As can be seen, the Ross model has the same limitations as the NOCT model, but at least considers mounting conditions (e.g. free standing, flat roof, sloped roof well cooled, sloped roof highly integrated). For more accurate estimates, models based on heat transfer equations with empirical parameters based on on-site measurements and the calculation of coefficients by linear regressions are also found in the literature.

The Faiman model [Faiman, 2008] includes a factor for wind speed and another for irradiance

dependence, both adjustable with on-site measurements. Measurements to fit this type of model and obtain viable values of the results are estimated in approximately 2 weeks minimum but only if these two weeks contain enough variation in the weather phenomena for the area of interest [Barykina and Hammer, 2017]. The temperature of the PV cells can also be estimated using fully empirical equations as in the case of Sandia's model [King et al., 2004].

In this work, we use the model developed by Skoplaki and Palyvos [Skoplaki et al., 2008]. This model is slightly different than Faiman's model, only by including a third factor to analyze different types of assemblies. The simplified correlation that Skoplaki proposes does not require on-site measurements and provides a standard deviation of less than $3^{\circ}C$. So the equation used to predict the temperature is shown below in Equation 2.3. Where ω corresponds to the mounting coefficient, its values are shown in the table 2.1 below. V_f corresponds to the local wind speed (close to the PV module area).

$$T_C = T_{amb} + \omega * \left(\frac{0.32}{8.91 + 2.0 * V_f} \right) * G_T \quad (2.3)$$

Table 2.1: Mounting Coefficient Values [Skoplaki et al., 2008].

PV array mounting type	ω
Free standing	1.0
Flat roof	1.2
Sloped roof	1.8 (1.0-2.7)
Facade integrated	2.4 (2.2-2.6)

2.2.3 Electrical performance

The electrical output of a PV system, corresponds to its ability to convert sunlight into usable electrical energy. The electrical behavior of a PV module is correlated and conditioned with the optical and thermal effects described previously. Some fundamental concepts to describe the electrical performance of a PV system will be explained below. First, the main variables in PV array modeling are voltage and current, which are illustrated in figure 2.1 with a single diode equivalent circuit.

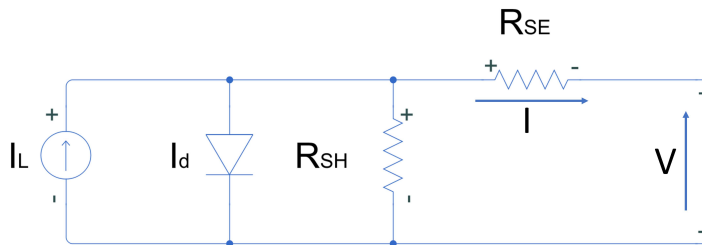


Figure 2.1: Single diode model.

Following the standard behavior of electrical circuits, connecting cells in series results in having the same current along the string. And connecting cells in parallel results in having the same voltage on each branch. In addition, the Current (I) and Voltage (V) have a specific behavior for each PV cell depending on its manufacturing process and the composition of materials. The relationship between these two variables is described in the characteristic “IV” curve. This is a graphical representation of the behavior of a photovoltaic device as a function of the irradiance level to which it is subjected.

The I-V curve is provided by PV device manufacturers, as is shown in figure 2.2 for the SunPower® used case. It allows for identifying the short circuit current, the open circuit voltage, the Maximum Power Point (MPP), and the values of voltage and current at which the maximum power point is obtained. The MPP is the point at which the product of current and voltage is the greatest. It corresponds to the point of maximum electrical efficiency of the device. And it is also represented in the Power-Voltage (P-V) curve, being the highest value on the vertical or power axis. Examples of I-V and P-V curves are shown below in the 2.3 section.

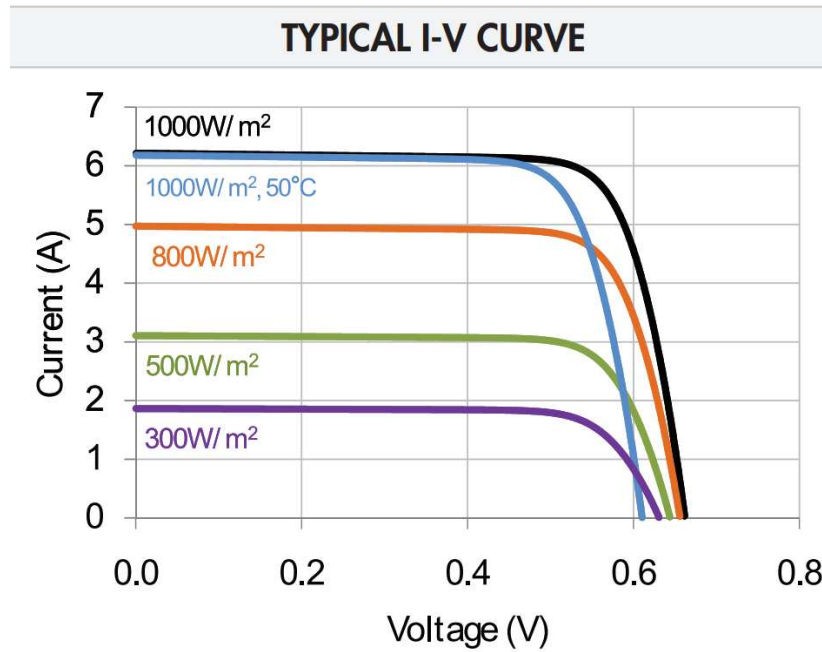


Figure 2.2: Typical I-V Curve [Surya and Rohman].

On the other hand, the efficiency η_{STC} of a PV panel is calculated as shown below in equation 2.4. Where P_{max} is the maximum power of the module, A_m is the PV surface area, and G_{STC} corresponds to the solar irradiance at STC.

$$\eta_{STC} = \frac{P_{max}/A_m}{G_{STC}} \quad (2.4)$$

STC refer to a set of conditions established by the International Electrotechnical Commission

(IEC) and the American Society for Testing and Materials (ASTM). These conditions consist of an irradiance level of 1000 watts per square meter (W/m^2), a cell temperature of 25 degrees Celsius ($^{\circ}C$), and an air mass of 1.5. Under these specifications, PV cells are tested in order to obtain comparable data sheets for all manufacturers.

The Fill Factor (FF) is the ratio between the maximum power output of the solar panel and the product of the open circuit voltage V_{OC} and the short circuit current I_{SC} . It is a parameter that measures the efficiency of a solar cell by quantifying how much of its maximum power can actually be used. Typically, commercially available solar cells have a fill factor ranging from 0.65 to 0.85, depending on the technology and manufacturing process. Table 2.2 shows the variables that are commonly involved in the modeling of PV systems.

Table 2.2: Framework Variables.

Symbol	Variable	Symbol	Variable
E_{GO}	Bandgap energy (GAP) of the semiconductor	K_I	Short-circuit current temperature coefficient under standard conditions
G	Solar irradiance	η	Diode ideality factor
G_n	Nominal solar irradiance (STC conditions)	N_S	Number of cells connected in series
I	Output current	q	Electron charge
I_D	Diode current	R_{SE}	Series resistance
I_{PH}	Photovoltaic current	R_{SH}	Shunt resistance
I_{RS}	Reverse saturation current	T	Operating temperature
I_S	Saturation current	T_n	Nominal temperature (STC conditions)
I_{SC}	Short circuit current	V	Output voltage
I_{SH}	Shunt current	V_{OC}	Open circuit voltage
k	Boltzman's constant	V_T	Seal thermal voltage PN

The following equations [Sumathi et al., 2015] allow modeling the values of the I-V curve for a PV module based on an irradiance G and a temperature of operation T :

- **Photovoltaic current:** total output current generated by the PV module.

$$I = I_{PH} - I_D - I_{SH} \quad (2.5)$$

- **Photocurrent:** current generated by exposure to radiant energy.

$$I_{PH} = [I_{SC} + K_i * (T - T_n)] * (G/G_n) \quad (2.6)$$

- **Diode current:** current that flows through the diode.

$$I_D = I_S * \left(\exp \left(\frac{V + I * R_{SE}}{\eta * N_S * V_T} \right) - 1 \right) \quad (2.7)$$

- **Junction thermal voltage PN:** voltage produced within the P-N junction due to the action of temperature.

$$V_T = (k * T) / q \quad (2.8)$$

- **Shunt current:** current losses typically due to manufacturing defects.

$$I_{SH} = \frac{V + I * R_{SE}}{R_{SH}} \quad (2.9)$$

- **Saturation current:** current that flows through the P-N junction.

$$I_S = I_{RS} * \left(\frac{T}{T_n} \right)^3 * \exp \left[\frac{q * E_{GO}}{\eta * k} * \left(\frac{1}{T_n} - \frac{1}{T_n} \right) \right] \quad (2.10)$$

- **Reverse saturation current:** current flowing through the P-N junction diode when it is reversed biased.

$$I_{RS} = \frac{I_{SC}}{\exp \left(\frac{V_{OC}}{N_S * \eta * V_T} \right) - 1} \quad (2.11)$$

2.3 Partial Shading Effects

The following is an explanation of the effects that occur when a photovoltaic module system operates under partial shading conditions. The consequences for current and voltage are also included. Moreover, the main strategies used to reduce shading losses are also described.

2.3.1 Mismatch Losses in PV Arrays

Mismatch losses are a phenomenon that occurs as a reduction in the power output of a PV array caused by differences in the electrical properties of the PV modules. Mismatch losses are always present in a PV system since panels are manufactured with certain tolerances in their electrical characteristics, such as current-voltage (IV) curves. As a result, the PV panels may have different individual performances [Roche et al., 1995].

Mismatch losses also occur when PV modules in an array are connected in series or parallel and operate at different voltage and current values due to their size, operating temperature, or irradiance. The result is an uneven current flow and a lower power output [Nguyen and Lehman, 2008a].

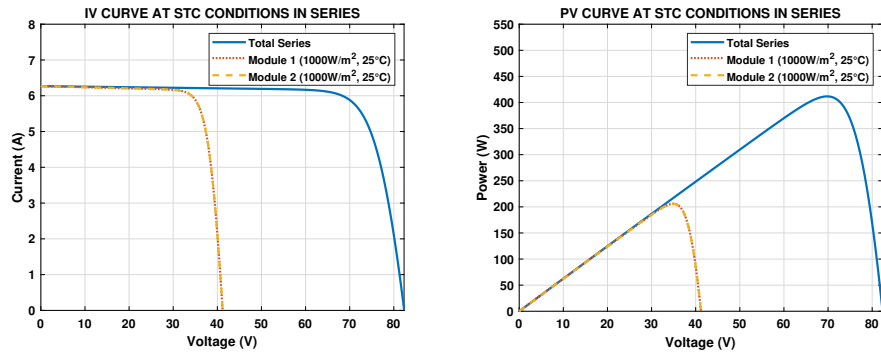
To achieve a better understanding of mismatch losses, an illustration of the behavior of I-V and P-V curves when connecting panels in series and parallel at different operating conditions will be presented. There will be assumed that there are no differences in manufacturing and material properties. So, for purpose of the explanation, losses will only occur due to differences in operating conditions.

Figures 2.3a and 2.3b show how a PV module behaves under STC conditions. Figures 2.3c and 2.3d show how it behaves if the temperature is maintained, but the irradiance is lowered to 500W. Figures 2.3e and 2.3f show the opposite, with an irradiance of 1000W and a temperature of 45°C.

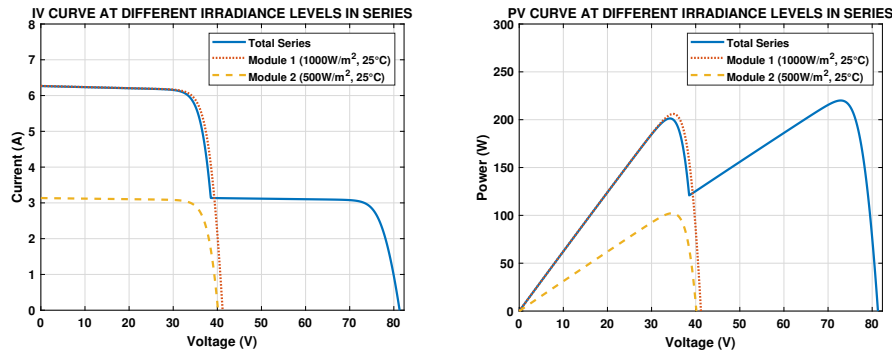
Finally, Figures 2.3g and 2.3h show the combined effect of reducing the irradiance level and increasing the temperature of the cells.

It can be seen in Figure 2.3¹, how by reducing the irradiance level the short circuit current I_{sc} is decreased almost in the same proportion, while the open circuit voltage V_{oc} decreases very slightly. On the other hand, as the temperature increases, the voltage V_{oc} decreases moderately. The same analysis is shown below for 2 interconnected panels, operating at different irradiance levels.

When 2 or more PV panels are connected in series, they are forced to operate at the same current. If they are at the same irradiance level as in figures 2.4a and 2.4b, the voltages are added symmetrically. However, if they are at different irradiance levels as in figures 2.4c and 2.4d, mismatch losses occur. This happens when the string current exceeds the lowest cell short-circuit current. Then the cells whose short-circuit currents are lower than the string current become reverse-biased, with an increasingly negative voltage [Bishop, 1988].



(a) I-V Curve at STC conditions in series connection. (b) P-V curve at STC conditions in series connection.



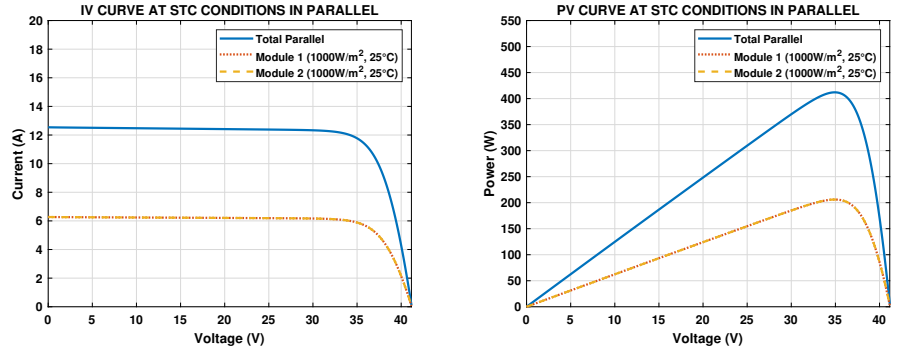
(c) I-V Curve at 1000W/m² and 500W/m² in series connection. (d) P-V curve at 1000W/m² and 500W/m² in series connection.

Figure 2.4: I-V and P-V curves for different irradiance levels and cells temperature in series connection.

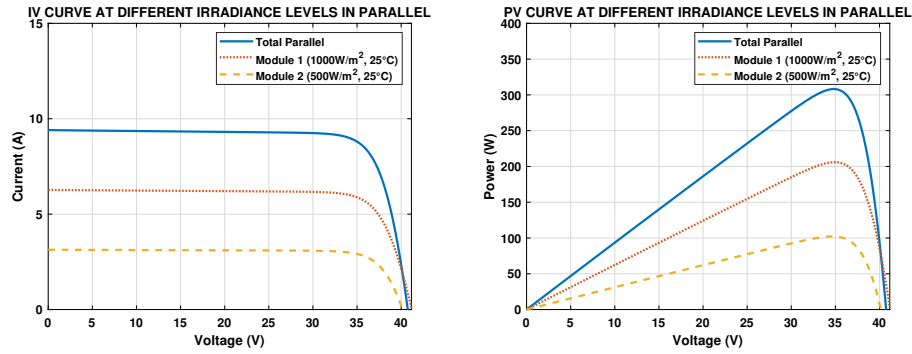
On the other hand, when connecting panels in parallel they are forced to operate at the same

¹See full-page Figure 2.3 at the end of the chapter

voltage. If currents are equal, then they are added symmetrically as shown in figures 2.5a and 2.5b. When the operating voltage exceeds the lowest string open-circuit voltage, this string becomes forward-biased with an increasing negative current, as shown in figures 2.5c and 2.5d. In both, series and parallel cases, there is a risk of damage to the photovoltaic panels due to the formation of hot spots.



(a) I-V Curve at STC conditions in parallel connection. (b) P-V curve at STC conditions in parallel connection.



(c) I-V Curve at 1000W/m² and 500W/m² in parallel connection. (d) P-V curve at 1000W/m² and 500W/m² in parallel connection.

Figure 2.5: I-V and P-V curves for different irradiance levels and cells temperature in parallel connection.

2.3.2 Techniques to reduce Mismatch Losses

There are several strategies to reduce mismatch losses in PV arrays. The first is to match the electrical characteristics of PV modules as closely as possible during the planning and installation stages. This can be achieved by grouping panels with similar properties. Cleaning and maintenance also help to maintain panel characteristics uniformly.

Bypass diodes are used as well for reducing the negative effects of partial shading on the performance of solar panels. They are connected in parallel with each cell or group of cells in a solar module. In series connections, bypass diodes provide an alternative way for the current to flow, diverting the current around the shaded cells and preventing them from limiting the current of the entire string.

The bypass diodes also help in parallel connections, preventing the cells to produce dangerous negative currents.

Another method to reduce mismatch losses is the use of power optimizers or microinverters, which can dynamically adjust the output of each panel to match the output of the entire array. However, these devices typically involve a more expensive investment.

There are also fixed interconnection topologies, which consist of interconnecting the PV array in such a way as it prevents shading losses or mismatch losses in general. Reviewing the literature, it is found that the most commonly used interconnection strategies as a benchmark are Series-Parallel (SP), Bridge-link (BL), Honeycomb (HC), and Total Cross Tied (TCT) [Belhachat and Larbes, 2021]. TCT and BL have a better performance, and the practical implementation of these schemes should not escalate the cost [Kaushika and Gautam, 2003]. Figure 2.6 shows these classical interconnection topologies in PV modules.

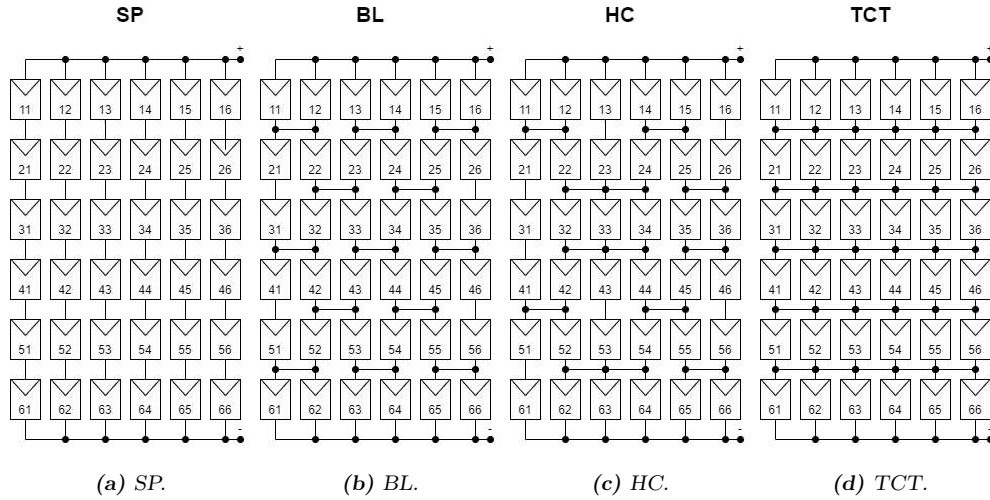
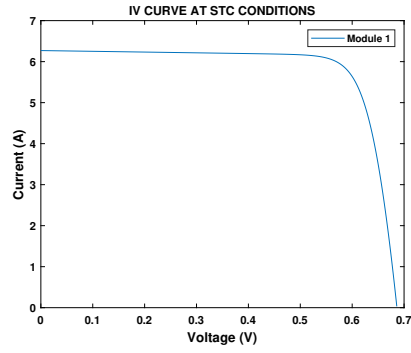


Figure 2.6: Classical interconnection topologies in PV modules.

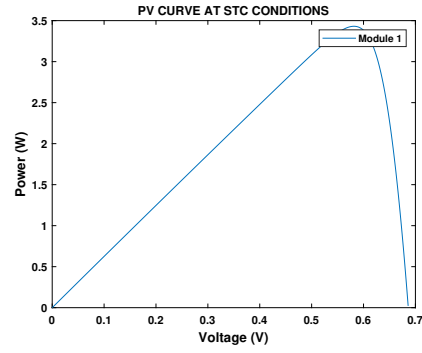
Finally, mismatch losses can also be avoided by dynamically reconfiguring the electrical interconnection of the array. For this method, there is a system that strategically interconnects the modules according to the irradiance conditions received by each of the modules at any given time. This is achieved by algorithms that compare the behavior of the modules and connect them through switches seeking to obtain the highest power. These switches grow quadratically with the number of modules [Calcabrini et al., 2021]. Therefore, for this application, it is convenient to try to reduce the number of modules by increasing their unit size. In the literature, there are some algorithms to reconfigure photovoltaic modules. Nguyen and Lehman [Nguyen and Lehman, 2008b] define two control algorithms, one consisting of voltage control whereas the other one of current control. Babu et al. [Babu et al., 2017] propose an algorithm for the extraction of maximum power under partial shading conditions

for a PV array based on particle swarm optimization. Deshkar et al. and Fathy look for the same goal but using a genetic algorithm [Deshkar et al., 2015] and a modified artificial bee colony algorithm [Fathy, 2015], respectively. Romano et al. [Romano et al., 2013] use a reconfigurable switching matrix controlled by an iterative algorithm that seeks to obtain the best configuration by comparing an equalization index defined as the differences between the operating currents in the PV array.

In this work, a comparison between implementing a fully reconfigurable array and fixed interconnection strategies will be analyzed. An alternative such as a fully reconfigurable array always achieves the best theoretical and reachable performance. However, for a tile-type solar roof, it may frequently suggest all-parallel connection due to the constant differences in the irradiance level because of the non-planar condition. Therefore, parallel connection (for similar voltages) is the best option in terms of power since current drops in one PV module will not affect the others. However, parallel connection leads to higher currents, so the transport and conversion of power downstream are more inefficient [La Manna et al., 2014].



(a) I-V Curve at STC conditions.



(b) P-V curve at STC conditions.

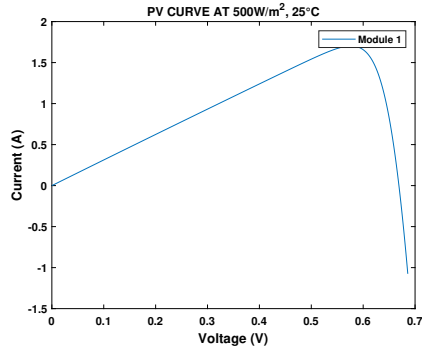
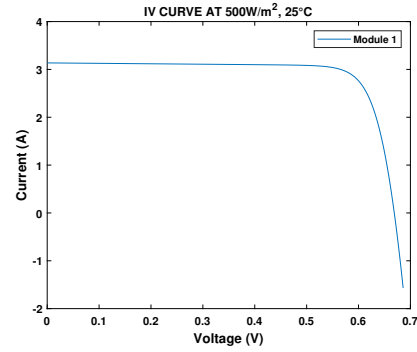
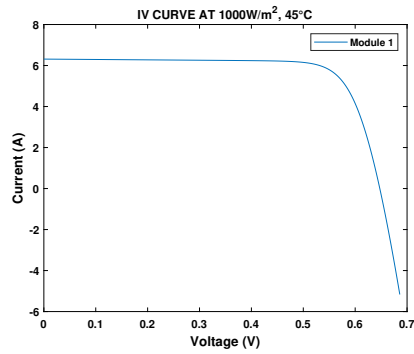
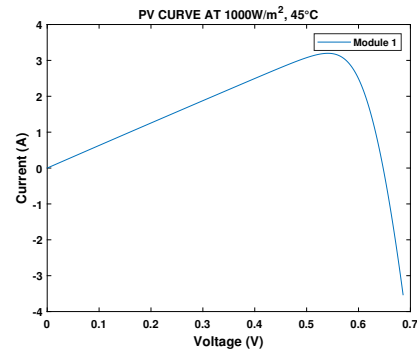
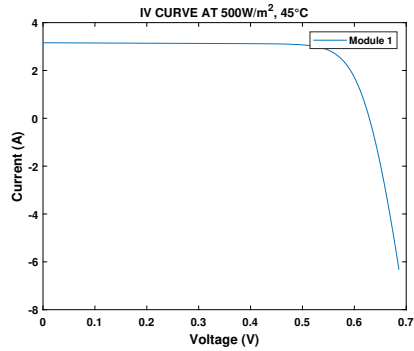
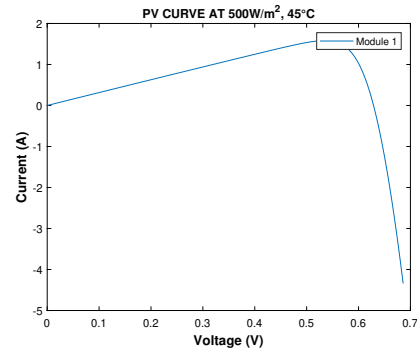
(c) I-V Curve at $500\text{W}/\text{m}^2$ and 25°C .(d) P-V curve at $500\text{W}/\text{m}^2$ and 25°C .(e) I-V Curve at $1000\text{W}/\text{m}^2$ and 45°C .(f) P-V curve at $1000\text{W}/\text{m}^2$ and 45°C .(g) I-V Curve at $500\text{W}/\text{m}^2$ and 45°C .(h) P-V curve at $500\text{W}/\text{m}^2$ and 45°C .

Figure 2.3: I-V and P-V curves for different irradiance levels and operation temperatures for a single cell.

Chapter 3

Proposed Approach

In this chapter, several techniques and computational tools will be used in order to select a PVs trapezoidal tile type alternative based on the principal characteristics of an initial set of commercial geometries. Figure 3.1 shows the main stages of the process. First, the geometries for the analysis are determined through a computational Design of Experiments (DoEs). Secondly, the estimation of power generation will be carried out using a thermoelectric model. And thirdly, a dynamic interconnection algorithm will be implemented to finally obtain an efficient trapezoidal photovoltaic tile type. The selected alternative could have a competitive performance in terms of power generation compared to a conventional flat photovoltaic module while retaining the geometrical advantages of a tile.

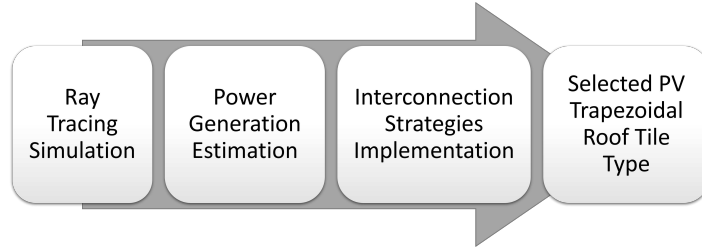


Figure 3.1: Main Diagram.

3.1 Geometrical Set-Up for Energetic Analysis

As it was analyzed in Chapter 2, trapezoidal roof geometries consist of several independent design variables (now denominated as factors for the DoE analysis). Each combination of factors define a geometric set-up that will have different behavior when simulating ray tracing. The inclusion of highly reflective elements such as mirrors diversifies the possible number of alternatives. To make a more comprehensive analysis, an experimental approach is applied to the proposed cases.

3.1.1 Main Variables of Trapezoidal Geometries

The reference cases are based on a trapezoidal tile type PV roof geometry, which is shown below in figure 3.2. From that basic geometry, two cases may be derived (lets name them as case A and case B) which have the same geometrical factors, with the difference that case B include mirrors on the leaned surfaces S_2 and S_4 , instead of photovoltaic cells. The purpose of this variation is to resemble case B to a V-Trough type concentrator and adopt its advantages in terms of power generation [Solanki et al., 2008].

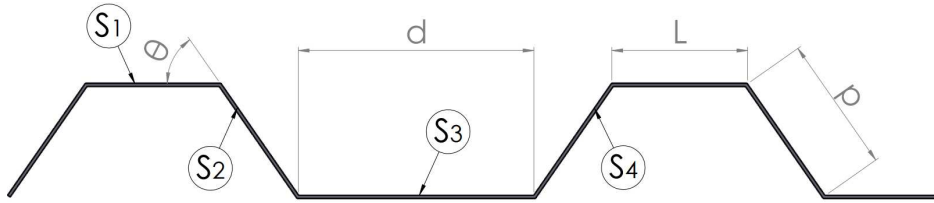


Figure 3.2: Traditional trapezoidal roof tile type.

Figure 3.3a shows how a complete photovoltaic roof tile type could be. Having in mind that a full tile is a set of multiple geometrically equivalent elements, only one of those elements would be simulated for each alternative (being the one shown in figure 3.3b). To obtain more accurate results, the element is modeled by parts since the PV roof would be made up of a reinforcement material such as UPVC, followed by cells encapsulated between epoxy resin (see figure 3.3c). The simulation software has built-in optical coefficients of absorption and transmittance for each material at predefined wavelengths. Refraction indexes for each material are extracted from the work of Bernal-del Río and Osorio-Gómez [2022].

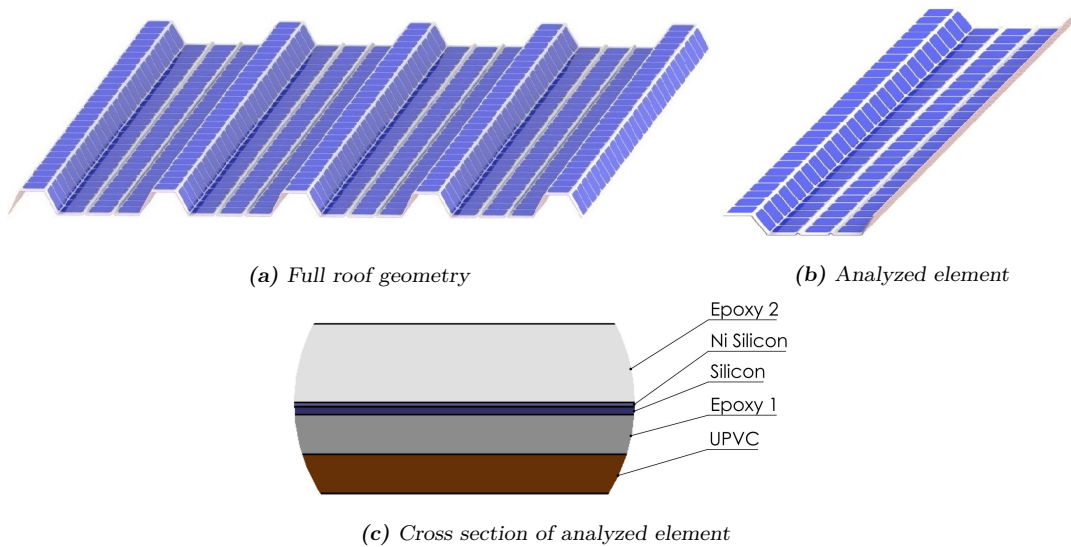


Figure 3.3: CAD model of the roof morphology.

3.1.2 Computational Experiment Design

One computational DoE was executed for each case. The selected experimental scheme was the L_{18} array for both A and B cases, this is shown below in Table 3.1. The first column corresponds to a factor with two levels, and the factors with 3 levels are assigned to the remaining columns.

Table 3.1: Taguchi L_{18} array [Gutiérrez Pulido et al., 2012]

Taguchi L_{18} array								
# Sim	# Column							
	1	2	3	4	5	6	7	8
1	1	1	1	1	1	1	1	1
2	1	1	2	2	2	2	2	2
3	1	1	3	3	3	3	3	3
4	1	2	1	1	2	2	3	3
5	1	2	2	2	3	3	1	1
6	1	2	3	3	1	1	2	2
7	1	3	1	2	1	3	2	3
8	1	3	2	3	2	1	3	1
9	1	3	3	1	3	2	1	2
10	2	1	1	2	3	2	2	1
11	2	1	2	1	1	3	3	2
12	2	1	3	2	2	1	1	3
13	2	2	1	2	3	1	3	2
14	2	2	2	3	1	2	1	3
15	2	2	3	1	2	3	2	1
16	2	3	1	3	2	3	1	2
17	2	3	2	1	3	1	2	3
18	2	3	3	2	1	2	3	1

According to the Taguchi theory for orthogonal arrays, L_{18} can be useful for 4 factors such as the present cases, since all factors except one can be varied in 3 levels. This allows a good trend analysis when simulating these variations. Table 3.2 shows the levels and factors for both cases. In addition, the proposed levels for each factor are also planned to be in accordance with the commercial sizes of Sunpower® photovoltaic cells (see table 3.3).

Table 3.2: Factors and levels for cases A and B (units in mm).

Factor	Description	Level 1	Level 2	Level 3
d	Bottom width	51,6	72,5	N.A
L	Upper width	72,5	135	260
p	Slope width	35	72,5	135
Θ	Tilt angle	45	55	60

Table 3.3: Commercial Sunpower PV cell sizes (units in mm).

Fraction	Size	Width
1/5	125*25	25
1/3	125*41,6	41,6
1/2	125*62,5	62,5
1/1	125*125	125

3.2 Radiation Simulation Through Ray Tracing

In order to explore the geometries, proposed in the previous section, a simulation workflow is going to be deployed. First, the program set-up will be shown, followed by the obtained results. Finally, the geometry with the best collection potential will be selected. In this section, geometries will be compared to each other based on the flux that they receive in each superior surface.

3.2.1 Ray Tracing Simulation Set-Up

The following table summarizes the implications of the main models and conditions used in the simulation setup.

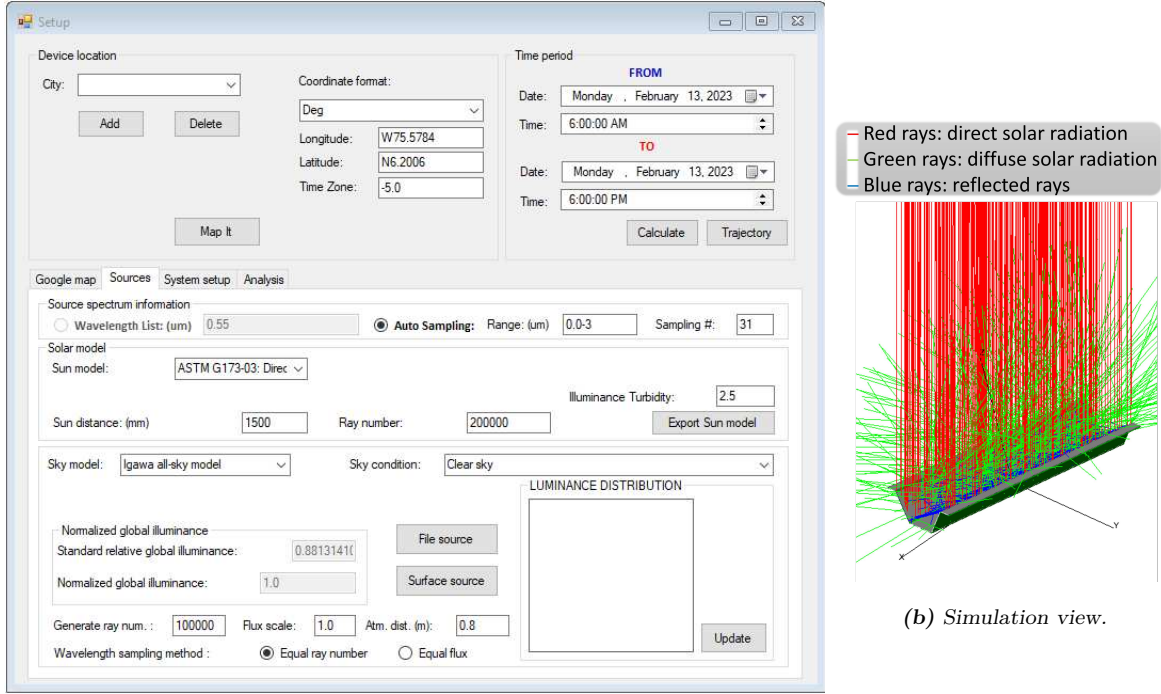
Table 3.4: Models and conditions

Model	Implication
ASTM G173-03: Direct+circumsolar - sun model	This model is an standards defined for terrestrial use, it has a defined spectrum for solar concentrator work, including the direct beam of the sun plus the circumsolar component in a 2.5 degree disk around the sun. It has an integrated power density of 900 W/m ² [Gueymard, 2001].
Igawa all - sky model	It is a model that allows to estimate the absolute values of the sky luminance and its distribution at any location for which the global illuminance is available [Igawa and Nakamura, 2001].
Clear sky	It is a sky condition that assumes that the sky is free from dullness or clouds [Oh et al., 2017].

Additionally, it is important to remark that the TracePro[®] simulation does not consider thermal phenomena that may affect the behavior of the rays. It is also assumed that all incident photons succeed in breaking the electron valence bond regardless of the fact that, physically, they might not have the necessary energy to do so.

However, despite the above, TracePro[®] allows to evaluate different geometries from its ray tracing to establish which of them could provide a better capture of the sun's rays. In this approach, this is beneficial prior to the implementation of a dynamic reconfiguration algorithm, since a geometry that receives more flux has more potential, in terms of generation, even considering the reconfiguration advantages.

Taking geometries as input, TracePro® simulates the path of rays from a source (the sun), and how they behave with respect to geometry (i.e. how reflection and absorption phenomena occur) and, finally, how they are translated into energy or power flow. Figure 3.4a shows the setup and Figure 3.4b shows a view of the ray tracing in the simulation.



(a) Simulation setup.

(b) Simulation view.

Figure 3.4: TracePro® simulation.

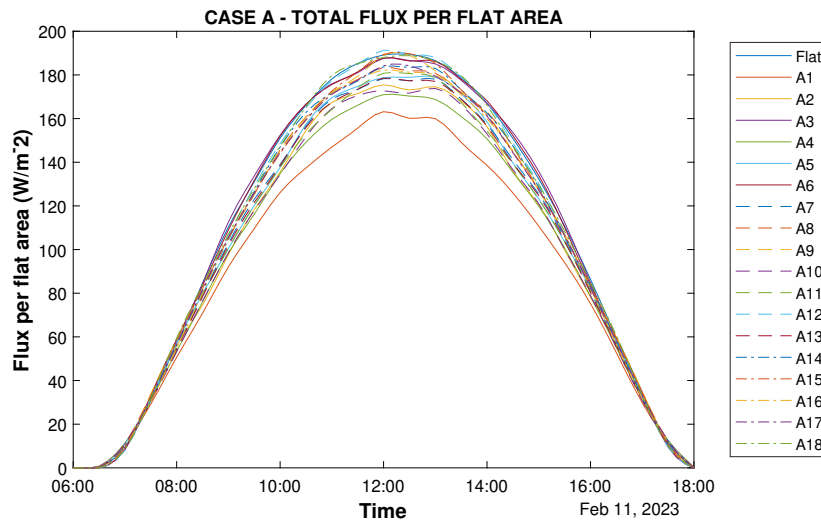
3.2.2 Ray tracing results

The radiation and irradiance that each row receives during the day is obtained with ray tracing simulation. This data is compiled for each geometry. Then, taking into account that due to the variation in the factors, each geometry occupies a different space. Thus we propose a quantity to normalize the simulation results, which consists on how much flux a geometry can receive, divided by the projected flat area that it occupies. In this way, the different geometries can be compared because this measure allows to equalize the results and to know which geometry can collect more solar energy in a roof of a greater area since it is directly proportional to the projected or flat area. Therefore, the results below are shown on a per square meter basis. Table 3.5 shows how much energy per flat area could collect each of the alternatives according to the factors of each geometrical configuration.

Table 3.5: Ray tracing simulation results for a complete day (February 13, 2023).

Simulation #	Independent factors				Total energy collected per flat area (Wh/m^2)			
	L	d	p	Θ	Case A		Case B	
1	51.6	51.6	35	45	A1	1101.09	B1	766.71
2	51.6	51.6	72.5	55	A2	1201.10	B2	634.05
3	51.6	51.6	135	60	A3	1298.54	B3	495.48
4	51.6	135	35	45	A4	1175.74	B4	965.23
5	51.6	135	72.5	55	A5	1229.79	B5	857.44
6	51.6	135	135	60	A6	1295.27	B6	725.63
7	51.6	262	35	55	A7	1226.21	B7	1113.39
8	51.6	262	72.5	60	A8	1260.58	B8	1034.44
9	51.6	262	135	45	A9	1268.74	B9	749.95
10	135	51.6	35	55	A10	1189.87	B10	1004.31
11	135	51.6	72.5	45	A11	1218.61	B11	783.87
12	135	51.6	135	55	A12	1287.99	B12	661.07
13	135	135	35	55	A13	1219.31	B13	1089.19
14	135	135	72.5	60	A14	1261.54	B14	997.71
15	135	135	135	45	A15	1268.35	B15	737.05
16	135	262	35	60	A16	1247.65	B16	1166.63
17	135	262	72.5	45	A17	1254.88	B17	1012.39
18	135	262	135	55	A18	1289.74	B18	928.94

A note to table 3.5, is that a flat PV module collects $1298.52 Wh/m^2$. Figures 3.5 and 3.6 show the flux collection profile per flat area for each geometry throughout the day. It can be observed that most of the geometries of **case A** have a similar curve to that of the flat case.

**Figure 3.5:** Ray tracing simulation results for case A.

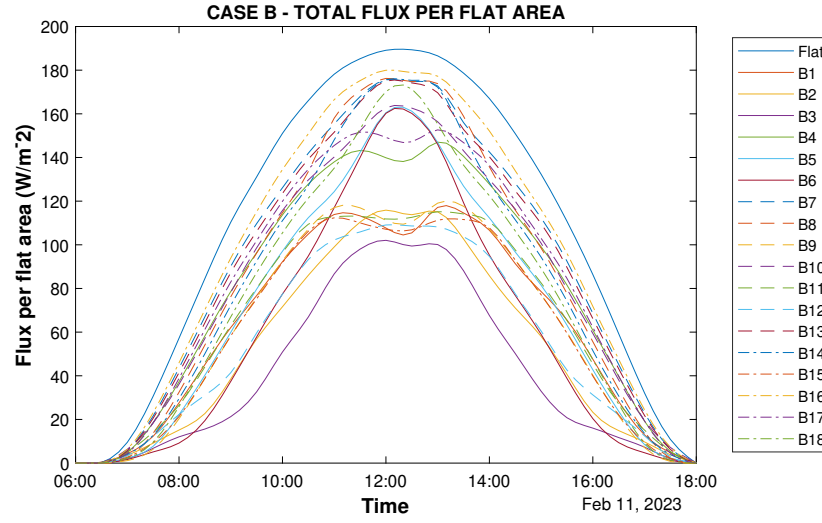


Figure 3.6: Ray tracing simulation results for case B.

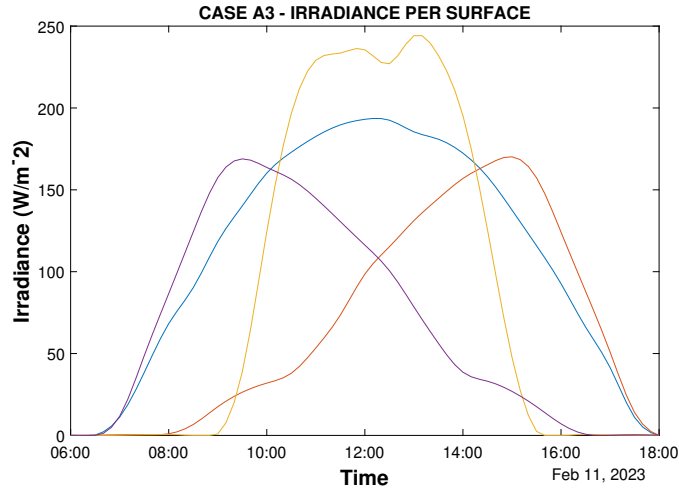


Figure 3.7: Ray tracing simulation results for case A3.

According to table 3.5, the **A3** geometry achieved the best performance in terms of energy harvesting. Figure 3.7 shows irradiance for each surface of **A3**. In the other hand, all **case B** geometries perform worse than most of the **case A** geometries. This may be because the mirrors focus well at certain times of the day but waste solar rays at others, and on balance become inefficient when evaluated by occupied area rather than concentration in a full day. However, the **B16** configuration achieves a very similar collection compared to a flat module, but without using the same amount of PV cells and using mirrors instead, which could be cheaper. So that the **B16** alternative has an interesting cost-economic potential. For the scope of this project, the analysis will continue with the **Case A** set of geometries because of its higher solar energy collection potential.

3.2.3 Trend analysis

In this instance, a trend analysis is presented to find patterns of interest that may complement the current level of understanding as to why certain geometries perform better than others. Tables 3.6, 3.7 and 3.8 shows, respectively, the analysis of variance, the model summary, and the coefficients table. It can be observed that the P-Val of the p factor is the lowest and therefore this is the most significant factor. Also, the R-sq coefficient has a value of 89.70%, which indicates a good fit between the model and the data obtained in the simulations for the present analysis.

Table 3.6: Analysis of Variance. Case A.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
L	1	1818	1817.9	4.14	0.0693
d	2	5318	2658.9	6.05	0.0189
p	2	25100	12550.1	28.57	0.0001
Θ	2	6025	3012.5	6.86	0.0133
Error	10	4392	439.2		
Total	17	42653			

Table 3.7: Model Summary. Case A.

S	R-sq	R-sq(adj)	R-sq(pred)
20.9575	89.70%	82.49%	66.64%

Table 3.8: Coefficients. Case A.

Term	Coef	T-Value	P-Value
Constant	1238.61	250.74	0.0000
L			
51.6	-10.05	-2.03	0.0693
d			
51.6	-22.41	-3.21	0.0094
135.0	3.06	0.44	0.6710
p			
35.0	-45.30	-6.48	0.0001
72.5	-0.86	-0.12	0.9043
θ			
45	-24.04	-3.44	0.0063
55	3.74	0.54	0.6036

Table 3.9: Response Table for Means, Case A.

Level	L	d	p	Θ
1	1229	1216	1193	1215
2	1249	1242	1238	1242
3		1258	1285	1259
Delta	20	42	91	44
Rank	4	3	1	2

Table 3.10: Response Table for SN Ratios, Case A.

Level	L	d	p	Θ
1	61.78	61.69	61.53	61.68
2	61.93	61.88	61.85	61.88
3		61.99	62.18	62.00
Delta	0.15	0.31	0.65	0.32
Rank	4	3	1	2

In addition to the above, tables 3.9 and 3.10 show the response for the means and the SN (Signal to Noise) ratios, respectively. There, the ranking of the factors can be observed, where p is the most significant and d is the least significant. This means that variations in p-factor produce greater changes in the response compared to the other factors. This is also reflected in figure 3.8, where it can be seen how all factors have a steep slope and therefore all are important. However, the one with the highest gradient in the response is p.

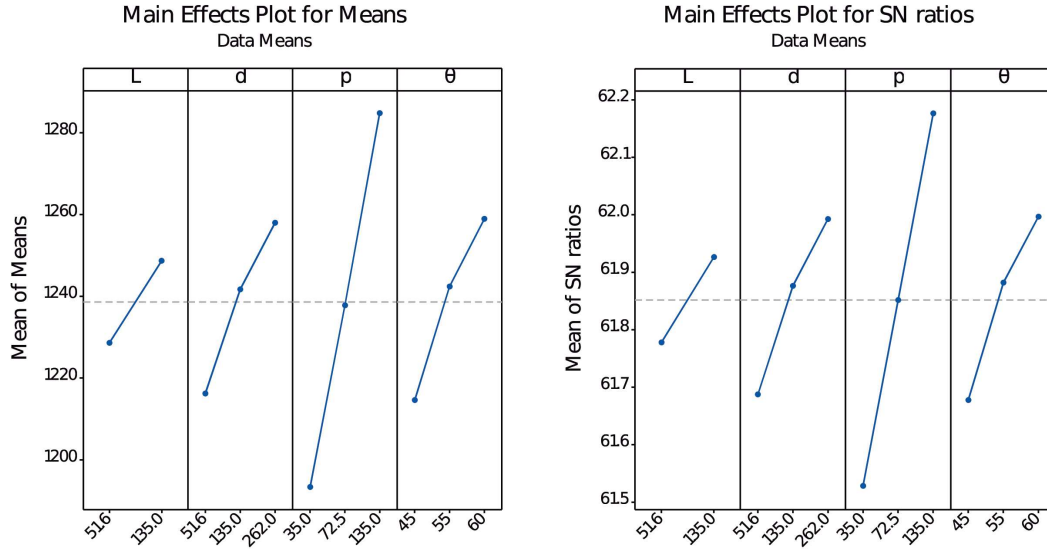


Figure 3.8: Main effects plots for case A.

The results of this part of the analysis establish that in order to obtain a better response for solar energy collection, large p values can be used as the main factor. Accompanied by also large values of d and Θ as secondary factors. Even high values of L can contribute, but only in a minor way. In order to obtain feasible results from the manufacturing point of view, 3 additional simulations are proposed following the patterns of the trend analysis and also the trade sizes of Table 3.3. The configurations are shown in Table 3.11 together with their results.

Table 3.11: Ray tracing additional simulation results.

Simulation #	Independent factors				Total energy collected per flat area (Wh/m ²)	
	L	d	p	Θ	Case	
19	51.6	135	135	65	A19	1307.44
20	135	135	135	65	A20	1306.65
21	135	262	135	65	A21	1309.01

3.3 Energy Improvement Through Interconnection Strategies

This section presents the analysis and the procedure performed to obtain the estimated power generation produced by the photovoltaic panels as a function of the operating temperature and irradiance for each surface, obtained in the previous section. It will be observed that each geometry has a unique behavior and that the irradiance curves and interconnection strategies must be properly selected in order to find the best solution that provides the highest power without increasing immoderately the operating current.

each geometry in order to find the combination of geometry and interconnection that provides the best performance. A dynamic interconnection called “Reconfigurable interconnection” will also be proposed, which will consist of choosing the best interconnection for each time of the day, but with the limitation of not exceeding a current of 10 A, otherwise the parallel interconnection will always be chosen. This occurs because in a fully parallel connection, when one of the elements fails or is shaded, the power generation of the other elements still contributes to the total generation of the array [Chang, 2003]. However, parallel interconnection has the disadvantage of operating at low voltage and high current values, which is not desired as it was explain in the previous chapter. Therefore, fully parallel scheme will be considered as a maximum achievable power model and also a desired one depending on the operation conditions. The proposed interconnections can be seen in Appendix B.

Additionally, it is worth mentioning that the proposed interconnection configurations are based on avoiding the effects of Mismatch losses exposed in chapter 2. The patterns of irradiance curves were then reviewed, and how these at certain times of the day may be favored by one interconnection or another. The results of this analysis show configurations based on TCT and variations thereof. It is necessary to use different topologies according to the number of rows of PV cells that are present on each alternative because geometries such as A7, A8, A9, A16, A17, A18, and A21 use 2 rows of cells on the S3 surface. Seven (7) configurations were simulated for 4-row geometries and Six (6) configurations were simulated for 5-row geometries. Figure 3.10 shows the performance for each geometry, choosing for each of them the best fixed interconnection configuration.

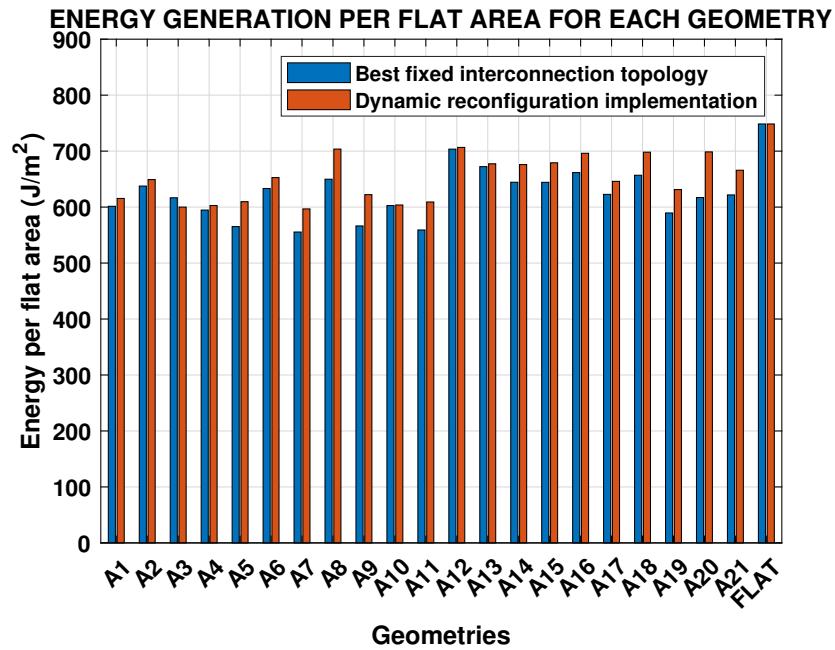


Figure 3.10: Power generation per flat area by best fixed interconnection topology and by dynamic reconfiguration implementation for each geometry.

Figure 3.10 also shows for each geometry the summary of how would be the performance of implementing a dynamic reconfiguration algorithm. There it is observed that for geometry A12, which has the best performance (of all except flat case), the difference between using a dynamic reconfiguration algorithm and connecting all the rows in parallel is about 4.8 %. And it is also reported that the difference between implementing configuration 3 or a dynamic reconfiguration algorithm in A12 geometry is less than 0.5 %. However, it is worth mentioning that a fixed topology has the advantage of having a simpler system, in terms of economy and maintenance. Also, implementing an algorithm for dynamic reconfiguration involves additional energy consumption for the operation of the controller, switches and sensors, mainly.

Table 3.12: Interconnection Strategies Summary

Geometry	Interconnection Strategy	Maximum Current (A)	Average Power (W/m ²)	Energy Generation per flat area (J/m ²)
A1	Configuration 4	1.72	49.43	601.43
A2	Configuration 3	3.35	52.40	637.58
A3	Configuration 6	7.59	50.68	616.60
A4	Configuration 5	7.64	48.88	594.65
A5	Configuration 5	8.70	46.45	565.18
A6	Configuration 3	5.29	52.04	633.20
A7	Configuration 4	3.11	45.65	555.45
A8	Configuration 4	4.43	53.41	649.82
A9	Configuration 4	5.21	46.55	566.32
A10	Configuration 5	7.55	49.54	602.79
A11	Configuration 3	4.37	45.95	559.10
A12	Configuration 3	6.82	57.83	703.54
A13	Configuration 2	5.76	55.25	672.27
A14	Configuration 2	6.57	52.96	644.39
A15	Configuration 3	8.40	52.95	644.24
A16	Configuration 4	5.20	54.38	661.68
A17	Configuration 5	4.36	51.18	622.71
A18	Configuration 5	5.33	53.99	656.88
A19	Configuration 3	4.88	48.45	589.47
A20	Configuration 2	7.52	50.72	617.08
A21	Configuration 5	4.43	51.10	621.73
FLAT	Configuration 1	10.15	61.52	748.53

Finally, Table 3.12 shows the summary of the interconnection strategies used. It is then reported which was the best configuration for each geometry, its maximum current, average power, and energy generation per unit of flat area. A12 geometry has the best results in implementing a dynamically reconfigurable algorithm as in using a fixed topology strategy. This is mainly due to the existing

synergy between its irradiance curves and how these are coupled to capitalize the energy received and avoid the effects of mismatch losses so that each surface can contribute to the total generation without interrupting it at times of the day when some surfaces are at lower irradiance levels due to trapezoidal geometry, sun position, or cloudy sky conditions.

In addition to the above, it is also reported that the difference in energy generated per flat area between the flat case and the A12 geometry is 6%. This data will be used in the experimental validation to check how close the simulated data is to the physical reality through the prototypes to be manufactured.

3.3.3 Selection of Geometry and Interconnection Strategy

According to Table 3.12, the A12 geometry is the one that achieves the best performance. Figure 3.11 shows the power generation graph for this geometry. In general, configuration 7 (all in parallel) is superior, and specifically for this geometry, the best one is configuration 3, since it closely resembles the performance of the parallel connection but produces lower currents (**6.82** amperes, compared to **13.64** amperes for parallel connection). The power generation simulation results for each configuration and geometry are shown in appendix C. The values reported correspond to the MPP, which was extracted from the V-I curve throughout the day for each combination of geometry and interconnection.

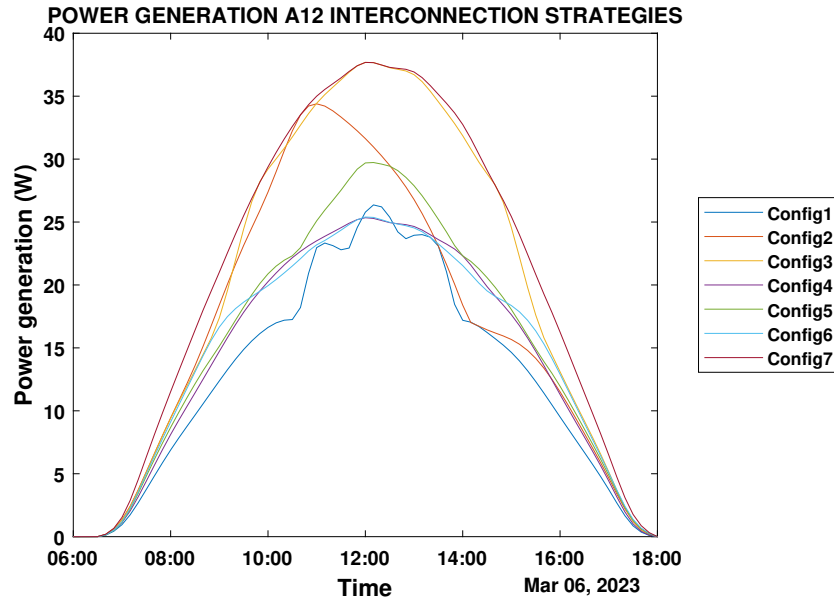


Figure 3.11: Power Generation by the configurations proposed for A12 geometry.

The connection scheme of configuration 3 in geometry A12 is shown in Figure 3.12 below. It consists of a TCT type connection, in which the parallel between surfaces S_1 and S_3 (non-inclined) is in series with the parallel between surfaces S_2 and S_4 (inclined).

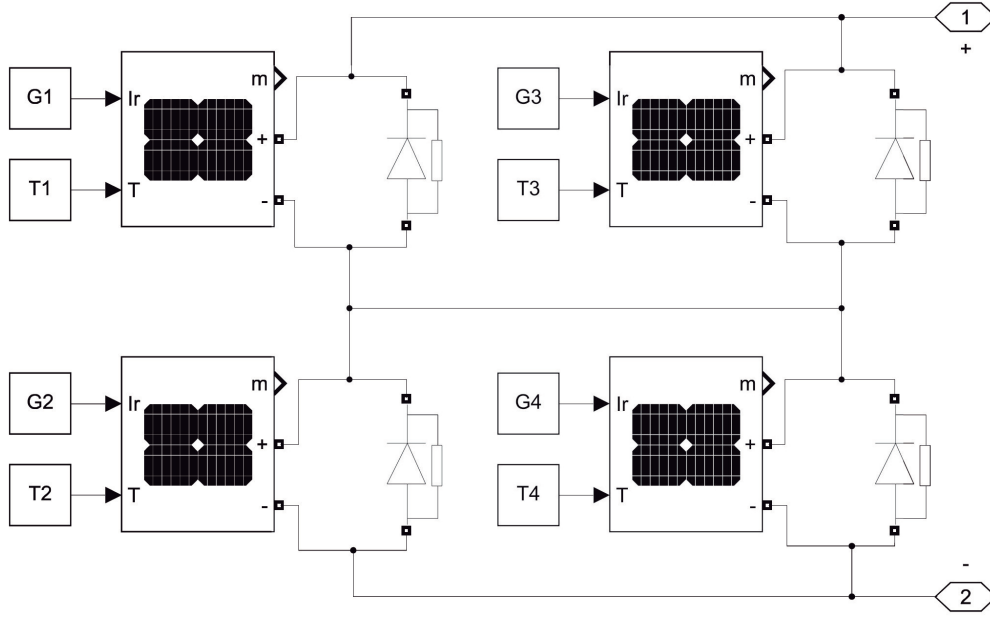


Figure 3.12: A12 with Configuration 3.

Figure 3.13 shows the incident energy flux curves for each surface of geometry A12. This figure illustrates, on one hand, how for each time of the day, the parallel between S_1 and S_3 manages to perform adequately since they contain a similar level of generation. And the surfaces S_2 and S_4 , on the other hand, the parallel works properly because always at least one of the two has a suitable level of flux and therefore the current flows through it. The bypass diode avoids mismatch losses due to parallel connection.

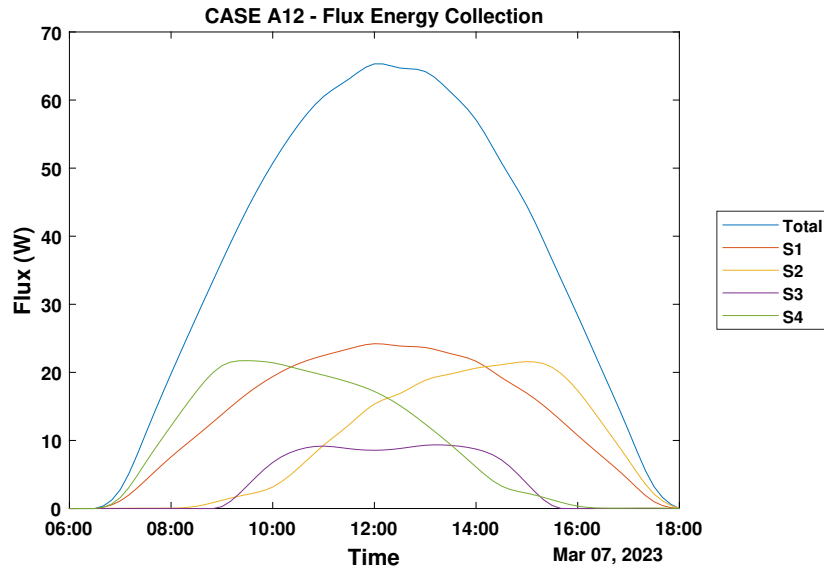


Figure 3.13: A12 with Configuration 3.

Chapter 4

Implementation

This chapter explains, step by step, how the implementation of the selected alternative in the previous chapter, was carried out. The objective of this part is to validate that the obtained behavior in the simulations, is consistent with the real performance of a physical prototype based on the main characteristics and attributes of the proposed geometry and interconnection. Initially, the process to build the proposed geometry and interconnection will be explained. Subsequently, details will be given on how the data was collected and general analysis about how the simulated data is projected on the real data.

4.1 Manufacturing process

The manufacturing process of the prototype begins with the fabrication of a layer called “reinforcement”. It provides the photovoltaic cells a support on which they can rest freely while the possible stresses are absorbed by this reinforcement layer. So the PV array composed of independent rows of PV cells starts with welding work and subsequent attachment to the reinforcement material. Finally, the process ends with the interconnection of the overall circuit.

4.1.1 Geometry and Reinforcement

The manufacturing method used to give the necessary geometry and reinforcement to the prototype is contact molding. This method consists of laminating with resin (epoxy in this case) on a reinforced plastic fabric such as fiberglass, resting on a mold that gives the desired geometry. The mold for this work was made of wood, as shown in Figure 4.1. This mold has the lengths, angles, and general measurements of alternative A12.



Figure 4.1: Wood mold

Mold release wax is applied to the mold and then it is covered by a peel-ply fabric. The previously cut fiber reinforcement fabrics are placed above the mold. Parts A and B of the epoxy resin are then mixed and applied with a brush following the geometry of the mold. Once it has been applied a resin impregnation percentage of approximately 50%, the resin is allowed to harden and the part is demolded. Finally, the part is cleaned and the edges are cut to give the desired details. The result is shown in figure 4.2.

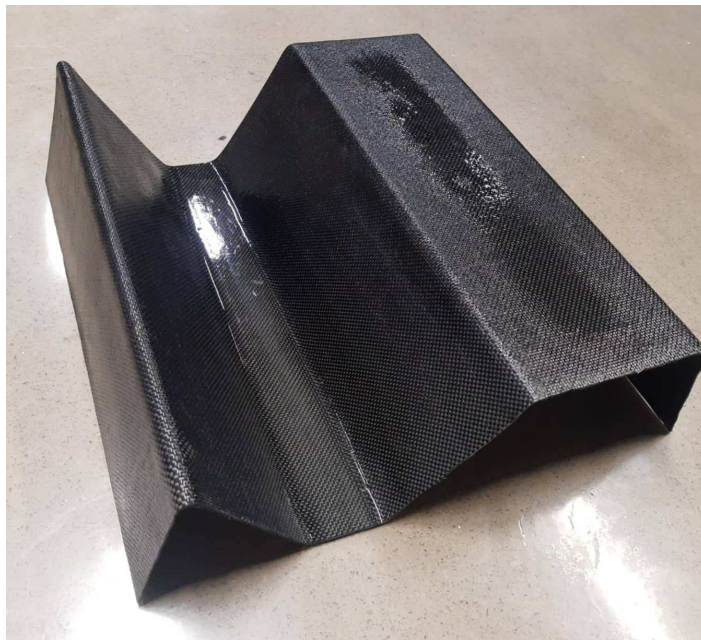


Figure 4.2: Reinforcing layer

4.1.2 PV module fabrication

The PV module manufacturing process starts with PV cell welding. This part consists of the preparation of the strings and dogbones (busbar cell connectors). This is followed by the application of flux, which is a substance designed to facilitate the soldering of surface mount circuits. Finally, tin solder is carefully applied to connect the cells together to form a PV module. Figure 4.3 shows the PV rows after the solder application.

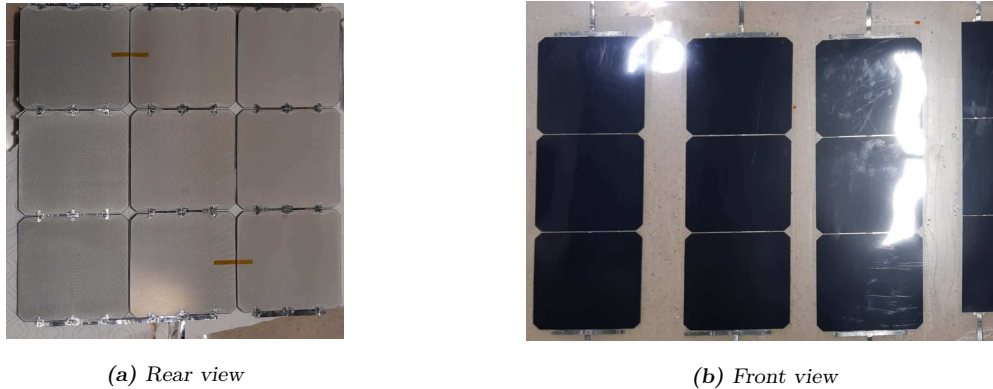


Figure 4.3: Cells welded according to alternative A12's surfaces

Subsequently, the lamination process begins. First, the necessary materials are prepared, such as plastic mylar layers, fiber fabrics, epoxy resin and catalyst, brushes, tow, resins, scales, gloves, among others. In general, the process consists of a manual lamination of two layers of fiberglass on a flat surface. The photovoltaic panels are placed on these layers, which in turn are coated with resin on top. Finally, the process ends with the application of vacuum pressure by means of a sealed bag and a vacuum pump. Figure 4.4 shows the application of vacuum to the system to extract the air and get better results.

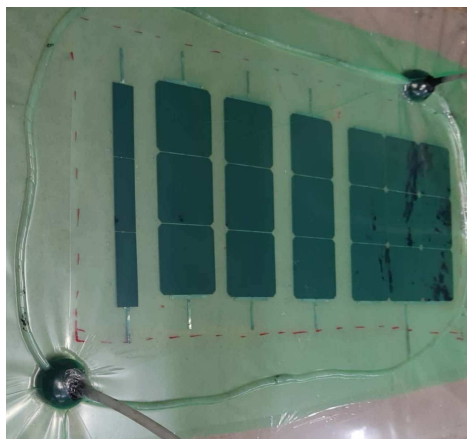


Figure 4.4: Vacuum application

4.1.3 Cells Interconnection

Finally, the PV strings are interconnected according to the electrical configuration selected in the previous chapter. Figure 4.5 shows the wiring of the interconnection following the circuit shown in Figure 3.12 (See Chapter 3). Including Bypass diodes and heat-shrinkable insulators to avoid interference and current leakage.

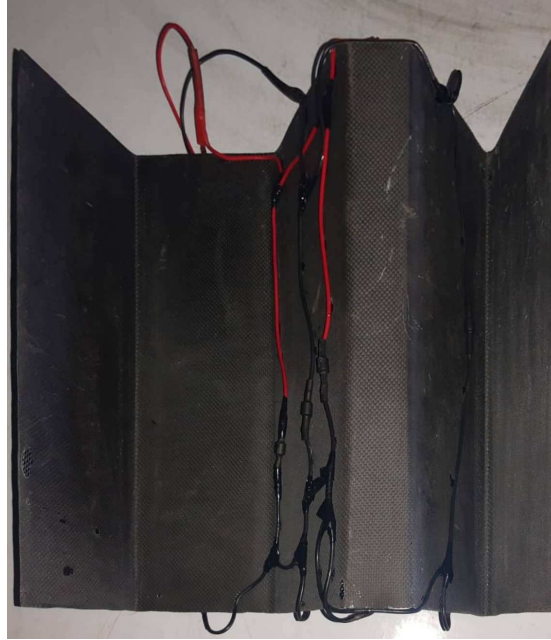
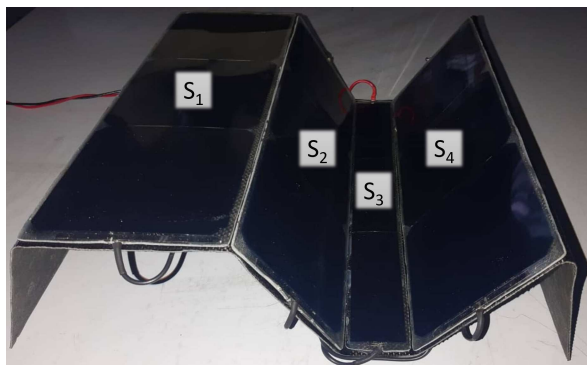


Figure 4.5: Rear view.

The finished prototype ready for testing is shown below in Figure 4.6. The final finishes of the selected trapezoidal geometry are shown here. The wiring was hidden as much as possible also thought about the development of the prototype as a possible product in later works.



(a) Frontal View



(b) Lateral View

Figure 4.6: Prototype views

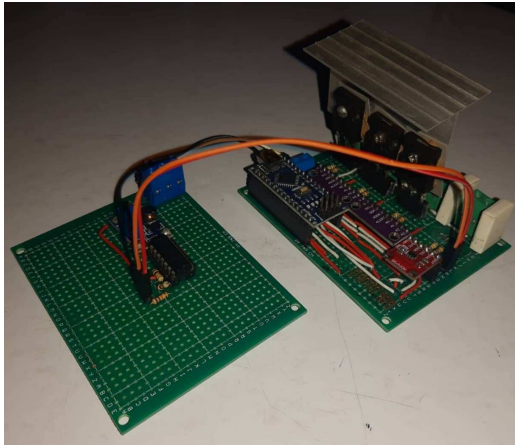
4.2 Data Collection

The following part describes how the data collection process was carried out during the experimental tests of the prototype. It emphasizes on the devices and instruments used, the results found, and their relationship with the simulations performed.

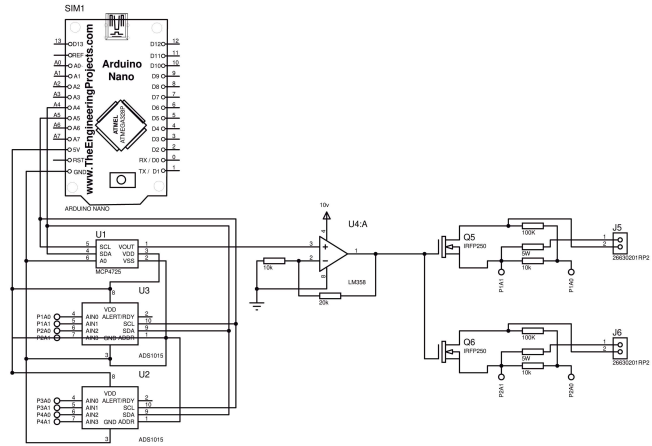
4.2.1 Devices for data acquisition

The main device that allowed the construction of the V-I curves of the prototype is shown below in Figure 4.7. The device uses an Arduino[®] Nano as the main microcontroller. There are also two ADC 12 Bit 4Ch Analog to Digital Converter units, which take the signal from the sensors and translate it into values that the Arduino[®] can interpret. There is also an LM358 amplifier, and the MCP4725 digital-to-analog conversion unit communicates with the IRFP250 MOSFETs to allow current flow.

The sampling rate is limited by the MOSFETs due to the risk of damage from overheating due to switching. Therefore the I-V curves are constructed by varying every 20 ms the voltage in a ramp function from open circuit to short circuit and thus obtaining for each voltage value the corresponding current point of the I-V curve. An I-V curve is built every 12 seconds, 5 per minute. The data acquisition is finally done by serial communication directly between Arduino[®] and Microsoft[®] Excel.



(a) Measuring device view



(b) Measuring device schematic diagram

Figure 4.7: V-I curve measuring device

In addition, a multimeter *UNI-T*, a clamp meter *UNI-T*, a pyranometer *SEAWARD*, and a thermographic camera *SEAWARD* were used in the tests. Using these instruments, the short circuit current, open circuit voltage, and thermal image of the panel at 1004 W/m^2 irradiance are reported in Figure 4.8.



Figure 4.8: Measuring devices

4.2.2 Experimental Data acquisition

Using the instruments described in the previous section, data were collected for analysis as shown below. Measurements were taken during a day with an irradiance level as shown in Figure 4.9. It can be observed that there were partly cloudy conditions in the morning and a continuous peak irradiance in the afternoon, with a final pronounced drop after 16:00.

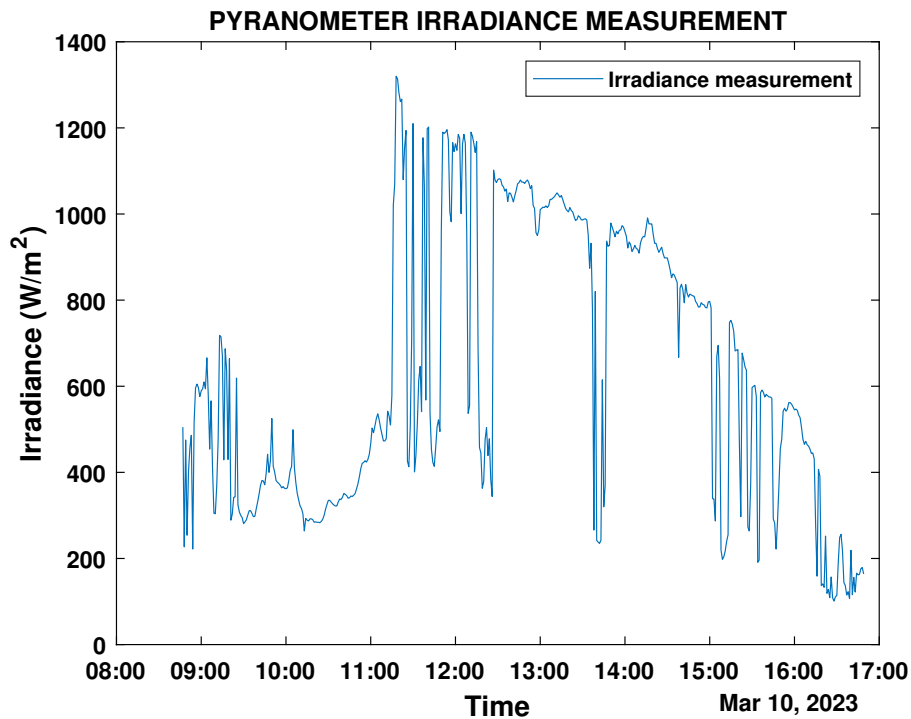


Figure 4.9: Experimental irradiance profile on measurement day.

The measurements were taken by time intervals; Table 4.1 reports the temperatures recorded at the beginning and end of each measurement period.

Table 4.1: Reported temperatures (measures in $^{\circ}\text{C}$)

Time	Flat PV	Surface S_1	Surface S_2	Surface S_3	Surface S_4
08:45:00 a. m.	31.5	31.4	28.9	29.3	52.0
10:00:00 a. m.	43.0	41.1	34.5	33.8	40.5
11:30:00 a. m.	50.2	53.2	38.9	52.1	39.4
01:30:00 a. m.	55.5	50.3	52.8	53.1	55.3
03:30:00 p. m.	51.8	51.6	53.4	51.1	33.7
05:15:00 p. m.	26.1	30.2	30.2	31.0	30.2

Finally, Figure 4.10 illustrates the behavior of the trapezoidal geometry with the implementation of the fixed interconnection configuration 3 for a 4-surface geometry. The generation curve of a flat module is also included in the plot as a reference value. It is worth mentioning that the recorded power values correspond to generation per flat or projected area. Since a trapezoidal geometry has a larger surface area, it can store more photovoltaic cells but occupies the same flat space compared to a regular flat module.

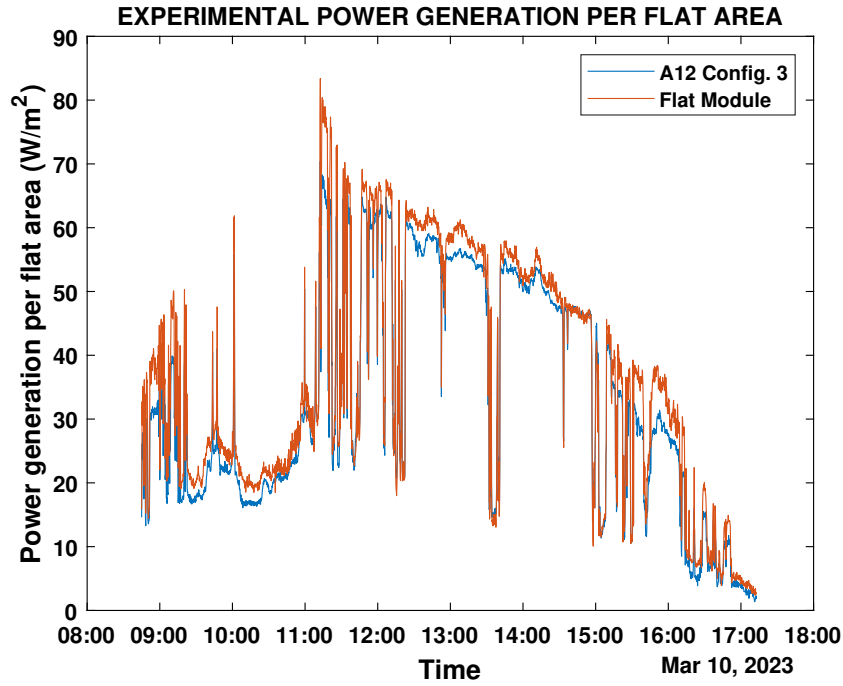


Figure 4.10: Experimental power generation

4.2.3 Analysis

From Figure 4.10, the area under the curve represents the energy produced. This energy is equal to 282.29 Wh for the trapezoidal tile-type geometry and is equal to 306.02 Wh for the flat geometry. This represents a difference of 7.75%. This value is relatively close to the expected 6% reported in the previous chapter. The differences may be due to different factors such as differences in the diffuse radiation model used in the CAD, and also by the winds that can alter the temperature of the cells and change the performance. Another factor may be that the tilt of the panels with respect to the sun's path axis may not be accurate as in the simulation and this causes a difference. In addition, yet the tendency predictions are reasonable, the models used to simulate power generation based on irradiance, ambient temperature, and surrounding wind speed also have a margin of error.

Table 4.1 shows how the temperature on the different surfaces of the trapezoidal geometry varies depending on the time of day, reaching its highest values when the sun's rays strike perpendicularly due to the angle of incidence. Despite the fact that during the day of the measurements there was no peak irradiance level during the morning hours, it is considered that the simulation is pertinent. Therefore a day with a complete peak hour distribution was not sought. Since the prototype is to be implemented under regular operating conditions, it is normal not to have a day with a perfect solar peak hours distribution.

A noteworthy note is that the A12 geometry, despite not being the best according to the simulations in the ray tracing stage, managed - with configuration 3 - to generate more energy than the others. This is because due to the trapezoidal geometry, the difference between the efficiencies achieved consists mainly of how well the used interconnection strategy, matches the irradiance curves of the surfaces. Due to mismatch losses, there may be a geometry with high irradiance levels on all surfaces, but if they do not complement each other well and the interconnection does not take advantage of the collected rays as it should, then the performance will not be as well as expected.

On the other hand, if there is a geometry whose irradiance curves act in a synergistic between them and with the interconnection topology then it will be possible to capitalize to the maximum the incident radiation. In that case, there will achieve the best performance. So it is not really about the best geometry or the best interconnection, but the best combination between these. In this case, the analysis was delimited to commercial PV cells dimensions for manufacturing a prototype as a partially developed product from the perspective of the technical field.

Chapter 5

Conclusions

In this work, a methodology was proposed and implemented to carry out a study of the application of BIPV technology on a trapezoidal tile roof. The objective of the study was to find, through optical, thermal, and electrical analysis, the best alternative in terms of power generation. This objective was completed and limited to photovoltaic cells of commercial sizes, with a set of fixed interconnection topologies based mainly on a TCT structure.

The analysis of ray tracing by means of the DoE with the Taguchi methodology allowed to find patterns of improvement in the geometries. It was found that geometries with mostly inclined surfaces obtain greater solar gain. This is due to the fact that the larger the PV surface area, the greater the collection of incident rays compared to a totally flat module.

Power generation simulations showed that the geometry that collects the most sunlight is not necessarily the one that provides the best performance (unless an appropriate interconnection strategy is implemented). The best performance is achieved by a geometry that better capitalizes the irradiance received by each of its surfaces during the course of the day, by implementing an appropriate interconnection strategy.

In this work, it was found that the best alternative is the A12 geometry implemented together with the interconnection of configuration 3 (See Table 3.12) for 4-surface geometries, as it has the highest energy generation potential. Using the interconnection of configuration 3 implies an energy cost of 5% compared to connecting all of its rows in parallel, also With the advantage of working with an average current of 4 amperes less than in that parallel interconnection.

Additionally, the selected configuration has a difference of less than 0.5% in power generation compared to implementing a dynamic interconnection algorithm. Consequently, it was determined that in this case, it is not feasible to implement a system to reconfigure the PV array because the performance gain is small compared to the investment and maintenance cost that such a system may require. In addition, it would also have a power consumption for powering the microcontroller,

sensors, and switches. This reaffirms that for this case, fixed topology interconnection is a more viable alternative, despite the advantages of such dynamic interconnection systems.

It is then established that for static applications such as roofs, facades, or BIPV in general, there is a fixed interconnection that takes advantage of the irradiance curves in a competitive way in relation to implementing a dynamic interconnection algorithm. This is because knowing the estimated behavior of the irradiance curves, then it is possible to find an arrangement that reduces the mismatch effects. In this case, an interconnection with TCT variation strategy is the topology with the best energy generation potential.

Implementing a reconfiguration algorithm may be feasible in Vehicle Integrated Photovoltaics (VIPV) or where irradiance or partial shading patterns are unknown. Since it is more versatile to adapt to new operating conditions. Although, even in these VIPV applications, such as those just mentioned, a fixed interconnection could also achieve competitive performance and provide a simpler and more cost-effective system.

Finally, it was also observed that the simulated performance of the system, corresponds to the experimental behavior. The difference between the selected alternative and a fully flat regular module is 6.75% for the simulations and 7.75% for the experimental data. The sacrificed amount of energy may be comparable to other benefits that could be achieved with trapezoidal profiles (e.g., mechanical, thermal, acoustic, aesthetic, assembly).

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Acronyms

BIPV Building Integrated Photovoltaics. i, ii, v, 2, 3, 5, 7, 41, 42

DoE Design of Experiment. 19, 21, 41

MPP Maximum Power Point. 11, 31

NOCT Nominal Operating Cell Temperature. 9

PV Photovoltaic. v–vii, 1–3, 6–17, 19, 20, 24, 25, 28, 29, 33, 35, 36, 40, 41

SRE Standard Reference Environment. 9

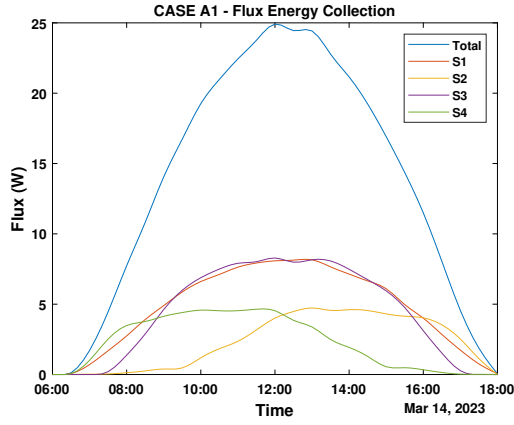
STC Standard Test Conditions. 9, 11

TCT Total Cross Tied. 16, 29, 31, 41, 42

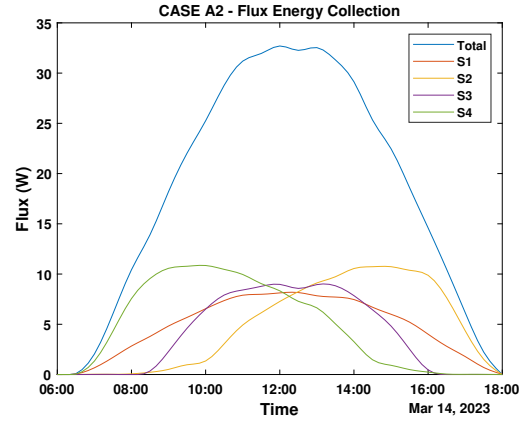
VIPV Vehicle Integrated Photovoltaics. 42

Appendix A

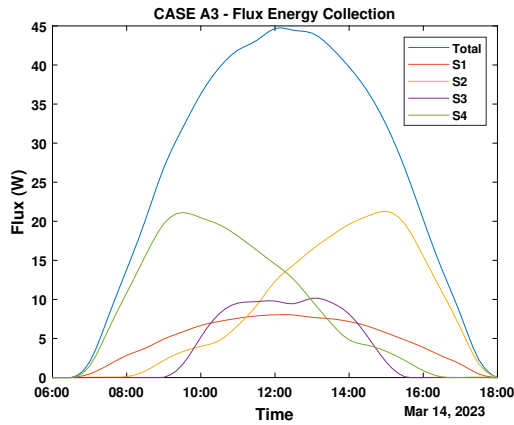
Flux Energy Collection Curves



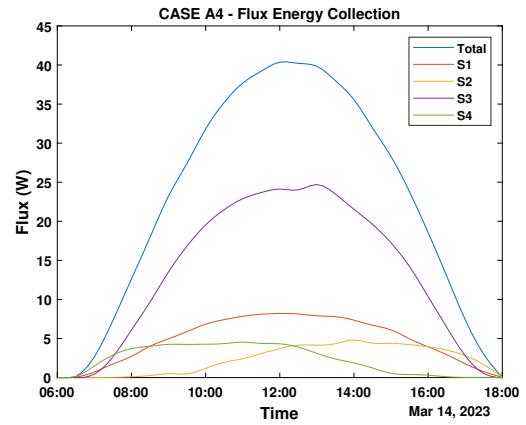
(a) Flux Energy Collection for A1 Geometry.



(b) Flux Energy Collection for A2 Geometry.

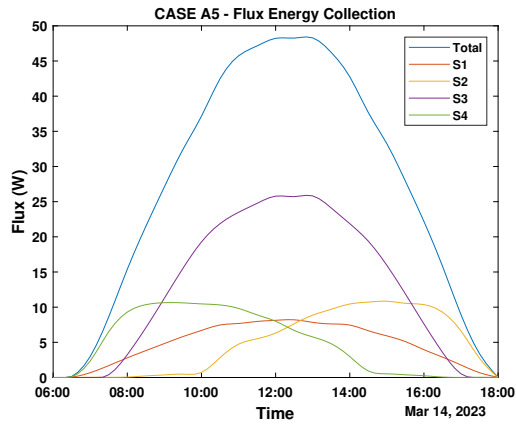


(c) Flux Energy Collection for A3 Geometry.

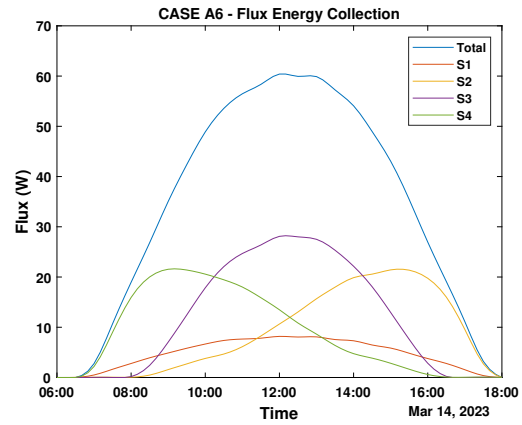


(d) Flux Energy Collection for A4 Geometry.

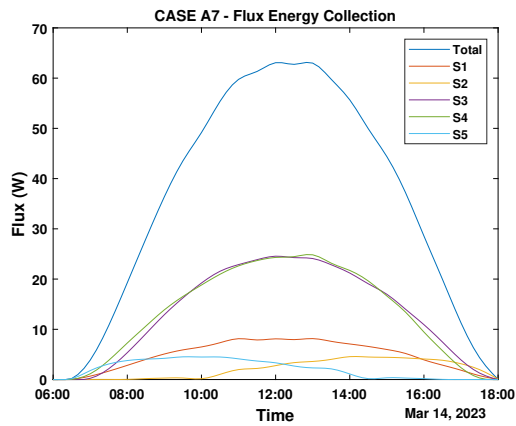
Figure A.1: Flux Energy Collection for A1 to A4 Geometries.



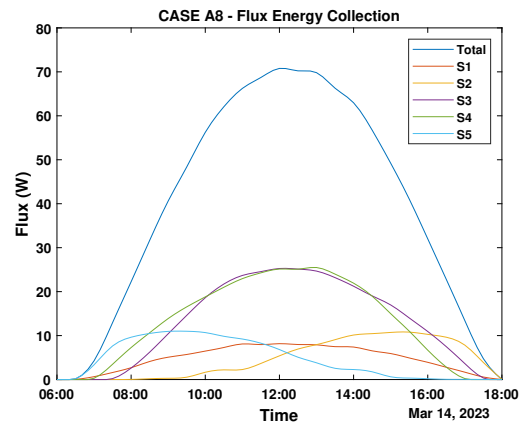
(a) Flux Energy Collection for A5 Geometry.



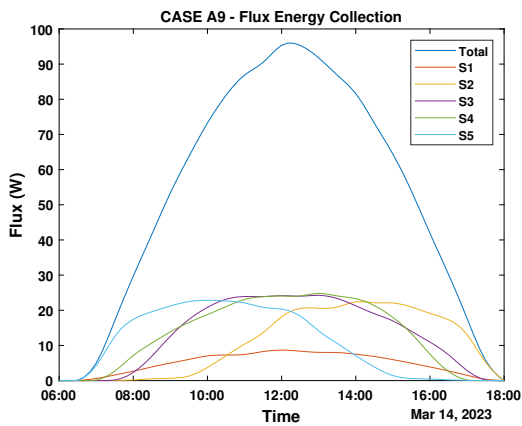
(b) Flux Energy Collection for A6 Geometry.



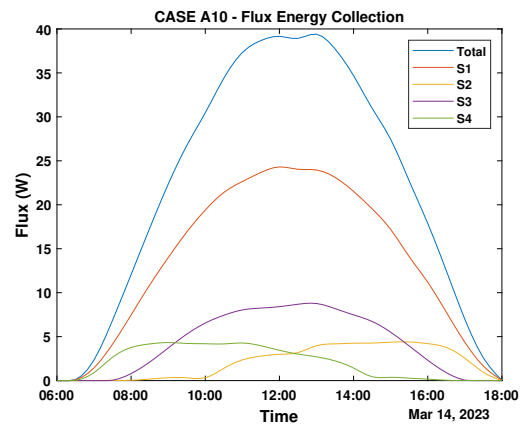
(c) Flux Energy Collection for A7 Geometry.



(d) Flux Energy Collection for A8 Geometry.

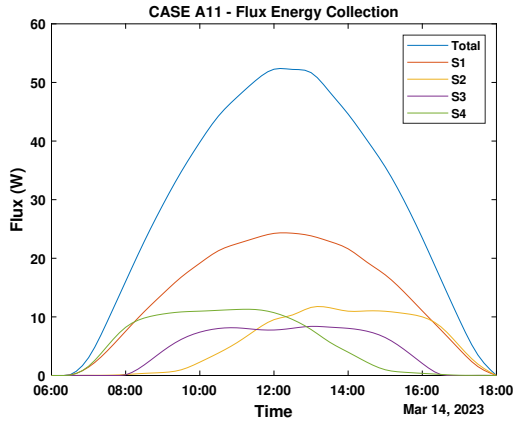


(e) Flux Energy Collection for A9 Geometry.

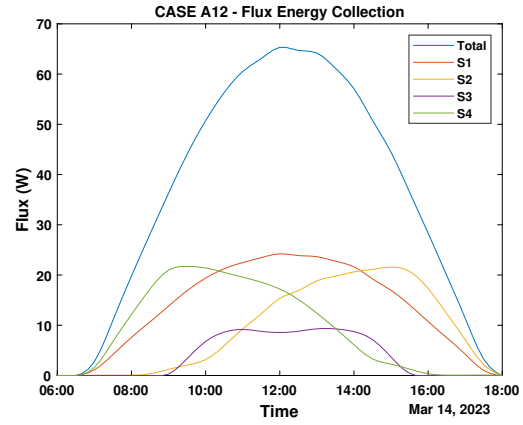


(f) Flux Energy Collection for A10 Geometry.

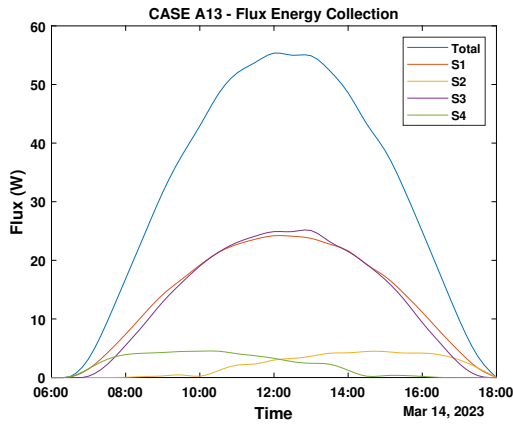
Figure A.2: Flux Energy Collection for A5 to A10 Geometries.



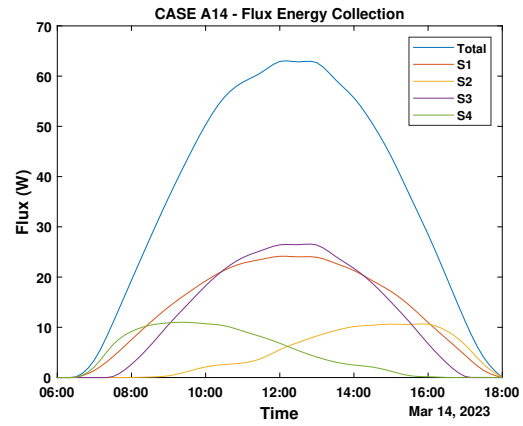
(a) Flux Energy Collection for A11 Geometry.



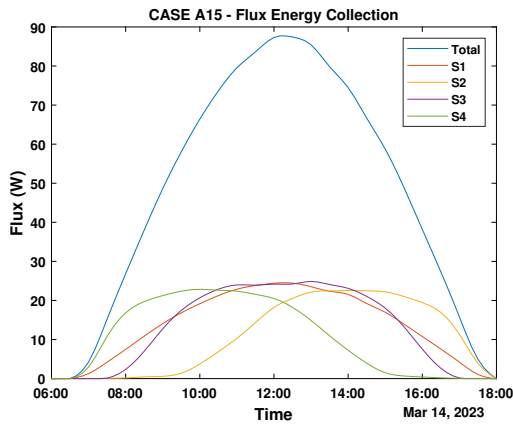
(b) Flux Energy Collection for A12 Geometry.



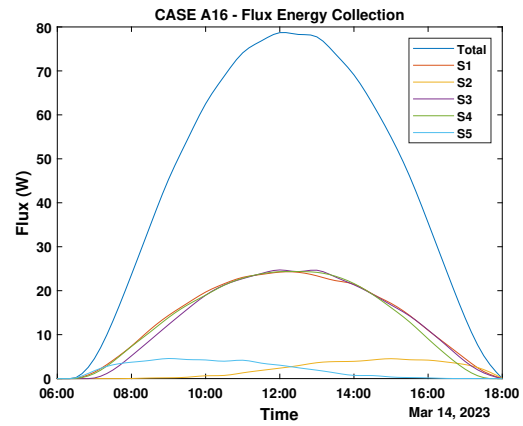
(c) Flux Energy Collection for A13 Geometry.



(d) Flux Energy Collection for A14 Geometry.

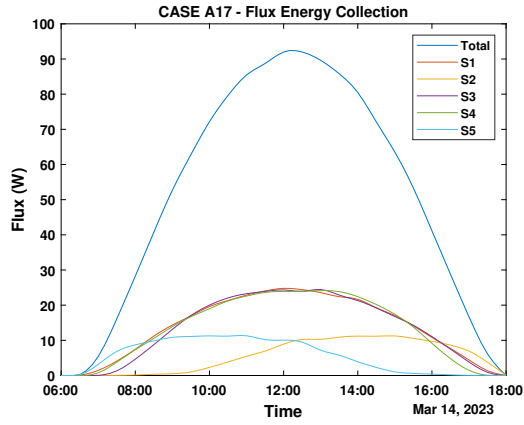


(e) Flux Energy Collection for A15 Geometry.

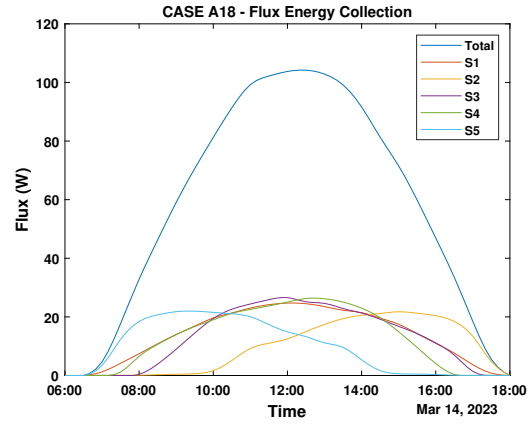


(f) Flux Energy Collection for A16 Geometry.

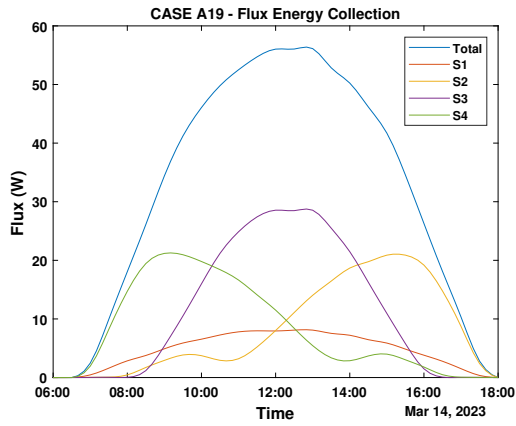
Figure A.3: Flux Energy Collection for A11 to A16 Geometries.



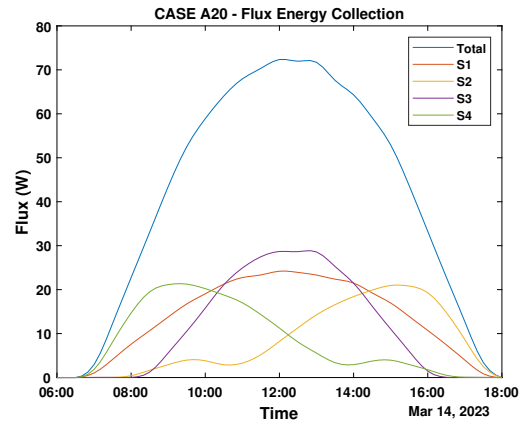
(a) Flux Energy Collection for A17 Geometry.



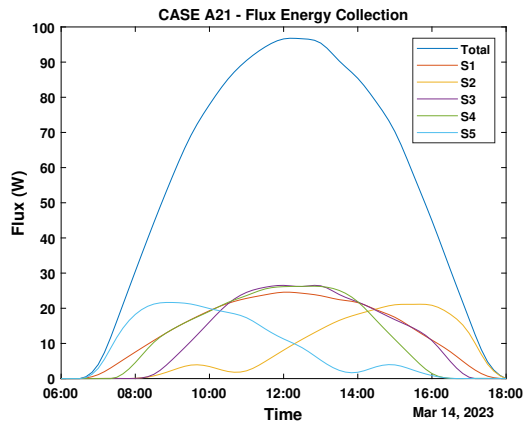
(b) Flux Energy Collection for A18 Geometry.



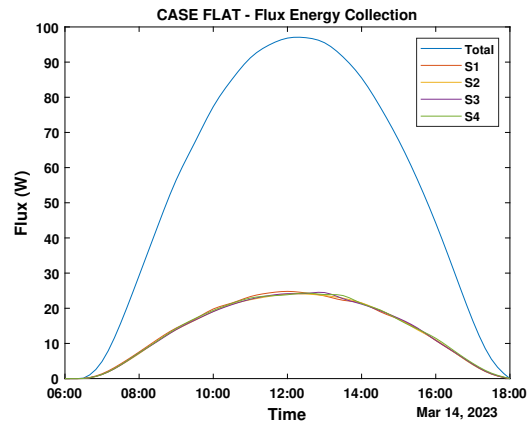
(c) Flux Energy Collection for A19 Geometry.



(d) Flux Energy Collection for A20 Geometry.



(e) Flux Energy Collection for A21 Geometry.



(f) Flux Energy Collection for Flat Geometry.

Figure A.4: Flux Energy Collection for A17 to A21 and Flat Geometries.

Appendix B

Proposed fixed interconnection topologies

B.1 Four Rows Geometries

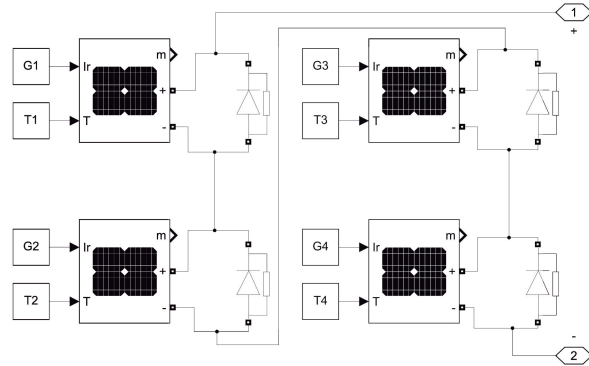


Figure B.1: Configuration 1 (4 surfaces).

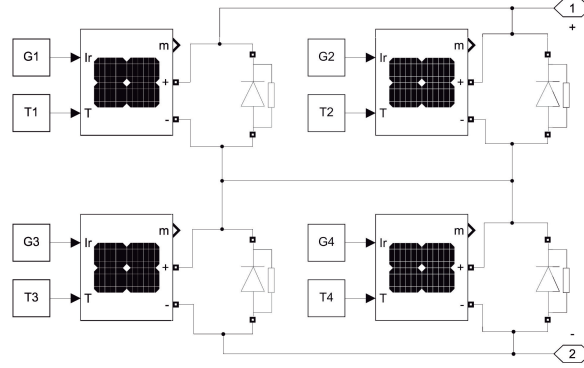


Figure B.2: Configuration 2 (4 surfaces).

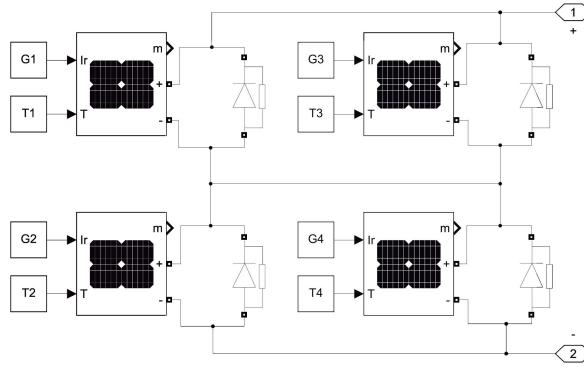


Figure B.3: Configuration 3 (4 surfaces).

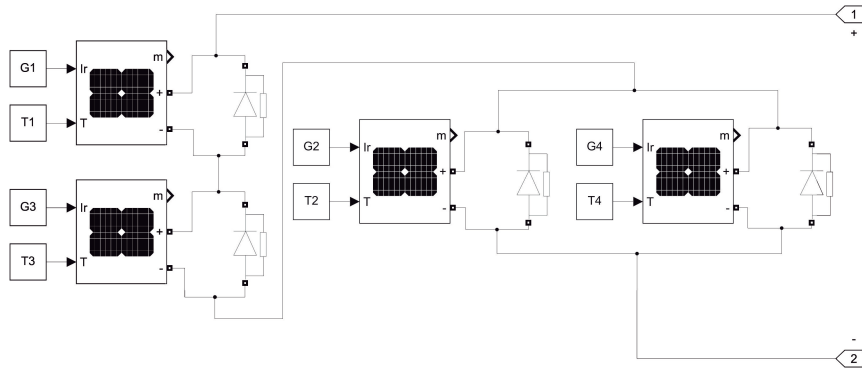


Figure B.4: Configuration 4 (4 surfaces).

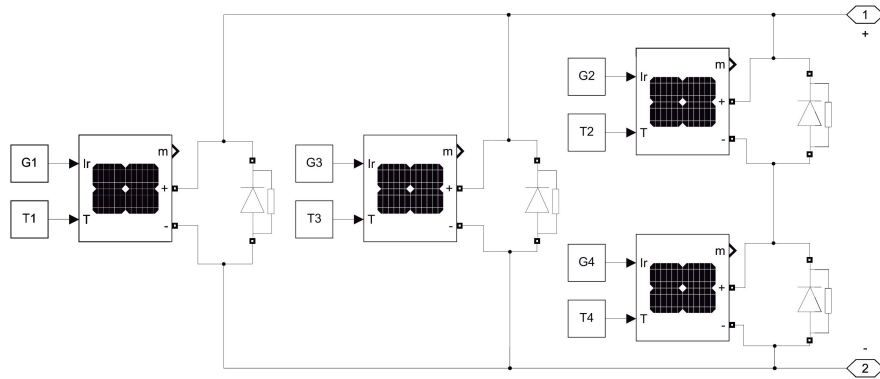


Figure B.5: Configuration 5 (4 surfaces).

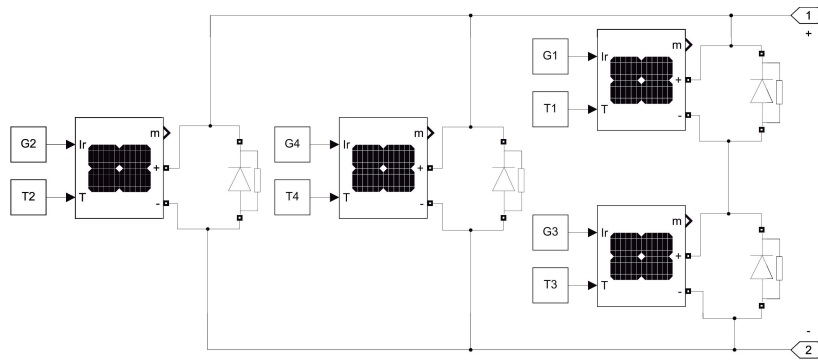


Figure B.6: Configuration 6 (4 surfaces).

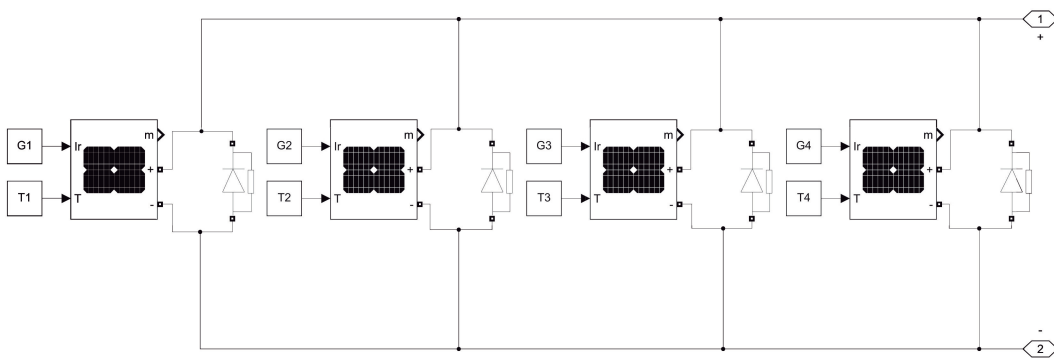


Figure B.7: Configuration 7 (4 surfaces).

B.2 Five Rows Geometries

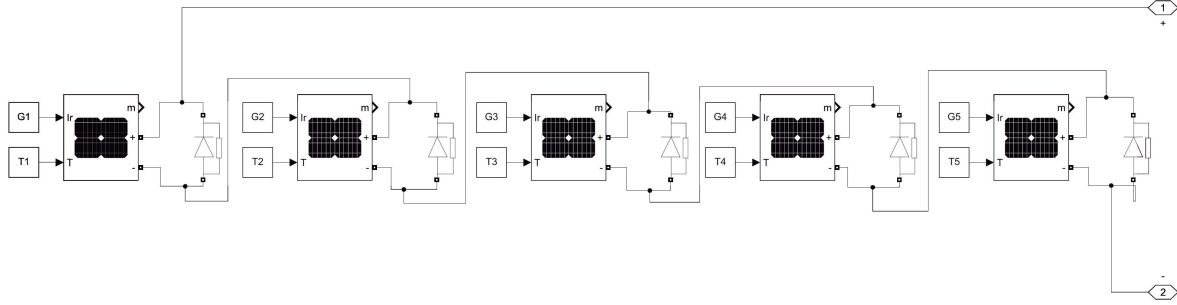


Figure B.8: Configuration 1 (5 surfaces).

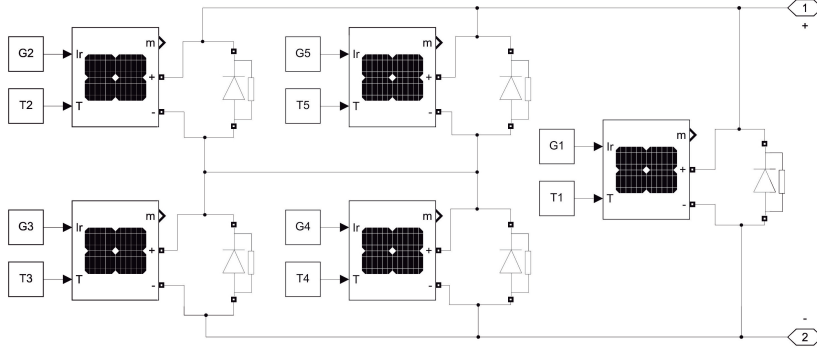


Figure B.9: Configuration 2 (5 surfaces).

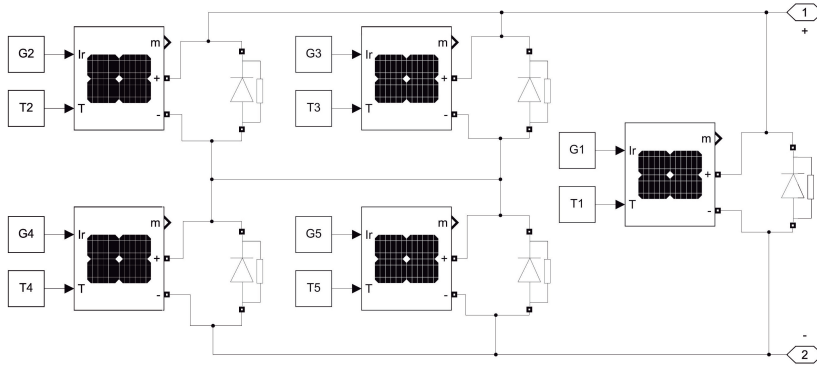


Figure B.10: Configuration 3 (5 surfaces).

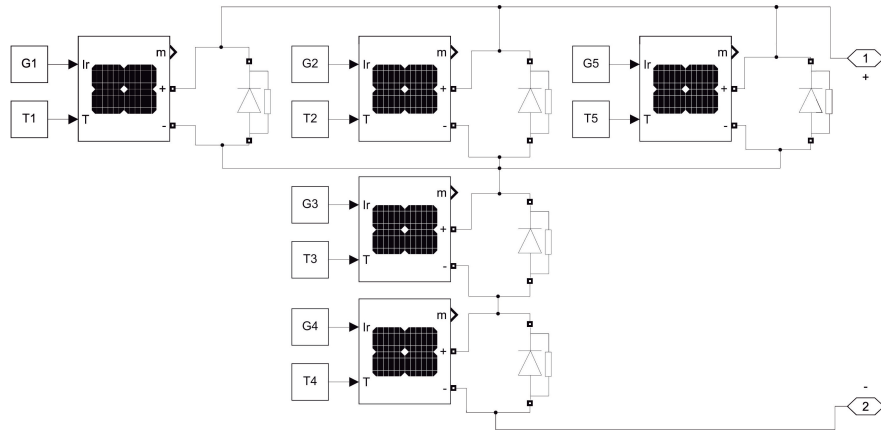


Figure B.11: Configuration 4 (5 surfaces).

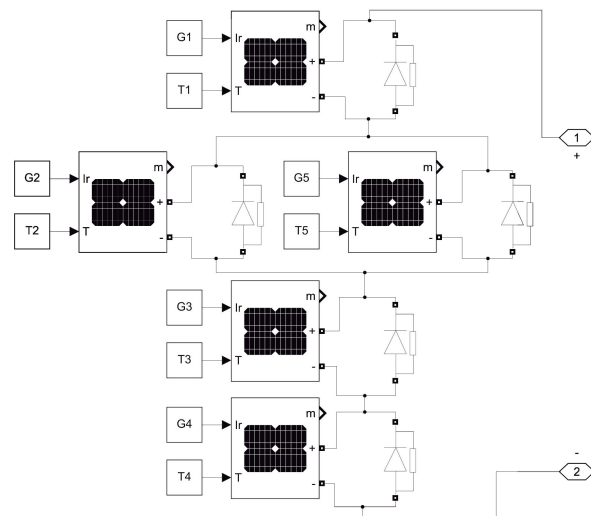


Figure B.12: Configuration 5 (5 surfaces).

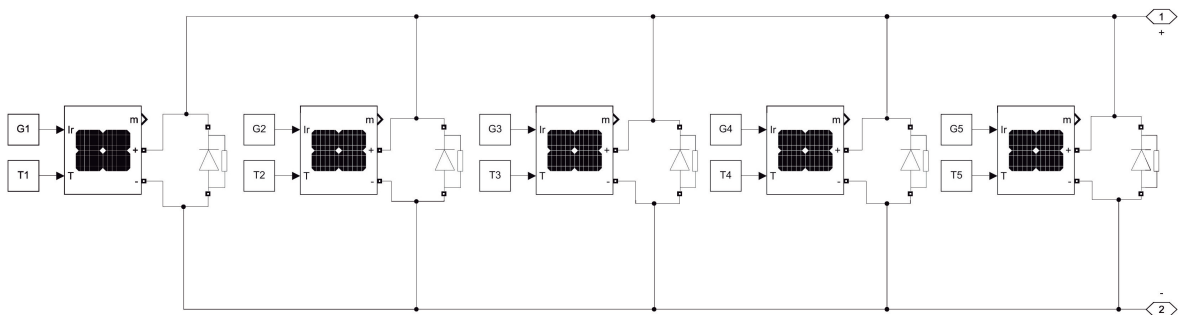
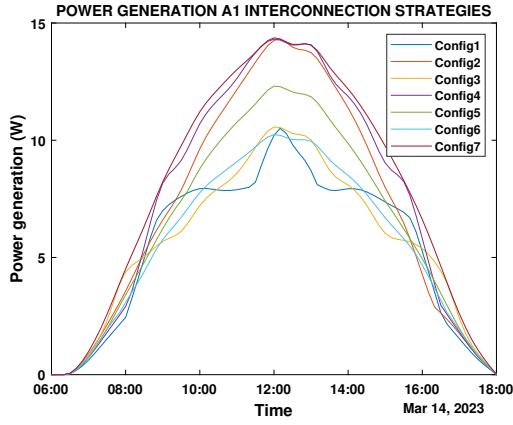


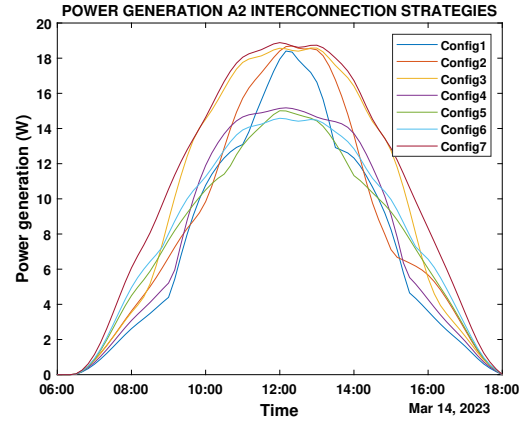
Figure B.13: Configuration 6 (5 surfaces).

Appendix C

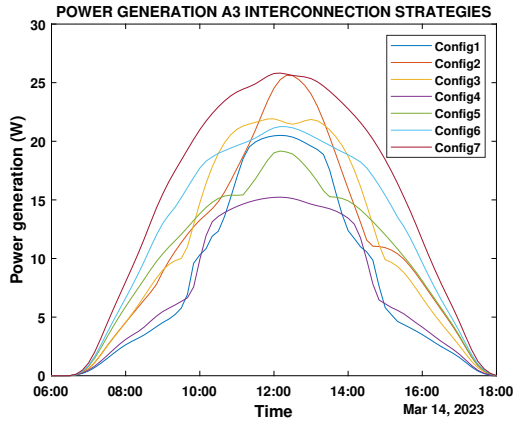
Power Generation Curves



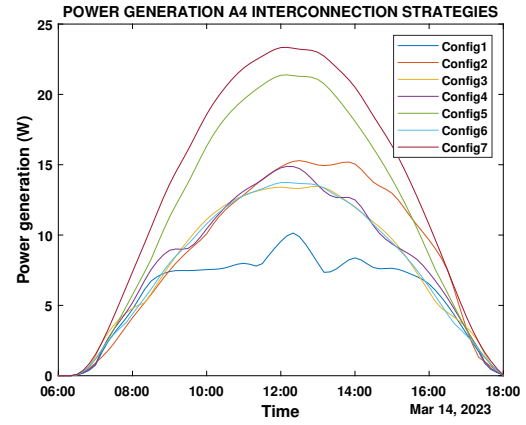
(a) Power Generation Curves for A1 Geometry.



(b) Power Generation Curves for A2 Geometry.

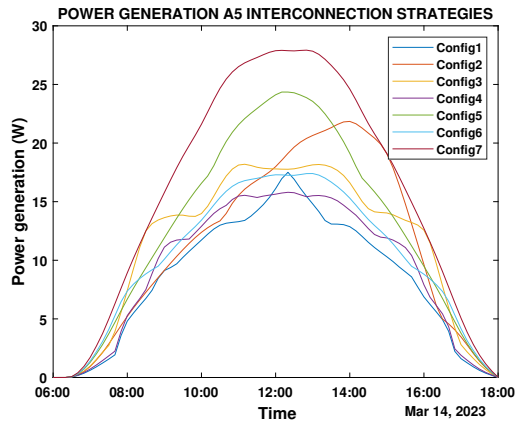


(c) Power Generation Curves for A3 Geometry.

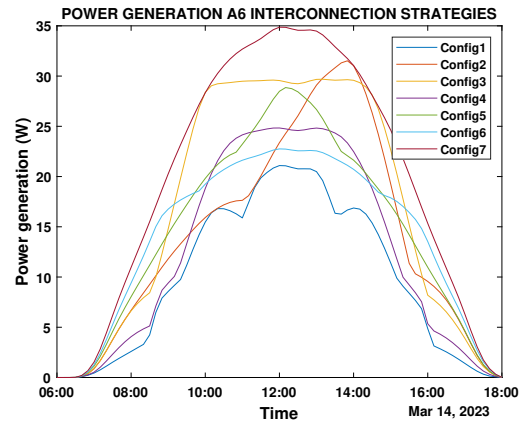


(d) Power Generation Curves for A4 Geometry.

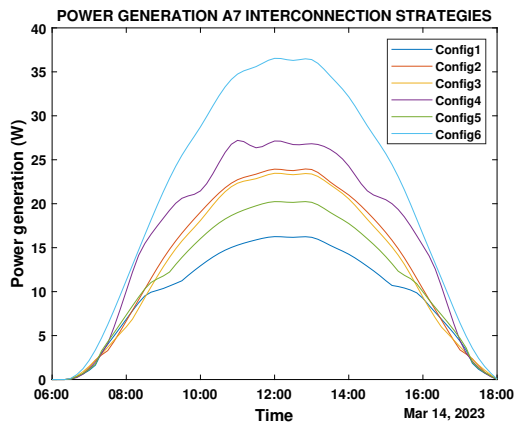
Figure C.1: Power Generation Curves for A1 to A4 Geometries.



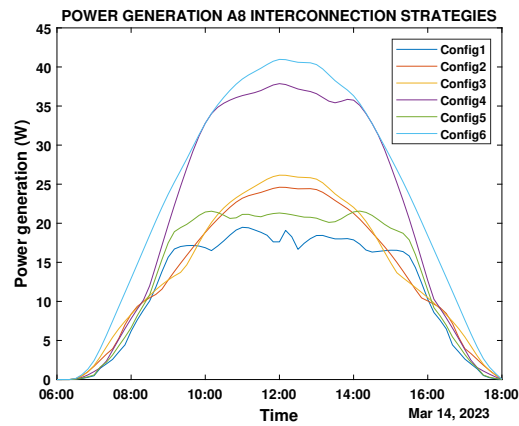
(a) Power Generation curves for A5 Geometry.



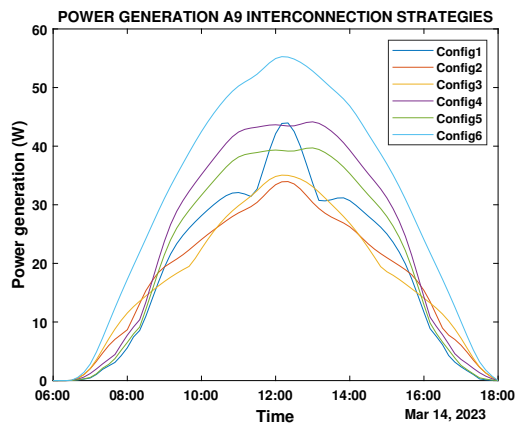
(b) Power Generation curves for A6 Geometry.



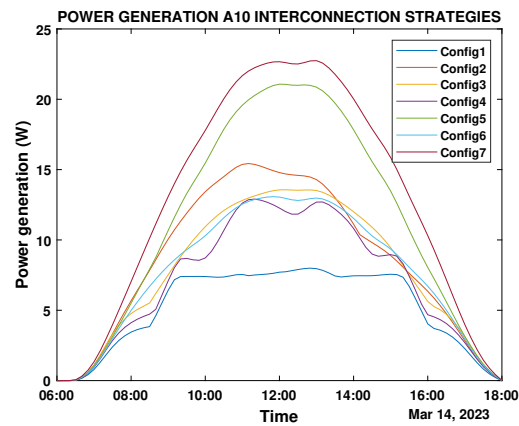
(c) Power Generation curves for A7 Geometry.



(d) Power Generation curves for A8 Geometry.

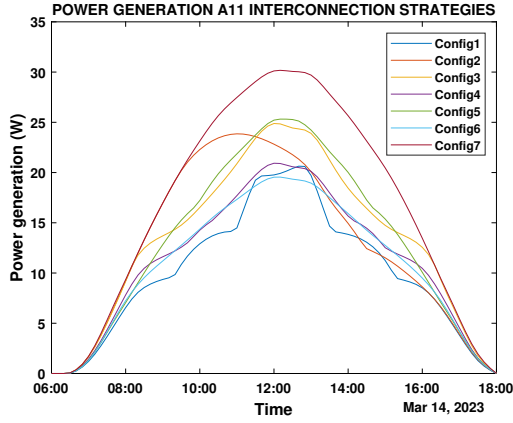


(e) Power Generation curves for A9 Geometry.

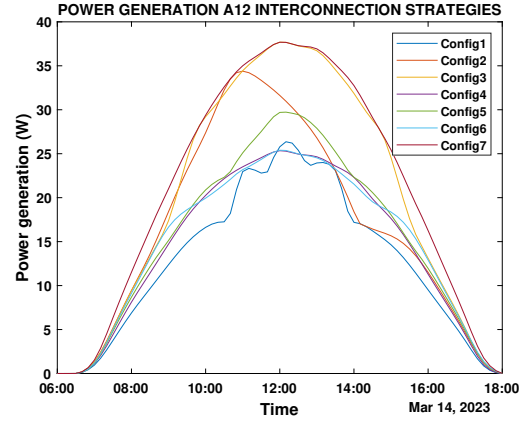


(f) Power Generation curves for A10 Geometry.

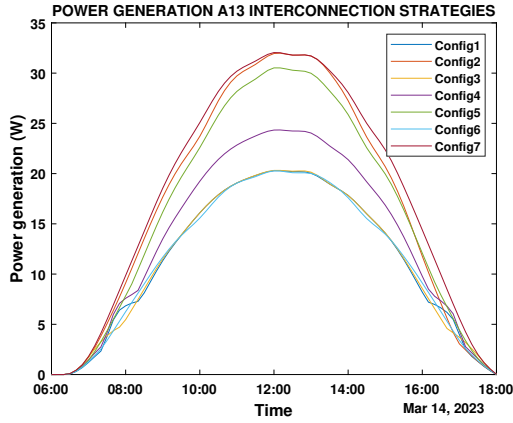
Figure C.2: Power Generation Curves for A5 to A10 Geometries.



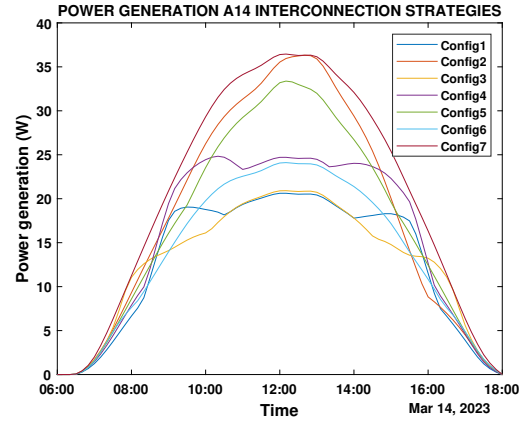
(a) Power Generation curves for A11 Geometry.



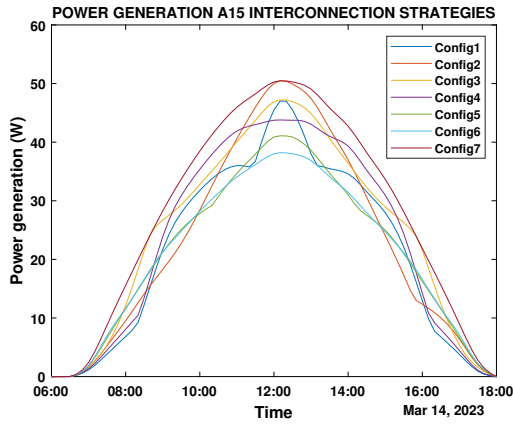
(b) Power Generation curves for A12 Geometry.



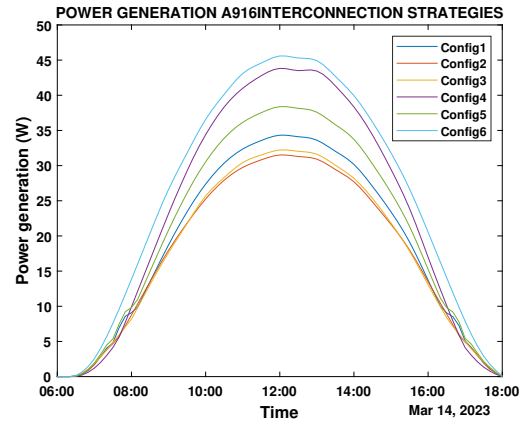
(c) Power Generation curves for A13 Geometry.



(d) Power Generation curves for A14 Geometry.

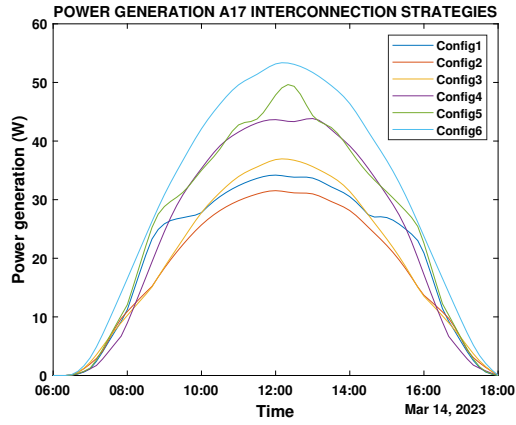


(e) Power Generation curves for A15 Geometry.

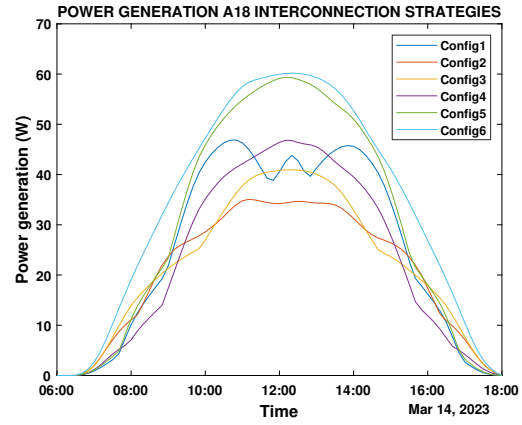


(f) Power Generation curves for A16 Geometry.

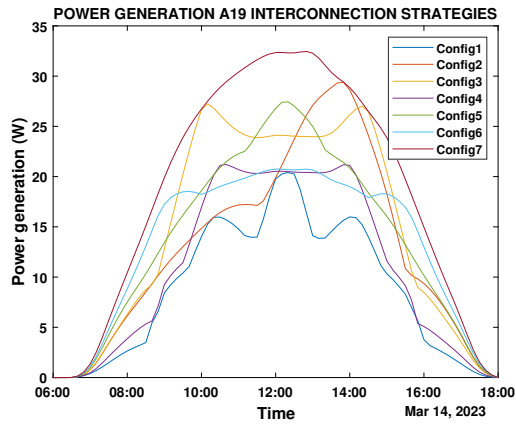
Figure C.3: Power Generation Curves for A11 to A16 Geometries.



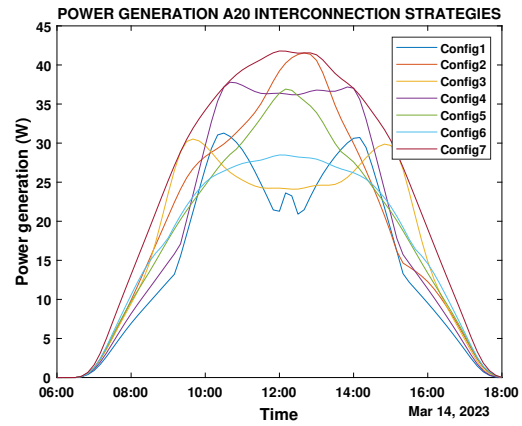
(a) Power Generation curves for A17 Geometry.



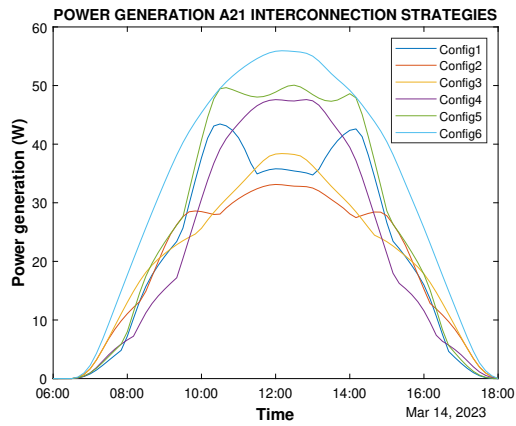
(b) Power Generation curves for A18 Geometry.



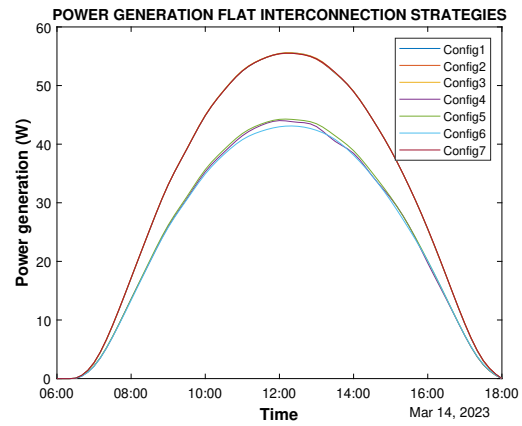
(c) Power Generation curves for A19 Geometry.



(d) Power Generation curves for A20 Geometry.



(e) Power Generation curves for A21 Geometry.



(f) Power Generation curves for Flat Geometry.

Figure C.4: Power Generation Curves for A17 to A21 and Flat Geometries.