MSc Program
Renewable Energy Systems

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Temperature Balance System for Big and Small-Scale Solar Energy Power Plants.

A Master's Thesis submitted for the degree of
“Master of Science”

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Vienna, 10.09.2024

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Affidavit

I, **CARLOS ROA, BSC.**, hereby declare

1. that I am the sole author of the present Master's Thesis, "TEMPERATURE BALANCE SYSTEM FOR BIG AND SMALL-SCALE SOLAR ENERGY POWER PLANTS.", 82 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

In recent years, the global energy landscape has been part of a remarkable transformation with the widespread inclusion of renewable energy sources, like solar photovoltaic (PV) systems. These systems, ranging from individual rooftop installations to expansive utility-scale solar parks, have emerged as pivotal players in the search for sustainable and clean energy generation. However, despite their promise, the performance of photovoltaic panels, especially in regions characterized by high irradiance levels, is not without its challenges. One of the biggest obstacles confronting the efficient operation of solar PV systems is the adverse impact of elevated temperatures resulting from intense solar irradiation. While sunlight is the primary source of energy for PV panels, excessive high temperatures can lead to a decline in their performance and efficiency, therefore diminishing the overall energy output. This phenomenon creates a significant concern for solar power generation, particularly in regions where irradiance levels have considerable heights.

This study aims to analyze the weather data such as temperature levels, wind speed and irradiance, as well as the overall performance of photovoltaic panels, with a specific focus on solar energy power plants. By understanding the underlying reasons of the degradation of solar panels under high temperature conditions, this research aims to provide valuable insights into solutions that might improve the efficiency of solar energy systems. In this context, the studied data was sourced from fully operational solar parks located in the north of Chile, which suffer of lower efficiency in generation when temperature is on its highest levels, according to both the owner and the operator of the solar park. Through this study the objective is to suggest a solution which would solve this rise of high temperature in solar panels, to do this, different tests were carried on the power plant, using the advantage of high wind speed and its cooling capacity, alongside with the tracking system of the facility. After these experiments and results, this paper's exposes the feasibility of a solution with the before mentioned characteristics, and supports further studies and recommendations for the proposed problem.

Contents

Introduction

1.1 Motivation

Maximizing the energy output of solar PV systems is not only important for meeting energy demands but also for reducing costs associated with energy production. If PV panel performance degrades under high irradiance conditions, it may need additional investments in cooling systems or alternative technologies to mitigate temperature related losses. Understanding the underlying technicalities allows for cost effective solutions to be developed.

Solar PV systems are expected to operate reliably over long periods, often in harsh environmental conditions, high irradiance environments can exacerbate the degradation of PV panels, potentially shortening their lifespan and increasing maintenance requirements. By investigating the mechanisms of performance degradation, a study like this can contribute to enhancing the reliability and durability of solar energy systems, reducing efficiency degradation and losses. Under ideal circumstances, a PV power plant shouldn't have an excess of losses or decay in energy generation due to weather conditions, especially regarding temperature, if the irradiation and ambience temperature of the geographical site where the solar park is installed is in any case high, then theoretically, the energy generation produced, based on the photoelectric effect, should benefit from these conditions. However, in reality this doesn't happen, instead the equipment used to generate energy, specially PV modules and inverters, have a decay in their generation curve as the temperature increases.

When the working conditions of an operational solar park reaches high or extreme levels of ambient temperature, panel temperature and irradiance, the generation curve of the complete plant reaches a limit of generation and soon after the performance starts to go down. The impact that these conditions have in the generation will depend on how high are their values, for an extreme case of a power plant located in the desert where there are no clouds and very low humidity, the decay on performance can be most noticeable during the times of the day when the sun at its peak (between 12:00hrs and 15:00hrs).

This effect of high temperature and irradiance is the reason why the performance ratio (relation between the actual energy generated and the expected) is usually lower during the summer months and higher during winter months, even though summer months are the ones were most energy is generated through the year. These losses also affect the economic income that a solar park has through the entire year, reaching high numbers during the periods were the plant generates most amount of energy (spring - summer). A potential solution that minimizes the economic and energetic damages that a big or small-scale PV power plant has, would be beneficial to the problems outlined above, and therefore, is the aim of this study.

1.2 Objectives

1.2.1 General Objective

The objective of this work is to investigate a solution to avoid excess generation losses in grid connected PV parks infrastructure (PV modules, Inverters, tracking system, MV and LV connections, etc.) in situations when weather conditions are of high ambience temperature. For this, real on site and SCADA from a fully operational PV power plant data will be used in order to have a real scope of the conditions and events that affect the generation of solar power plants subject to high ambient temperatures.

1.2.2 Specific Objectives

a) Study the economic losses from a Utility and distributed generation scale solar power plant.

b) Investigate already existing possible solutions to balance infrastructure T^{o}.

c) Study the possibility of real inclusion of these type of solutions into already energized solar power plants that are affected by the proposed problem.

1.2.3 Scope

This work will be orientated for already fully operational grid connected PV generation parks, Utility Power Plant (UPP) level, as well as Commercial & Industrial (C&I) level power plants. The following paper will seek to contribute with the research of cooling systems for PV generation parks. This study will use real data from a fully operational Power plant located in Chile, where the high temperature and irradiance are extreme.

1.2.4 Work Structure

The following Thesis work will have seven chapters, described as it follows:

Chapter one corresponds to the introduction of the work topic, general objective and the specific objectives set, the scope of the report and the structure that follows.

The second chapter presents the background used in the report. Solar energy generation is described, types of power plants and their different scales and objectives of each of them, daily problems and inconvenience's that these types of generation facilities have to deal with day to day, seen from an operation and maintenance perspective.

Chapter three establishes the methodology followed for the development of memory work, in order to meet the stated objective.

The fourth chapter studies the possible solutions for the problem presented in this report and its configuration in C&I and Utility scale power plants

Chapter five presents the results obtained from studying the data of fully operational power plants and the theoretical study of the type of technology necessary and its possibilities of implementation.

The sixth chapter contains the conclusions of this thesis report.

Chapter seven presents the bibliographical references used.

Theoretical Framework

2.1 Introduction

This framework provides a comprehensive analysis of the operation of solar power plants, focusing on both large and small-scale systems. It explores the essential components, energy conversion processes, and the impact of environmental factors like temperature on system performance. Special attention is given to thermal degradation of solar panels due to high temperatures, and the associated technical and economic losses.

2.2 Photovoltaic Energy Generation Process

The energy generation process in a solar power plant involves several key steps, each crucial for converting sunlight into usable electrical energy.

Inversion

PV panels are able to generate direct current (DC), however, the electricity grid and most electrical appliances operate on alternating current (AC)[1]. Therefore, inverters are required to convert DC to AC.[2]

- **DC to DC Conversion:** Inverters often include a DC-DC converter stage to boost the voltage to the required level.[3]
- **DC to AC Conversion:** The main function of the inverter is to convert DC to AC. This is achieved using pulse-width modulation (PWM) techniques, where the inverter switches the DC input on and off at high frequencies to create a waveform that approximates a sine wave.[4]

[1] M. A. Green et al., "A Review on PV Cells: Materials and Technologies," *IEEE Journal of Photovoltaics* 3, no. 1 (2013): 462-468.

[2] M. A. Green et al., "A Review on PV Cells: Materials and Technologies," *IEEE Journal of Photovoltaics* 3, no. 1 (2013): 462-468.

[3] Dunlop, *Photovoltaic Systems*, 130-135.

[4] Nelson, *The Physics of Solar Cells*, 55-60.

- **Smoothing and Filtering:** The output waveform is then passed through filters to smooth out high-frequency components, resulting in a clean sinusoidal AC output that matches the grid's frequency and voltage.[5]

Voltage Transformation

After the DC-to-AC conversion, the voltage of the electricity needs to be stepped up for efficient transmission over long distances. This is done using transformers.[6]

- **Primary and Secondary Windings:** A transformer consists of primary and secondary windings wrapped around a magnetic core.[7] When AC voltage is applied to the primary winding, it creates a magnetic field that induces a voltage in the secondary winding.[8]
- **Step-Up Transformation:** The voltage transformation is represented as follows:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$ [9]

where:

- V_s is the secondary voltage (output voltage).[10]
- V_p is the primary voltage (input voltage).[11]
- N_s is the number of turns in the secondary coil.[12]
- N_p is the number of turns in the primary coil.[13]

[5] Dunlop, *Photovoltaic Systems*, 140-145.
[6] John Twidell and Tony Weir, *Renewable Energy Resources* (New York: Routledge, 2015), 278-280.
[7] Duffie and Beckman, *Solar Engineering of Thermal Processes*, 290-295.
[8] Duffie and Beckman, *Solar Engineering of Thermal Processes*, 290-295.
[9] Twidell and Weir, *Renewable Energy Resources*, 282-285.
[10] Twidell and Weir, *Renewable Energy Resources*, 282-285.
[11] Twidell and Weir, *Renewable Energy Resources*, 282-285.
[12] Twidell and Weir, *Renewable Energy Resources*, 282-285.
[13] Twidell and Weir, *Renewable Energy Resources*, 282-285.

By increasing the voltage, transformers reduce the current, this minimize the energy losses in transmission lines.[14]

Grid Injection

The final step in the energy generation process is injecting the transformed, high-voltage AC electricity into the transmission grid.[15]

- **Synchronization:** Before injection, the inverter ensures that the AC output is synchronized with the grid's frequency and phase. This is critical to maintain grid stability and ensure efficient power transfer.[16]
- **Grid Connection:** The high-voltage AC electricity is fed into the grid through interconnection points, where it is distributed to consumers.[17]

2.3 Solar Power Plants

A solar power plant is a facility that converts sunlight into electricity using photovoltaic (PV) cells or concentrating solar power (CSP) systems. These plants play a crucial role in renewable energy production by harnessing solar energy, which is abundant and sustainable. On this paper, it will be studied mainly the nature and characteristics of a PV power plant[18].

Components and Their Purposes

- **PV Panels:** They convert sunlight into electricity through the photovoltaic effect, the efficiency and quality of the PV panels determine the performance of a solar power plant.[19]

[14] M. A. Green et al., "A Review on PV Cells," 470.
[15] Nelson, *The Physics of Solar Cells*, 61-65.
[16] Dunlop, *Photovoltaic Systems*, 150-155.
[17] International Energy Agency, "Renewable Energy Policies in a Time of Transition," IEA Report, 2018, 34-38.
[18] Dunlop, *Photovoltaic Systems*, 3-9.
[19] Dunlop, *Photovoltaic Systems*, 180-185.

- **Inverters:** Convert the DC electricity generated by PV panels into AC electricity, which is required for compatibility with the grid and most electrical appliances.[20] Inverters are crucial for maintaining the stability and efficiency of the power output.[21]

- **Mounting Systems:** Structures that provide stability and optimize the angle of incidence for sunlight. There are two main types:

  - **Fixed-Tilt Systems:** Fixed at an optimal angle to maximize annual energy production based on geographic location.[22]
  - **Tracking Systems:** Move to follow the sun's path, increasing energy capture by up to 25-35%.[23]

- **Transformers:** Modify the voltage of the generated electricity for efficient long-distance transmission, reducing current and minimizing energy losses.[24]

- **Monitoring and Control Systems:** Track the performance of the plant, ensuring optimal operation and identifying issues promptly. These systems help in detecting underperforming panels, shading issues, and potential faults.[25]

2.3.1 Large-Scale PV Power Plants

Definition and Description

Large-scale solar power plants, also known as utility-scale solar parks, are designed to generate substantial amounts of electricity.[26] These plants cover extensive areas, often spanning hundreds or thousands of acres, and consist of thousands to millions of photovoltaic (PV) panels.[27]

[20] Green et al., "A Review on PV Cells," 472.
[21] Green et al., "A Review on PV Cells," 472.
[22] Twidell and Weir, *Renewable Energy Resources*, 300-305.
[23] Duffie and Beckman, *Solar Engineering of Thermal Processes*, 312-315.
[24] Green et al., "A Review on PV Cells," 475.
[25] Nelson, *The Physics of Solar Cells*, 70-75.
[26] U.S. Department of Energy, "Large-Scale Solar Power," DOE Solar Energy Technologies Office, 2019.
[27] U.S. Department of Energy, "Large-Scale Solar Power," DOE Solar Energy Technologies Office, 2019.

Impact on Energy Generation Matrix and Environment

Large-scale solar plants contribute substantially to the energy generation matrix by providing a significant portion of a country's renewable energy supply.[28]

Small-Scale Solar Power Plants

Definition and Description

Small-scale solar power plants include residential rooftop installations, commercial rooftop systems, and small ground-mounted systems. They typically produce electricity in the kilowatt (kW) range and are designed to meet the energy needs of individual homes, businesses, or small communities.[29]

Components and Their Purposes

- **PV Panels:** Convert sunlight into DC electricity. The design and efficiency of the panels are tailored to the specific needs and space constraints of the installation.[30]
- **Inverters:** Convert DC to AC; microinverters and string inverters are commonly used. Microinverters are connected to individual panels, optimizing the output of each panel and improving overall system efficiency.[31]
- **Mounting Systems:** Fixed-tilt systems optimized for the location's latitude. Roof-mounted systems must consider structural integrity and wind loads.[32]
- **Net Metering Systems:** Allow excess energy to be fed back into the grid, providing credits against electricity consumption, thereby creating an economic incentive for owners.[33]

[28] Ibid.

[29] SEIA, "Small-Scale Solar: Benefits and Policies," Solar Energy Industries Association, 2020.

[30] Dunlop, *Photovoltaic Systems*, 210-215.

[31] Green et al., "A Review on PV Cells," 480.

[32] Twidell and Weir, *Renewable Energy Resources*, 320-325.

[33] SEIA, "Small-Scale Solar: Benefits and Policies."

Benefits and Suitability

- **Decentralized Power Generation:** Reduce the load on the central grid and minimize transmission losses, especially beneficial in remote or off-grid areas.[34]
- **Energy Independence:** Allow homeowners and businesses to generate their own electricity, reducing reliance on utility companies.[35]
- **Environmental Benefits:** Contribute to reducing greenhouse gas emissions and promoting renewable energy use.[36]

Impact on Energy Generation Matrix and Environment

Small-scale solar power plants contribute to a decentralized energy generation model, enhancing energy security and resilience. They enable consumers to produce their own clean energy, reducing the overall carbon footprint and supporting national renewable energy targets.[37]

2.4 Solar Panel

A solar photovoltaic (PV) panel converts the sunlight energy into electrical energy, and is made of several layers and components:

- **Photovoltaic Cells**: The Cells are the basic building blocks of a solar panel, they are typically made from semiconductor materials, primarily silicon[38].
- **Encapsulation**: Photovoltaic cells are encapsulated within protective layers to shield them from environmental damage[39]. This encapsulation usually involves[40].:

[34] U.S. Department of Energy, "Distributed Solar Power," DOE Solar Energy Technologies Office, 2020.
[35] Nelson, *The Physics of Solar Cells*, 80-85.
[36] IEA, "Renewable Energy Policies in a Time of Transition," 45-50.
[37] SEIA, "Small-Scale Solar: Benefits and Policies."
[38] Nelson, "The Physics of Solar Cells", p. 45.
[39] Jäger, "Advances in Photovoltaics: Part 3", p. 70.
[40] Jäger, "Advances in Photovoltaics: Part 3", p. 70.

– **Front Cover**: A layer of tempered glass that protects the cells from impact and weather[41].[42].

– **Encapsulant**: An EVA (ethylene vinyl acetate) film that cushions the cells and bonds the glass to the cells[43].

– **Back-sheet**: A protective layer on the rear side of the panel, often made from durable plastic materials like PVF (polyvinyl fluoride)[44].

- **Frame**: A sturdy aluminum frame that holds the entire assembly together, providing structural integrity and ease of installation[45].

These components can be seen on Figure 2.1:

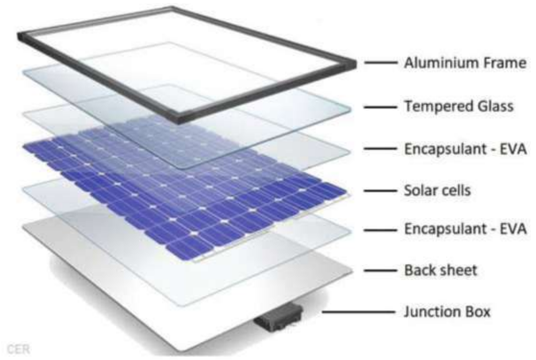

Figure 2.1: Diagram showing the basic construction of a solar photovoltaic panel, including PV cells, encapsulation layers, frame, and junction box.

Source: Sunpower, 2017.

2.4.1 Performance Downgrade of PV Panels at High Temperatures

Solar PV panels are sensitive to temperature. As the temperature increases, the efficiency of PV panels typically decreases, higher temperatures increase the internal resistance of the panels, reducing the voltage and the overall power output[46]. This can be represented as shown in the Figure 2.2 below.

[41] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 182.
[42] Jäger, "Advances in Photovoltaics: Part 3", p. 70.
[43] Jäger, "Advances in Photovoltaics: Part 3", p. 67.
[44] Jäger, "Advances in Photovoltaics: Part 3", p. 70.
[45] Markvart, "Practical Handbook of Photovoltaics", p. 223.
[46] Luque and Hegedus, "Handbook of Photovoltaic Science and Engineering", p. 189.

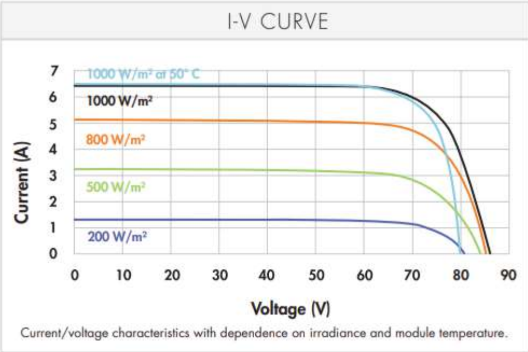

Figure 2.2: Chart showing the decrease in efficiency of solar PV panels as the temperature increases.

Source: Sunpower, 2017.

The efficiency drop is typically quantified by a temperature coefficient, which indicates the percentage decrease in efficiency per degree Celsius increase in temperature[47]. For most silicon-based PV panels, the temperature coefficient is around -0.4% to -0.5% per °C.

2.5 Inverter

Photovoltaic inverters are essential for converting the direct current (DC) generated by solar panels into alternating current (AC), suitable for household appliances and feeding into the grid[48]. They include several components and use specific materials for construction, leveraging various principles and technologies to perform their function.

2.5.1 Construction and Components

2.5.1.1 DC-DC Converter

- **Function**: Adjusts the variable DC voltage from solar panels to a stable DC voltage[49].
- **Components**: Typically includes inductors, capacitors, and semiconductor

[47]Luque and Hegedus, "Handbook of Photovoltaic Science and Engineering", p. 190.
[48]Dunlop, "Photovoltaic Systems", p. 155.
[49]Dunlop, "Photovoltaic Systems", p. 160.

switches[50].

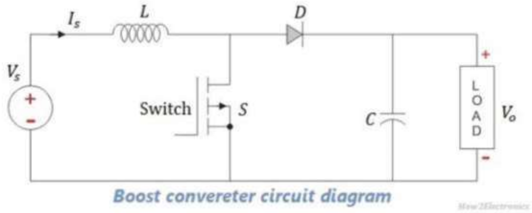

Figure 2.3: Schematic of a Boost Converter Circuit

Source: Hayt, W.H., Kimberly & Durbin, S.M. (1993).

2.5.1.2 Inverter Bridge

- **Function**: Converts the stable DC voltage to AC[51].
- **Components**: Uses semiconductor devices to switch the DC current on and off rapidly[52].
- **Types**: Full-bridge inverters are common, consisting of four switches arranged in an H-bridge configuration[53].

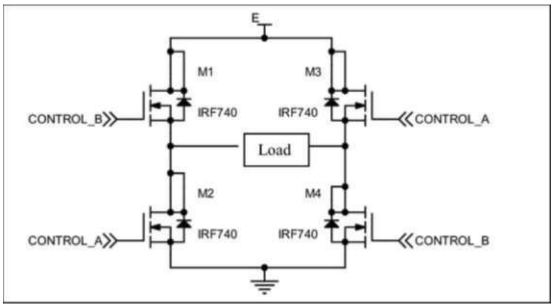

Figure 2.4: H-Bridge Inverter Circuit

Source: Hayt, W.H., Kimberly & Durbin, S.M. (1993).

[50] Erickson and Maksimovic, "Fundamentals of Power Electronics", p. 285.
[51] Dunlop, "Photovoltaic Systems", p. 164.
[52] Erickson and Maksimovic, "Fundamentals of Power Electronics", p. 316.
[53] Dunlop, "Photovoltaic Systems", p. 167.

2.5.1.3 Control Unit

- **Function**: Manages inverter operations including MPPT (Maximum Power Point Tracking), grid synchronization, and protection features[54].
- **Components**: Micro-controllers or digital signal processors (DSPs)[55].
- **MPPT Algorithms**: Perturb and Observe (P&O), Incremental Conductance, etc.[56].

$$P = V \cdot I \tag{2.1}$$

The algorithm adjusts V and I to maximize P[57].

2.5.1.4 Filters

- **Function**: Remove harmonic distortion and smooth the AC output[58].
- **Components**: Inductors (L) and capacitors (C) arranged in LC or LCL filter configurations[59].

$$Z = \sqrt{\frac{L}{C}} \tag{2.2}$$

where L is inductance and C is capacitance. This can be represented in the Figure 2.5

2.5.1.5 Cooling System

- **Function**: Manages heat generated by electronic components[60].
- **Components**: Heat sinks, fans, or liquid cooling systems[61].

[54] Villalva, Gazoli, and Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays", p. 1208.
[55] Villalva, Gazoli, and Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays", p. 1210.
[56] Esram and Chapman, "Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques", p. 443.
[57] Esram and Chapman, "Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques", p. 445.
[58] Hart, "Power Electronics", p. 332.
[59] Hart, "Power Electronics", p. 335.
[60] Blaabjerg et al., "Overview of Control and Grid Synchronization for Distributed Power Generation Systems", p. 1339.
[61] Blaabjerg et al., "Overview of Control and Grid Synchronization for Distributed Power Generation Systems", p. 1341.

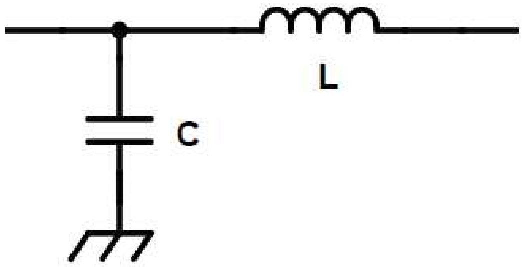

Figure 2.5: LC Filter Circuit

Source: Hayt, W.H., Kimberly & Durbin, S.M. (1993).

2.5.1.6 Housing

- **Function**: Encloses and protects all components[62].
- **Materials**: Typically made from metal (aluminum or steel) or high-durability plastic[63].

2.5.2 Working Principle

2.5.2.1 DC-DC Conversion

- **Boost Converter**: Increases the tension from the PV panels to a voltage level accepted by the inverter[64]. As shown in the Figure 2.6

2.5.2.2 Inversion Process

- **PWM (Pulse Width Modulation)**: Converts a DC signal into a series of pulses and then modifies the pulse width to control the output waveform[65], as shown in the Figure 2.7.

$$v(t) = V_{DC} \cdot \sin(\omega t) \cdot modulation\_index \tag{2.3}$$

[62] Markvart, "Practical Handbook of Photovoltaics", p. 242.
[63] Markvart, "Practical Handbook of Photovoltaics", p. 245.
[64] Markvart, "Practical Handbook of Photovoltaics", p. 245.
[65] Hart, "Power Electronics", p. 359.

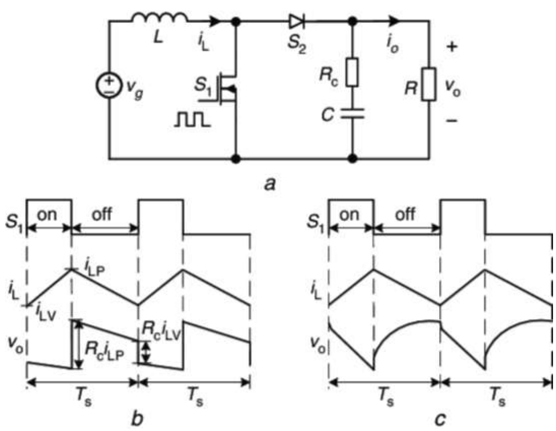

Figure 2.6: Boost Converter Operation

Source: Hayt (1993).

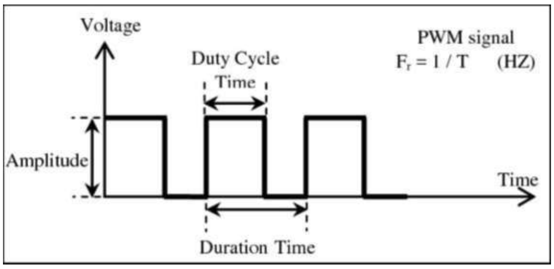

Figure 2.7: PWM Waveform

Source: Hayt, W.H., Kimberly & Durbin, S.M. (1993).

2.5.2.3 Filtering

- **Function**: Uses LC filters to smooth the pulses into a sine wave[66].

2.5.2.4 Synchronization and Output

  - **Grid-Tied Systems**: Ensures the AC output matches grid voltage and frequency using phase-locked loops (PLLs) for synchronization[67].

$$V_{AC} = V_{grid} \cdot \cos(\phi) \tag{2.4}$$

Where ϕ is the phase difference.

[66] Hart, "Power Electronics", p. 362.

[67] Blaabjerg et al., "Overview of Control and Grid Synchronization for Distributed Power Generation Systems", p. 1345.

2.5.3 Purpose and Applications

- **Grid-Tied Systems**: Convert DC from solar panels to AC that matches the grid[68].
- **Off-Grid Systems**: Provide AC power in remote areas[69].
- **Hybrid Systems**: Combine grid-tied and off-grid functionalities, with battery storage[70].

2.5.4 Conversion from DC to AC

- **Switching**: High-frequency switching of transistors converts DC to a form that approximates AC[71].
- **PWM**: Varies the width of pulses to control output and ensure it approximates a sine wave.
- **Smoothing**: Filters convert the PWM signal into a clean sine wave[72].
- **Control Algorithms**: Manage switching sequences and ensure output matches desired characteristics.

2.6 Mounting System

The mounting system in a photovoltaic plant is important for securing the solar panels in place, it secures the positioning correctly to optimize sunlight exposure and stand normal environmental conditions as wind, rain and snow[73]. There are two main types of systems: **Fixed Tilt Systems** and **Tracking Systems**[74].

[68] Dunlop, "Photovoltaic Systems", p. 180.
[69] Dunlop, "Photovoltaic Systems", p. 183.
[70] Dunlop, "Photovoltaic Systems", p. 185.
[71] Erickson and Maksimovic, "Fundamentals of Power Electronics", p. 420.
[72] Hart, "Power Electronics", p. 370.
[73] Markvart, "Practical Handbook of Photovoltaics", p. 290.
[74] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 196.

2.6.1 Fixed Tilt Systems

2.6.1.1 Construction and Design

1. **Structure:** Fixed tilt systems consist of a frame made from materials such as galvanized steel or aluminum[75]. These frames hold the solar panels at a specific angle, as shown on the Figure 2.8

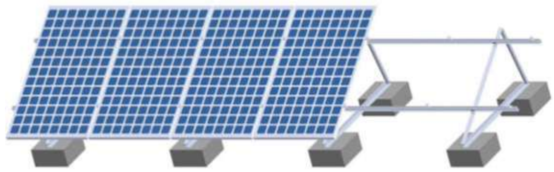

Figure 2.8: Diagram of a fixed tilt system structure, showing the frame and panel arrangement.

Source: Dunlop, James P. (2012).

2. **Foundation:** The system can be mounted on various foundations depending on the site. Common foundations include ground screws, concrete footings, and driven piles.
3. **Tilt Angle:** The tilt angle is usually optimized based on the geographical location to maximize the annual energy yield. This angle is typically fixed between 20 to 40 degrees.

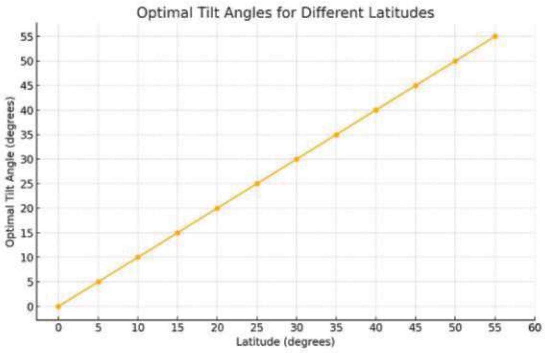

Figure 2.9: Graph showing optimal tilt angles for different latitudes.

Source: Sunpower SpA. (2015).

[75] Markvart, "Practical Handbook of Photovoltaics", p. 296.

4. **Installation:** Panels are mounted on the frames using clamps and bolts. The system is designed to resist wind and snow loads specific to the installation site[76].

2.6.1.2 Working Mechanism

Static Position: Once installed, the panels remain in a fixed position, the angle is calculated to capture the maximum sunlight over the course of the year but cannot adjust for changes in the sun's position[77].

2.6.1.3 Mechanical Equipment

- **Mounting Frames:** These hold the solar panels[78].
- **Fasteners:** Clamps, bolts, and nuts secure the panels to the frame[79].
- **Foundation Materials:** Concrete, screws, or piles provide stability[80].

2.6.1.4 Benefits

- **Cost-Effective:** Lower initial cost compared to tracking systems[81].
- **Simplicity:** Fewer mechanical parts reduce maintenance needs and potential points of failure.
- **Durability:** Designed to withstand extreme weather conditions. This can be seen on the Figure 2.10

2.6.1.5 Drawbacks

Lower Efficiency: Cannot adjust to the sun's movement, resulting in lower overall energy capture[82]. As shown on the Figure 2.11.

[76] Markvart, "Practical Handbook of Photovoltaics", p. 305.
[77] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 205.
[78] Markvart, "Practical Handbook of Photovoltaics", p. 310.
[79] Markvart, "Practical Handbook of Photovoltaics", p. 312.
[80] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 210.
[81] Markvart, "Practical Handbook of Photovoltaics", p. 318.
[82] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 220.

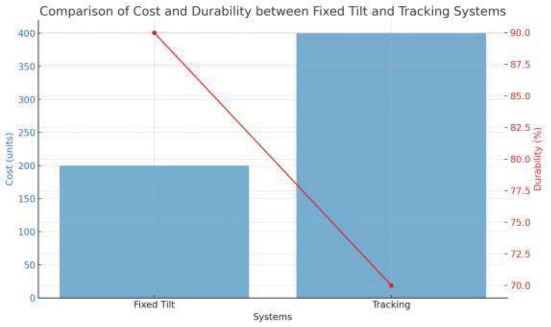

Figure 2.10: Comparison chart of cost and durability between fixed tilt and tracking systems.

Source: Sunpower SpA. (2015).

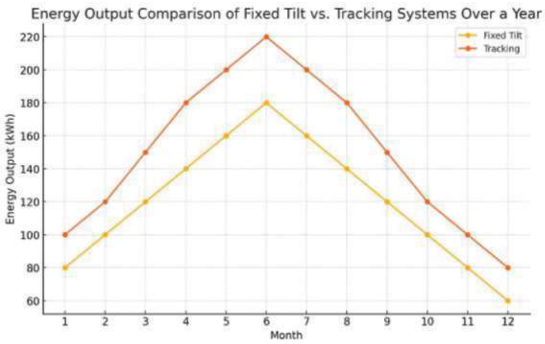

Figure 2.11: Graph comparing energy output of fixed tilt vs. tracking systems over a year.

Source: Trina Solar (2015).

2.6.2 Tracking Systems

Tracking systems create movement of the PV panels in order to follow the sun position, optimizing the irradiance captured perpendicularly by the PV panel through the day[83]. These systems are divided into two main types: single-axis trackers and dual-axis trackers[84].

1. **Single-Axis Trackers:** These systems rotate around one axis, typically the north-south axis, tilting the panels east to west to follow the sun's daily movement[85].

2. **Dual-Axis Trackers:** These systems rotate around both the north-south and east-west axes, allowing the panels to follow the sun's daily

[83] Markvart, "Practical Handbook of Photovoltaics", p. 328.

[84] Markvart, "Practical Handbook of Photovoltaics", p. 329.

[85] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 225.

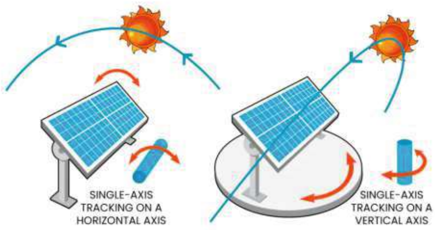

Figure 2.12: Diagram of a single-axis tracker showing its rotation mechanism.

Source: Dunlop, James P. (2012).

and seasonal movement[86].

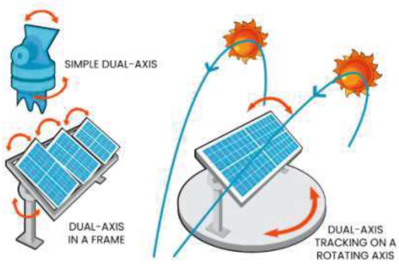

Figure 2.13: Diagram of a dual-axis tracker showing its dual rotation mechanism.

Source: Dunlop, James P. (2012).

2.6.2.1 Working Mechanism

- **Motor and Actuators:** Trackers use motors and actuators to adjust the panel angles[87].
- **Control System:** Sensors and controllers detect the sun's position and adjust the panel orientation accordingly[88].
- **Power Supply:** Trackers require a power supply, often sourced from the PV system itself, to operate the motors and control system[89].

2.6.2.2 Mechanical Equipment

- **Actuators:** Linear or rotary actuators adjust the panel orientation[90].

[86] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 228.
[87] Markvart, "Practical Handbook of Photovoltaics", p. 332.
[88] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 230.
[89] Markvart, "Practical Handbook of Photovoltaics", p. 334.
[90] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 233.

- **Motors:** Electric motors drive the actuators[91].
- **Control Systems:** Sensors, controllers, and software to automate tracking[92].
- **Structural Components:** Similar to fixed systems but with additional components to allow movement[93].

2.6.2.3 Benefits

- **Increased Energy Yield:** Can increase energy production by 20% - 30% for single-axis and up to 40% for dual-axis systems by optimizing panel orientation[94].
- **Better Performance:** More efficient energy capture throughout the day and year[95].

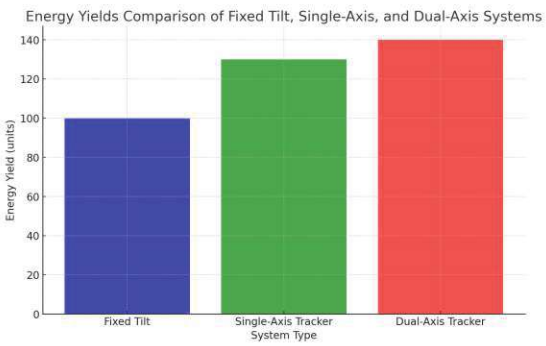

Figure 2.14: Bar graph comparing energy yields of fixed tilt, single-axis, and dual-axis systems.

Source: Sunpower SpA. (2015).

2.6.2.4 Drawbacks

- **Higher Cost:** Increased initial investment due to additional mechanical and control systems[96].
- **Maintenance:** More mechanical components require regular maintenance and potential repairs[97].

[91] Markvart, "Practical Handbook of Photovoltaics", p. 338.
[92] Markvart, "Practical Handbook of Photovoltaics", p. 340.
[93] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 235.
[94] Trina Solar, "Single-Axis and Dual-Axis Solar Trackers", 2015, p. 5.
[95] Trina Solar, "Single-Axis and Dual-Axis Solar Trackers", 2015, p. 7.
[96] Trina Solar, "Single-Axis and Dual-Axis Solar Trackers", 2015, p. 8.
[97] Trina Solar, "Single-Axis and Dual-Axis Solar Trackers", 2015, p. 9.

– **Complexity:** More sophisticated systems need skilled installation and maintenance[98].

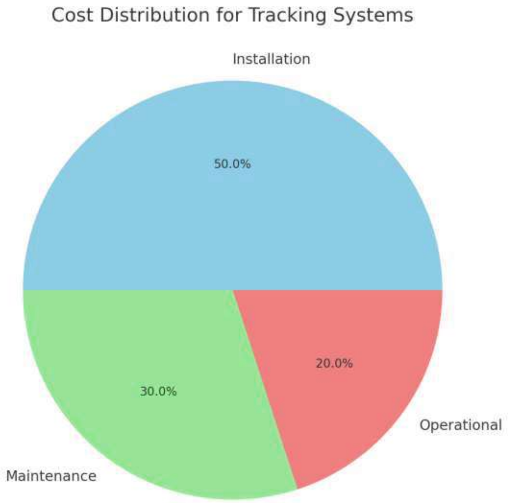

Figure 2.15: Pie chart showing the cost distribution for installation, maintenance, and operational costs of tracking systems.

Source: Sunpower (2015).

2.6.3 Differences and Benefits of Fixed Tilt vs. Tracking Systems

2.6.3.1 Fixed Tilt Systems

– **Cost:** Lower initial cost and simpler installation.

– **Maintenance:** Minimal maintenance requirements.

– **Durability:** More robust against harsh weather conditions.

– **Efficiency:** Lower energy capture compared to tracking systems.

2.6.3.2 Tracking Systems

– **Cost:** Higher initial investment and increased operational costs[99].

– **Maintenance:** Regular maintenance needed for mechanical and control systems.

[98] Trina Solar, "Single-Axis and Dual-Axis Solar Trackers", 2015, p. 10.

[99] Trina Solar, "Single-Axis and Dual-Axis Solar Trackers", 2015, p. 12.

– **Durability:** More prone to damage from weather, requiring sturdy design.

– **Efficiency:** Higher energy capture, resulting in greater electricity generation over time.

2.7 Transforming Substation

A transforming substation, also known as a substation, is an essential component of a photovoltaic plant. It serves as the intermediary between the PV panels and the electrical grid. The main function of the transforming substation is to convert the direct current (DC) produced by the solar panels into alternating current (AC) and to adjust the voltage levels to match the requirements of the transmission or distribution network[100].

2.7.1 Transforming Stations

Transforming stations are crucial for the following reasons:

– **Voltage Conversion**: PV panels generate DC at relatively low voltages. For efficient transmission over long distances, this needs to be converted to high-voltage AC[101].

– **Power Quality**: The transforming station includes equipment to ensure that the power fed into the grid meets quality standards, including stable voltage and frequency[102].

– **Protection and Control**: Protects the equipment of the PV plant and the grid[103].

The transforming station is a critical infrastructure component of a photovoltaic plant, enabling the efficient and safe transfer of electricity from solar panels to the electrical grid. Its design and implementation involve various specialized equipment and processes to ensure reliability and compliance with grid standards.

[100] Bose, "Modern Power Electronics and AC Drives", p. 270.
[101] Bose, "Modern Power Electronics and AC Drives", p. 272.
[102] Bose, "Modern Power Electronics and AC Drives", p. 275.
[103] Bose, "Modern Power Electronics and AC Drives", p. 277.

2.8 Monitoring System

A monitoring system in a PV plant is typically used to detect issues and maintaining the overall performance of the facility. This document explains how these systems work, the types of systems typically used, and their purposes[104].

2.8.1 SCADA-Based Systems

- Used in large-scale PV plants[105].
- Provide real-time monitoring, control, and data acquisition from multiple sources within the plant[106].

2.8.2 Centralized Monitoring Platforms

- Cloud-based platforms that aggregate data from multiple PV installations[107].
- Used by utilities and large operators to monitor and manage a portfolio of solar assets[108].

Since the purpose of this study is to understand and analyse the performance and operations of field, this work won't go into further details in the description of the monitoring systems of a PV site and its communications.

2.9 Grid Integration and Energy Sale

2.9.1 Income Generation for Solar Power Plants

Solar power plants generate income through the sale of electricity and how the electrical market is configured in the territory that the PV plant is planning to operate[109].

[104] Villalva, Gazoli, and Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays", p. 1250.
[105] Villalva, Gazoli, and Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays", p. 1252.
[106] Villalva, Gazoli, and Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays", p. 1255.
[107] Villalva, Gazoli, and Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays", p. 1258.
[108] Villalva, Gazoli, and Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays", p. 1260.
[109] Markvart, "Practical Handbook of Photovoltaics", p. 400.

2.9.1.1 Large-Scale Solar Power Plants

Big scale solar power plants usually sell electricity to large energy consumers, such as big industries, through Power Purchase Agreements (PPAs)[110]. PPAs are long-term contracts that specify the price, duration, and volume of electricity to be sold, these agreements provide financial stability and predictability for both the solar power producer and the buyer[111].

- **Power Purchase Agreements (PPAs)**: Contracts that establish a price for electricity over a specified period, providing a stable revenue[112].
- **Feed-in Tariffs (FiTs)**: Fixed payments for electricity generated from renewable sources, guaranteed for a certain period[113].
- **Renewable Energy Certificates (RECs)**: Certificates representing the environmental benefits of generating one megawatt-hour (MWh) of renewable energy[114].

2.9.1.2 Small-Scale Solar Power Plants

Small-scale solar power plants often utilize net metering arrangements[115]. Net metering allows excess energy generated by small-scale systems to be fed back into the grid, with the owner receiving credits that offset their electricity consumption[116].

- **Net Metering**: Allows residential and commercial consumers with a PV system installed to receive profit for their excess electricity generated and feed into the grid[117].
- **Self-Consumption**: Using the electricity generated on-site to reduce or eliminate reliance on grid electricity[118].

[110]Markvart, "Practical Handbook of Photovoltaics", p. 402.
[111]Markvart, "Practical Handbook of Photovoltaics", p. 405.
[112]Markvart, "Practical Handbook of Photovoltaics", p. 408.
[113]Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 320.
[114]Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 322.
[115]Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 325.
[116]Markvart, "Practical Handbook of Photovoltaics", p. 412.
[117]Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 328.
[118]Markvart, "Practical Handbook of Photovoltaics", p. 415.

- **Feed-in Tariffs (FiTs)**: Similar to large-scale plants, small-scale systems may also benefit from feed-in tariffs, though typically at lower scales and rates[119].

2.9.2 Electricity Trade Market

The electricity trade market operates through various mechanisms to facilitate the sale and purchase of electricity[120]. The market is typically divided into the wholesale market and the retail market[121].

- **Wholesale Market**: Large-scale producers sell electricity to utilities, large consumers, and energy aggregators[122].
- **Retail Market**: Utilities and energy suppliers sell electricity to end consumers. Retail prices include costs associated with generation, transmission, distribution, and other regulatory charges[123].

2.9.3 Grid Integration

2.9.3.1 Transmission Grid Integration

Large-scale solar power plants are typically connected to the transmission grid. This allows the generated electricity to be transported over long distances to areas with high demand[124].

- **High Voltage Transmission**: Reduces energy losses and improves efficiency over long distances[125].
- **Grid Stability**: Requires careful management to maintain stability and prevent issues such as voltage fluctuations and frequency imbalances[126].

[119] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 330.
[120] Markvart, "Practical Handbook of Photovoltaics", p. 420.
[121] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 335.
[122] Markvart, "Practical Handbook of Photovoltaics", p. 425.
[123] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 340.
[124] Markvart, "Practical Handbook of Photovoltaics", p. 430.
[125] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 345.
[126] Markvart, "Practical Handbook of Photovoltaics", p. 435.

2.9.3.2 Distribution Grid Integration

- **Decentralized Generation**: Reduces the load on the transmission grid and enhances local energy resilience[127].
- **Grid Management**: Integration at the distribution level requires systems to manage bidirectional energy flows and ensure grid reliability[128].

2.9.4 Challenges and Curtailment

When there are too many power plants connected to the same grid, it can lead to grid congestion and instability[129]. In cases like this, grid operators may need to limit (curtail) the amount of electricity generated in order to maintain grid stability, this means curtailing the total generation of one or more power plants[130].

- **Grid Congestion**: Excess generation can exceed the grid's capacity to transport and distribute electricity, leading to congestion[131].
- **Curtailment**: Reducing the output of solar power plants to prevent overloading the grid. This can result in financial losses for plant operators[132].
- **Advanced Grid Management**: Solutions such as energy storage and grid modernization are essential to minimize curtailment and optimize grid flexibility[133].

2.10 Measuring Performance

The performance of a solar power plant is measured using several key metrics:

[127] Markvart, "Practical Handbook of Photovoltaics", p. 440.
[128] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 355.
[129] Markvart, "Practical Handbook of Photovoltaics", p. 450.
[130] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 360.
[131] Markvart, "Practical Handbook of Photovoltaics", p. 455.
[132] Green, "Solar Cells: Operating Principles, Technology, and System Applications", p. 365.
[133] Markvart, "Practical Handbook of Photovoltaics", p. 460.

2.10.1 Capacity Factor

The capacity factor is the ratio of actual energy output over a period to the maximum possible energy output if the plant operated at full capacity [134].

2.10.2 Performance Ratio (PR)

The performance ratio measures the efficiency of a PV system, taking into account losses by temperature, soiling, and other factors that might affect the PV plant[135]. It is a key indicator of the overall effectiveness of the solar power plant, a generalized calculation equation for the PR calculation is described as follows (IEC 61724, "Photovoltaic System Performance Monitoring" (2022):

$$Performance\ Ratio = \frac{Actual\ Energy\ Output\ (kWh)}{Theoretical\ Energy\ Output\ (kWh)} \tag{2.5}$$

2.11 Impact of High Temperature on PV Panels

High temperatures can significantly affect the performance of PV panels. The efficiency of PV panels decreases as temperature increases due to several factors[136]:

2.11.1 Decreased Open Circuit Voltage (Voc)

As temperature rises, the semiconductor material's band-gap narrows, reducing the open-circuit voltage[137]. This relationship can be expressed as:

$$V_{oc}(T) = V_{oc}(T_{ref}) - \beta_v(T - T_{ref}) \tag{2.6}$$

where:

- $V_{oc}(T)$ is the open-circuit voltage at temperature T˙

[134] Markvart, "Practical Handbook of Photovoltaics", p. 470.
[135] IEC 61724, "Photovoltaic System Performance Monitoring", p. 18.
[136] Luque and Hegedus, "Handbook of Photovoltaic Science and Engineering", p. 190.
[137] Luque and Hegedus, "Handbook of Photovoltaic Science and Engineering", p. 193.

$V_{oc}(T_{ref})$ is the open-circuit voltage at reference temperature.

- β_v is the temperature coefficient for voltage.

2.11.2 Technical and Economic Losses

- **Reduced Efficiency**: High temperatures lower PV panel efficiency, reducing power output and revenue. This is quantified by the temperature coefficient of power (β_P), typically ranging from -0.4% to -0.5% per °C for silicon-based PV cells[138].

$$P(T) = P_{ref}\left[1 + \beta_P(T - T_{ref})\right] \tag{2.7}$$

- **Increased Maintenance Costs**: Accelerated material degradation necessitates more frequent repairs and replacements, increasing operational costs[139].

2.11.3 Thermal Degradation

Persistent high temperatures can cause thermal degradation of materials in the PV panels, such as encapsulants and back-sheets, leading to long-term performance issues[140]. The rate of degradation can be modeled using the Arrhenius equation[141]:

$$k = A \exp\left(-\frac{E_a}{RT}\right) \tag{2.8}$$

where:

- k is the degradation rate.
- A is the pre-exponential factor.
- E_a is the activation energy.
- R is the universal gas constant.
- T is the absolute temperature.

[138] Luque and Hegedus, "Handbook of Photovoltaic Science and Engineering", p. 200.
[139] Luque and Hegedus, "Handbook of Photovoltaic Science and Engineering", p. 202.
[140] Luque and Hegedus, "Handbook of Photovoltaic Science and Engineering", p. 205.
[141] Luque and Hegedus, "Handbook of Photovoltaic Science and Engineering", p. 208.

The temperature coefficient, β, quantifies the efficiency loss per Celsius degree (ºC) rise in temperature. For silicon-based PV cells, β typically ranges from -0.4% to -0.5% per °C[142]. Understanding and mitigating the effects of high temperatures is crucial for optimizing the performance and longevity of solar power plants.

2.12 Conclusions of the Chapter

This chapter outlines the key components, processes, and performance metrics of solar power plants at both large and small scales. It emphasizes the importance of understanding the impact of high temperatures on PV panel performance and the overall energy generation process. By integrating these insights, the study aims to develop strategies to enhance the efficiency and reliability of solar power plants, ensuring their effective contribution to the energy grid. Addressing the challenges of thermal degradation is crucial for maximizing the lifespan and economic viability of solar power installations.

High temperatures can significantly affect the performance of solar panels. Although solar panels are designed to absorb sunlight and convert it into electricity, their efficiency can decrease as the temperature rises. This decrease in efficiency is primarily due to the following reasons:

– **Increased Resistance**: As the temperature of the PV panels increases, reduces the flow of electrons, thereby decreasing the overall current and power output.

– **Reduced Voltage**: The voltage output of a solar cell is inversely related to its temperature. Higher temperatures cause a reduction in the open-circuit voltage (Voc), leading to lower overall efficiency.

– **Thermal Degradation**: Prolonged exposure to high temperatures can lead to thermal degradation of the materials used in the solar panels. This degradation can affect the longevity and durability of the panels, resulting in a decline in performance over time.

– **Thermal Expansion**: Repeated cycles of heating and cooling can cause thermal expansion and contraction of the panel materials. This

[142] Luque and Hegedus, "Handbook of Photovoltaic Science and Engineering", p. 222.

mechanical stress can lead to micro-cracks in the cells and solder joints, further impacting performance and reliability.

Manufacturers often provide a temperature coefficient, indicating the rate at which the panel's efficiency decreases with rising temperatures. For instance, a typical temperature coefficient might be around -0.5% per degree Celsius. This means that for every degree Celsius increase in temperature, the panel's efficiency decreases by 0.5%.

In summary, high temperatures can significantly impact the performance of solar panels by reducing their efficiency and power output. One promising solution involves using the tracking system of solar panels to align them in the direction of the wind. This dynamic positioning could enhance the cooling effect provided by natural wind flow.

By adjusting the orientation of the panels to face in a more direct way the wind flow direction, and making a good use of the wind speed, the heat transfer from the panel surface to the air can be optimized. This method would be particularly effective in regions with consistent wind patterns and during times of high solar insolation when temperatures are most likely to peak.

2.12.1 Feasibility and Implementation

For this solution to be feasible, several conditions must be met:

- **Consistent Wind Patterns:** The location must have relatively predictable wind directions and speeds.
- **Advanced Tracking Systems:** The tracking system must be capable of responding to real-time wind direction data, requiring integration with meteorological sensors and adaptive control algorithms.

2.12.2 Theoretical Temperature Decrease

Based on studies of convective cooling and the thermal properties of solar panels, it is estimated that aligning panels with the wind can decrease their surface temperature by approximately 2 to 5 degrees Celsius. This reduction in temperature can lead to a significant improvement in efficiency, potentially increasing the overall energy output by 1% - 3%.

2.12.3 Potential Benefits

Implementing wind-facing tracking adjustments can provide several benefits:

- **Improved Efficiency:** Lower temperatures help maintain optimal panel efficiency.
- **Increased Energy Yield:** Even marginal improvements in efficiency can result in substantial increases in total energy production over the lifespan of the system.

In conclusion, leveraging wind direction to cool solar panels through adaptive tracking systems presents a viable solution to mitigate the adverse effects of high temperatures on solar panel performance. Further research and development into the integration of meteorological data with tracking algorithms will be essential to optimize this approach and fully understand its potential benefits.

Methodology

3.1 Bibliography & References Revision

The present work is theoretical in nature and consisted of studying a proper way to solve the performance loss of solar panels, and solar parks in general, when temperatures reach high values during the operation of such facility. To achieve the proposed objective, it is necessary to acquire the necessary knowledge to work with the suggested devices.

The acquisition of this knowledge can be divided into two stages. First, the documentation related to the problem to be addressed was collected, with references guided by the external tutor, who provided part of the material used, along with material suggested by experts from other areas of the O&M provider for the selected PV site of study. For this, manuals, academic books, reports, papers, and other background information were used to find a solution to the need. Second, real data from operating solar parks, mostly located mainly in the northern desert of Chile, were used.

The literature review was carried out throughout the duration of the work, initially with a theoretical and general nature, and in a second part more technically oriented.

3.2 Meeting with Guide Team

The work presented in this document is part of a larger project aimed to provide to the O&M company of the selected PV site with a study on possible solutions that can be adapted to the operation and maintenance system they already have. These solutions aim to mitigate the generation losses experienced by photovoltaic sites where temperatures reach levels higher than those allowed by the equipment installed for their correct operation. In this way, the O&M provider will be able to carry out various experiments and studies in the future that will allow for advances in research in the field of generation losses of solar panels due to high temperatures.

The research group inside the O&M provider was led by the Director of Operations, together with him and professionals from other areas of the company, particularly site managers of the studied site. Meetings were planned with multiple purposes: to report on the progress of the work carried out, clarify doubts, obtain assistance for more significant problems, provide feedback, and receive suggestions. As with the literature review, these meetings were held throughout the entire work horizon and were a fundamental support for carrying out the study.

3.3 Study of the Operations of a Solar Park

Before proposing intervention and changes in the operation of a solar park, it is necessary to know the state in which it is found and its normal functioning over an extended period of time. In particular, the solar park to be studied is constructed in a fairly homogeneous manner and without major complications regarding geographical conditions or the technical equipment they possess. However, analyzing the performance of a solar park and specifically studying the losses associated with it, means a more complex and therefore more valuable task, since this is an area of research that is in constant study and modifications.

3.4 Study of Performance of Solar Parks

Based on the above, it was identified that there is a possibility of reduced performance in certain solar parks operated by the O&M provider, specifically in installations located in geographical areas where the ambient temperature is extremely high. To address this problem, a particular PV site was selected in order to study its performance, the real conditions affecting the park operated by the company were investigated, especially those that exhibit lower performance in the months of the year when solar irradiance and temperature are highest. For these cases, different methods to solve the issues of equipment affected by high temperatures were studied.

3.5 Results and Conclusions

For this section, data corresponding to an extend study regarding the performance of the selected solar park was evaluated. In this manner, the obtained results were analyzed in order to verify whether the overall objective of the assigned work was achieved. Finally, this work presents the conclusions obtained as a result of the analysis of the work carried out in its entirety, where a solution to the low performance of solar parks in cases of high temperatures was defined, along with recommendations for future work related to the same problem addressed in this study.

Modelation

In this chapter, the arguments justifying the need to correct or improve the status of the proposed problem are presented, then, the modeling of the chosen solutions that meet the defined objective is presented. Subsequently, the way in which the solutions should be implemented, the reason for their choice, and their operation are detailed. For this purpose, data collected between the years 2023 and 2024 from a real on operation UPP site located in the north of Chile will be used. This research is aimed to conduct field tests on a PV site that already suffers downgrades on its generation when temperatures reach high levels.

Due to confidentiality and because of legal causalities, this study cannot expose any type of confidential detail, like for example: commercial name of the PV Site, commercial name of the owner of the site and the O&M provider, the exact location and geographical coordinates of the facility, specific personnel identity that provides services to the site, among others. So, from now on the owner of the PV site of study will be addressed only as the "Owner" and the site of study will be addressed only as the "PV Site". Given these reasons, all data will be treated as technically generalized as possible, keeping the integrity and objectivity of a proper analysis of a utility scale PV power plant.

4.1 Necessity

The owner of the site to study already suffers economic losses due to periods when the temperatures reach high levels and the UV irradiance is at its highest, which has meant unplanned expenses for the company. So far, the owner hasn't been able to fix this issue due to the expensive nature of the solutions proposed by the market, such as usage of water to create a cooling system, or the installation of fans to cool the equipment on site, such as PV panels and inverters. Furthermore, currently there is no solution that fully addresses the proposed problem without a high value investment, that is, the owner in this case hasn't been able to find or propose a solution that would address this problem without having to make a big re-design of the site, due to the complexity of the fundamentals.

It is for this reason that the owner needs to innovate in terms of high temperatures affecting the performance on their PV sites, aiming to reduce or eliminate the losses due to the downgrade of efficiency.

4.2 Selected Site of Study

For the purposes of this study, the selected site is a UPP PV power plant of 105 MW of installed capacity located in the northern side of Chile. This site has been running since 2017 onwards and is connected directly to the transmission line that feeds the distribution and load of the nearest by city.

A summary of the PV site is as follows:

- The PV site has a total of 105 MW DC.
- The total amount of inverters consist of 59 centralized SMA Central 850 CP, each of them with 2 inverter modules of 0.890 MWp DC each, making a total of 118 inverters for the whole facility.
- Each inverter module is associated to 3 single axis movement trackers, each of them is associated to 72 strings, making a total of 216 strings for per inverter.
- Each string consist of 10 PV modules model Sunpower E20/435 connected in series.
- In total there are 9 pyranometers installed on site, 6 that measure the irradiance in the plane of the array (POA) of the tracker, 3 that measure the horizontal irradiance on a fix position perpendicular to the terrain where the site is located.
- There are 3 temperature sensors aimed to measure the ambient temperature and 6 that measure the panel temperature, this last ones are installed on the back surface of the PV modules located on strategic positions of the site layout.
- There are 3 wind speed sensors installed on posts that are at the PV module and tracker level, located in the 2 main edges of the site layout and 1 one the center.
- In total, the PV site consists of the following equipment:
    * 59 centralized inverters, each of them consisting of 2 operating modules (118 inverter modules in total).

* 354 single axis trackers.
* 25488 strings.
* 254880 PV panels/modules.
* 9 pyranometers (6 on the plane of array, 3 horizontal).
* 9 Tº sensors (3 for ambient Tº and 6 for panel Tº).
* 3 wind speed sensors.

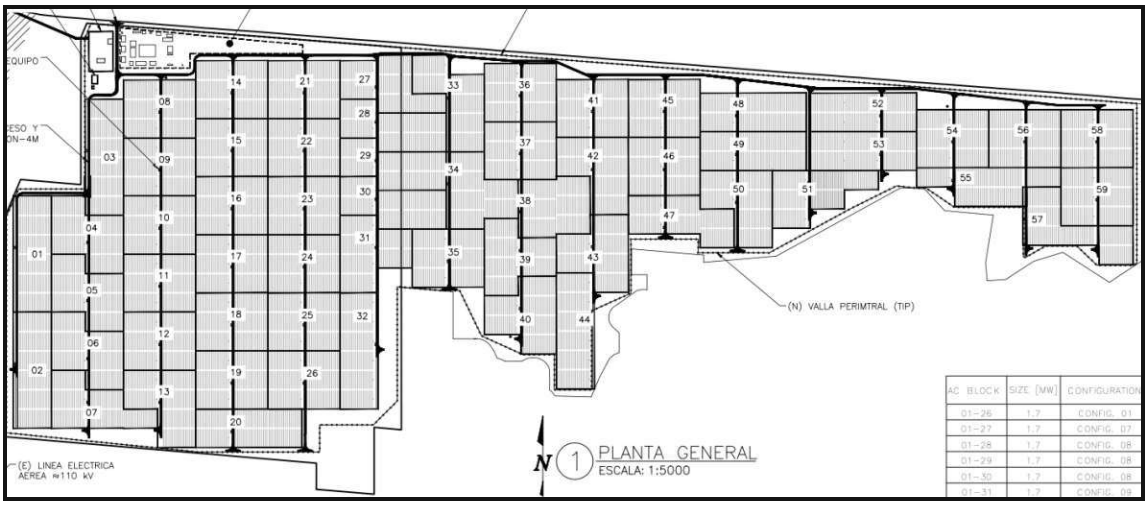

Figure 4.1: PV site main layout.

Source: O&M provider company.

Figure 4.1 shows a panoramic view of the main layout of the PV site which is separated by 59 blocks, each block corresponds to 1 Transforming Center (TC), were each of them consists of 2 inverter modules operating. For a better understanding of the site's weather measurement configuration, the location of each meteorology sensor is as follows:

- POA pyranometers are located in blocks 1, 24, 37, 46, 53, 59.
- Horizontal pyranometers are located in blocks 1, 37, 59.
- Ambient Tº sensors are located in blocks 1, 37, 59.
- PV panel Tº sensors are located in blocks 1, 24, 37, 46, 53, 59.
- Wind speed sensors are located in blocks 1, 37, 59.

In order to understand and study or test any method applied to the site and see the results, any change will be done at least at an String or Tracker level, so that there can be a point of comparison between the equipment working at standard contusions and the one at special conditions. In this way any type of changes in the standard performance, as minimum as it can be, can be identified and studied better.

4.2.1 Site Performance 2023 - 2024

This work will be based on real data taken from the site of study for the period of comprehended between January 2023 and June 2024, in this way a "standard condition" pattern can be associated to the day-to-day performance of the site. For the purposes of this study, the year 2023 will be used as a "normal" status, meaning the site working without any type of modifications on its day to day operations, and the period of 2024 will be used as a "testing" period, on which any type of small to big modification will be done to the site in order to test any methodology that would be relevant for this study. The following Figure 4.2 presents the historical data of energy generation, weather conditions and overall performance of the site during 2023.

Month	Energy Generated (kWh)	POA Irradiation (kWh/m2)	GHI Irradiation (kWh/m2)	Ambient Temperature (C°)	Panel Temperature (C°)	Wind Speed (m/s)	Performance Ratio (%)
Jan-23	30,376,203	373.73	289.85	18.74	28.54	2.82	83.45%
Feb-23	25,283,267	306.65	236.41	19.56	28.47	2.70	82.76%
Mar-23	23,672,600	298.18	225.42	18.63	26.26	2.49	81.20%
Apr-23	18,662,112	213.85	160.80	15.18	19.94	2.13	82.80%
May-23	16,411,560	190.95	143.02	15.00	18.50	2.15	87.47%
Jun-23	14,000,109	153.08	115.60	14.63	16.87	2.67	89.97%
Jul-23	14,066,087	165.31	127.21	13.33	16.00	2.96	89.97%
Aug-23	14,320,142	211.45	161.50	14.83	19.37	2.63	88.87%
Sep-23	12,302,191	242.42	189.54	14.13	20.40	2.79	83.93%
Oct-23	16,928,184	303.88	240.42	15.00	22.30	3.02	84.02%
Nov-23	17,768,213	340.57	267.68	16.23	25.95	2.90	84.53%
Dec-23	21,814,660	379.07	298.07	17.76	28.86	2.93	84.41%

Figure 4.2: Performance Data 2023.

Source: PV Site SCADA system.

As shown on Figure 4.2, it can be seen that the site has a consistent high irradiation during the months of summer, between December and February, with a total monthly Plane of Array Irradiance (POA) going in between 300 kWh/m^2 and 400 kWh/m^2, see Figure 4.3, average daily Ambient Temperature of almost 20 ºC, with peaks of 28 to 29 ºC, and an average daily solar Panel Temperature of 29 ºC.

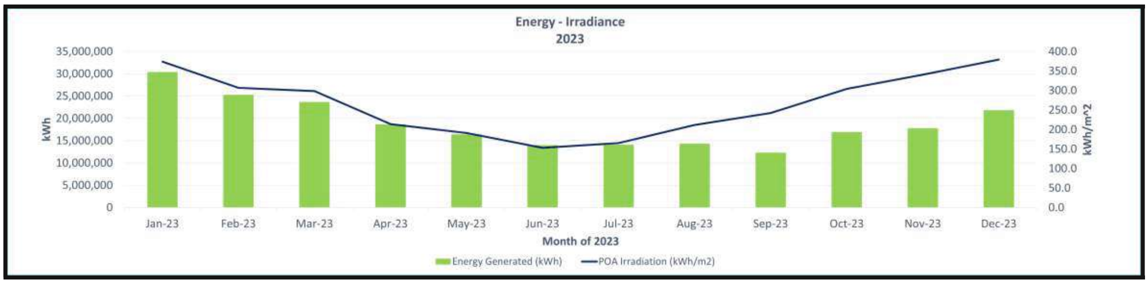

Figure 4.3: Energy & POA Irradiance data for 2023.

Source: PV Site SCADA system.

All these conditions make this site a good example of a location with great irradiation and high temperatures in the hottest months. Figure 4.4 summarizes the temperature analysis above.

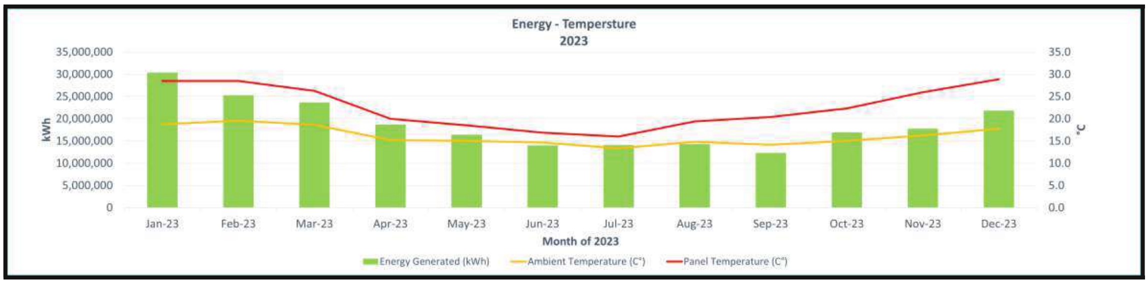

Figure 4.4: Energy & Temperature data for 2023.

Source: PV Site SCADA system.

Now that the condition of high Tº has been established on the site, it is important to understand which should be the boundaries of the data that will be analyzed, meaning under which exact condition or conditions this data must be worked on. The yearly summary shown on Figure 4.2 shows the data obtained by gathering the full daily data of the site, taken from 00:00 hrs until 23:59 hrs of each day of the year, based on raw data with a granularity of 15 minutes intervals. The main problem with doing this is that by applying no filters or no points of reference, all the data can look similar and it can be harder to establish a pattern, specially when the data of study is temperature and any weather condition that may affect this parameter, like irradiance or wind speed for example. So in order to have a good point of comparison between parameters, this study will use a minimum value of POA as a point of reference.

Because the Power Plant of study it has been operating since 2017, through the whole lifespan it has had a Performance Guarantee (PeGu) contract between the operator and the owner of the facility, in this contract it is established that in order to study the performance of the plant, meaning any type of calculation such as: PR, Availability, Weather Adjustment, and others; there must be a minimum POA irradiance level of 90 W/m^2. This means that to do any type of study or analysis, the data gathered must be filtered for this minimum POA value at the beginning and at the end of solar generation, therefore the data studied will be concentrated mainly in the hours of high irradiance and high temperatures.

Taking this into account, it can be established that the minimum value of POA Irradiance to perform the analysis of this study will be also of 90 W/m^2. With this, the following Figure 4.5 represents the summary of the weather data of 2023 when the established POA threshold is applied:

Month	Ambient Temperature (C°)	Panel Temperature (C°)	Wind Speed (m/s)	Performance Ratio (%)
Jan-23	21.79	42.50	3.72	82.08%
Feb-23	22.28	42.29	3.69	81.47%
Mar-23	21.77	40.89	3.43	79.28%
Apr-23	20.50	36.74	3.16	76.54%
May-23	19.42	33.69	2.82	86.16%
Jun-23	18.87	30.40	3.38	87.53%
Jul-23	18.03	30.43	2.95	85.15%
Aug-23	19.11	34.34	3.47	83.70%
Sep-23	18.49	35.95	3.71	75.68%
Oct-23	18.84	36.71	4.12	79.50%
Nov-23	19.50	40.78	3.83	84.28%
Dec-23	20.68	43.35	3.77	83.64%

Figure 4.5: Weather data 2023 with a minimum POA irradiance of 90 W/m^2

Source: PV Site SCADA system.

Given this data filtered by POA irradiance values, the following analysis will use this information as a base of study.

4.2.1.1 Economic losses due to low PV modules efficiency

During 2023 and for the past years the PV site of study has been going through lower efficiency on the installed PV modules because of the high working temperature that they have to take during the time frame of the day with highest temperature and irradiance, as stated already in Section 4.2.1.2. This low efficiency means a lower energy output from the panels and, therefore, revenue losses for the site's owner.

4.2.1.2 Performance Differences With Temperature

As shown on Figure 4.5, it can be seen that the Performance Ratio corrected by weather conditions has a very distinct variation when the temperatures, both ambient and panel, rises at least on a monthly basis. It is also clear that the most visible rise on temperature comes within the sensor on the panel, this is because the PV module is not only receiving big amounts of irradiation, is also producing current which in the end also adds up to the heat of the equipment. This actual behaviour of the PR response to temperature of the site is summarized for the year 2023 on a monthly basis in Figure 4.6.

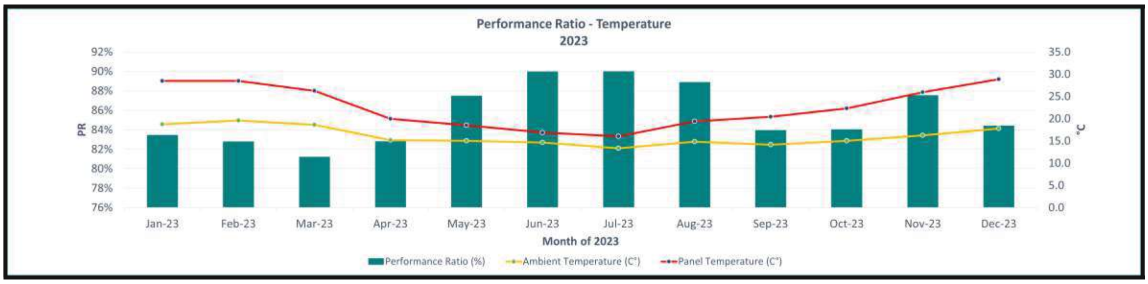

Figure 4.6: Comparison of weather corrected PR and temperature.

Source: PV Site SCADA system.

For a better understanding of the performance variations related to high temperatures on the site of study, a more precise profile analysis must be presented, for this, the month with highest temperature will be selected and from this period of time the daily profile of the days with highest T^{o} values will be studied in more detail. Following this method, it will be established the real incidence of high T^{o} on the performance.

From the data presented in Figure 4.5, January is a period in which the ambient and panel Tº are considerably high, therefore, this is a good period to study into more detail the possible relation between performance and temperature, for this, Figure 4.7 presents the profile of the whole month of January 2023.

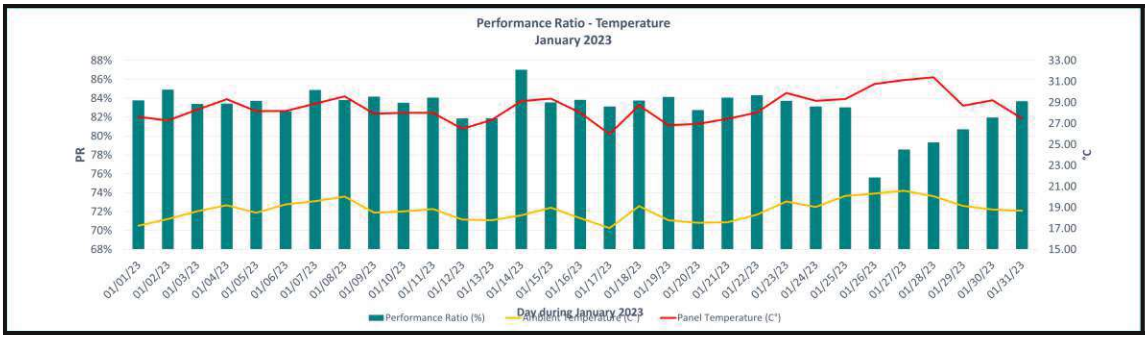

Figure 4.7: January monthly PR and temperature profile.

Source: PV Site SCADA system.

Figure 4.7 shows that the days with the lowest PR values are between the 26/01/2023 and 30/01/2023, at the same time, these days are also the ones with the highest panel and ambient Tº of the month. The day with the lower PR is the 26/01/2023, therefore, this is a good example to analyze and understand the conditions that could have affected the site's performance, Figure 4.8 shows the daily profile of PR and Tº, while Figure 4.9 shows the irradiance and Tº of the site during the selected day.

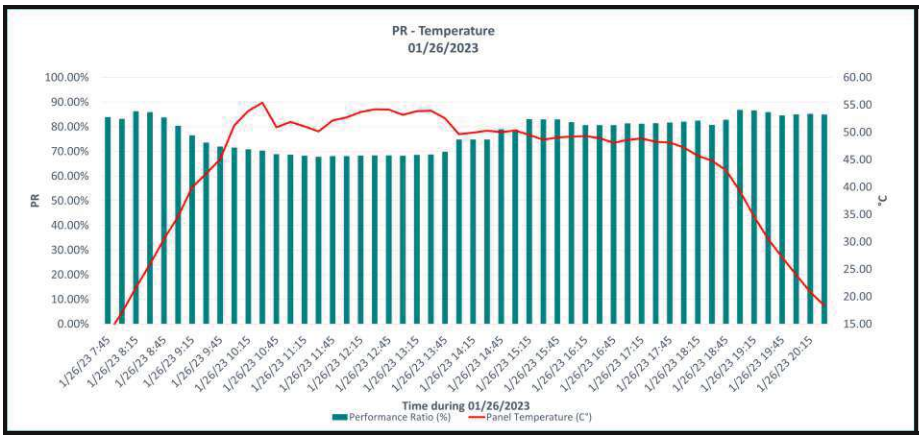

Figure 4.8: PR and temperature daily profile of 26/01/2023.

Source: PV Site SCADA system.

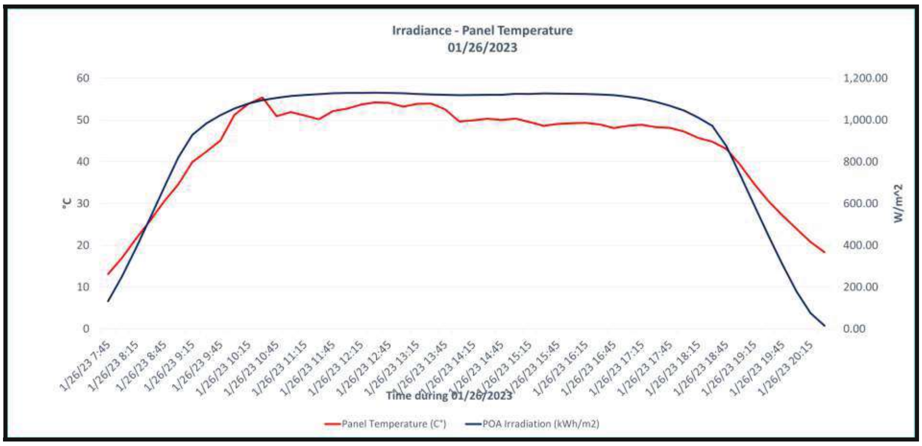

Figure 4.9: Irradiance and panel temperature daily profile of 26/01/2023.

Source: PV Site SCADA system.

As shown in Figure 4.8, the selected day has panel Tº values greater than 50 ºC between approximately 10:00 hrs and 14:00 hrs, during this same time frame the PR values are the lowest of the day, with an average of 69.86 %, and according to Figure 4.9, during the same time frame the irradiance levels were above 1000 W/m^2, with an average value of 1115.02 W/m^2. This low efficiency and lower performance for this condition of high temperature is no surprise, since the panel datasheet indicates that the efficiency starts to decay once the panel temperature is of at least 50 ºC or higher and the irradiance is above 1000 W/m^2, see Figure 2.2. Now that the lower performance of the site when high temperatures are present is established, the next step is to understand what would be the best way to attack this problem and what methods would be the possible to implement on site.

As mentioned on Section 2.12.2, using the cooling capacity of the wind present on site can result into a beneficial effect on the PV panels affected by high working temperatures. If the same example of the performance during the 26/01/2023 is taken, then an analysis of the panel temperature and the possible effect of wind speed can be done. Figure 4.10 shows a comparison of the behaviour of wind speed and panel temperature for 26/01/2023, for a better look of the data, the chart shows the values between 09:45 hrs and 18:30 hrs, because is during this gap of time when the irradiance levels are above 1000 W/m^2.

From Figure 4.10, tendencies can be drawn from both curve's behaviours,

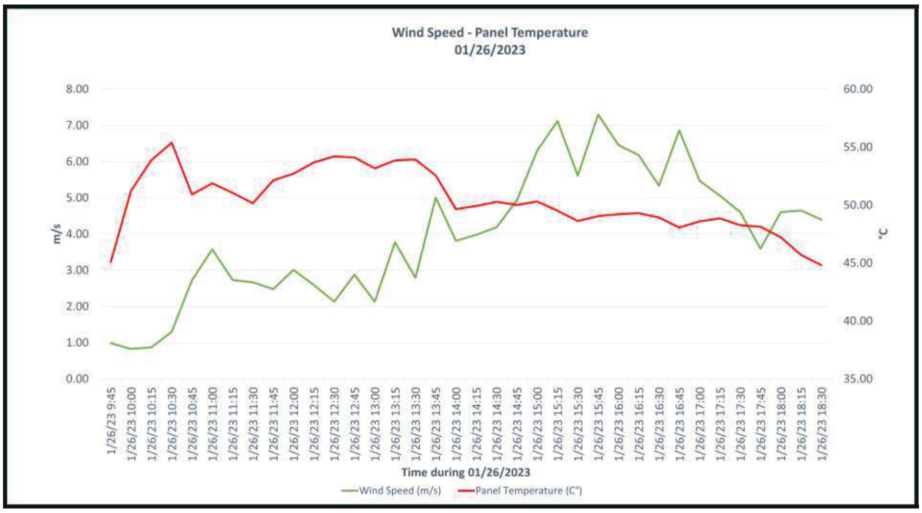

Figure 4.10: Wind speed and panel temperature daily profile of 26/01/2023.

Source: PV Site SCADA system.

there is a clear change on the panel temperature as the wind speed rises, this last curve shows that the starting values (between 09:45 hrs - 13:45 hrs) are considerably low, ranging between 1 m/s and 3 m/s, at the same time frame the panel temperature is considerably stable with values generally above 50 ºC. However, at around 14:45 is when the wind speed values start to rise, reaching peaks of 7 m/s and above, at the same time the curve of panel temperature starts to drop consistently up to values below 50 ºC. This behaviour is consistency with the premise exposed earlier in this paper, see Section 2.12.2, showing that with high wind speed levels the panel temperature tends to decrease due to the cooling capacity of the wind flow.

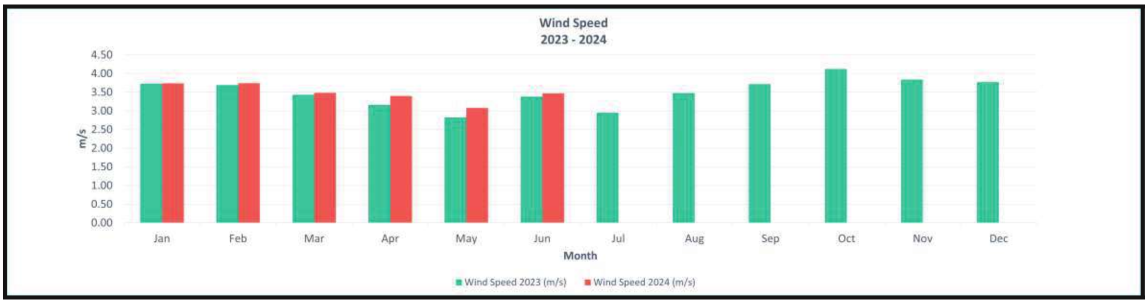

Figure 4.11: Wind speed levels through the year 2023.

Source: PV Site SCADA system.

Figure 4.11 shows the behaviour of the wind speed at different stages of the year 2023 and 2024, from where it can be seen high levels usually from November to February, which would be from spring to summer, and then another peak at June, which is the beginning of winter, on the other hand, Figure 4.11 also shows a similar pattern, with this, it can be established a base reference of data that is useful to analyse in order to comprehend a potential benefit of the wind speed of the PV park. So, given the wind speed information on Figure 4.11, it can be established that a good time to try and test any methodology that would need a consistent amount of wind speed, would be the time between January and June of 2024, this way the data used will have both spectrum's of wind speed. Alongside with this, the time of the year with highest temperature levels are the summer months, between December and March, so a good time of the year for possible testing would be a cross between a time of the year with high levels of wind speed and temperature.

On the next sections of this study, the cooling capacity of the wind running through a PV power plant will be linked to the movement of a single axis tracker system, like the one installed in the PV Site of study, in order to analyse the feasibility of changing the tilt angle of the tracker on order to take as much advantage as possible of the wind speed of the PV park, the same way as it was mentioned on the Theoretical Framework of this study, on Section 2.12.2.

4.3 Solution Proposal

The purpose of this work is to study and propose a possible solution that efficiently integrates a temperature balance method on a site with a single-axis tracking system. The premise is that, giving the fact that wind speed is present through the whole year on a site with the characteristics of a UPP, then this same effect of the wind can be used to transfer the heat away from the PV panels, in order to create a cooling effect, just by modifying the tilt angle of the selected tracker (see Section 2.12.2).

4.3.1 Tracker Tilt Angle

Given that the site of study is built with a single-axis tracking system, it every string moves following the movement of the sun, based on the irradiation readings by the POA irradience sensors (pyranometers) on the site, as specified on Section 2.6.2. This movement can also be modified to satisfy the user's needs, therefore, the tracking tilt can be changed in order to adapt its angle so that the whole string of panels associated to the tracker can face the wind speed in a more direct way as in their normal automatic movement, taking advantage of the cooling nature that the effect of wind has on the equipment installed on site.

To do this, the trackers that will be subject to study on the PV site, must be studied at the time of maximum POA irradiance, to define this time of the day it is necessary to look at the weather data in a more detailed profile, since this paper is focused on the performance of a solar power plant under high levels of temperature, the ideal time of tests and study is during the highest levels of irradiance and Tº of the year, which is January and February of any given year in Chile, with this established, for the purposes of this study the selected time of analysis for high temperature levels is February 2024.

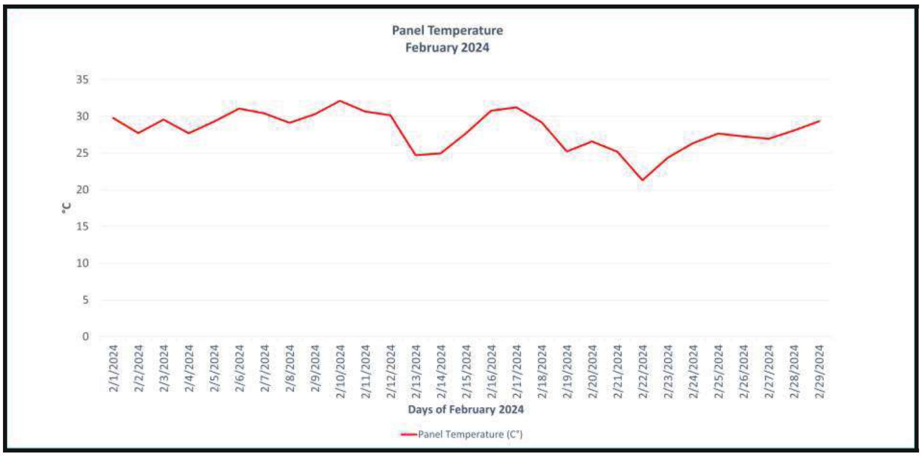

Figure 4.12: Panel temperature profile during February 2024.

Source: PV Site SCADA system.

Figure 4.12 shows that the days with the highest levels of panel temperature are the 5th and 11th of February, therefore, these can be taken as good points of comparison in order to study their daily profiles and see between what times of the day the temperatures reach their highest points, this way a consistent time frame of study can be applied as a general rule for the days of February 2024 and at the same time a pattern of behaviour can be assumed through the month. Figure 4.13 shows the daily profile of panel temperature for the days with the highest levels (between the 5th and the 11th), from this curve there is a clear tendency of high values between 13:00 hrs and 15:00 hrs, at the same time, this is usually when the trackers have a tilt angle between 5º and 30º, this way, modifying the tilt can assure a visible change in the panels generation.

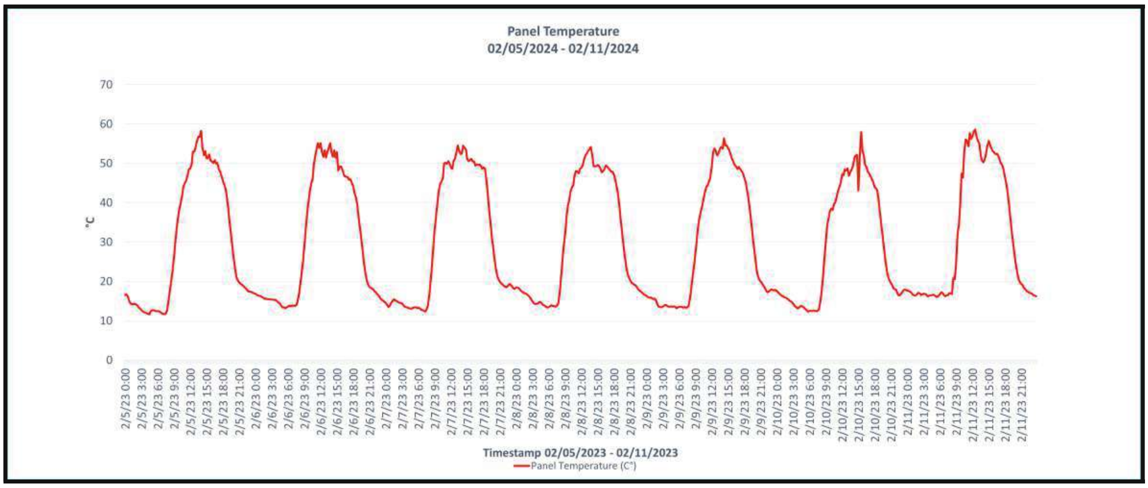

Figure 4.13: Panel temperature between 02/05/2024 - 02/11/2024.

Source: PV Site SCADA system.

Figure 4.14 shows the normal tracking movement that each tracker has throughout a sunny day on the PV site, it can be seen that at the beginning and end of the movement there is a slope on the chart, this represents backtracking, a condition that the arrays of PV modules associated to the trackers have because of shading created by geographical conditions, mainly elements like mountains that surround the area of the PV site. Since all of the studies and experimentation will be done in the middle of the generation through the day, there will be no issues with this condition, because at this time of the day there is no backtracking, as shown in Figure 4.14. To ensure a change in the tilt angle that allows the modules to face wind in a more direct way without compromising completely the incidence angle

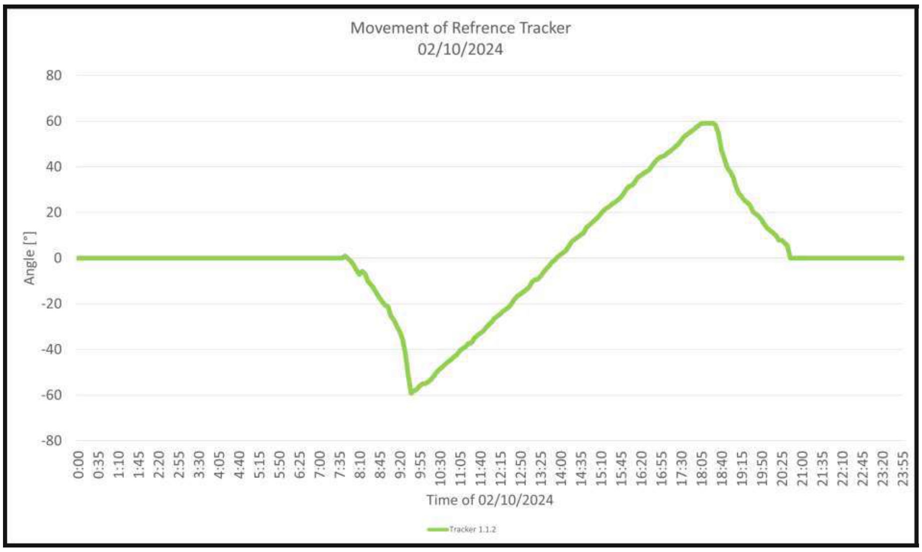

Figure 4.14: Normal tracking movement on site.

Source: PV Site SCADA system.

of irradiance, a tilt angle variation must be defined. This configuration is illustrated in the Figure 6.1, were θ_1 represents the angle of the tracker at its normal movement, and θ_2 the modified movement by increasing the angle in a certain amount of degrees.

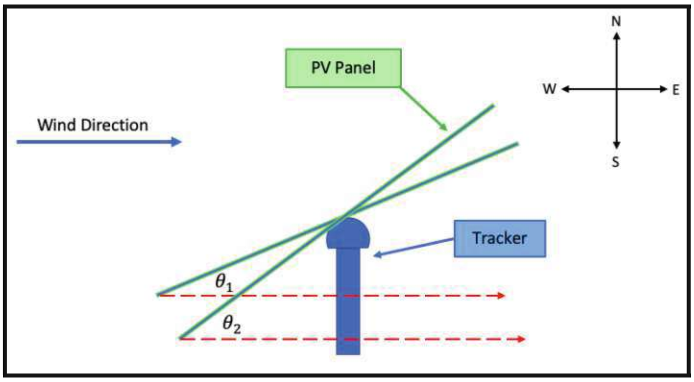

Figure 4.15: Configuration of solution proposal.

Source: Own elaboration.

Testings of the tilt angle modification were taken in place on site by the operation team during January 2023 by request of the owner of the site for other study purposes, comparing the generation in different days at the same time gap during peak irradiance. The results showed that en maximum angle variation that compromises the generation by a 2% or less (limit established by the owner of the sites) was between 20% and 30% increase of the tilt angle, as shown on Figure 4.16, therefore, the tilt angle variation selected for the tests for the purpose of this paper is of a 30% increase.

Tracker	Energy Generated 10% Tilt [kWh]	Energy Generated 20% Tilt [kWh]	Energy Generated 30% Tilt [kWh]	Energy Generated 40% Tilt [kWh]	Energy Generated 50% Tilt [kWh]
Modified Tracker	2,173.6	2,135.6	2,149.3	2,097.9	1,991.8
Normal Tracker (no tilt modificaion)	2,176.4	2,160.7	2,185.9	2,182.2	2,184.3
Difference	0.13%	1.16%	1.68%	3.86%	8.81%

Figure 4.16: Energy generation comparison between a tracker with normal movement and a tracker with an increased tilt of 10%, 20%, 30%, 40% and 50% from the normal tracking

Source: PV Site SCADA system.

4.4 On site testing

To be able to do a proper testing on site of the proposal exposed on Section 4.3, a good location where the meteorological data has a good data quality and that can represent in a good way the overall PV site has to be selected, and also the exact tracking equipment that will be modified and tested. The owner of the facility allowed to do test that would last no longer than a week (7 days in a row) on a single testing cycle, this means, that the testing can go only on a by-weekly basis, which for the results aimed to have is no problem at all. For this, the months selected for the testing cycles was during February 2024, because of their high wind speed normal conditions and because in this way the performance is being tested in a high temperature month. The cycles of testing consisted of 2 weeks in total (14 days), the first week of the month was a "reference week" were a normal behaviour was established, the second week was the first testing cycle, the third week was again with no modifications, and the fourth week was the second testing cycle. Each testing cycle was taken into place by selecting the testing subjects, which were divided into 3 groups in accordance with the size of the PV Site and with the availability of good quality data. The testing groups and their location were chosen as follows:

- Each testing group was located in strategic zones of the PV site, in order to get the best quality data possible.
- Since each inverter is associated to 3 trackers, 3 inverters were selected and from each inverter 1 tracker was selected as the "testing subject" and the other 2 trackers were, therefore, the reference subjects.
- The testing took place by modifying the tilt angle of the testing tracker, as mentioned on Section 4.3.1, for 7 days in a row, for 14 days through the selected month.

By executing the testing this way, the data gathered from the testing tracker can be easily compared with the neighboring 2 reference trackers associated to the same inverter, which had a normal behaviour with no modifications, so it can be easily seen if there is any difference on performance when the test is applied.

4.4.1 Testing group selection

For the tests that took place on site during February 2024 by the operating team on field, 3 specific locations of the PV site were chosen due to their good data quality and the fact that each of them is a good representation of their neighboring equipment, in functionality and data, making the combination of the 3 testing groups a good representation of the overall power plant. Figure 4.17 indicates the location of each testing group. Following this, and based on the data exposed on Section 4.3.1, the time frame selected for testing was between 14:00 hrs and 15:00 hrs of each day of the week, this not only assures a high panel temperature value, also is the time on which the irradiance is at its peak level and therefore the generation is also at its maximum. Table 4.1 represents the schedule and time frame for which the tests took place on each testing group.

Month	**Week 1**	**Week 2**	**Time Frame**
February 2024	02/05/2024 - 02/11/2024	19/02/2024 - 02/25/2024	14:00 hrs - 15:00 hrs

Table 4.1: Testing schedule.

As shown on Figure 4.17, the testing groups are TC block 1, TC block 37 and TC block 59, given the fact that each TC is represented by 2 inverter

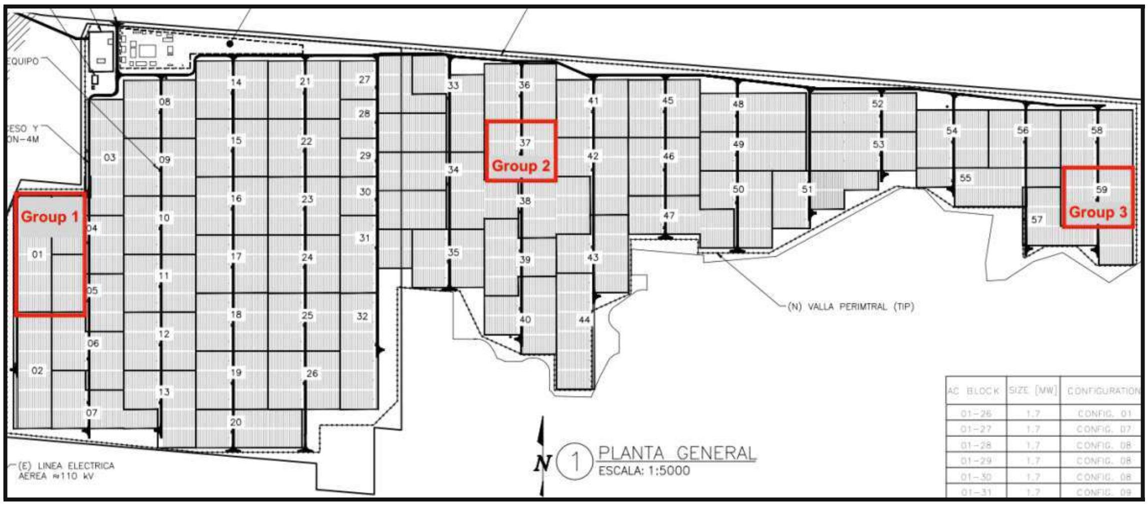

Figure 4.17: Location of each "Testing Group".

Source: PV Site Layout.

modules, from now on they will be addressed referencing their block and module number, for example, inverter module 2 of block 37 will be: "inverter 37.2". Following the same logic, each tracker associated to each inverter module will be tagged with number from 1 to 6. Since each TC block has 6 trackers in total divided into two groups of 3, each of them associated to an inverter module, following the same example form before, the first tracker of the 3 tracker group associated to inverter 31.2 will be: "tracker 37.2.4". The exact trackers selected for the test and their respective reference neighbour location are as follows:

– Group 1: The testing tracker is Tracker 1.1.1 and the reference is Tracker 1.1.2, as shown on Figure 4.18.

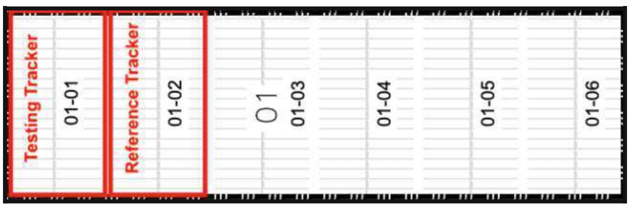

Figure 4.18: Group 1: testing and reference tracker (TC block 1).

Source: PV Site Layout.

– Group 2: The testing tracker is Tracker 37.1.1 and the reference is Tracker 37.2.4, as shown on Figure 4.19.

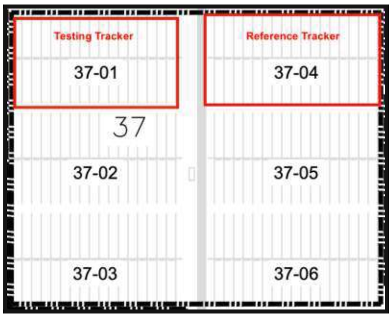

Figure 4.19: Group 2: testing and reference tracker (TC block 37).

Source: PV Site Layout.

– Group 3: The testing tracker is Tracker 59.1.1 and the reference is Tracker 59.2.4, as shown on Figure 4.20.

Figure 4.20: Group 3: testing and reference tracker (TC block 59).

Source: PV Site Layout.

The results of these tests are discussed in the next chapter.

Results

On this chapter, the measurements and results obtained during the tests carried out in February and June of 2024 by the operating team on the PV site are shown. These results provide information with the potential of benefit for both the owner of the site and the operator. The analysis of the tests presented in this work corresponds to unpublished information that will be officially exposed and studied for the first time. For a better understanding of the data presented on this section, all measurements of irradiance are shown in [kWh/m^2], temperature in [ºC], wind speed in [m/s], monetary values in [USD] and PR in its respective percentage calculated value. For the purposes of this study, the PR is calculated through all the report on a weather adjusted basis using only unmodified raw data from the SCADA system available on the PV site (IEC 61724, 2022), and is defined as follows:

$$PR = \frac{\sum Real\ Energy\ Output}{PSTC\ *\ \sum(\frac{POA_{irr}}{4}\ *\ (1 - \alpha\ *\ (t_m\ - t_i)))} \tag{5.1}$$

Where:

- $Real\ Energy\ Output$: Sum of the total energy generated and measured by the revenue meter on the connection point to the transmission system grid, measured in [kWh].
- $PSTC$: Sum of the installed PV modules in the system, measured in [kWp]. For the purpose of this study, the selected PV site has a PSTC value of 105,000 [kWp].
- POA_{irr} : Plane of array irradiance measured by the pyranometers installed on the PV Site at the same tilt as the tracker movement, measured in [kWh/m^2]. Since pyranometers deliver a value in [W/m] every 15 minutes, this value has to be divided by 4 in order to get the specified measuring unit for the formula.
- α : Temperature coefficient of the PV modules installed on the system, defined by the manufacturer with a constant value of 0.38%.
- t_m : Estimated average panel temperature established by the original simulation of the PV Site defined in monthly basis, measured in [ºC]. This value was already define during the developing phase of the PV site by the EPC company (see Table 5.1).

– t_i : Measured panel temperature by the sensors installed on the PV Site, measured in [ºC].

Month	**Simulated Module Temperature [ºC]**
January	45.3ºC
February	44.9ºC
March	44.5ºC
April	40.1ºC
May	35.7ºC
June	32.7ºC
July	32.0ºC
August	35.0ºC
September	40.4ºC
October	44.3ºC
November	46.7ºC
December	46.2ºC

Table 5.1: Monthly simulated panel temperature of the PV site.

Source: O&M Provider.

5.1 Measurements during tests

The measurements in this section were carried out during the test week specified on Section 4.4.1, using meteorological sensors such as POA irradiance, temperature, and wind speed. The purpose of these measurements was to understand the effects of modifying the movement angle of the trackers defined for the test and to identify if there is any difference or advantage compared to the results of the trackers defined as reference. The data used for every calculation shown through the content of this report was taken directly from the SCADA system source associated to the PV site of study, for the purpose of not having extended views of data and values, the numbers presented in this study are only the ones relevant to the testings and taken within the minimum granularity of 15 minutes, to then be treated as processed values, such as PR, or as average in some occasions. For a view of the whole raw data during these tests used for the study without modification, refer to the Annex A.

5.1.1 Measurements during February

A deep detailed analysis of the data during testings will be carried out for the week and days with the best conditions for the trials periods, with peak panel temperature, irradiance and wind speed, in order to extend these results to the rest of the testing period for each specified week, so to do this, the period selected for a detailed look is the test week 1 of February (02/05/2024 - 02/11/2024). For this period, the selected testing trackers and reference trackers had the movement as described on Figure 5.1, where it can be established that the movement of both trackers, at least before and after the tests, is exactly the same, any possible angle difference would be minimum and doesn't really created a deviation on the movement, therefore, shows that the reference tracker has at least the same movement condition as the testing one if there was no modification from the automatized tracking movement, this is the same case for every other pair of trackers (test and reference) for every other test group during all other testing periods.

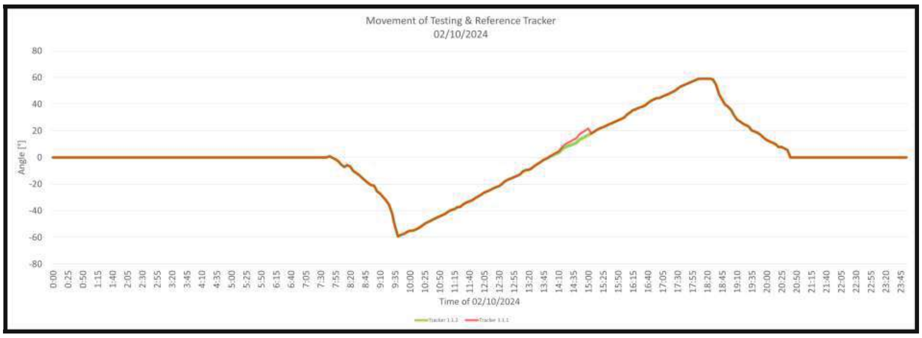

Figure 5.1: Tracking movement for group 1 during testing week 1 of February.

Source: PV Site SCADA system.

Table 5.2 shows the angle variation during the tests, resulting on a maximum angle variation was of 5.0217º of increase.

In order to understand and choose the day to study in detail with the conditions that can show evidently the effect of the proposed change on the trackers tilt, Figure 5.3 presents the average weather data for each day of the testing week, from this conditions it can be isolated the day with the best weather levels that will serve as a good example to analyze in detail. The numbers shown on Figure 5.3 are average daily values and the only

Date	Reference Tracker Angle [°]	Tested Tracker Angle [°]	Difference [°]
2/10/24 13:00	-13.89	-13.89	-
2/10/24 13:15	-11.00	-11.00	-
2/10/24 13:30	-7.94	-7.94	-
2/10/24 13:45	-4.90	-4.90	-
2/10/24 14:00	1.47	1.92	0.4422
2/10/24 14:15	5.55	7.22	1.6659
2/10/24 14:30	9.19	11.95	2.7567
2/10/24 14:45	13.31	17.30	3.9930
2/10/24 15:00	16.74	21.76	5.0217
2/10/24 15:15	19.33	19.33	-
2/10/24 15:30	22.77	22.77	-
2/10/24 15:45	26.75	26.75	-
2/10/24 16:00	28.75	28.75	-

Figure 5.2: Comparison of the angle increase in the tested tracker of group 1.

Source: PV Site SCADA system.

purpose is to show a broad idea of the conditions for each day, the selected day will be studied deeper with a data granularity of at least 15 minutes and without using generalized average values.

Date	Ambient Temperature (C°)	Wind Speed (m/s)	Panel Temperature (C°)	Performance Ratio Reference Tracker (%)	Performance Ratio Testing Tracker (%)
02/05/24	21.3	3.4	43.0	80.78%	81.51%
02/06/24	21.1	3.5	44.5	73.93%	75.41%
02/07/24	21.8	4.0	43.1	81.62%	83.15%
02/08/24	22.1	4.1	40.1	72.77%	74.24%
02/09/24	23.3	3.9	44.8	77.87%	79.98%
02/10/24	24.0	3.6	47.1	74.80%	77.84%
02/11/24	22.3	3.9	45.6	85.00%	87.42%

Figure 5.3: Average daily weather data and Performance Ratio of Group 1 during test week 1.

Source: PV Site SCADA system

Figure 5.3 shows that the day with the highest daily average irradiance and panel temperature level is the 02/10/2024, therefore, this is a good candidate for the performance of the testing and reference tracker to be analyzed into detail. Figure 5.4 shows the performance every 15 minutes of both trackers between 13:00 hrs and 16:00 hrs of the analyzed day, this is to isolate the PR values of both equipment 1 hour before and after the testings, in order to understand their behaviour during this interval and see if there is any visible tendency in their values for a future comparison.

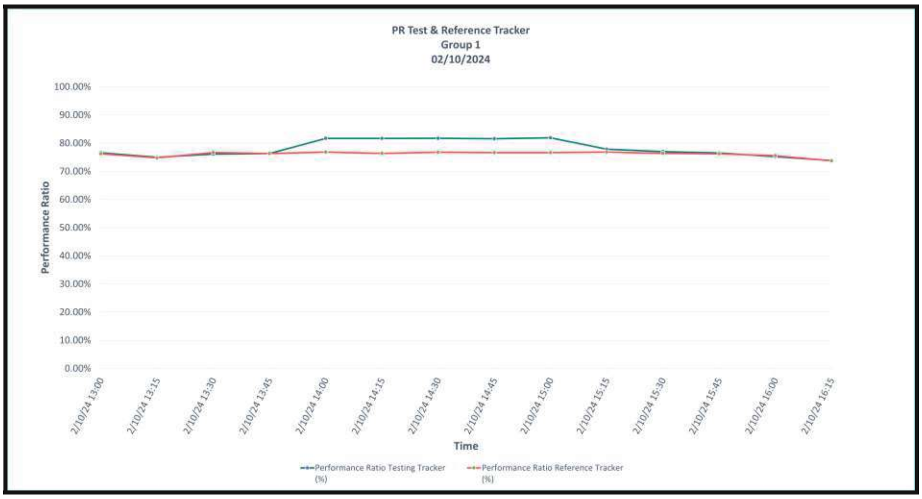

Figure 5.4: Daily profile of PR of testing and reference tracker between 13:00 hrs and 16:00 hrs of 02/10/2024

Source: PV Site SCADA system

To properly study the relation between the values of the reference and tested tracker before and after the modification, a comparison curve is used to obtain the equation that represents the real tendency between them, the values compared are shown on Figure 5.5. Figure 5.6 shows the linear equation that represents the relation between the trackers, with this, and since the weather conditions of irradiance, temperature and wind speed are exactly the same due to their proximity, an extrapolation can be taken into place in order to estimate the PR values that the testing tracker would have had if the tilt would have stayed with no modification and following the normal automatized movement, just like the reference tracker did.

The relation is also represented on the linear equation 5.2:

$$Testing\ Tracker\ PR\ (\%) = 0.9858 * Reference\ Tracker\ PR\ (\%) + 0.8688 \tag{5.2}$$

With the established equation to estimate the PR values for the testing tracker of group 1 during the time of the trial under normal movement, a comparison between both values can be made in order to see the effect of the modification on the performance of the tested tracker, for this, Figure 5.7 shows a comparison between the real measured PR values of the tested tracker and the estimated ones.

From the PR difference between the values presented on Figure 5.7, the mean average value can be calculated, and by doing so the result is that

Date	PR Reference Tracker (%)	PR Tested Tracker (%)
2/10/24 13:00	76.1971%	76.5690%
2/10/24 13:15	74.7870%	74.9746%
2/10/24 13:30	76.6631%	76.1053%
2/10/24 13:45	76.3021%	76.3037%
2/10/24 14:00	76.8037%	81.6646%
2/10/24 14:15	76.3461%	81.6653%
2/10/24 14:30	76.7531%	81.6852%
2/10/24 14:45	76.6119%	81.5767%
2/10/24 15:00	76.6252%	81.8579%
2/10/24 15:15	76.8334%	77.8284%
2/10/24 15:30	76.3622%	76.9828%
2/10/24 15:45	76.2141%	76.5238%
2/10/24 16:00	75.5427%	75.1969%
2/10/24 16:15	73.7113%	73.8051%

Figure 5.5: PR values of testing and reference tracker between 13:00 hrs and 16:00 hrs of 02/10/2024

Source: PV Site SCADA system

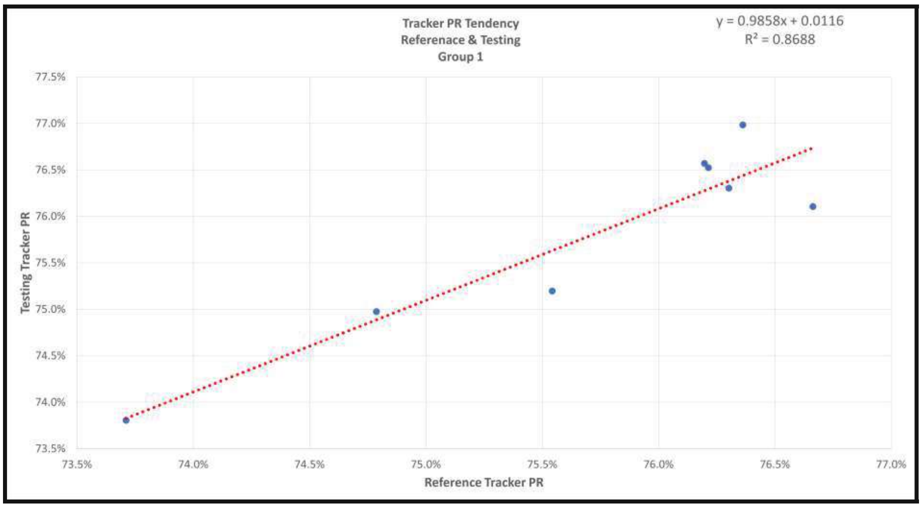

Figure 5.6: Tendency curve between the PR of the reference and tested tracker.

Source: PV Site SCADA system

on average the PR gain during the time of tilt modification is of 4.9900%. Assuming that the behaviour between the testing and reference tracker follow the same conditions during the tests period of February, the same calculation logic can be applied to calculate the PR gain of the other tested trackers during the same testing week, following a similar method than for

Date	Real PR Tested Tracker (%)	Estimated PR Tested Tracker (%)	Difference
2/10/24 14:00	81.6646%	76.8731%	**4.7915%**
2/10/24 14:15	81.6653%	76.4220%	**5.2433%**
2/10/24 14:30	81.6852%	76.8232%	**4.8620%**
2/10/24 14:45	81.5767%	76.6840%	**4.8927%**
2/10/24 15:00	81.8579%	76.6971%	**5.1608%**

Figure 5.7: Comparison between estimated and measured PR values of the tracker with modified tilt.

Source: PV Site SCADA system

testing weeks 1, the PR gain can also be estimated for test week 2, these results are summarized on Figure 5.8.

Week	PR Gain Test Group 1	PR Gain Test Group 2	PR Gain Test Group 3
02/05/2024 - 02/11/2024	4.9900%	4.9210%	5.1029%
02/19/2024 - 02/25/2024	6.3856%	6.8993%	5.1981%

Figure 5.8: Estimated PR gain of each test groups during both testing weeks of February.

Source: PV Site SCADA system

By taking the average PR gain of both testing weeks of February, it can be established that the overall PR gain of the PV Site during the tests was of 5.5828%.

5.2 Results analysis

On this section the overall results are analyzed in conjunction with the possibilities of expanding the findings and extrapolating them into a broader spectrum of time during the year, when the conditions that will be studied as follows are achieved.

5.2.1 Results during test on February 2024

The results shown on previous Section 5.1.1, show a PR gain tendency estimated for the whole tests time span, based on the performance upgrade measured for the 02/10/2024, since these condition of enhancement are strictly dependable on the weather that affect the performance of PV panels, it is important to understand and define the limits of the weather parameters that have incidence in the success of a PR gain. Since the test taken in place on the PV site consists on modifying the tilt angle of the tracker movement and use more efficiently the cooling effect of the wind to lower the overall panel temperature, the weather parameters involved on this are irradiance and wind speed; these values define the minimum conditions that must be present in the environment in order for the tested method to be successful. To get a view of the weather data present and to define their boundaries, Figure 5.9 shows the specified weather data present on each testing group during 02/10/2024, which has been already established as a comparison point for the difference between a tracker following the normal movement and the modified one.

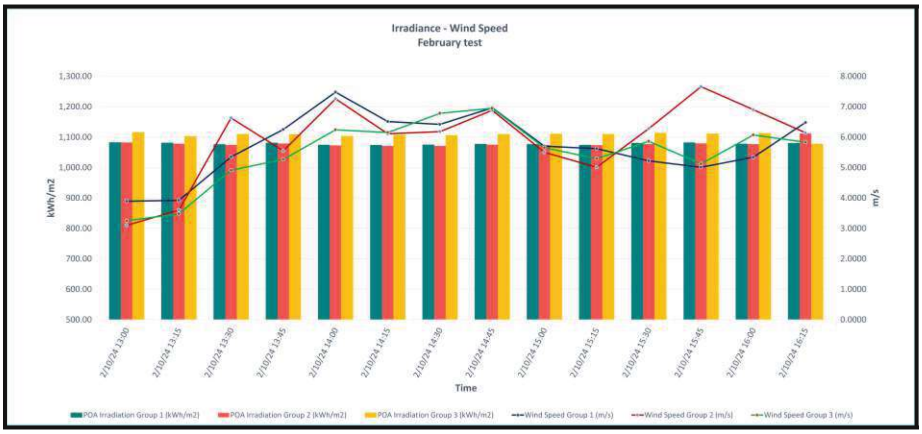

Figure 5.9: Weather data during the tests of 02/10/2024.

Source: PV Site SCADA system

It is important now to understand the possibilities and efficiency of using the tested solution through a year, to do this, it has been established before that the performance of the modules associated to the testing tracker had an improvement during the testing time frame, Figure 5.9 shows that during this time interval the average minimum weather conditions for all tested groups were an irradiance of 1082,5232 [W/m^2] and wind speed of 5.6167 [m/s], thus, for the purpose of this paper it is safe to say the minimum meteorological limits that the system has to be under in order to have the expected good result of the proposed solution will be established as 1000.00 [W/m^2] of POA irradiance and a wind speed of 5.00 [m/s]. These values can now be extrapolated to analyze the total weather data of a whole year and from there obtain the total amount of hours per year when the weather conditions are favourable for a modification like this, therefore, understanding how feasible and useful would be the solution tested through this paper. Figure 5.10 shows the total amount of hours when the irradiance and wind speed achieve values higher than the limits established before during the year 2023.

Month	Hours of 2023 (POA > 1000 [W/m2] & Wind Seed > 5 [m/s])	Full Load Hours of 2023
January-23	77.75	420.75
February-23	65.75	362.00
March-23	45.00	375.00
April-23	12.75	339.25
May-23	0.00	327.50
June-23	0.00	307.00
July-23	0.00	320.25
August-23	2.50	339.75
September-23	49.75	353.50
October-23	85.50	390.50
November-23	73.00	403.25
December-23	83.75	428.50
Total 2023	**495.75**	**4,367.25**

Figure 5.10: Hours during 2023 with an irradiance $\geq 1000.0[W/m^2]$ and wind speed $\geq 5.0[m/s]$.

Source: PV Site SCADA system

From the extrapolation shown on Figure 5.10 it can be well established that the total amount of hours with the appropriate weather conditions for the proposed solution during a whole year are 495.75 [h]. Figure 5.10 also shows that the amount of total production hours of the studied PV site during 2023 was of 4367.25 [h], this means that the hours of the year where the proposed solution is beneficial represents a 11.3515 % of the total amount. Now that the total hours with the weather conditions has been established, Figure 5.11 shows the total energy generated on 2023 and the specific amount of energy generated during the 495.75 [h] when the solution would be beneficial.

As shown on Figure 5.11, the total value of production during 2023 when the benefit occurs is of 32,738,065.76 [kWh], and can now be compared to understand the total benefit on the performance during the whole year by applying the average PR gain of 5.5828%, already established on Section 5.1.1, as shown on the equation 5.3, from which can be concluded that the estimated energy generation gain when the benefit occurs is of

Month	Energy Generated in 2023 [kWh] When the Benefit Ocurrs (POA > 1000 [W/m2] & Wind Seed > 5 [m/s])	Total Energy Generated in 2023 [kWh]
January-23	6,807,873.68	30,376,203.01
February-23	5,706,944.85	25,283,267.00
March-23	3,512,071.53	23,672,599.99
April-23	867,658.64	18,662,112.01
May-23	0.00	16,411,560.03
June-23	0.00	14,000,109.00
July-23	0.00	14,066,086.99
August-23	144,031.62	14,320,142.01
September-23	2,257,159.39	12,302,191.01
October-23	4,720,616.05	16,928,183.97
November-23	3,790,013.20	17,768,212.97
December-23	4,931,696.81	21,814,660.00
Total 2023	**32,738,065.76**	**225,605,327.99**

Figure 5.11: Total amount of energy generated during hours with appropriate established weather conditions for the proposed solution and during the whole 2023.

Source: PV Site SCADA system

1,827,705.79 [kWh].

$$32,738,065.76\ (kWh) * 5.0046\ (\%) = 1,827,705.79\ (kWh) \tag{5.3}$$

This estimated gain on energy during 2023 can now be added to the real energy generation measured by the revenue meter of the PV site, this way a total energy estimation for 2023 can be achieved, as shown on Table 5.2.

Year	Real energy generated during 2023 [kWh]	Estimated energy for 2023 [kWh]	Difference [%]
2023	225,605,327.99	227,433,033.78	0.81 %

Table 5.2: Comparison between total amount of estimated energy gain during 2023 and real measured energy during the same period.

Source: PV Site SCADA system.

With the results and comparison exposed on Table 5.2 it can be now established that the overall estimated gain on performance that the proposed solution could achieve, as long as it is taken place during the beneficial weather conditions, is of a 0.81% of gain of the total energy generated through a year. This value can now be translated into economical profit, by estimating the revenue of the 1,827,705.79 [kWh] of gain through 2023, for this the average energy selling price used is the one established for 2023 by the CEN (National Commission of Energy), which represents the Chilean entity responsible o balancing the national electrical market and energy sell prices of the SEN (National Electrical System), as presented on Figure 5.12.

Precio Medio de Mercado SEN [US$/MWh]				
Sistema	Promedio 2023	abr-23	Δ% mes	
			mar-23	abr-22
SEN	118,1	118,4	▲1,0%	▲19,7%

Figure 5.12: Average energy selling price for generators in Chile during 2023.

Source: Comisión Nacional de Energía, Chile, 2023

Finally, the estimated revenue of the energy gain for 2023 is shown on Table 5.3.

Year	Estimated energy for 2023 [kWh]	Average energy selling price for 2023 [USD/MWh]	Estimated revenue gain [USD]
2023	226,433,033.78	118.1	215,852.05

Table 5.3: Estimated revenue of the energy gain for 2023.

Source: PV Site SCADA system.

The conclusions of the results exposed are discussed on next chapter.

Conclusions

The work carried out consisted of the study of a methodology that could be implemented on a big scale solar power plant, that could help on reducing the panel temperature on the installed PV modules, with the objective of reducing the lower efficiency that this equipment has when the working temperatures are too high. For this, a sequence of experimental testings were carried out during specific time frames of 2024. Through these experiments, specific equipment installed on the PV plant of choice was intervened, in order to verify the effectiveness of the proposed solution.

Therefore, after conducting the study and by analysing the results, the following conclusions are drawn:

a) By analysing the losses on which the owner of the PV sites experience as in response of lower efficiency of PV modules when the temperature on field reach high levels, it is possible to identify the owner's need to explore new ways to balance the temperature condition under which PV modules generate energy. This justified the request to modify the normal working conditions of the equipment installed on site, such as the movement of single axis trackers or control of weather data sensors.

b) During the study of the proposed solution high panel temperature balance, it is concluded that the methodology of modifying the tilt angle of the PV modules arrays associated to the tracker, in a way that faces in a more direct angle the wind speed, was verified in the field through tests conducted on site during February 2024, bringing up the performance of the tested PV modules on an average of 5.5828%.

c) With the final results of performance and energy generation comparison between the trackers with a modified tilt and trackers with no intervention, and extrapolating the performance gain in a whole year, such as 2023, a positive difference came as a result with an estimated amount of 1,827,705.79 [kWh] of energy gain for 2023.

d) Considering the points above, finally the proposed solution consists of modifying the tilt angle of the trackers, for example, for the case of the PV site of study were the wind goes in direction from west to east, the panels must be tilted so that most of their structure face the mass of wind, in this way, the panel temperature goes down and so the modules become more efficient. This configuration is illustrated in the Figure 6.1, were θ_1 represents the angle of the tracker at its normal movement, and θ_2 the modified movement by increasing angle.

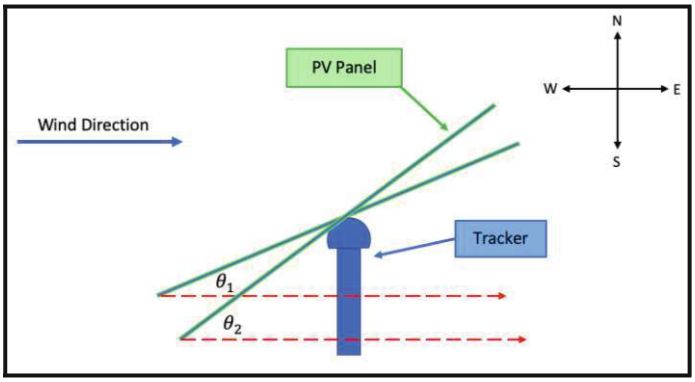

Figure 6.1: Configuration of solution proposal.

Source: Own elaboration.

In this proposed configuration, the tilt angle of the tracker has to be increased in 30% in order to reach the effectiveness shown through this study. This ensures that the structure of the PV module will be facing as much wind mass as possible. The modification should be carried out during the times when the solution would be most beneficial according to the weather conditions of 1000 [W/m^2] of irradiance, 5 [m/s] of wind speed, and a minimum increase on the tracker tilt of 5º to 6º, in order to optimize the level of efficiency of the solution.

e) As a final recommendation, an study of this nature must be carried out at least once a year and taking into consideration any possible characteristic of the selected PV site that might interfere with the performance of the site, whether is of internal or external nature, such as uneven surface due to hills or soft terrain of the of the facility, mountain or any other geographic factor that could produce shading, zones with excess soiling (higher than 2%), backtracking during peak irradiance due to a bad design of the power plant, along with other factors that affect the performance of the site. This way the minimum weather values that affect the benefit of the proposed solution, such as irradiance, wind speed and tilt angle increase, can be studied and adjusted according to the site's nature and necessities.

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Annex A

Date	Tamb_01	Tamb_02	Tamb_03	Tmod_01	Tmod_02	Tmod_03	Tmod_04	Tmod_05	Tmod_06	GHI_01	GHI_02	GHI_03	POA_01	POA_02	POA_03	POA_04	POA_05	POA_06	Wspeed_1	Wspeed_2	Wspeed_3	Plant_kWh
2/10/24 13:00	22.3452	22.9972	29.5547	53.9324	52.1128	53.9324	57.9564	51.1211	58.0502	1,028.1786	1,041.8373	1,136.6437	1,082.3135	1,115.6362	1,082.2749	1,099.9700	1,080.6454	1,115.6362	3.8900	3.1000	3.2500	22,500.4614
2/10/24 13:15	22.5160	23.1317	28.6072	60.0366	50.3833	52.0610	58.0247	56.2638	58.1887	1,036.6204	1,045.4958	1,143.4630	1,081.0518	1,101.8739	1,078.4309	1,089.0631	1,076.6389	1,101.8739	3.9200	3.6000	3.4800	22,499.7671
2/10/24 13:30	22.3467	23.5373	28.9452	57.2021	47.7577	55.2411	46.7732	54.3374	54.1261	1,046.4706	1,065.9359	1,157.0824	1,075.9779	1,109.6069	1,074.5880	1,098.0472	1,076.3851	1,109.6069	5.3500	6.6300	4.9100	22,500.3809
2/10/24 13:45	22.5502	23.3011	28.8105	55.2411	46.9376	54.1261	45.8125	52.6474	52.7883	1,058.0900	1,073.2356	1,166.9038	1,080.8481	1,108.6444	1,078.9171	1,098.0876	1,078.0258	1,108.6444	6.2500	5.5500	5.2700	22,499.8022
2/10/24 14:00	22.4136	23.4026	28.2013	47.4754	47.4754	46.0926	46.0926	52.8114	45.5058	1,054.9324	1,065.5476	1,163.8843	1,074.0912	1,102.9598	1,072.6903	1,090.1150	1,071.4491	1,102.9598	7.4800	7.2600	6.2400	23,250.5797
2/10/24 14:15	22.5494	23.2654	28.7441	47.6143	47.6143	46.7237	46.7237	54.0114	45.8803	1,049.3206	1,066.6449	1,161.2385	1,073.4834	1,106.2914	1,071.2283	1,095.5122	1,075.3992	1,106.2914	6.5100	6.1100	6.1500	23,249.7896
2/10/24 14:30	22.4813	23.4010	28.7432	47.2401	47.2401	46.2088	46.2088	54.5033	45.7632	1,042.2756	1,056.4352	1,151.0297	1,074.7269	1,105.2551	1,071.1263	1,095.2823	1,071.6375	1,105.2551	6.4200	6.1800	6.7800	23,249.6064
2/10/24 14:45	22.3450	23.4007	28.4045	47.1225	47.1225	46.3725	46.3725	54.9960	46.7482	1,033.1459	1,045.1318	1,139.7144	1,076.6715	1,109.1415	1,075.3126	1,096.7831	1,073.0625	1,109.1415	6.9600	6.8800	6.9500	23,250.4329
2/10/24 15:00	22.4810	23.4005	29.8926	46.2550	46.2550	45.3878	45.3878	53.5157	46.6086	1,014.1786	1,028.7213	1,119.3374	1,076.4655	1,110.3690	1,074.1617	1,098.3163	1,073.5476	1,110.3690	5.7000	5.5000	5.6500	23,249.8683
2/10/24 15:15	22.2768	23.7048	28.7432	51.6794	45.5058	49.8838	44.9901	53.8692	49.3980	991.6910	1,003.5468	1,094.4414	1,073.6565	1,109.7596	1,073.4740	1,097.2391	1,071.8704	1,109.7596	5.6200	5.0100	5.2900	22,499.8330
2/10/24 15:30	22.3108	23.4682	28.8106	53.0337	45.8803	51.3090	45.0600	55.3014	50.7143	969.1965	982.0201	1,066.5221	1,080.0575	1,113.1841	1,077.5818	1,101.2231	1,071.7446	1,113.1841	5.2200	6.2800	5.8600	22,500.3735
2/10/24 15:45	22.4469	23.2994	28.5056	54.1518	45.7632	52.7106	44.9428	55.6295	53.0189	940.3658	950.2668	1,041.2410	1,082.0479	1,111.0250	1,079.5419	1,098.5480	1,078.0273	1,111.0250	5.0100	7.6600	5.1200	22,499.7832
2/10/24 16:00	22.3107	23.3674	29.7232	56.6089	46.7482	54.9787	45.9982	56.2632	55.7230	908.7284	915.9650	1,001.9845	1,077.6862	1,112.5646	1,076.9369	1,099.9215	1,074.6836	1,112.5646	5.3400	6.9000	6.0700	22,219.1543
2/10/24 16:15	22.3107	23.3344	29.4186	55.2622	53.6556	46.6086	46.6321	55.1592	54.7599	871.4667	882.0302	961.9739	1,080.0817	1,076.7975	1,112.3513	1,099.6666	1,041.4269	1,076.7975	6.4800	6.1400	5.8300	21,749.2969
2/25/24 13:00	23.3736	21.4115	23.2150	53.8842	43.2108	52.5136	44.2454	37.1030	52.5136	1,028.2832	1,041.4512	1,143.5532	1,116.8775	1,083.8967	1,128.1591	1,116.8775	1,059.9010	1,095.7000	5.3500	5.5900	4.7700	23,435.8026
2/25/24 13:15	23.1019	19.1494	22.8766	57.4290	43.1402	55.4913	43.7055	36.3039	55.4913	1,042.6910	1,062.2751	1,163.5702	1,117.0713	1,080.5840	1,128.3549	1,117.0713	1,056.1517	1,091.2740	5.1600	5.5900	4.9400	21,800.1703
2/25/24 13:30	23.0672	15.9083	23.8918	56.2695	45.8890	54.9699	45.5569	38.2538	54.9699	1,043.7610	1,049.8677	1,166.2209	1,119.2767	1,065.3365	1,130.5825	1,119.2767	1,051.9402	1,087.2721	6.0900	3.5400	4.2600	21,799.9659
2/25/24 13:45	23.0672	18.4741	24.5686	54.8005	46.7583	53.6427	46.6815	38.9350	53.6427	1,052.2510	1,056.8019	1,183.2018	1,117.8510	1,067.4620	1,129.1425	1,117.8510	1,047.8568	1,081.7095	5.5600	7.0200	4.9200	21,800.1618
2/25/24 14:00	23.0349	17.1911	24.0249	43.4390	42.5968	41.5014	47.8293	41.1167	48.7511	1,095.8541	1,106.7782	1,214.5199	1,118.9970	1,104.1051	1,130.3000	1,118.9970	1,078.4314	1,114.2853	6.0700	6.3500	6.0700	22,176.5281
2/25/24 14:15	23.0353	21.2087	23.8212	46.7950	45.3893	44.5975	47.4622	43.7918	47.5481	1,074.7991	1,088.5397	1,178.2997	1,118.4546	1,104.1051	1,129.7521	1,118.4546	1,045.5052	1,079.7737	6.3800	6.3000	6.3800	21,999.9527
2/25/24 14:30	22.8312	19.7570	25.2723	46.1086	44.7047	42.6587	47.7982	42.7784	47.0248	1,092.7471	1,103.1372	1,200.1829	1,118.5309	1,116.0614	1,129.8292	1,118.5309	1,074.0959	1,110.8912	5.9300	6.3500	5.9300	21,999.9248
2/25/24 14:45	23.0348	17.7651	24.6965	45.1875	43.7877	42.9427	46.6184	42.0963	46.1965	1,122.2813	1,132.3300	1,238.2891	1,119.0269	1,116.0614	1,130.3302	1,119.0269	1,115.4368	1,153.7036	6.0700	6.3000	6.0700	22,344.4547
2/25/24 15:00	22.9661	19.1493	24.5582	42.4692	40.0721	40.2008	46.0246	38.7331	47.9230	666.4190	620.7225	641.0272	1,118.9970	1,104.1051	1,130.3000	1,118.9970	1,078.4314	1,114.2853	6.3000	5.8300	6.3000	21,708.7453
2/25/24 15:15	22.8304	21.1739	24.4565	52.3001	55.8574	49.4645	44.1947	54.9413	51.4913	997.1786	1,014.4628	1,115.6661	1,119.4446	1,104.1051	1,130.7521	1,119.4446	1,045.5052	1,079.7737	5.9200	5.0000	3.1200	21,210.4335
2/25/24 15:30	22.9670	21.5794	24.2189	54.8997	53.0373	52.9148	40.6795	52.2857	54.9699	846.3928	902.7914	945.8925	1,119.2767	1,116.0614	1,130.5825	1,119.2767	1,074.0959	1,110.8912	5.4500	5.8800	2.0200	21,733.6143
2/25/24 15:45	23.0355	20.6343	22.7968	53.8842	52.0699	52.5136	40.0236	51.2477	53.6427	973.6392	957.1533	943.6705	1,117.8510	1,121.9169	1,129.1425	1,117.8510	1,115.4368	1,153.7036	6.6700	5.6000	1.8700	21,332.0323
2/25/24 16:00	23.3080	20.8032	23.8772	57.4290	52.8913	55.4913	43.2113	52.0222	47.1176	910.7261	941.0927	1,025.9280	1,118.9970	1,097.6735	1,130.3000	1,118.9970	1,073.5543	1,107.5009	5.8600	4.7400	0.2400	21,395.3652
2/25/24 16:15	22.8985	20.6345	23.3333	56.2695	54.2966	54.9699	40.7974	53.4981	50.0461	852.7307	869.1932	1,011.6069	1,118.4546	1,069.5337	1,129.7521	1,118.4546	1,092.6173	1,127.9266	4.7100	3.5500	1.2500	22,898.6348