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Study of the benefits in optimizing the placement and configuration of photovoltaic panels

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Abstract

Shading and low irradiance hinder PV energy production. Optimizing the design of photovoltaic systems is therefore essential for increasing energy output while reducing losses from electrical mismatches.

This thesis proposes a comprehensive simulation-based framework for optimizing panel architecture, rooftop placement tactics, and series grouping procedures, which makes use of irradiance data analysis and algorithmic decision-making.

The study's initial phase evaluates the shading resilience of different PV layouts with respect to the same irradiation pattern. The outcomes highlighted better performance of shingled and half-cell modules compared to conventional full-cell panels, using in-depth I/V characteristic analysis and long-term energy production models.

Starting from these findings, the study presents a data-driven approach to improve panel installation on rooftops. Building on previous research, the approach employs irradiance mapping and clustering to improve panel location.

Furthermore, an automatic series grouping technique based on Pearson time-series correlation is applied in order to ensure reduced losses due to current limitations. In this way, panels operating under similar irradiance conditions are connected in series to the same inverter.

Several real-world-inspired rooftop scenarios are simulated in order to assess the efficacy of the suggested methodology. The automatic panel placement algorithm and grouping strategy are contrasted with manual (by-eye) choices. The results reveal a production increase over hand placement, particularly in complex shading scenarios.

Lastly, a ROI analysis evaluates cost-benefit trade-offs in panel selection, grouping, and inverters.

This study emphasizes the relevance of data-driven decision-making in PV system design, by showing that algorithmic methodology provides a safe economic return reducing most mismatch losses. The created framework offers a scalable tool for researchers and industry to optimize solar energy.

ACKNOWLEDGMENTS

To my family and friends, and their unwavering support;
to those who reignited in me the joy of discovery,
especially to my supervisor, Sara Vinco.

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Acronyms

PV	Photovoltaic.
MPP	Maximum Power Point.
ROI	Return Of Investment.
MPPT	Maximum Power Point Tracking.
G	Irradiance.
I	Current.
V	Voltage.
T	Temperature.
DC	Direct Current.
AC	Alternate Current.
GIS	Geographic information system.

Chapter 1

Introduction

Environmental concerns are driving the transition from fossil fuel-based energy generation to renewable alternatives.

PV technology is an important option for future energy needs, as it promotes localized power generation and reduces carbon emissions. In addition, it is currently the most widely used renewable energy source because of its low cost, minimal impact on existing infrastructure, and economic incentives. However, various obstacles remain that limit the efficiency of PV systems, leading to energy losses and hindering PV systems from reaching their full potential.

One of the most significant design challenges for PV systems is determining how to optimally position and connect panels to maximize energy output while reducing losses. Due to panel layout issues and net production discrepancies, shading effects with uneven distribution of irradiance can cause significant drops in energy production. Moreover, inverter constraints that dictate the law of series-parallel connections introduce additional complexity, which requires a systematic approach to ensure optimal power conversion.

The goal of this thesis is to create a thorough methodology to maximize the efficiency of photovoltaic systems using sophisticated grouping techniques, intelligent placement tactics, and panel layout analysis. The study focuses on:

1. Evaluating the behavior of several PV module configurations (half-cell, full-cell, and shingled) by simulating and contrasting them under the same shading conditions.

2. Using clustering and spatiotemporal analysis methods to identify rooftop regions with high levels of irradiation.

3. Exploiting temporal correlation to optimize series and parallel panel grouping, in order to minimize mismatch losses.

4. Analyzing the economic feasibility of various system configurations using a Return of Investment (ROI) study to balance cost and performance.

To achieve these objectives, the proposed methodology will be implemented in a Python-based simulation framework that combines electrical simulation models with

GIS-based irradiance data. By using greedy placement and clustering techniques, it will provide design recommendations based on meteorological and building data. Furthermore, the framework will be able to simulate the energy output of PV systems over long time periods within tolerable computational timescales.

In order to present the above-mentioned themes with precision and clarity, the thesis is organized as follows:

- **Chapter 2** provides fundamental information on photovoltaic technology and associated components, shading effects, and existing optimization techniques.
- **Chapter 3** explains the adopted process to model the configurations of the PV modules and assess their effectiveness.
- **Chapter 4** describes the panel placement optimization framework and the clustering-based technique.
- **Chapter 5** examines the parameters of a ROI analysis, studying the trade-offs between inverter size, panel positioning, and selection.
- **Chapter 6** emphasizes comparing automated and manual settings, validating and testing the suggested methods, and performing ROI assessments.
- **Chapter 7** wraps up the study by highlighting the main conclusions and suggesting future directions.

In general, this study aims to offer designers and installers a practical, scalable, and computationally efficient methodology to optimize the design of photovoltaic systems by addressing both technical and financial difficulties.

Chapter 2

Background

2.1 Introduction

The constant popularity growth of photovoltaic energy has led to a significant improvement in the technologies used in relation to production efficiency and cost reduction. PV technology is widely regarded as one of the most promising sources of clean energy, with benefits like as environmental sustainability, energy security, and decentralized power generation.[1]

However, there are still many obstacles to overcome in order to have a production system that can be applied regardless of the characteristics of the scenario. Using some free quotations of articles that deal with the topic [2] [3], the efficiency of the photovoltaic system is highly dependent on various external and internal elements, including solar irradiation, temperature changes, module connectivity schemes, and shading circumstances. Among these, shading and significant variations in the radiation values captured on the panels remain among the factors with the greatest impact on losses, causing mismatches that have a major effect on overall energy production.

This chapter provides an overview of the fundamentals of photovoltaic systems, the effects of shading, the most suitable metrics to evaluate irradiance oscillations and recent research contributions aimed at improving energy extraction in environments mainly affected by non-constant shading. We pay special attention to shade mitigation methods, PV module configuration tactics, and GIS-based PV placement optimizations.

2.2 Photovoltaic Systems: Fundamentals and Performance Factors

2.2.1 Overview of PV Technology

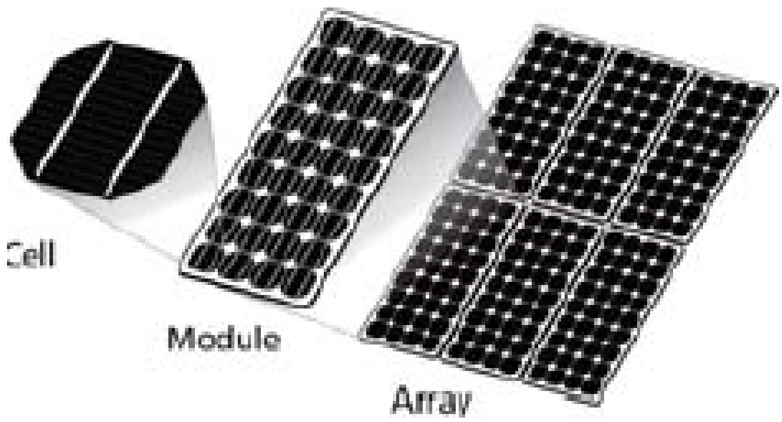


Figure 2.1: Panel hierarchy

A photovoltaic system is an energy conversion system that converts solar radiation into electricity using the photovoltaic effect. The main components of a PV system are:

- **Photovoltaic Cell:** Semiconductor device, generally made of silicon, which generate current when exposed to sunlight. The electrical behaviour of a cell can be described by an ideal current source, proportional to solar irradiance, and by a diode connected in anti-parallel. A cell is described by a voltage-current (IV) characteristic curve, which, at a given cell temperature, changes as a function of the irradiance G. When G increases, the open-circuit voltage V_{OC} increases logarithmically and the short-circuit current I_{SC} increases proportionally. With fixed irradiance G, a temperature increase yields a slight increase of the short-circuit current I_{SC} which gives a decrease of the open-circuit voltage Voc (solid line).[4]

- **Photovoltaic Modules:** More commonly called panels, agglomeration of cells connected in series or in parallel according to a predefined scheme.

- **PV Arrays:** Multiple panels connected in series or in parallel to meet the required power demand

- **Inverter:** Converts direct current (DC) generated by PV modules into alternating current (AC) suitable for general purposes.

- **Charge Controller and Battery System (not mandatory):** Used in off-grid or hybrid systems to collect energy for later use.

Photovoltaic systems are generally classified into 3 categories based on the use of the produced power.

- **Grid-connected systems:** Systems directly connected to the grid, to which they immediately supply the produced power, using the same grid as an energy backup.
- **Off-grid systems:** The system operates independently from the grid. The generated power is usually stored in batteries to compensate for the shortage in times of low or absent production.
- **Hybrid systems:** The energy produced by the panels is compensated by that produced by other sources (wind, carbon, etc..), connected to the same grid to promote constant availability (Fig. 2.1).

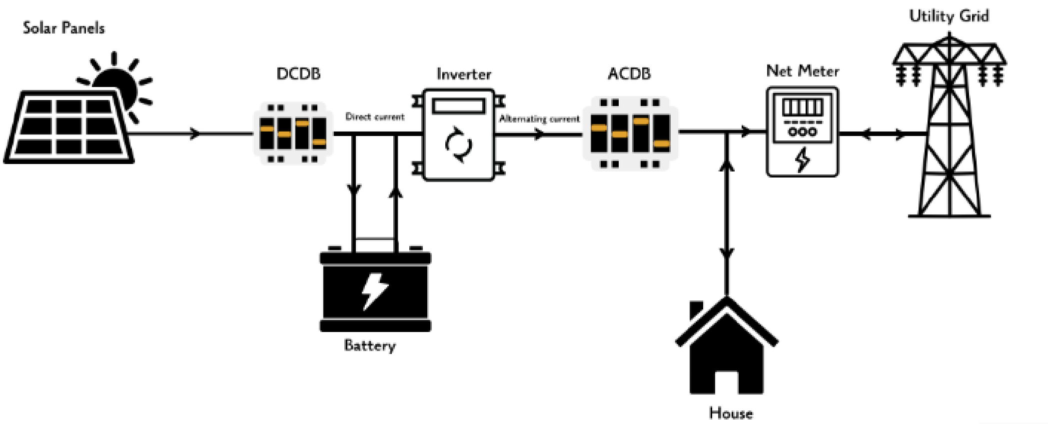


Figure 2.2: Hybrid system schema

2.2.2 Factors Affecting PV Module Performance

Numerous elements that fall into the categories of intrinsic (related to design) and extrinsic (related to environment) factors affect the energy output and efficiency of PV systems.

1. **Solar Irradiance**

   The most important factor influencing the performance of PV systems is solar irradiation, that refers to the total solar power per unit area radiating the PV module (measured in W/m²).

   Freely quoting one of the articles cited below, higher irradiance leads to greater power generation, while clouds, atmospheric dust, and seasonal variations reduce available sunlight [2]. In ideal conditions, the relationship between irradiance and power output is linear, which means that doubling irradiance leads to virtually doubled power generation.[1]

Since the performance of photovoltaic cells is strongly influenced by the intensity of sunlight exposure, it is essential to ensure that this is as homogeneous and constant as possible..

2. **Temperature effects**

   Although, as previously mentioned, the photovoltaic cell's current production depends on solar exposure, excessive temperature reduces its efficiency. This behavior is caused by the following factors:

   - A decrease in open-circuit voltage V_{OC} as temperature rises.
   - An increase in short-circuit current I_{SC}, but at a lower rate than the voltage drop, resulting in net power loss[1]

   As stated in the article *GIS-Based Optimal Photovoltaic Panel Floorplanning for Residential Installations*[4], quantitatively speaking, higher module temperatures (above 25°C STC) cause a typical power loss of 0.4-0.5% per °C for standard crystalline silicon PV cells.

3. **Shading effect and mismatch losses**

   Partial shadowing from clouds, buildings, trees, or debris can have a significant impact on the output of PV systems. When a single panel in a series string is shaded, it functions as a resistor, limiting the current flow throughout the string. When PV modules are under 20% partial shading conditions, and the irradiance is between 1000 and 700 W/m2, maximum power declines by around 6.22% for every 100 W/m2 drop in irradiance.[5]

2.2.3 Array configurations

The performance of the system is greatly impacted by the electrical configuration between the PV modules. Among the most popular configurations are:

- **Series Connections:** Connecting modules in series increases the output voltage while keeping the current constant. However, a single shaded panel affects the entire string.

- **Parallel Connections:** Modules connected in parallel cause the voltage to remain constant in the circuit, while the total current is the sum of the currents of the modules in series, reducing the impact of shading on individual panels.

The connection scheme between the modules of the system therefore plays a crucial role in the power produced by the entire system, closely linked to the components that regulate the conversion of the DC produced by the modules into AC, i.e. the inverters. They maintain grid compatibility by controlling voltage, frequency, and phase, and they maximize energy production by tracking the maximum power points.

A more detailed analysis of these behaviors is provided in Section 4.3.

2.2.4 Maximum power point tracking

MPPT techniques are crucial for enhancing the efficiency of photovoltaic systems by continuously adjusting the operating voltage to extract the maximum available power under varying solar irradiance and temperature conditions.[6]

MPPT algorithms are implemented into PV inverters and charge controllers, ensuring that solar panels provide their maximum power output despite variations in sunshine. Since a PV module's power-voltage (P-V) characteristic is nonlinear, the system would function at a suboptimal point without MPPT, resulting in large energy losses. Although there are several MPPT methods, Perturb & Observe is the most widely used because it is straightforward, while incremental conductance offers faster reaction times in situations when the irradiance changes quickly. Advanced approaches, such as Fuzzy Logic MPPT and Neural Networks, enhance tracking accuracy and adaptability, making them appropriate for smart grid applications in partially shaded areas. An effective implementation of MPPT can boost the energy yield by up to 25%, greatly improving the overall performance and viability of photovoltaic systems from an economic point of view.

2.3 Shading and Irradiance Variability in PV Systems

Shading and non-uniform irradiation are major issues for developing efficient PV systems. Understanding and predicting solar irradiance fluctuations throughout the day is critical. When a solar panel is partially shaded, its output current decreases, and in string-connected configurations, the weakest panel limits the current flow through the entire string, reducing the overall power production.

The impact of static impediments such as buildings, poles, and trees was the main focus of early study on shading effects, which have been researched for decades. Modern research now examines dynamic shading conditions, such as cloud motions and seasonal fluctuations. In the case of areas intended for the installation of PV systems such as roofs of houses or industrial warehouses, shading originates from multiple sources:

- **Fixed Obstructions:** At some times of the day, permanent shade is produced by trees and surrounding structures.
- **Self-Shading:** Panels arranged in rows can cast shadows on one another, particularly in densely packed solar farms.
- **Dynamic Shading:** Rapid variations in sun irradiance are caused by moving clouds and transient obstacles (such as dust buildup or bird droppings).

Partial shading can lead to the formation of hot spots, increasing the internal temperature of the shaded cells and ultimately accelerating module degradation.[1]

In order to limit the resulting issues, some technologies have been adopted over the years. Here follow some of the main ones:

- **Bypass diodes:** Mitigate shading effects in solar panels by creating an alternate current path when a cell is shaded (Fig.2.2). Without them, the high resistance of shaded cells can produce hotspots, decreasing efficiency and even causing panel damage. Because the diodes and cell strings are connected in parallel, current can flow through blocked areas. This keeps the system from failing or overheating and guarantees a steady power output.

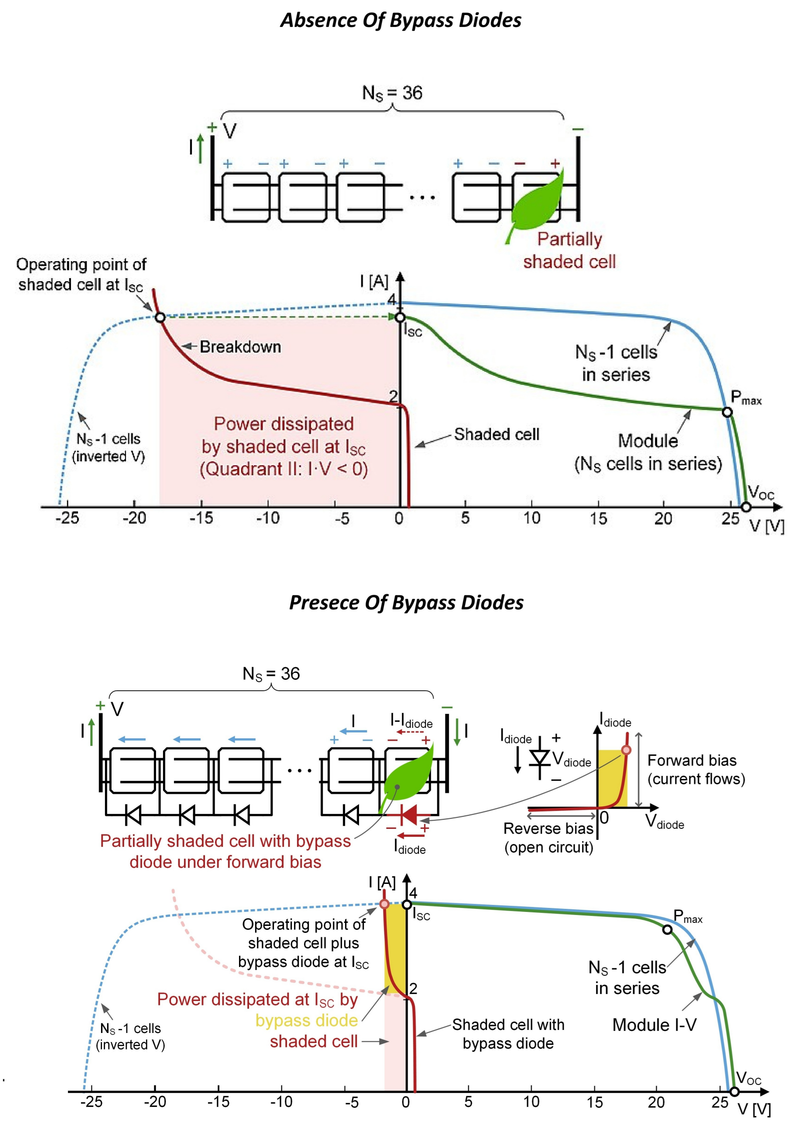


Figure 2.3: Presence and absence of Bypass Diode effect on shading area. image taken from *César Domínguez*, avaiable on *[7] and [8]*

- **Series and parallel module schema:** Reconfiguration techniques are one of the most important method for minimizing partial shading conditions. The reconfiguration techniques are SP (Series-Parallel), TCT (Total Cross Tied), BL (Bridge Link), Su Du Ku, Fixed and so on. The average mismatch loss reduction for the shifting based static reconfiguration technique has 22%. [3]

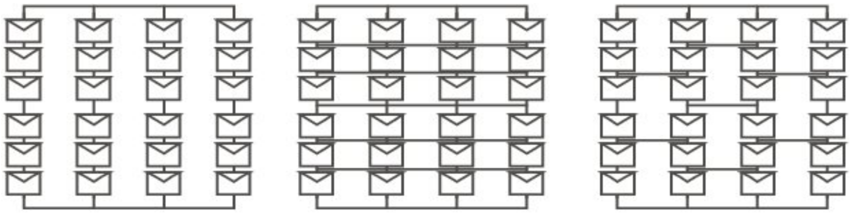


Figure 2.4: SP, TCT, BL comparison schema *Smita Pareek*, avaiable on *[9]*

- **Half-cut cells:** Using solar panels with half-cells can be one of the solutions to reduce the impact of high temperatures on the energy generated by solar panels. This is possible thanks to the presence of low resistance connection bars, as well as the reduction of the current passing through the conductors due to the division of the cells and the solar panel into two halves.

  For a standard configuration of full-cell panels with 3 bypass diodes, when some cells of a string are exposed to the shade, a third of the panel's power will be lost, but in the case of the half cut cell exposed a string to the shade, a sixth of the panel's power will be lost.[10]

- **Micro-inverters:** Instead of converting direct current (DC) to alternating current (AC) for a whole string of modules, micro inverters are module-level power electronics that do so at the individual panel level. Unlike standard string inverters, where the weakest panel limits the performance of the entire series, micro inverters function independently, increasing energy extraction even when shaded or partially obstructed. Micro inverters and power optimizers significantly improve energy yield in shaded conditions by allowing each panel to operate at its own maximum power point.[11]

  A more in-depth analysis on the advantages and disadvantages of this technology is done in chapter 5 dedicated to ROI.

- **Shadow Tracking and GIS-Based Solutions:** Geographic Information Systems (GIS) play an important part in current PV system design by analyzing geographical and environmental data to maximize solar energy production. To identify the ideal sites for solar panel installations, GIS-based technologies combine information on solar radiation, topography elevation, weather patterns, and shading studies. GIS-based techniques enable precise modeling of solar potential in urban and rural landscapes, identifying areas with the least shading interference and highest energy yield[4].

  Furthermore, by estimating temporal fluctuations in sunlight exposure using topography analysis and cloud movement prediction models, GIS makes it possible to forecast shading events. The integration of GIS with real-time weather monitoring has been shown to improve energy yield predictions by up to 15%. [4]

  This technique is explored below in the next section.

2.4 Related Work: GIS-Based Optimal Photovoltaic Panel Floorplanning

Traditional methods rely on rule-of-thumb placement, often ignoring the spatial and temporal distribution of solar irradiance. Instead, as was covered in the previous section, information from Geographic Information Systems (GIS) is crucial to the optimization of photovoltaic (PV) system floorplanning. GIS provides high-resolution irradiance maps, topography models, and environmental restrictions, which provide the basis for algorithmic panel positioning, energy yield forecasts, and cost-benefit evaluations. Numerous research studies have expanded these GIS datasets to improve efficiency evaluation, layout optimization, and PV site selection.

The method described in the cited article determines an optimal irregular panel arrangement that maximizes solar energy capture by utilizing historical solar data and GIS research.

2.4.1 Using Time-Series Data for Irradiance Analysis

In order to evaluate how the selected area is irradiated during a long time span, it is important to work on values that retrace temporal instants for the entire duration, such as time series. Time series are important to predict the evolution of irradiation and shadow patterns over time in order to predict the most irradiated areas.

In the case that lays the foundation for this thesis work, the historical solar data and GIS research are transformed into a three-dimensional G matrix in order to realize a framework that tries to select the panel positions on the most irradiated areas of the map by relying on the resulting data set.

2.4.2 Importance of Metrics in PV Optimization

In order to use the temporal data, it is important to define an aggregation metric that can provide the necessary information to summarize solar exposure. The suitability metric should distill the temporal traces into a compact signature that synthesizes the distribution of G and T values. The obvious choice of using the average is not a good choice because the typical distributions of irradiance and temperature are strongly skewed towards smaller values, and the average is not a representative value. As a more aggregate indicator, the study suggests using the 75th percentile of irradiance values derived from long-term GIS solar mapping data as a compact metric. Therefore, the suitability metric should combine the percentiles of G (favoring larger values since larger G values are beneficial) and T (favoring smaller values, since smaller T values are beneficial).[4]

2.4.3 Algorithmic Positioning of PV Panels

After processing the GIS data, algorithmic techniques can be used to optimize PV panel placement.

The calculation of an optimal placement requires an exhaustive enumeration of all possible candidate grid points, which becomes quickly unfeasible even for small areas. The solution space has a worst case size of $O(10^{67})$ solutions. [4] For this reason, it was preferred to opt for a greedy positioning approach. The greedy placement algorithm is a popular method that prioritizes the most irradiated areas by iteratively selecting the best locations first.

Their findings show a 20-30% increase in energy production compared to traditional compact placements, emphasizing the necessity of a fine-grained placement technique over simple uniform layouts.

2.4.4 A Microservices-Based Framework for PV System Design and Optimization

Incorporating the steps described above, the cited article [12] discusses a possible microservices-based framework that integrates multiple design and optimization aspects into a modular architecture.

- Allows dynamic selection of PV modules and their series-parallel configuration.
- Utilizes high-resolution spatio-temporal irradiance data for precise optimization.
- Implements flexible simulation models, incorporating well-defined placement algorithms and performance forecasting.

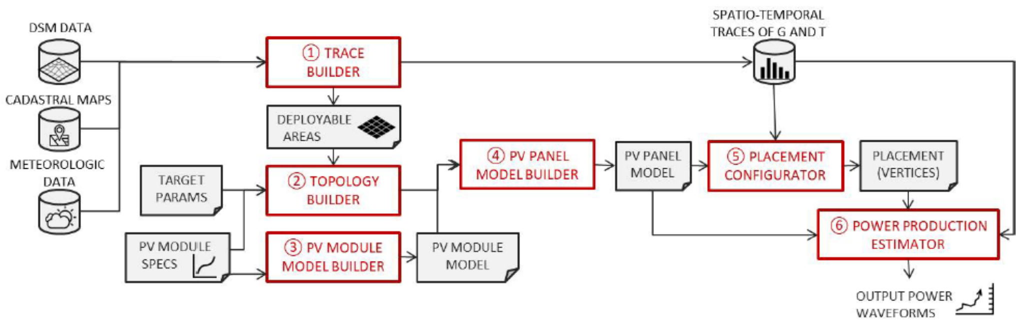


Figure 2.5: Microservices structure for GIS-based Photovoltaic Panel Floorplanning [12]

This method's modular adaptability is a crucial feature since it allows users to include unique algorithms for inverter selection, shading analysis, and panel arrangement.

Analyzing Figure 2.4:

- **The trace builder** takes care of the previously mentioned operation of data generation and cleaning aimed at creating the three-dimensional matrix of G, T and shadow patterns.

- **Topology builder** uses algorithms that extrapolate the most suitable configuration in terms of number of panels, inverters and other configurations related to the system topology.
- **Blocks 3 and 4** deal with the creation of a system capable of simulating the behavior of a single module, based on the I/V characteristics of the selected cell and of connecting series of panels
- **Placements configurator** module uses the output of previous blocks to provide the best placement and grouping configuration solution in order to minimize losses and also energy output.
- **The Power Production Estimator** block estimates the power production of the PV installation, given the placement of PV modules, their connection and the traces of G and Tsolair over time [12].

The study demonstrates that flexible design approaches yield greater efficiency and financial benefits than strict pre-established patterns, laying the foundation for the development of the simulation framework carried out during this thesis work. In the following chapters, the modules ranging from the topology decision and the simulation of a single cell to the production estimate of the plant will be studied in detail, taking for granted the part of the generation of the three-dimensional matrix commanded to the trace builder.

2.5 Summary

Principles of photovoltaic systems were examined in this chapter, with an emphasis on important performance elements like shading, temperature effects, and sun irradiance. The effects of various electrical connectivity systems (parallel and series) on mismatch losses and energy efficiency were examined.

Several shading mitigation techniques, including bypass diodes, half-cell modules, and micro inverters have been introduced, demonstrating their effectiveness in improving power production under non-uniform irradiance. GIS-based PV placement approaches were mentioned, focusing on the 75th percentile irradiance parameter to locate high-energy regions for optimal panel placement.

Furthermore, relevant studies on PV modeling and optimization were examined with the benefits of algorithmic panel placement and GIS-driven floorplanning, also highlighting how crucial flexible design strategies are to optimize energy yield.

This foundation serves as the groundwork for the subsequent chapters, which will go deeper into simulation methodology, panel comparisons, and optimization strategies, in order to improve PV system performance and economic feasibility.

Chapter 3

Approach and Methodology for PV Module Simulation

3.1 Introduction to the Methodology

The approach focuses on maximization of the energy output of photovoltaic (PV) panels taking into account the importance of various production limits, such as variability in irradiance and shading effects. Providing a detailed analysis of individual cells and modules, this approach progresses to a systematic comparison of panel configurations to evaluate their performance under various conditions. The goal is to offer a solid framework for understanding how electrical connections and shade patterns affect panel efficiency. In particular, designs that reduce the effect of shading are evaluated in order to minimize losses resulting from current mismatches in series connections. The flow of the application involves several steps, each of which is built on the previous one:

- **Simulation of individual photovoltaic cells:** The first step is based on understanding the I / V characteristics of individual cells under varying irradiance and shading conditions, which provides the basis for the module-level analysis.
- **Modeling of entire modules:** At that point, the key challenge is to add the impact of shading, layout configuration (series and parallel connections), and the presence of bypass diodes on overall module performance.
- **Comparison of different panel layouts:** Progress with the comparison of various panel designs to determine the most efficient under partial shading conditions.

This methodology is built to provide a systematic approach for evaluating and optimizing photovoltaic panel designs, allowing informed decisions on the selection of the layout and enhancing overall energy production. It sets the groundwork for future studies into system-level optimization by concentrating on individual cells and module configurations.

3.2 Simulation of Single Cell Behavior

The initial phase of this process entails simulating the electrical performance of individual photovoltaic cells under different irradiation conditions. This simulation provides a foundational knowledge of how a single cell responds to changes in sunlight intensity, with the aim of building the basis for the more complex analysis of module and array performance. Instead of directly using equations like the Shockley diode model, this approach models representative I/V curves (for example, derived from graphs like the one shown in Figure 3.1) to simulate the electrical response of individual cells under different irradiance conditions. This strategy simplifies the process while providing accurate data for the subsequent simulation of modules.

3.2.1 Model Assumptions

The model provides data on how irradiance directly impacts the cell's performance, independent of module-level effects such as shading or connections. Here follows the parameters, with appropriate key assumptions, adopted for the simulation of single-cell behavior

- **Irradiance:** A wide range of irradiance levels, which represent the amount of solar power incident on the cell's surface, are studied. This factor is a major determinant of cell performance.
- **Shading effects:** The effects of shading are not considered at the cell level but are incorporated later at the module level, where the interactions between cells become significant.
- **Fixed Temperature:** The cell behavior is modeled at a constant temperature of 25°C (in standard test conditions). Temperature fluctuations is also a key factor that can influence performance, however they are not considered in this simulation to better focus on the impact of irradiance and shading.
- **Electrical Characteristics:** The current-voltage (I/V) characteristics of the cell are modeled to illustrate its behavior under different levels of irradiance and temperature. The goal is achieved showing how current and voltage are related and how these values change with varying environmental conditions.

3.2.2 Simulation Process

The I/V characteristics of a PV module are obtained from graphs that represent the ideal performance of the module under different levels of irradiance at a fixed temperature of 25 ° C (Fig. 3.1). The following steps are performed to derive the I/V curves for a single cell.

1. **Data Extraction:**

- The shapes of the I/V curves for different irradiance levels are obtained directly from the graph due to different colors. A specific function extrapolate some points from each identified curve, corresponding to a specific irradiance level (e.g., 1000 W/m², 800 W/m²).
- The extracted data includes all identified curves represented as labeled voltage-current point lists for the entire module. This structure is illustrated in the following pseudo-code:

```
FUNCTION:
    extract_curves_by_color
INPUT:
    - image_path: Path to the image containing I/V curves
    - max_I: Maximum current for scaling (A)
    - max_V: Maximum voltage for scaling (V)
    - num_curves: Number of curves to identify in the graph

OUTPUT:
    - all_curves: A list of labeled I/V curves (voltage-current
    points)

STEPS:
1. Load the image from the given path.
2. Convert the image to the HSV color space to facilitate color
    segmentation.
3. Define color ranges (HSV bounds) for each curve based on user
    selection or pre-defined values.
   - Use these ranges to isolate each curve in the image.
4. Initialize variables for the image dimensions and the real-
    world ranges of voltage and current.
5. For each defined color range:
   a. Create a mask to isolate pixels corresponding to the curve'
    s color.
   b. Apply the mask to the image to extract only the relevant
    curve.
   c. Detect contours in the masked image using edge detection.
   d. For each contour:
      i. Extract pixel coordinates (x, y) along the curve.
      ii. Convert these pixel coordinates into real-world voltage
     and current values using scaling based on the image
    dimensionsnand max_I/max_V.
   e. Filter and clean the extracted points to remove outliers
    and noise.
   f. Store the filtered curve points with the corresponding
    label.
6. Return all extracted curves as labeled voltage-current point
    lists.
```

2. **Normalization for Single Cell:**

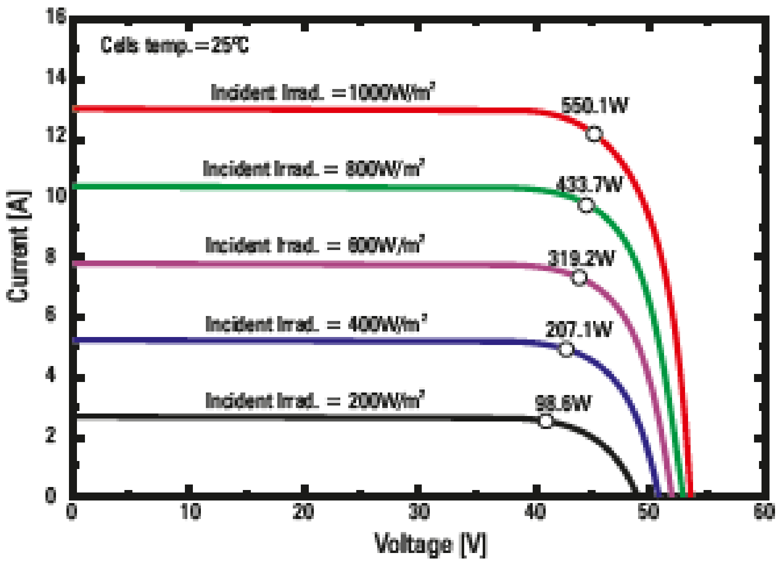


Figure 3.1: I/V characteristic of the module

- The next step is to derive the behavior of a single cell. the voltage and current values are therefore divided by the total number of cells in the module configuration:
  - **Voltage normalization:** The module voltage is divided by the number of cells connected in series.
  - **Current normalization:** The module current is divided by the number of parallel-connected cells.
- The result is a representative I/V curve for a single cell under the specific irradiance conditions.

3. **Interpolation for Intermediate Levels:**

   With the aim of obtaining irradiance levels not directly available in the extracted data, the I/V curves are interpolated between the nearest curves. If the irradiance value is below the one of the lowest available curve, is possible to obtain the resultant interpolating between the closest one above and a fixed curve at 0 A. This allows the simulation to provide a continuous range of single-cell behavior across all possible irradiance values.

3.2.3 Key Outputs

Following the simulation steps, the outputs obtained for the single-cell behavior are the subsequent:

- The correlation between current and voltage of an individual photovoltaic cell is obtained for continuous irradiance levels.

- The corresponding curve, derived from normalized and interpolated data, accurately represents the electrical response of the cell.

- The maximum power point (MPP) can be obtained for each curve, which is representative of the highest power output achievable under specific irradiance conditions.

The resulting single-cell I/V curves establish the basis for the foundational dataset, to model the performance of larger systems.

The next section focuses on the simulation of photovoltaic modules, where cells are interconnected; and their interactions are modeled to account for real-world conditions.

3.3 Simulation of a Single Module

A module is made up of cells connected in series/parallel, which leads to the fact that his performance is an extension of the analysis of individual cells (analyzed in the previous section), combined with the affection of the interconnection scheme. This simulation uses the single-cell I/V curves generated in 3.2, which are modeled for various irradiance conditions, to scale performance to the module level. Additionally, the simulation incorporates the effects of non-uniform irradiance (shading), which introduces current mismatches between cells and impacts module performance.

3.3.1 Scaling Single-Cell Data to Module Level

In order to simulate the performance of a specific configuration of a PV module, is essential to aggregate the single-cell I/V curves in a way that mirrors the series/parallel connections. This involves scaling the voltage and current reflecting inner panel's interconnection:

1. **Series Connections:**

   - In series, the module voltage is the sum of the voltages of all cells, while the current remains constant:

$$V_{\text{module}} = N_{\text{series}} \cdot V_{\text{cell}}$$

$$I_{\text{module}} = I_{\text{cell}}$$

```
 FUNCTION:
    sum_series_modules
INPUT:
    - V1, I1: I/V curve of the first module in series.
    - V2, I2: I/V curve of the second module in series.

OUTPUT:
    - V_total, I_total: Combined I/V curve of the two modules
     in series without bypass diodes.

STEPS:
```

```
1. Determine the limited current range based on the overlap
   of the two modules.
2. For each current point in the limited range:
    a. Interpolate the corresponding voltage for each module.
    b. Add the module voltages to calculate the total voltage
    .
3. Return the combined I/V curve.



```

2. **Parallel Connections:**

   - In parallel, the module current is the sum of the currents of all cells, while the voltage remains constant:

$$I_{\text{module}} = N_{\text{parallel}} \cdot I_{\text{cell}}$$

$$V_{\text{module}} = V_{\text{cell}}$$

```
FUNCTION:
    sum_parallel_modules
INPUT:
    - V1, I1: I/V curve of the first module in parallel.
    - V2, I2: I/V curve of the second module in parallel.

OUTPUT:
    - V_total, I_total: Combined I/V curve of the two modules
     in parallel.

STEPS:
1. Combine the voltages of both modules into a unified set of
     voltage points.
2. For each voltage point:
    a. Interpolate the corresponding current for each module.
    b. Add the module currents to calculate the total current
    .
3. Sort the combined I/V curve data.
4. Add points to extend the curve to zero voltage and maximum
     current, if necessary.
5. Return the combined I/V curve.

```

3. **Combination of Series and Parallel Connections:**

   - In a case when the module electric configuration is a combination of series and parallel connections:

$$I_{\text{module}} = N_{\text{parallel}} \cdot I_{\text{cell}}$$

$$V_{\text{module}} = N_{\text{series}} \cdot V_{\text{cell}}$$

This aggregation allows the I / V characteristics of the module to be derived under uniform irradiance conditions.

3.3.2 Shading Effects

Non-uniform irradiance, in the majority of the cases, is caused by shading or partial obstructions. These can introduce current inequalities in series-connected cells, affecting the overall module performance. That section is going to address this issue.

1. **Impact of Shading:**
   - Cells receiving less irradiance produce a lower current, which limits the current for the entire series string.
2. **Bypass Diodes:**
   - To mitigate shading effects, modules include bypass diodes. These diodes allow current to bypass shaded cells, reducing power losses.
   - When the current in a shaded cell falls below a certain threshold, the bypass diode is engaged, thereby removing the cell from the series.

```
FUNCTION:
    sum_series_moduled_with_diodes
INPUT:
    - V1, I1: I/V curve of the first module in series.
    - V2, I2: I/V curve of the second module in series.
    - Vd: Voltage drop across bypass diodes.

OUTPUT:
    - V_total, I_total: Combined I/V curve of the two modules
     in series, considering bypass diodes.

STEPS:
1. Combine the currents of both modules into a unified set of
     current points.
2. For each current point:
    a. Interpolate the corresponding voltage for each module.
    b. Add the module voltages to calculate the total voltage
    .
    c. If the current exceeds the limit for either module,
    account for the voltage drop due to the bypass diode.
3. Sort the combined I/V curve data.
4. Add points to extend the curve to zero current and zero
    voltage, if necessary.
5. Return the combined I/V curve.
```

3. **Resulting Curve:**

   - The resultant module I/V curve is then generated by combining the I/V curves of all cells, taking into account the series and parallel connections, as well as the activation of bypass diodes where necessary.

3.3.3 Key Outputs

The simulation produces the following outputs:

1. **I/V Curves:**

   - The module's I/V curves are generated for various irradiance conditions, including both uniform and shaded scenarios.
   - Therefore, the resultant illustrate the module's performance, including the effects of current limiting and bypass diode activation.
   - Taking into account the non-uniform irradiance on the module, the I/V curve gets a humpbacked silhouette (fig. 3.2)

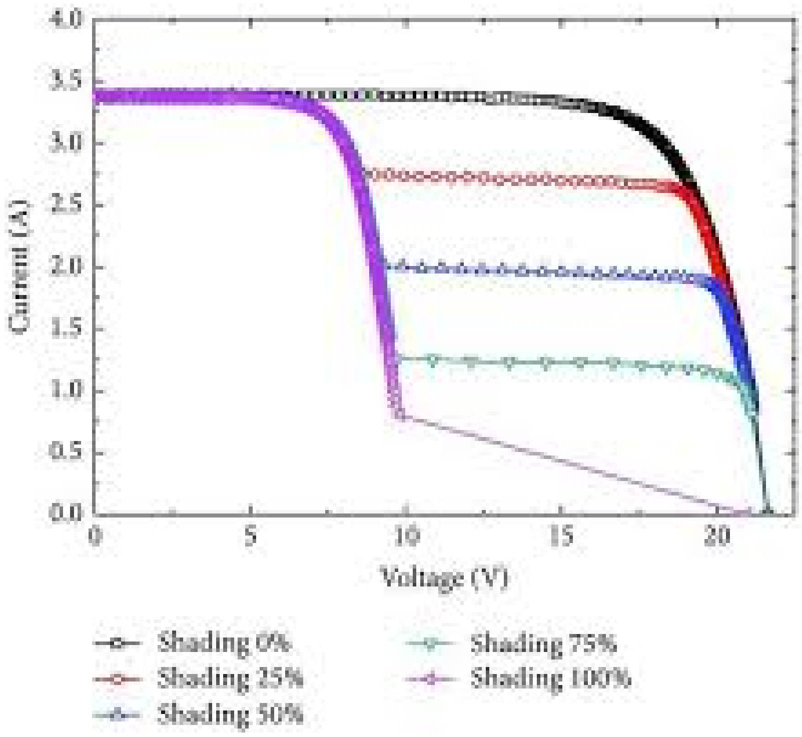


Figure 3.2: I/V characteristic of the module with shadowing

```
FUNCTION:
    simulate_module
INPUT:
    - V1, I1: I/V curve of the first module in series.
    - V2, I2: I/V curve of the second module in series.
    - Vd: Voltage drop across bypass diodes.

OUTPUT:
    - V_total, I_total: Combined I/V curve of the two modules
     in series, considering bypass diodes.

STEPS:
1. Combine the currents of both modules into a unified set of
     current points.
2. For each current point:
    a. Interpolate the corresponding voltage for each module.
    b. Add the module voltages to calculate the total voltage
    .
    c. If the current exceeds the limit for either module,
    account for the voltage drop due to the bypass diode.
3. Sort the combined I/V curve data.
4. Add points to extend the curve to zero current and zero
    voltage, if necessary.
5. Return the combined I/V curve.
```

2. **Power Output:**

- Like for the single-cell behavior, for each scenario, the power output of the module at the maximum power point (MPP) is calculated:

$$P_{\text{MPP}} = V_{\text{MPP}} \cdot I_{\text{MPP}}$$

- Consequence of the current mismatches, the MPP position can be found at lower values of V, respecting to ideal conditions.

3.3.4 Insights

Each cell in the module experiences a different irradiance level, which directly affects its I/V curve. Using these individual cell irradiance values, the corresponding single-cell I/V curves are scaled accordingly. The resultant module I/V curve is then generated by combining the I/V curves of all cells, taking into account the series and parallel connections, as well as the activation of bypass diodes where necessary.

3.4 Simulating and Comparing Panel Electrical Layouts

The design of a photovoltaic panel's electrical layout plays a crucial role in determining its performance. Different layouts are achieved by varying the interconnections between cells in series and parallel, influencing how the panel behaves under uniform and non-uniform irradiance conditions.

This section outlines the workflow for simulating and comparing the performance of different electrical configurations of a panel. The focus is on the software's ability to flexibly model these configurations and generate the resulting I/V curves for analysis.

3.4.1 Workflow for Configuring Cell Connections

The software supports the flexible definition of cell interconnections within a panel, allowing users to experiment with various electrical layouts. The key steps in this process are as follows:

1. **Input Data Preparation:**
    - A panel-sized irradiance matrix is provided as input. This matrix captures the spatial distribution of irradiance across the panel's surface, representing the irradiance levels experienced by each cell under specific conditions.
    - The I/V curves for individual cells, obtained through the process detailed in Section 3.2, serve as the basis for simulating the electrical behavior of each cell within the panel.
2. **Defining Series and Parallel Connections:**
    - Users specify how the cells are interconnected:
        - **Series Connections:** Cells are connected end-to-end, summing their voltages while maintaining the same current.
        - **Parallel Connections:** Cells are connected side-by-side, summing their currents while maintaining the same voltage.
    - The software supports defining combinations of series and parallel connections, allowing complex layouts to be simulated.
3. **Simulation Process:**
    - For each configuration, the software calculates the overall panel I/V curve by:
        - Combining cell I/V curves based on the specified connections.
        - Simulating current mismatches and applying bypass diode behavior to account for shading effects.
        - Aggregating series and parallel connections to create the complete electrical response of the panel.
4. **Output:**
    - The software provides:
        - The I/V curve of the panel for the defined configuration.

- Key performance metrics, including Maximum Power Point (MPP), which identifies the optimal voltage, current, and power output of the panel under the given irradiance.

3.4.2 Implementation of the workflow

This section provides a detailed explanation of how the software models the electrical behavior. To ensure clarity and reproducibility, the workflow is accompanied by pseudocode, which offers a high-level representation of the key algorithms and processes used in the simulation. The pseudocode highlights the modular and flexible design of the software, which allows users to define and simulate various panel configurations efficiently. The key components and their implementation are described below:

1. **Cell-Level I/V Curve Integration:**
   - Each cell's performance is represented by an I/V curve, scaled according to its irradiance value from the panel-sized irradiance matrix. This allows the software to model the electrical behavior of each cell accurately.
2. **Series and Parallel Connection Simulation:**
   - Building on the module simulation workflow in Section 3.3, this step combines cell I/V curves to generate the overall panel I/V curve.
   - **Challenge:** Current mismatches due to shading can limit the performance of series-connected cells.
   - **Solution:**
     - The software includes algorithms to handle current mismatches by simulating the activation of bypass diodes when necessary.
     - Parallel connections enhance the panel's resilience to shading, as current mismatches are less impactful than in series connections.
3. **Bypass Diode Modeling:**
   - The bypass diode modeling in this section expands on the concepts introduced in Section 3.3.2, where their role in mitigating shading effects at the module level was discussed.
4. **I/V Curve Aggregation:**
   - After processing all series and parallel connections, the software combines the results into a single I/V curve representing the panel's overall performance.

```
FUNCTION:
    compare_instant_module
INPUT:
```

```
    - irradiance_matrix: Matrix of irradiance values for the panel (
    cell-level granularity).
    - single_cell_curves: Precomputed I/V curves for a single cell.
    - layout_config: Configuration specifying series and parallel
    connections.
    - bypass_diode_positions: Positions of bypass diodes in the panel.

OUTPUT:
    - panel_iv_curve: Combined I/V curve of the panel.
    - mpp: Maximum Power Point of the panel (voltage, current, power).

STEPS:
1. Initialize the panel's total voltage and current as empty arrays.
2. For each string of cells in the layout:
    a. Combine the I/V curves of cells in series:
        - Sum the voltages for each current point.
        - Account for current limiting due to mismatch.
    b. If bypass diodes are present:
        - Activate bypass diodes for strings with significantly lower
    current.
3. Combine the I/V curves of all strings in parallel:
    - Sum the currents for each voltage point.
4. Calculate the Maximum Power Point (MPP) from the combined I/V curve
    .
5. Return the panel's I/V curve and MPP.
```

3.4.3 Capabilities of the Workflow

The software is designed to provide a robust framework for simulating panel layouts by leveraging its flexible and modular architecture. Its core capabilities include:

1. **Flexible Configuration:**
    - The software supports arbitrary series and parallel configurations, enabling the modeling of diverse panel layouts. Users can define connection schemes at the cell level, tailoring the simulation to meet specific design requirements.
2. **Realistic Irradiance Inputs:**
    - Incorporates detailed irradiance inputs for each cell, enabling realistic simulations of panel behavior.
3. **Bypass Diode Presence:**
    - The software incorporates bypass diode modeling to handle shading scenarios effectively. This ensures realistic simulations by accounting for current mismatch and isolating shaded sections without penalizing the performance of the entire panel.

4. **Scalability:**

   - The simulation engine is designed to handle various panel sizes and configurations efficiently.
   - As demonstrated in the module simulations of Section 3.3, this workflow is designed to adapt seamlessly to larger systems, such as arrays or full installations.

5. **Output:**

   - The software generates the panel I/V curve and key performance metrics, including the Maximum Power Point. These outputs are suitable for detailed analysis and serve as the basis for further comparisons or optimizations.

3.5 Outcome

The methodology presented in this chapter establishes a flexible and modular framework for simulating and comparing different photovoltaic panel layouts. The workflow provides a rich tool for investigating various design options by allowing exact modeling of series and parallel connections and adding sophisticated features such as bypass diode behavior.

The results lays the groundwork for evaluating the trade-offs between efficiency, shading resilience, and overall performance for the multitude of configurable layouts. The insights gained from these simulations not only support informed decision-making in panel design but also provide the foundation for scaling up to array-level analyses, where layout choices can significantly impact system-level efficiency and reliability.

Chapter 4

Panel Placement Strategies for Enhanced Energy Output

4.1 Introduction

The placement of photovoltaic panels is a key factor in optimizing the energy output of solar systems. Like for the modules, rooftops often present challenges such as uneven irradiance distribution, derived mostly from shading of nearby objects, and geometric or structural constraints. With the aim of gaining the most efficient energy production, it is therefore important to define a systematic approach to overcome losses.

This chapter introduces a methodology to determine the optimal placement of panels on non-uniformly irradiated roofs, based on the panel specification and irradiance data, along with specific derived metrics. In addition to maximizing energy production, the approach considers the electrical interconnections between panels and their impact on inverter performance. Proper configuration of series and parallel connections is essential to minimize mismatch losses and maintain compatibility with inverter voltage and current limits.

The key challenges addressed include:

- **Identifying areas of the rooftop with the highest irradiance potential over time:** Roofs are mostly irradiated with varying levels of sunlight on their surface due to variances in orientation, tilt and obstructions. The optimization process involves analyzing the irradiance data on temporal scales to account for these variations. To address this, the methodology incorporates metrics such as mean irradiance and the 75th percentile (detailed in Chapter 2) to identify regions that consistently receive the most sunlight. According to these high-irradiance areas, is possible to strategically place panels to maximize their energy output over their useful life.

- **Mitigating shading effects to reduce energy losses:** As detailed in chapter 3.3, shading from nearby structures, trees, or other rooftop components can significantly impact panel performance by creating current mismatches also between panels. This aim to the necessity of incorporates shading analysis to identify and avoid areas prone to frequent or severe shading.

- **Balancing panel placement with inverter constraints:** The performance of PV panels is heavily influenced by how they are electrically interconnected and the capabilities of the inverter. Panels connected in series must operate within the inverter's maximum voltage range, while those connected in parallel must respect its current limits. The optimization framework guarantees that panels grouped in series or parallel share similar irradiance and relative I/V curve characteristic, minimizing mismatch losses remaining within the optimal operating range of inverter.

The resulting framework provides an optimal use of irradiance data within optimization algorithms, designing rooftop PV installations that maximize energy production while adhering to practical constraints. These insights are essential for developing efficient and scalable solar energy systems.

4.2 Identifying Panel Positions in High-Irradiance Areas

4.2.1 Overview

Once the angle and the direction are determined, in absence of detailed irradiation and thermal data, rooftop panels are typically placed according to one basic rule: avoid as much as possible evident visible or possible shadings due to local or remote obstacles. When the position is identified, the N modules of the panel are conventionally laid out by packing them together tightly[4]

- **Criticality of less irradiated areas:**

  Since the prediction is fundamentally correct, that rough approximation could lead to an important energy loss.

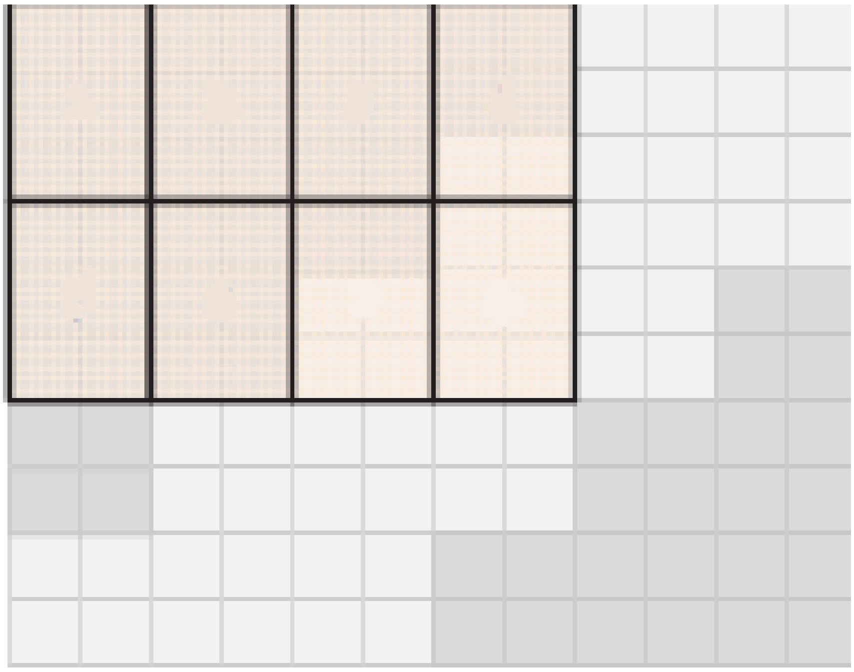


Figure 4.1: Panel placement approximation

As shown in the example of figure 4.1 and 4.2, a more compact placement by eye would neglect more irradiate areas, represented by darker squares, including portions that may be affected by partial shading. The end outcome would be a loss of productivity in the areas impacted by shading, because of the current cap that the shaded panels would generate in the others (Similar behavior detailed in 3.2.2).

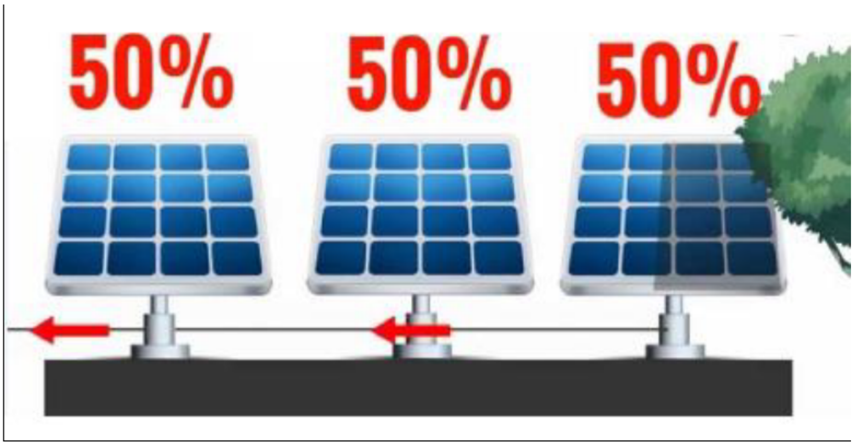


Figure 4.2: Current cap propagation

- **Importance of temporal irradiance data and metrics:**

  Irradiance data plays a crucial role in identifying best potential areas on rooftops for panel placement.

- Considering that sunlight exposure varies throughout the day and across seasons, the availability of meteorological data for long term period is therefore essential.
- Metrics such as mean irradiance and percentile are particularly valuable in this context, since relying on a single snapshot of irradiance becomes insufficient in the identification of shadow patterns.
- Previous studies identifies in 75th percentile, as the figure 4.3 highlights, the most valuable metrics to effectively capturing periods of peak sunlight.

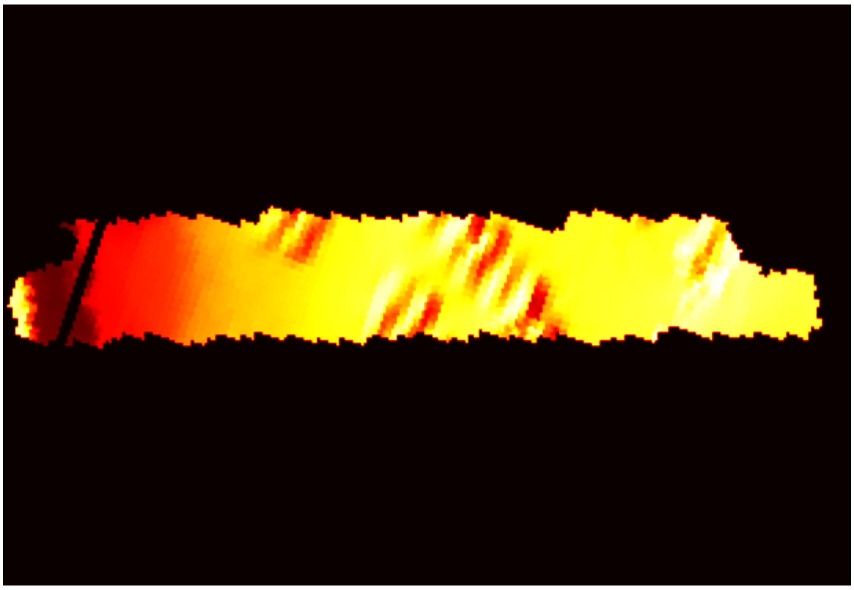


Figure 4.3: heat-map of 75th percentile on rooftop

By measuring irradiance over time and using these metrics, it is feasible to find regions on the rooftop that regularly receive high levels of sunlight, assuring maximum energy output and effective use of available space.

4.2.2 Methodology

4.2.2.1 Key Assumptions

- The proposed panel placement algorithm builds upon the assumption that fine-grain irradiance distributions are available for a roof over a significant period of time.
- The number of PV panel to place for this step, on the selected area, is predetermined.

4.2.2.2 Irradiance Map Metrics

The identification process of shadow pattern determines the usable roof area for PV panels, which is then aligned to a grid for placement calculations. Weather data, combined with the shadow model, is used to estimate temperature and irradiance over time.

A tridimensional matrix is therefore build for the established area over a specific period, with grain granularity of each cell set at 20cmx20cmx15min. Cells contain irradiance with a value of W/m^2, ranging from 0 (total dark zone), to values close to 1000 (full irradiated area).

The totality of the matrix, with all the information of temporal and variations of the roof's irradiance, can be too large to be directly used in calculations. Metrics could be a strong compromise to highlight areas with consistently high irradiance levels. By summarizing the matrix in this way, it is possible to find the most potential regions for energy production without having to process the complete dataset in its raw form. Average, sum and percentile are the most eligible, it only remains to decide which of the ones is the most suitable.

As discussed previously and highlighted in the figure 4.1, 75th percentile emerges as the most suitable. The 75th percentile metric is especially effective for highlighting regions that consistently receive high levels of sunlight, mostly because it emphasizes the upper range of irradiance values while neglecting less impactful readings.

4.2.2.3 K-Means Clustering

The first step for the algorithm is the definition of the comparing point adopted to select the best panel. Having identified the average of the 75th metric values on the surface of the PV panel as the best comparative factor, is easy to realize how this is not enough on its own.

The comparison between panels in figure 4.4 clearly shows the reason why:

- The top panel is the first panel identified by an algorithm based only on the average value on the panel surface. It figure out that, even if the panel has the most average, the position also include a little shadowed area.As widely discussed in chapter 3, this would realize a loss in the power production, due to the current cap.

- The bottom panel is instead without shadows, despite a similar average to the previous one. It is selected on the section of the roof covered by only the most valuable cells, thanks to the clusterization of irradiance areas performed by k-means algorithm.

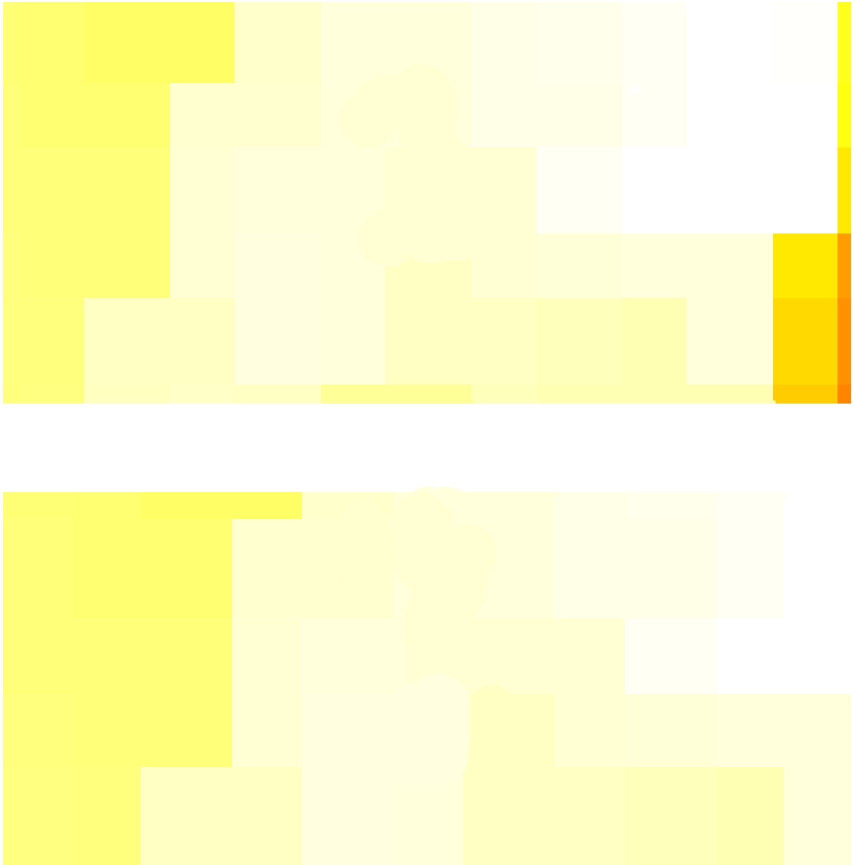


Figure 4.4: k-means and non-k-means panel identification comparison

The outcome advise to divide the whole area into a predefined number of clusters based on irradiance values, allowing for a granular focus on the most promising areas (Fig. 4.5). The k-means algorithm becomes the most suitable to perform the task, since it groups data points (representing roof sections) minimizing the variance within clusters. Therefore, it ensures that each cluster represents a region with similar irradiance characteristics.

The number of cluster to divide the roof become so quickly another key factor. While it may appear natural that increasing the number of sections would increment effectiveness, after a certain point, additional clusters may become computationally heavy, with no adds of significant insights. This balance guarantees that the system remains efficient while correctly identifying high-potential sites for panel placement.

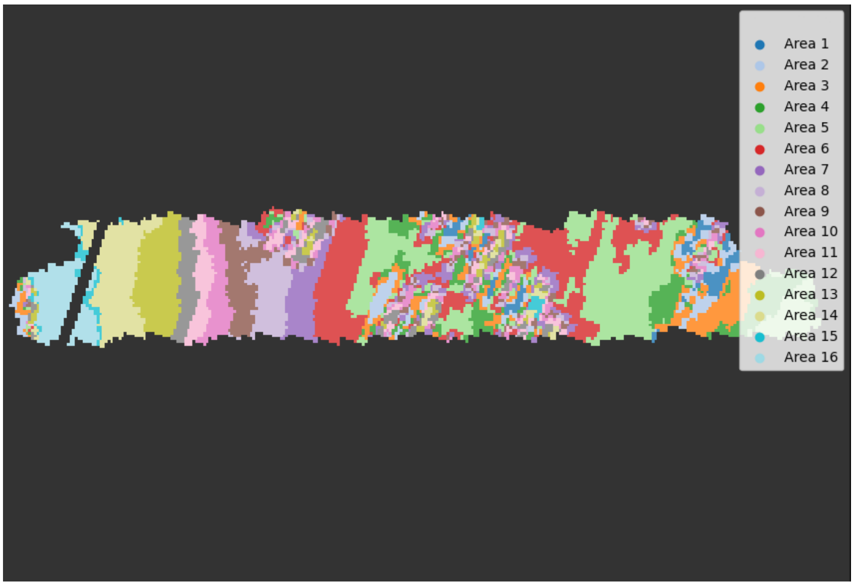


Figure 4.5: k-means clusters on roof example

4.2.2.4 Panel Placement in High-Irradiance Areas

As expected, identifying the coordinate of the panel on the roof surface is the core part. The proposed algorithm aim to consider both horizontal and vertical position for the panel, selecting the one with the best score. As previous mentioned, the average of 75th percentile values covering PV panel surface is the comparison factor between panels.

An optimal positioning would require the assessment of all the possible positions and combination, becoming exponential. This will happens because of the NP-complete nature of the problem. That leads to a greedy approach of the situation.

1. Starting from the metrics irradiance matrix of the section, the algorithm search for the best panel.

2. Removes the area covered by the selected panel and searches again for the panel with the highest average.

3. The recursion ends when no more panels fit in the area.

```
FUNCTION: select_best_panels_for_areas
INPUT:
    - metrics_irradiance_matrix: matrix containing irradiance metrics
   for selected area.
    - panel_size: Tuple indicating the dimensions of a panel.
    - percentage_to_keep: Fraction of panels to retain after filtering
   .
    - overlap_threshold: Threshold for allowable panel overlap (0 to
   1).
    - weight_mean, weight_var, weight_dev, weight_75per, weight_90per:
     Weights for prioritizing irradiance metrics.
    - panel_to_keep: Optional, fixed number of panels to retain.
```

```

OUTPUT:
    - selected_panels: List of panels with their positions and scores.

STEPS:
1. Initialize ‘metrics_matrix‘ as a deep copy of the input matrix.
2. Create an empty list ‘panel_tasks‘ to store candidate panel positions for parallel processing.

3. Define a helper function ‘process_panel‘:
    a. Calculate irradiance statistics (mean, variance, deviation, 75th percentile, 90th percentile) for the panel at a given position.
    b. If any calculated value is invalid, return ‘None‘.
    c. Compute a weighted score using the input weights and irradiance metrics.
    d. Return the position, score, and orientation.

4. Iterate over all possible panel orientations (horizontal and vertical):
    a. For each orientation, calculate the corresponding panel height and width.
    b. Loop through all possible positions in the ‘metrics_matrix‘ where the panel fits:
        - Add the position and orientation to ‘panel_tasks‘ if valid (non-zero values in the matrix).

5. Parallelize the panel scoring process:
    a. Use a thread pool to process all ‘panel_tasks‘ with ‘process_panel‘.
    b. Filter out invalid results (‘None‘) from the results list.

6. Sort the valid panels (‘score_sorted_selected_panels‘) in descending order of their scores.

7. If ‘overlap_threshold‘ < 1.0:
    a. Initialize an R-tree index to manage panel overlap checks.
    b. For each panel in the sorted list:
        - Check for overlap with previously selected panels using the R-tree.
        - If overlap exceeds the threshold, skip the panel.
        - Otherwise, add the panel to the ‘selected_panels‘ list and update the R-tree with its position.
8. Otherwise:
    a. Select all panels without filtering for overlap.

9. Retain only the top panels:
    a. Determine the number of panels to keep:
        - Use ‘panel_to_keep‘ if specified, otherwise calculate it as ‘percentage_to_keep‘ of the total.
    b. Truncate the ‘selected_panels‘ list to the desired length.

10. Return the ‘selected_panels‘ list.
```

The whole system positioning is therefore a recursive sequence, combination of the detailed searching algorithm and the k-means. It is simply described in the following flowchart.

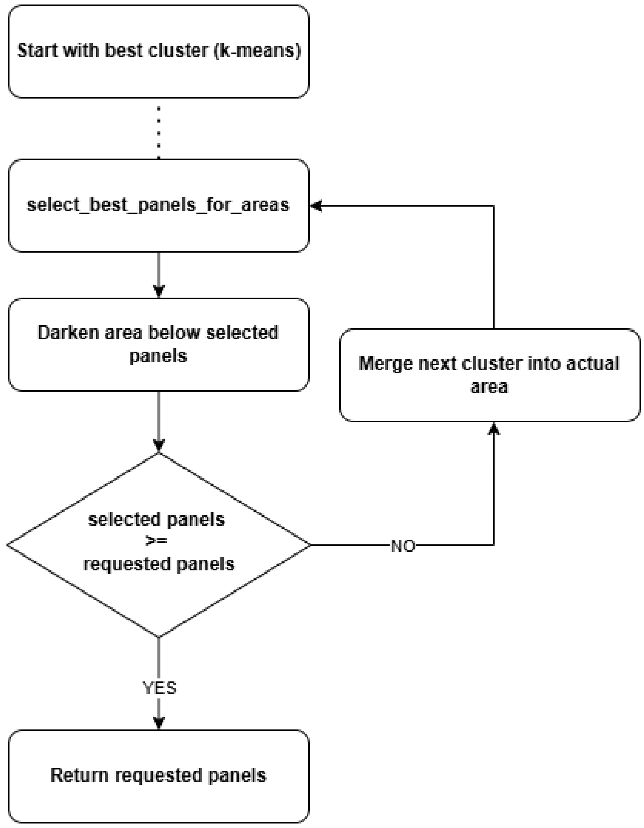


Figure 4.6: Panel placement flowchart

4.2.3 Considerations

- **Geometric contraints:**

  The division of the area into a grid is essential to helps fitting of panels, due to the geometric constraints such irregular rooftop shape and obstacles. Area affected by obstructions is marked as unusable, while irregular shape problem is treated and overcome by the panel placement algorithm. This systematic approach ensures optimal panel placement within the rooftop's physical limitations.

- **Trade-Off Between Maximizing Irradiance and Rooftop Space:**

  In order to maximize production, it is probably necessary to avoid panel positioning in areas below a threshold of sunlight exposure. However, prioritizing only high-irradiance areas can leave a portion of optimal spaces unused, reducing overall installation capacity. The compromise is still acceptable, because positioning panels in less irradiated areas could not only provide a lower production/expense ratio, but lead to problems related the current cap.

4.2.4 Outcome

The selected panels arising from the sequence represents the best trade-off between computational efficiency and power production potential. The incremental placing of panels in top-clusters leads to gradual increase of system efficiency while maximizing rooftop coverage, maintaining economic feasibility through strategic placement and performance clustering.

The next crucial step is to define the appropriate electrical connections between panels to maximize energy production. In order to reduce to an acceptable minimum the mismatch losses brought on by variations in panel performance and to guarantee compatibility with the inverter's voltage and current restrictions, series and parallel connections must be properly configured.

4.3 Grouping of Panels for Inverter Efficiency

4.3.1 Overview

Once the highest production panels have been placed on the rooftop, the next step is to identify the best interconnection scheme to provide the maximum power output, minimizing mismatch losses. Series and parallel connections to group panels are essential for the system's energy production, in order to ensure voltage and current levels that mirror the inverter's operating constraints. Several scientific studies state that a strong relationship between the configuration of PV panels and inverter capacity could increase both performance and efficiency, indicating this as a crucial aspect in system design.

- **Relation between panel production and energy demanding:**

  The output voltage range of the PV module is deficient when compared with the demand voltage peak of 350–400V for single-phase and 600–800V peak in the case of three-phase alternating current (AC) loads. So the voltage is needed to be boosted up and also inverted. [13] Connecting panels in series could be the first solution to reach the set goal, despite the advantage of a parallel connection under the non-optimal conditions addressed in this work, as already highlighted in previous chapters.

- **Optimization of system connections:**

  A key challenge lies in avoiding losses due to connection between panels with substantial differences in I/V characteristic. Is important to ensure that panels wired together in series maintain similar current trend, while the ones connected in panels share similar voltage level. With the aim of maintaining efficiency without sacrificing accuracy, is crucial remaining computationally efficient, allowing for acceptable optimization even as the number of panels grows.

This section paves the way for a well-defined methodology for panel grouping:

- Without calculating each individual I/V curve, Pearson's time series correlation is used to group panels with comparable performance over time.
- Defining sub-areas within panels (e.g., for half-cell configurations) to improve similarity assessments.
- Optimizing topologies based on inverter restrictions, ensuring effective series/-parallel combinations while preserving computational efficiency.

Using this approach, the system maintains a high level of panel grouping accuracy while drastically cutting down computational overhead, which makes it scalable also for a large PV system installation. This improved process and its benefits for maximizing energy output are described in detail in the following section.

4.3.2 Methodology

4.3.2.1 Key assumptions

To simplify the optimization process while preserving efficiency and scalability, a few heuristics were implemented to simulate inverter restrictions in optimizing the grouping process:

- The approach makes the assumption of identifying a maximum number of panels per inverter, rather than dynamically modifying inverter input restrictions. This streamlines the system design and assure that each inverter performs within its efficiency range without requiring real-time recalculation.
- The number of series group of panels is in that way determined, allowing for the simplification to divide the total number of panel for the maximum number of panels for single series.

The addressed methodology part is also sensitive to layout configurations, especially in the identification of similarities between modules, based on cross-time-series correlation. To maintain clarity and highlight the workflow over panel-specific characteristics, this study focuses on a single panel layout: half cut cell module with 3 bypass diode (fig. 4.7).

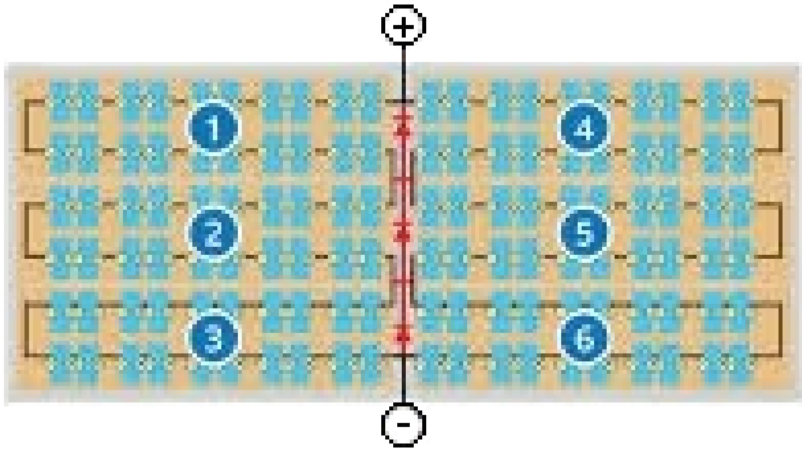


Figure 4.7: Half cut cells: standard layout

Even if the principles applied can be extended to different panel layouts, this method prefers to show the optimization technique and computational workflow above layout-specific performance variances.

4.3.2.2 Approach to the optimal Grouping Strategy

The first methodology tried was a direct one-to-one comparison of each I/V panel curve with the aim of determining the best matches for series connections.

1. Each panel's I/V characteristic was generated with the simulation of the module on the panel irradiance data, based on own inner configuration.

2. Group of panels were put together by selecting those with the most similar electrical characteristics.

3. This guaranteed minimal energy losses, as current cap were minimized due to researched near-identical curves.

However, the above approach was impractical as the complexity of the system increased, due to the exponential growth in the number of comparison of all the possible pair or panels. The need to simulate an I/V curve for each panel at every timestamp made the method inappropriate for real-world scenarios.

4.3.2.3 Defining Panel Similarity Using Pearson Correlation

To group PV panels in efficient series connections minimizing mismatch losses, is necessary to find panels that share similarities in I/V characteristic. Since similar irradiance profile leads to a similar I/V characteristic, the first idea results in the development of a measure that compare panels' radiation grid. Solar irradiance fluctuates over time, so panels that experience similar variations in irradiance are more likely to perform uniformly when connected in series.

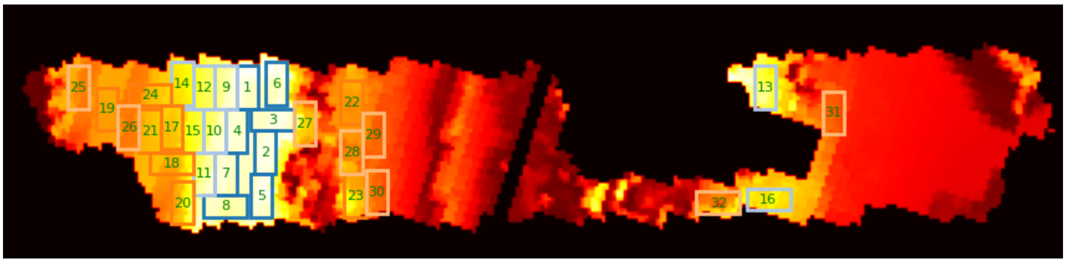


Figure 4.8: Heatmap of 75th percentile with the 32 best panels found by the placement algorithm on an example roof

Let's consider the panels found by the positioning algorithm on the roof example in Figure 4.8. Once identified, the classical approach would lead to a grouping of the panels from best to worst, in this case by groups of 8 panels. Paying particular attention to panels 9 and 13 of the second cluster, it is possible to notice how the two panels have a radiation coverage based on the 75th percentile that is rather similar, even though they are located in two opposite areas of the roof. This could lead to the assumption that the two panels share a similar behavior over time, so at first glance a series connection might seem reasonable.

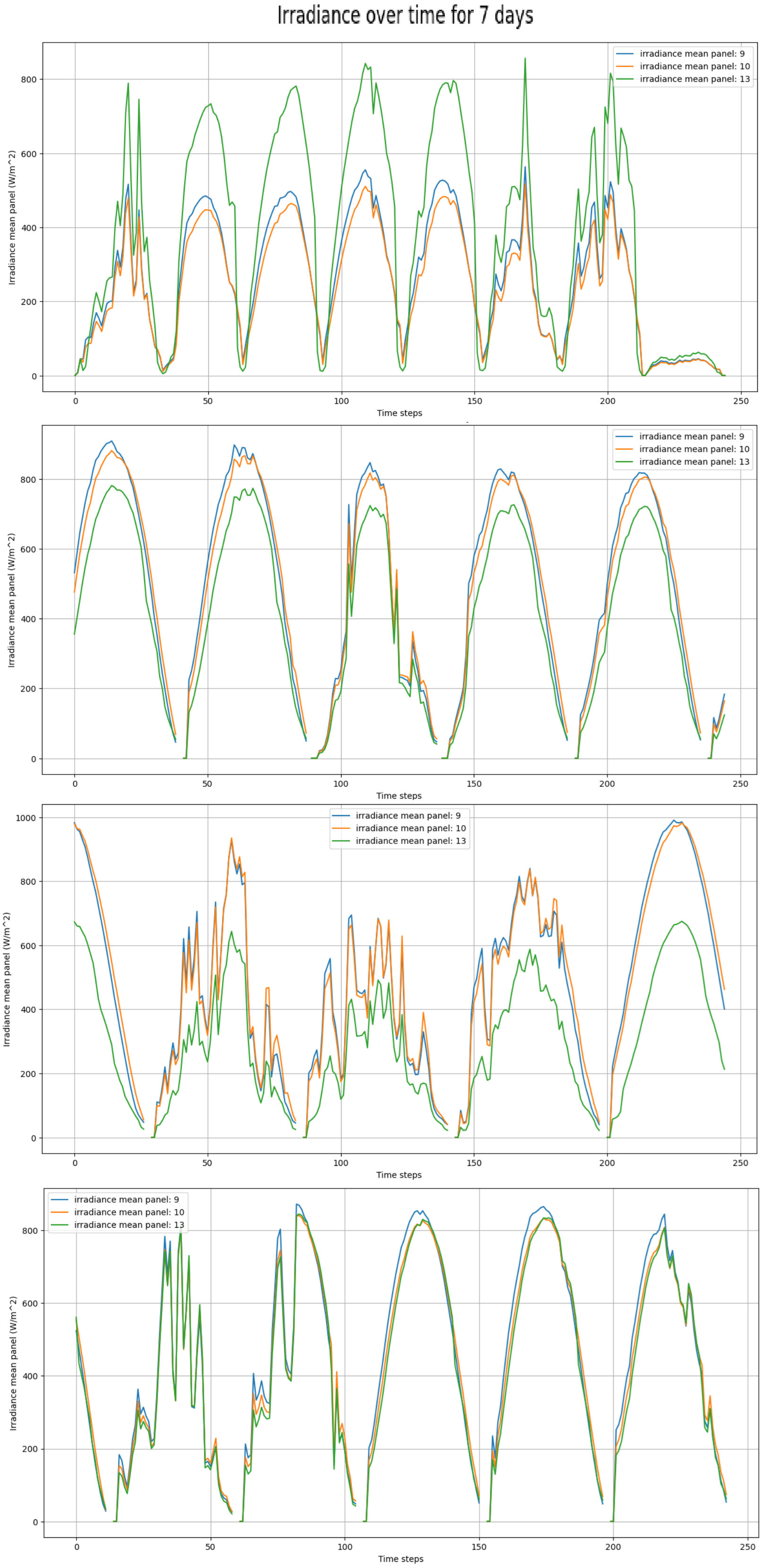


Figure 4.9: Comparison of the average trend of irradiation of 3 panels: 9,19,13; in the 4 seasons, along 7 consecutive days

Figure 4.9 shows 4 graphs representing the trend of the average radiation incident on panels 9, 10 and 13, over a time span of one week used to represent each season. Reading the graphs, you can notice how the trend of the curves of panels 9 and 10 are almost superimposable, while panel 13 behaves in a visibly different way. Panel 13 follows the trend of the other two only in the autumn period (the last one), it behaves much better in the winter period, while it is visibly less performing in the generally more productive seasons. This trend can lead to significant production losses due to the current cap in series connections, as explained both in this chapter and in previous chapters.

It is therefore important to define an algorithm capable of creating a group of panels that can be connected in series including panels 9 and 10, but not panel number 13.

1. **Defining Pearson's Time-Series Correlation:**

   Pearson correlation is a statistical method used to establish linear correlation similarity between two variables.

   In the case in question, each identified panel is associated to a grid of irradiance time series, representing how sunlight exposure varies over time. Therefore, it is possible to ascertain if the two panels under investigation will continue to exhibit the same behavioral pattern over time by confirming the correlation between the trends of the most appropriate metric for irradiation values in two panels. The computation of the standard Pearson's correlation coefficient between two variable A and B follows:

$$r(A,B) = \frac{\sum_t (A_t - \bar{A})(B_t - \bar{B})}{\sqrt{\sum_t (A_t - \bar{A})^2}\sqrt{\sum_t (B_t - \bar{B})^2}}$$

   - A_t and B_t are the irradiance values for variable A and B at time t.
   - $\bar{A}$ and $\bar{B}$ are the mean irradiance values over time.
   - the resulting $R(A,B)$ can take values in the range [-1, 1], where 1 indicates a positive correlation, -1 indicates a negative correlation and 0 indicates no correlation.

   It is crucial to keep in mind that the correlation does not account for the distance between the absolute values; rather, it simply considers how similar the values' trends are.

   A good solution is to multiply the Pearson correlation by a penalty based on the distance of the absolute values.

$$R(A,B) = r_{\text{pearson}} \times e^{-\lambda \cdot MAE}$$

   - r_{pearson} Pearson normal (measures trend).
   - λ measures the weight of the penalty (the higher it is, the more important the distance between the values is).

- Mean Absolute Error (MAE), i.e. the average of the absolute differences between the two series.

$$MAE = \frac{\sum_t |A_t - B_t|}{N \times \bar{A}}$$

  - $\bar{A}$ is the mean irradiance values over time.
  - A_t and B_t are the irradiance values for variable A and B at time t.
  - N stands for the number of values in the series.
- $e^{-\lambda \cdot MAE}$ Exponential penalty that reduces the value if the two series have very different numbers.

Panels with correlation coefficients closer to 1 are more suited for series connecting, because they retain similar energy output patterns throughout time.

2. **Subdividing Panels into Macro-Areas:** Given the specific configuration described in a previous section, figure 4.7 illustrates how the panel layout can be divided in to 6 relevant areas. Since bypass diodes can exclude several of these areas, due to shading effect, is crucial to consider the association between each section rather than the panel as a whole. Therefore, the similarity between two panels is computed:

   (a) **Computing Pearson's correlation using the minimum of the subarea as a metric**

   Since the cells of each selected subarea are connected in series, referring to the current cap detailed in section 3.3.1, it may be inferred that the current of the series follows that of the worst cell.

   (b) **Averaging the correlation scores to extrapolate the resultant similarity measure for the entire panel**

   We can approximate by considering the sub-areas of the panels as "independent" of each other, given the 3 bypass diode and two half configuration of the examined panel.

3. **Building the Panel Similarity Matrix:**

   Once correlations are computed for all panel pairs, the results are organized into a panel similarity matrix, where each couple (i, j) represents the correlation between panel i and panel j.

$$S = \begin{bmatrix} 1 & R(A,B) & R(A,C) & \dots \\ R(B,A) & 1 & R(B,C) & \dots \\ R(C,A) & R(C,B) & 1 & \dots \\ \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

   Since panels with the highest correlation values probably share similar I/V characteristic, this matrix forms the basis for panel series grouping.

```
FUNCTION create_similarity_matrix_macroareas
INPUT:
    - selected_panels: List of selected panels (position, orientation,
     score).
    - irradiance_matrix: 3D matrix of irradiance values [time, height,
     width].
    - panel_size: Dimensions of the panel.
    - d_num, hor_par: Parameters defining macro-area structure.

OUTPUT:
    - similarity_matrix: NxN matrix of similarity values between
   panels.

STEPS:
1. Initialize an empty NxN similarity matrix, where N is the number of
     selected panels.
2. Create a dictionary to store time-series data for each panel's
   macro-areas.
3. FOR each panel i in selected_panels:
    a. Extract its position and orientation.
    b. Compute its time-series for macro-areas using
   extract_panel_macroareas_time_series.
    c. Store the result in panel_macroareas_series dictionary.
4. Compute pairwise similarity scores in parallel:
    a. FOR each unique pair (i, j) of panels:
        - Compute the similarity between panel i and panel j using
   calculate_similarity_for_macroareas.
    b. Store the similarity scores in the similarity matrix (both [i,
   j] and [j, i] positions).
5. RETURN the similarity_matrix.
```

The aforementioned pseudocode provides guidance on how to create a similarity matrix by identifying panel subareas, ensuring that panels with similar internal irradiance distributions have high correlation values.

Not being possible to make use of an optimal combination, the utilization of Pearson's time-series correlation ensures anyway that panels with similar temporal irradiance behavior are connected together, reducing mismatch losses and optimizing system performance.

The following section details how this similarity matrix is used to iteratively group panels taking into consideration inverter constraints.

4.3.2.4 Forming Optimized Series Groups

After the computation of the similarity matrix, the next step involves the formation of optimized series groups of panels. Once the number of panels for each cluster is established, this process aims to minimize mismatch losses while ensuring that those with similar irradiance profiles are connected in series.

```
FUNCTION calculate_cluster_combinations(metrics_matrix, selected_panels, irradiance_matrix, panel_size, d_num, hor_par, num_clusters, num_panels, folder, time_index=3000, time_range=40)
INPUT:
    - metrics_matrix: 2D matrix containing the 75th percentile irradiance values for each grid cell.
    - selected_panels: List of selected panels (position, orientation, score).
    - irradiance_matrix: 3D irradiance matrix [height, width, time].
    - panel_size: Dimensions of a single panel (height, width).
    - d_num, hor_par: Parameters defining panel macro-area structure.
    - num_clusters: Desired number of panel groups.
    - num_panels: Total number of panels to be grouped.

OUTPUT:
    - clusters: List of optimized panel groups, each containing panels with high similarity.

STEPS:
1. **Initialize Variables**
    a. Compute ‘cluster_size = num_panels // num_clusters‘ (panels per group).
    b. Create ‘remaining_panels‘, a deep copy of ‘selected_panels‘, to track unassigned panels.
    c. Create an empty set ‘selected_positions‘ to store assigned panel locations.
    d. Create an empty list ‘candidate_clusters‘ to store possible groupings.

2. **Compute Similarity Matrix**
    a. Generate ‘similarity_matrix‘ using ‘create_similarity_matrix_macroareas‘, which evaluates panel similarity based on irradiance time-series correlation.
    b. Save ‘similarity_matrix‘ for future use.

3. **Iterate Over Panels to Form Clusters**
    a. FOR each ‘panel_idx‘ in ‘remaining_panels‘:
        i. If the panel is already in ‘selected_positions‘, SKIP.
        ii. Initialize a ‘candidate_cluster‘ with the current panel.

    b. **Find the Most Correlated Panels**
        i. WHILE ‘candidate_cluster‘ has fewer than ‘cluster_size‘ panels AND at least one nonzero similarity score exists:
            - Identify ‘best_corr_idx‘, the index of the most correlated panel.
            - Retrieve ‘best_corr_panel‘ from ‘selected_panels‘.
            - ADD ‘best_corr_panel‘ to ‘candidate_cluster‘ if it does not conflict with previously assigned panels.
            - UPDATE ‘similarity_matrix[panel_idx][best_corr_idx] = 0‘ to prevent re-selection.

4. **Compute Cluster Performance Score**
    a. Calculate ‘sum_75per_cluster‘ as the sum of the 75th percentile
```

```
    irradiance values for all panels in ‘candidate_cluster‘.
   b. IF ‘candidate_cluster‘ has ‘cluster_size‘ panels:
       - ADD ‘candidate_cluster‘ to ‘candidate_clusters‘.
       - UPDATE ‘selected_positions‘ to mark panels as assigned.

5. RETURN the final list of ‘clusters‘.
```

The above pseudo-code aims to find panels with similar irradiance behavior clustering them efficiently, following these flow:

1. **Compute Similarity Matrix**
   - As detailed in previous section.
2. **Initialize Cluster Formation**
   - Determine cluster's size based on inverter characteristic.
   - Create a list of available panels and an empty set to track assigned positions.
   - Prepare an empty list of candidate clusters.
3. **Iterate Over Panels to Form Groups**
   - Select the highest-performing panel as the starting point for a new cluster.
   - Identify most correlated panels based on the similarity matrix.
   - Assign panels to the cluster until the required number is reached.
4. **Finalize Optimal Clusters**
   - Save and rank candidate clusters based on their irradiance performance.
   - Return the finalized panel groups for optimized series connections.

4.3.3 Considerations

The methodology aimed to build an optimized interconnection scheme of the system, provides a structured approach to minimize power loss due to current cap while ensuring computational efficiency. Anyway, several aspect must be considered when implementing proposed schema:

- **Trade-Off Between Accuracy and Computational Efficiency**

  As discussed previously in 4.3.2.2, a direct I/V curve comparison would result in the most precise panel grouping, but it is computationally impractical for big systems. An optimal compromise was found in the custom Pearson's correlation approach, striking a balance between accuracy and efficiency by finding common irradiance patterns rather than modeling full electrical action.

- **Dependence to Panel Layout and Structure**

  Bypass diodes or the series/parallel interconnection scheme between cells play a fundamental role in similarity calculations. The internal structure of the panel affects this section of the methodology for the division of panels into macro-areas, in the act of locating relevant shading effects to prevent mismatch in I/V characteristic.

- **Fixed Cluster Size Constraint**

  A fixed series size simplifies the behavior of inverter construction but may not always match the ideal operating voltage. Further refinements could consider a more precisely grouping method based on inverter efficiency curves.

4.3.4 Outcome

Using the custom Pearson correlation and macro-area analysis, the proposed methodology successfully:

- Combine panels that exhibit comparable irradiance behavior, lowering mismatch losses and improving system performance.
- Keeps computing feasible by avoiding direct comparisons of I/V curves for big datasets.
- Simplifies inverter configuration by verifying that series connections are compliant with operational parameters.
- Provides a scalable behavior, allowing efficient panel clustering across different system dimensions and rooftop peculiarities.

The next chapter focuses on the validation of this methodology in real-world scenarios, addressing the impact on power generation, system stability, and long-term return on investment.

4.4 Insights and Future Directions

4.4.1 Insights

The techniques described along the chapter highlights the importance of several aspect in the definition of a solid placement approach for PV system. Optimizing panel placement and series grouping address key challenges related to irradiance variability, shading effects, and inverter constraints, highlighting various important insights that help with both theoretical knowledge and practical application of PV system design.

- **Irradiance data leveraging**

  One of the best takeaways turned out to be the needing of using irradiance data to make intelligent placement and grouping decisions. The analysis highlighted and treated the non-uniform irradiance distributions due to shading from nearby structures, variances in panel orientation, and seasonal variations. Through the use of irradiance-based k-means clustering approaches, the system efficiently determines the rooftop's most productive areas, accordingly choosing best fit system layout.

- **Similarity correlation**

  Moreover, Pearson correlation as a similarity metric for panel grouping provides an alternative method for I/V curve comparisons. This technique allows panel grouping without the requirement for computationally costly comprehensive electrical modeling, whereas natural approach would rely on explicit electrical simulations to identify the optimal panel connections. By searching for panels with looks a like irradiance behavior over time, it largely ensures that series connected panels run under similar conditions, reducing mismatch losses and increasing overall power production.

- **Integration of inverter constrains**

  Another grouping limit faced in this approach is the inclusion of inverter limitations. It is essential to make sure that the panels connected in series maintain compatible current levels while respecting the inverter voltage constraints, remaining steady and effective over time. The predefined series size constraint simplifies the procedure, eliminating complex real-time optimizations while remaining practical and scalable.

- **Macro-areas division of panel**

  The last approach factor focused on the macro-area splitting of the panels was useful in improving the similarity assessments of the panels. The methodology makes sure that even panels with localized shade fluctuations are appropriately categorized and grouped by breaking each panel into smaller irradiance-sensitive sections, with ones that share similar shading patterns. This method enhances the system's resilience to panel's layout and increases its ability to adjust to actual shading situations.

In general, this methodology offers a scalable and computationally efficient solution to optimize photovoltaic systems, making it appropriate for both small-scale rooftop installations and larger distributed solar systems.

4.4.2 Future directions

Although the structured approach defined in this thesis provides a useful foundation for optimizing the interconnection clustering and the placement of the PV panel, a number of possible enhancements could further increase its accuracy, adaptability and practicality.

- **Machine Learning for predictive irradiance analysis:**

An autonomous optimization system that dynamically modifies panel placement as environmental conditions change could be made possible by the application of machine learning techniques for predictive panel grouping. Machine learning algorithms could use historical irradiance data to find patterns in solar exposure and anticipate the best future setups.

- **Optimizing Inverter Grouping:** The current focus of the methodology is to ensure that panel groups adhere to inverter constraints, including voltage and current limits. However, as PV system increases, the importance of inverters peculiarities scales up, becoming way more effective. Future work should then investigate:

  - **Adaptive inverter distribution:** An optimization model could identify the optimal arrangement and positioning of panels per inverter, considering low irradiance effect and improving load balancing, as an alternative to set inverter architectures.
  - **Multiple inverter balancing:** More than one inverters are mostly needed for large rooftop system installations. Real-time efficiency data could be used to dynamically shift panels between inverters as part of an intelligent power-sharing plan.

  With the aim of refining the inverter clustering approach, the next step can lead to a better focus of both energy yield and system durability with the aim of a better power distribution, reducing stress on single inverters.

- **Incorporating Temperature Effects:**

  In order to transmit solar exposure to panel prediction behavior, the current methodology optimizes panel grouping based on irradiance statistics. Temperature changes goes hand in hand with radiation affecting panel performance, so much so, in future studies, adding temperature analysis into the panel selection procedure may help preventing voltage mismatches due to temperature-induced variations. In addition, it could be necessary to better organize the panel placement in order to prevent overheating effect, also improving the panel lifespan.

  This improvement would increase the approach's accuracy in real-world settings, particularly those where heat dissipation is essential (such as closely spaced rooftop installations).

- **Panel sizing based on energy demand:**

  An effective topic of investigation could be the transition from a panel production optimization strategy to a more specific demand-driven approach. Future studies should look at ways to size and distribute panels based on real energy needs rather than optimal energy production based only on irradiance. The number of panels and their optimal interconnection will be derived from energy consumptions profiles, where inverter and panel configurations are selected to match specific demand curves.

By incorporating demand-side variables, this system has the potential to mature into a comprehensive solar energy planning tool, not only placing panels as efficiently as possible, but also making sure that installations match actual usage trends.

Chapter 5

Return of Investment Analysis

5.1 Introduction

Maximizing the energy produced is a very important aspect in the design of electrical production systems. Evaluating it in a long-term balance with a study of installation and maintenance costs might become the key factor in defining an economically sustainable project. Therefore, it's important to study both elements of the problem concurrently.

This chapter assesses the return on investment by looking at panel positioning techniques, panel type selection, inverter sizing, and overall system setup. Finding the ideal cost-production efficiency ratio while taking into account practical limits like as shading, inverter restrictions, and financial viability is the goal.

5.2 Panel Layout Choice: Maximizing Cost-Benefit Ratio

The choice of the topology and arrangement of the photovoltaic panels for the construction of a system directly impacts both the initial installation costs and the long-term financial gains. As highlighted in Chapter 3, different panel layouts respond differently to shading situations and require distinct interconnection procedures, affecting their overall production efficiency and resulting economic return.

5.2.1 Best Panel Type Fitting Conditions

Each type of panel has some peculiarities that could make it more attractive in the initial choice of the key element of the system, which can be financial, related to availability or merely productive. Even the aesthetic factor can sometimes be decisive in choosing types of panels, so as to have a lesser visual impact on the harmony of the elements involved.

Considering the three main types of panels on the market: Half-cells, Full-cells, and Shingled-cells; it is possible to make a brief analysis of the conditions that would make one topology preferable to another.

- **Full-cell**

  Represents the cheapest panel topology in circulation and is suitable in most nominal cases. The simple internal connection scheme does not react optimally to shading effects, therefore it is not generally recommended for scenarios with a high presence of nearby obstacles that could generate shadows.

- **Half-cell**

  It maintains the same operating logic as a full-cell, with a slight increase in average cost. takes advantage of the division in half of the cells to guarantee greater overall efficiency and resilience towards environmental challenges. This makes this topology of considerable interest in the presence of strong shadows that could affect the highlighted area.

- **Shingled-cell**

  Like roof tiles, these panels are made of strips of overlapping solar cells. Efficiency is increased when there are no spaces between cells and visible busbars, increasing the active area exposed to sunlight. Even when there is partial shadowing, shingled panels can continue to produce a substantial amount of energy because of the cells' series and parallel arrangement. The panels' overlapping design also provides them a consistent, beautiful look, which makes them perfect for upscale home and commercial applications.

5.2.2 Effect of Rooftop Shading on Panel Selection

Shading has a direct impact on energy production efficiency and ROI. It is one of the problems that could lead to opting for topologies that guarantee less negative effect on productivity. As shown in the next chapter, the cost-aware simulation framework compares different panel technologies under various shading circumstances to evaluate the impact of shading on instant energy production.

The results of the long-term plant production simulation can also be used for a more precise lifetime profitability evaluation by modeling energy output under shading effects and incorporating them into the cost calculation.

$$\text{Efficiency} = \frac{C \times N}{P_T}$$

- C is the unitary cost of a panel.
- N represents the number of panels in the system.
- P_T is the final production considering losses.

5.3 The Trade-Off Between Number of Panels and Energy Production

The size of a photovoltaic system, which includes the amount of panels, wiring, inverters, and all the electronic components involved, has a cost. This must be carefully balanced with the gain deriving from the energy produced in order to to reach a good compromise.

Adding more panels increases the system's ability to generate power, but it also increases the initial investment and may result in lower returns due to issues such as shading, soiling, and system losses.

5.3.1 More Panels = More Production?

The relationship between the number of panels and energy produced rarely produces a linear trend.

$$R = \frac{\Delta P}{\Delta N}$$

- R is the production increase ratio for each panel added.
- ΔP is the variation in energy production ($P_{finale} - P_{iniziale}$) measured in kWh o Wp
- ΔN represents the number of added panels ($N_{finale} - N_{iniziale}$)

Additional panels may get less than ideal exposure when a rooftop hits its high-irradiance saturation point, which would result in smaller marginal increases in energy output.

Key considerations freely quoted from *SAM Photovoltaic Model Technical Reference*[14]:

- **Energy Output:** Increasing the number of panels generally boosts energy production, but the efficiency gains may decrease if the system is not optimally designed.
- **Shading and Soiling:** More panels can lead to increased shading and soiling losses, which can reduce the overall efficiency of the system.
- **System Losses:** Electrical losses in wiring, inverters, and other components can increase with larger systems, impacting the net energy output.

In-depth tests on the topic are carried out and commented on in Section 6.4.

5.3.2 System Sizing for Economic Efficiency

More panels mean higher upfront costs for purchasing and installing the panels. The optimal number of panels depends on the specific site conditions, available space, budget, and energy needs. Balancing these factors ensures maximum energy production and cost-effectiveness. [14]

Analyzing the ratio of energy production to demand is necessary to determine the optimal system size. When a PV system is oversized, it might lead to:

- Increased costs caused by producing more energy than used (excess energy wasted).
- Lower earnings efficiency, as excess production does not directly lead to higher profits.

On the other hand, an undersized system may not be able to meet energy demand, requiring external supplies. A balanced configuration based on demand forecasting is necessary to maximize financial efficiency.

5.4 Impact of Panel Series Grouping and Inverter Selection

Efficiency and economic performance are directly influenced by the presence of parallel or series connections between modules in the system connection schema. DC to AC current conversion technology is another key factor, controlled by the presence of central inverters, string inverters or micro-inverters.

Proper optimization of these aspects is critical for maximizing power generation while minimizing losses, resulting in higher returns on investment and increased overall system reliability.

5.4.1 Optimized Series and Parallel Grouping

The interconnection schema of PV panels, represented by a circuit with connections in series and parallel, plays an essential role in figuring out the system's voltage and current properties. An higher number of panels in series raises the system voltage while keeping the current constant, ensuring that losses due to overheating of the wiring are lower. On the other hand, a parallel arrangement requires thicker cabling and more robust inverters, but increases current at the same voltage and improves resilience to shading, as thoroughly explained in Chapter 3.

Several studies, carried out on the best layout configurations, show how optimizing groupings in series leads to a significant increase in efficiency. The Fraunhofer ISE Photovoltaics Report states that larger modules and better electrical connections have produced power ratings of over 700 W, which enhances performance in large-scale installations.[15] On the other hand, the Cost-Aware Design and Simulation of Electrical Energy Systems study stresses the significance of balancing power dynamics and cost concerns while building panel layouts to maintain economic feasibility.[6]

The output of these relations can be adapted with respect to the connections between panels, as these are strongly linked to the internal connections.

5.4.2 String Inverter vs. Micro-inverters

The choice of which type of inverter to use when defining the system components is critical. Micro inverters or string inverters each have advantages and disadvantages that directly impact energy yield and long-term profitability.

5.4.2.1 String Inverters

String inverters convert the power generated by a series of panels from DC to AC. They are cheaper and widely used in large installations, as they allow a variable number of panels to be connected in series. They present a good affinity with the presence of batteries for storage as the series current of the panels remains in DC until it reaches the inverter.

Figure 5.1: String inverter schema

On the other hand they have a single point of failure and their main disadvantage is the susceptibility to losses due to shading, as a single shaded panel can reduce the yield of the entire string.

5.4.2.2 Micro-inverters

Micro inverters operate the DC to AC conversion directly at the panel level, trying to maximize the energy produced in conditions in which a difference in irradiation caused by shading could lead to production disparity between panels.

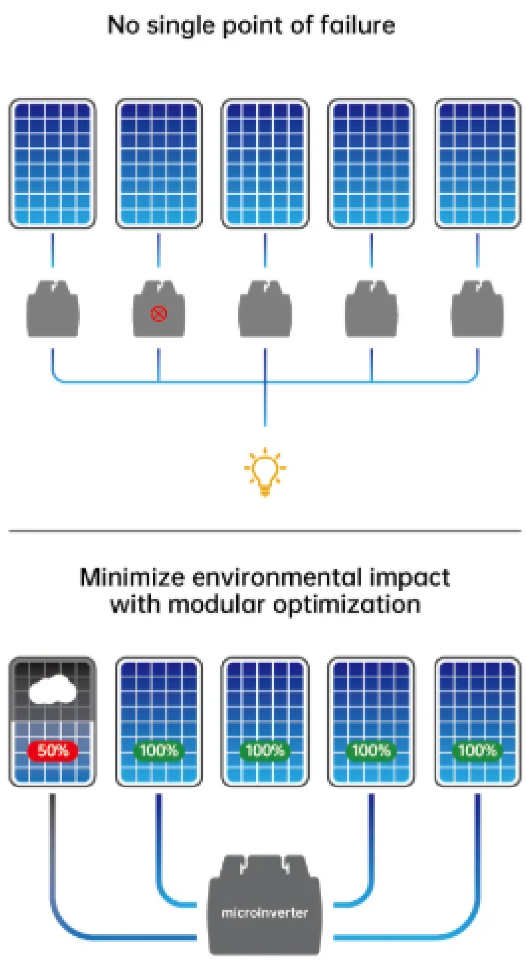


Figure 5.2: Micro-inverters pros: no single point of failure; behavior against shadowing

A study comparing micro-inverters with string inverters discovered that micro-inverters considerably boost energy yield under shade conditions, achieving up to 20.17% greater performance in enhanced analysis settings.[11]

Furthermore, a rigorous investigation indicated that even in non-shaded settings, micro-inverter-based systems maintained greater energy output due to individual MPPT tracking for each module, while string inverters incurred performance losses.[11]

Despite the advantages listed above, a micro-inverter configuration is still more expensive than a more traditional string inverter configuration. According to research on the cost efficiency of the PV system, string inverters cost approximately 0.03€ to 0.17€ / Wp, while micro-inverters cost around 0.25€ / Wp, increasing the appeal of string inverters for extensive deployments.[11]

In the event that storage is required, however, because micro-inverters feature an AC conversion directly on the panel, coupling with normal DC batteries is challenging due to large power losses. AC storage systems that are most similar to the situation have higher costs, which would further exacerbate the gap in the system's beginning prices.

5.4.3 Inverter characteristic impact on profitability

The efficiency with which a PV system transforms DC energy into usable AC electricity depends on the power capacity of the inverter. Oversized inverters may result in underutilization and extra costs, while undersized inverters may cause energy loss. In summary, inverter technology selection has a substantial impact on the levelized cost of power and overall profitability of a PV system.

Key elements include:

- **Performance Ratio:** As previously stated, micro-inverters achieve a higher energy yield than string inverters, especially in conditions with significant shading.
- **System Longevity:** Micro-inverters may decrease stress on individual panels by allowing separate MPPT control, potentially increasing the system's lifespan.[16]
- **Economic Efficiency:** The Cost-Aware Design and Simulation study emphasizes how crucial it is to strike a balance between startup and ongoing expenses in order to maximize system profitability.[6]

5.5 Final considerations

The financial analysis of creating a well-structured photovoltaic system is based on multiple design choices, ranging from choosing the most suitable type of panel to choosing the appropriate number and the connections between them.

The main conclusions of this chapter are as follows.

- Panel technology and placement strategies must balance shading tolerance and costs.
- More panels do not automatically equal more profitability; appropriate size is essential.
- Energy efficiency and return on investment are significantly impacted by series grouping and inverter selection.
- A modular, simulation-driven strategy improves financial returns over the system's lifetime.

The developed simulation framework can be adapted to allow for an in-depth financial analysis, using the following formula, to ensure that technical design choices are in line with economic feasibility.

$$\text{Cost for kWh} = \frac{C_{\text{initial}} + C_{\text{battery}} + C_{\text{maintenance and replacements}} + C_{\text{management}}}{P_{\text{annual}} \times 25}$$

$$\mathbf{C}_{\text{Initial}} = (C_{\text{panel}} \times N_{\text{panels}}) + (C_{\text{inverter}} \times N_{\text{inverters}}) + C_{\text{additional}}$$

The production-weighted cost is calculated over the estimated and guaranteed lifetime of classic photovoltaic systems of approximately 25 years, and involves all the initial and long-term costs expected, such as failures of system components (Fig.5.3).

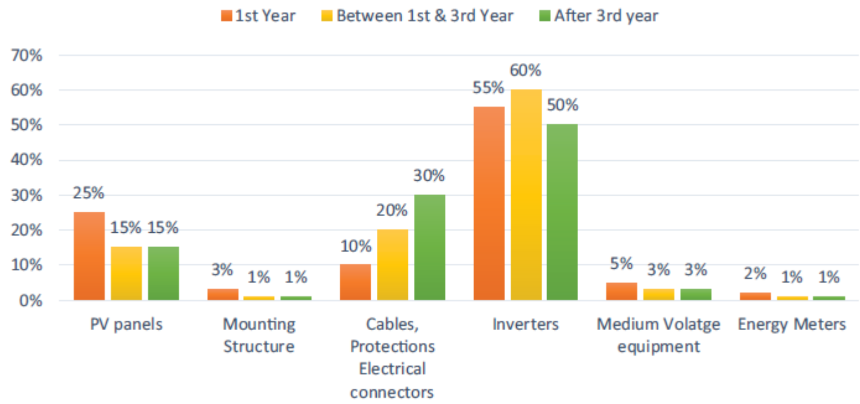


Figure 5.3: Failure incident rate concerning the components of PV plant (adapted from [5]).

In the following chapter, the steps that summarize these strategies are evaluated for a full quantitative analysis, providing details and insights on economic optimization in some real-world scenarios.

Chapter 6

Testing and Validation in Real-World Scenarios

6.1 Introduction to Testing Approach

The discussed methodology sets the groundwork for the realization of a solid framework, automatizing the process of building a PV system, in order to optimize energy production. The validation approach requires a step testing structure to evaluate the effectiveness of panel simulation, panel placement algorithm, connection clustering, and economic performance.

The present chapter exposes four main experiments that address all the key aspects discussed in previous chapters, analyzing power production, shading effect, and efficiency.

1. Comparison of three different panel layout under shading condition, using same irradiance dataset.
2. Evaluation of the algorithm proposed in Chapter 4 vs a "by eye" placement, across three different rooftop scenarios.
3. Analysis of how the changes in inverter constrains affect total system energy output.
4. Efficiency test to evaluate the impact in changing number of panels and series grouping in order to obtain a better production/cost balance.

Each experiment is designed to represent real-world rooftop photovoltaic systems, in which shading, fluctuations in sunlight, and electrical layout influence the total efficiency of the system. The simulation results show whether the suggested optimization strategy increases energy output, reduces mismatch losses, and improves overall system efficiency, offering quantitative proof of its efficacy.

6.1.1 Simulation Framework and Implementation

A Python-based simulation framework developed for this study is used to perform the validation procedure. The framework is capable of:

- Process irradiance matrix representing rooftop irradiance data over time.
- Simulate the I/V characteristic of panels across a wide spectrum of configurations, as highlighted in Chapter 3.
- Run the proposed optimization algorithms detailed in Sections 4.2 and 4.3.
- Display images and graphs that represent the simulation results.
- Compare PV system power output under different configurations.

The experimental design, performance evaluation standards, and particular test scenarios are described in depth in the following sections.

6.2 Comparing Panel Layouts Under Shading Conditions

As widely discussed, one of the most critical factors affecting the efficiency of a PV panel is the shading effect, which causes power losses and mismatch issues in module interconnections.

This experiment compares the performance of the three major photovoltaic panel technologies (half-cell, full-cell, and shingled-cell) under identical shading conditions. The purpose is to evaluate the impact of interconnection design in power production, determining how it mitigates current mismatch losses and increases energy yield.

6.2.1 Case setup

6.2.1.1 Irradiance Data

The present simulation requires irradiance matrices that represent the irradiance profile of a single PV module. To make the simulation as realistic as possible, these profiles are taken directly from the 3D irradiance matrix of an existing rooftop. As shown in the following heat maps, three specific rooftop areas were selected, each representing a specific shadow pattern that can occur on a panel.

- The position highlighted in the top image presents a shadow that covers a limited area of the panel, localized in the bottom-right angle.
- In the left profile of the bottom heat map, the irradiance matrix present less irradiated area in the right section of the panel.
- The remaining panel position presents the top area of the panel covered by an evident shadow.

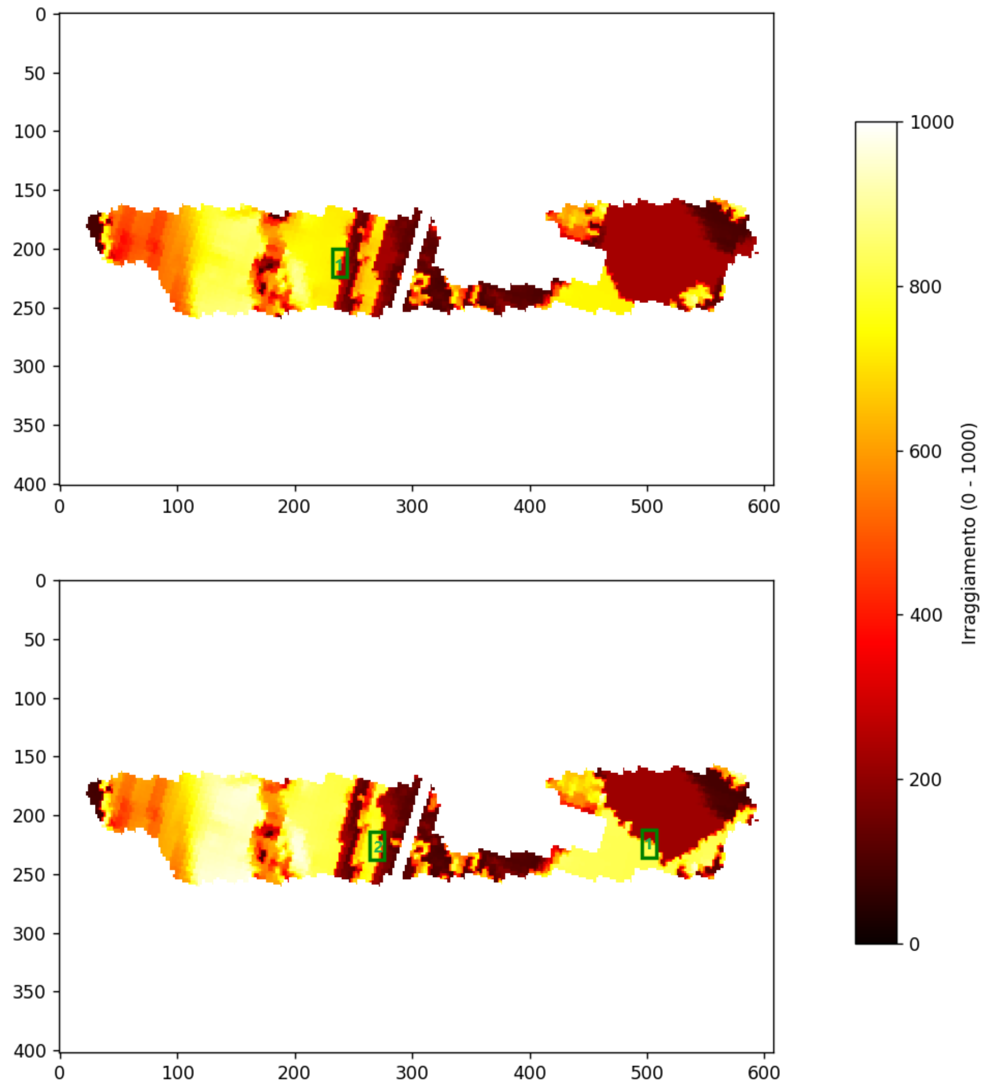


Figure 6.1: Heat-map of two instant: 5080, 5082 of a rooftop irradiance matrix, with panel positions outlined in green

The three identified irradiance matrices are therefore applied to all panel layouts, ensuring identical test conditions.

6.2.1.2 Panel Configuration

Each panel layout is modeled using electrical characteristics based on standard manufactures specifications. To simplify the test, focusing on resilience to shading effect without losing the meaning of the simulation, the same cell (and thus the same I/V characteristics) are used for all panel simulations. These characteristics are obtained from graphs that represent the performance of the module shown in Fig. 3.1.

The tested panel layouts are:

- **Half-cell module** – Expected to provide generally better shading resilience due to bypass diodes and smaller sub-module areas connected in parallel.

The proposed panel consists of 72 physical solar cells, each split in half to form 144 half-cells. The panel is split horizontally into two symmetrical halves, parallel connected, each electrically split into three separate portions, coupled to a bypass diode.

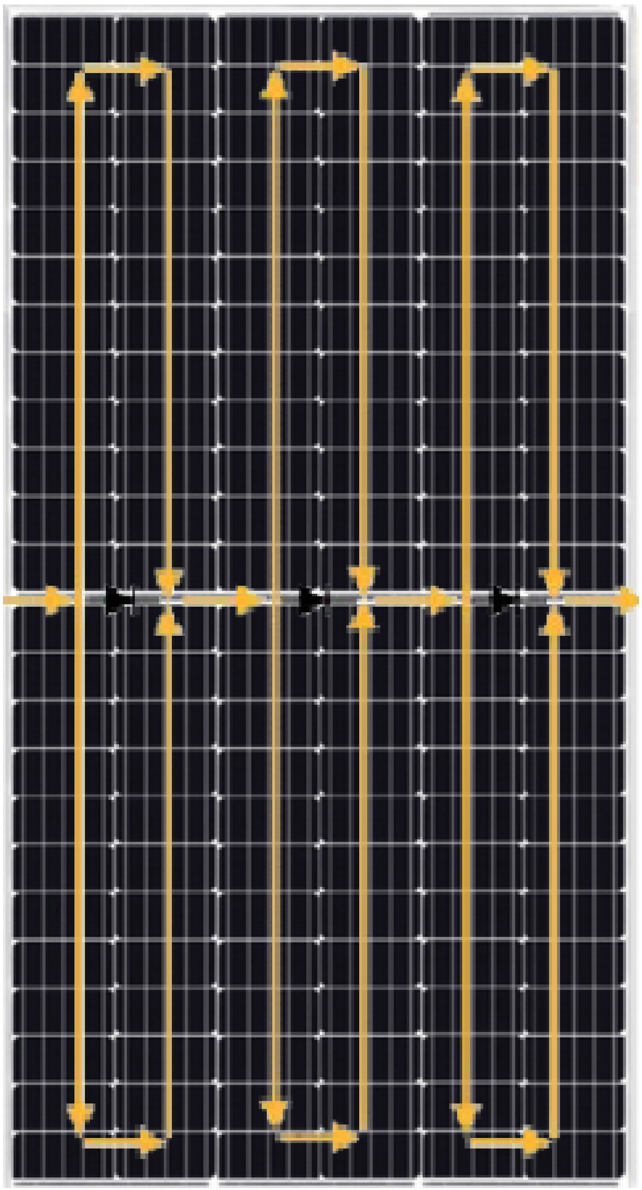


Figure 6.2: Half-cell module: 24x6 cells, 3 bypass diodes

- **Full-cell module** – More susceptible to shading-induced losses due to larger series-connected cell groups. A 72 full-cell module consists of 72 solar cells arranged in six columns and twelve rows. Cells are connected in series and divided into 3 sections, like half-cell ones. Three bypass diodes in the junction box protect each section.

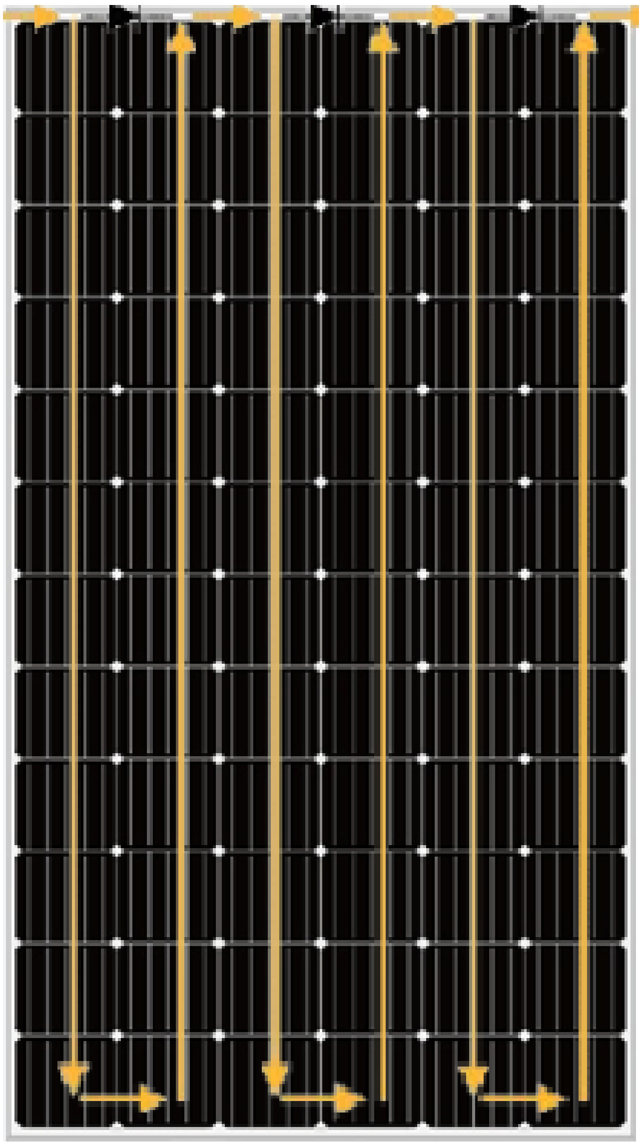


Figure 6.3: Full-cell module: 12x6 cells, 3 bypass diodes

- **Shingled-cell module** – A shingled-cell panel consists of overlapping solar strips arranged in parallel strings. Generally resilient to shadowing effect due to their series-parallel cell arrangement, which isolates the effects of darkened areas to reduce power loss.

  Taking a look at figure 6.3, on the left side there is a panel arranged with 12 horizontal strips, while on the left we have a panel with 6 vertical strips.

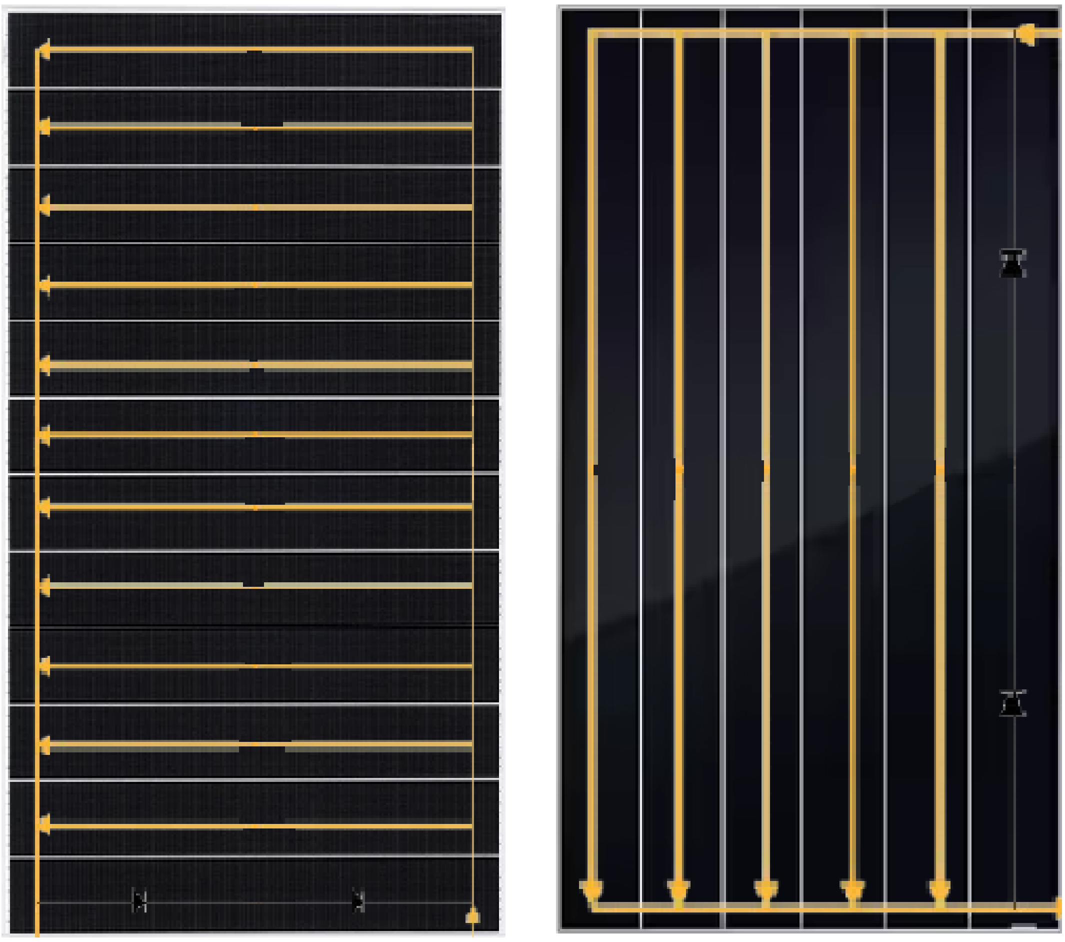


Figure 6.4: Left: 12 horizontal series sections, Right: shingled module: 6 vertical series sections

6.2.1.3 Simulation Procedure

```
FUNCTION:
    compare_modules

INPUT:
    - image_path: Path to the image containing I/V curves.
    - rooftop_matrix_path: Path to the 3D irradiance matrix
   representing rooftop shading over time.
    - num_total_cells: Total number of cells in the panel.
    - max_V, max_I: Maximum voltage and current values for I/V curve
   extraction.
    - num_curves: Number of I/V curves to extract from the image.
    - num_columns: Number of columns in a single panel.
    - position_array: List of panel placement positions in the rooftop
     irradiance matrix, with reference to the instant in 3D matrix.
    - panels_data: List of panel configurations for comparison.
    - range: Time range for evaluating energy output.
    - sampling_time_minutes: Time step for power integration
   calculations.

```

```
OUTPUT:
    - Maximum Power Point (MPP) comparison for different panel layouts
    .
    - Graphical visualization of I/V curves and power output trends
    over time.

STEPS:
1. Load the rooftop irradiance matrix from rooftop_matrix_path.
2. Extract the I/V curves from image_path using max_V, max_I, and
    num_curves.
3. Display the rooftop irradiance matrix with the selected panel
    positions in specific instant.
4. FOR each instant i and panel position set in position_array:
    a. Extract the panel's irradiance sub-matrix for the given
    position, at the moment of interest.
    b. FOR each panel configuration in panels_data:
        i. Simulate the I/V curve based on the panel's electrical
    parameters.
        ii. Compute the Maximum Power Point (MPP) for the panel.
        iii. Display the I/V curve and energy output.
5. FOR each panel configuration:
    a. Initialize total energy production.
    b. FOR each time step t from instant to instant + range:
        i. Extract the irradiance matrix for the given time.
        ii. Simulate the panel's I/V curve.
        iii. Compute the MPP and accumulate the power output.
    c. Convert total power into energy based on sampling_time_minutes.
    d. Display the power output trend over time.
6. Return MPP data and graphical results.
```

The above pseudo-code is useful to visualize the step involved in the simulation:

1. Extract the irradiance matrices for the profiles of the examination panels.
2. Apply each irradiance matrix to each panel layout.
3. Simulate the I/V characteristic for each shading configuration.
4. Display the I/V characteristic of the panel in the instant of interest (showed in Fig. 6.1) and calculate Maximum Power Point (MPP)
5. Calculate the energy production and display the MPP trend over 800 temporal instant, to be evaluated in the neighborhood of interest.

6.2.2 Expected result

Specific PV panel topologies react uniquely to shading conditions, due to differences in the topology of cell interconnections and the presence of bypass diode arrangements. The expected behavior of each panel type tested under all irradiation conditions is described in this section.

- **Half-Cell Modules**

  Generally demonstrates an high resilience to small shaded areas, due to the presence of bypass diodes. Thus, paired with the presence of two half of the panel operates independently, halve mismatch losses even when the shadow covers the panel along the entire length of the short side.

- **Full-Cell Modules**

  The classic layout provides a greater vulnerability to shading. The presence of bypass diodes, compared to the half-cell topology, reduces energy losses less when shading is present only on one half of the panel. Mismatch effects are therefore more pronounced, as shading on a single cell impacts a larger area of the panel.

- **Shingled-Cell Modules**

  Shingled-cell modules have the best shading tolerance due to their overlapping strip design, which allows power generation even when partially shaded. They outperform full-cell panels in lowering electrical resistance and shading losses, allowing several parallel current channels. With respect to half-cells, the comparison relies on whether the shadow aligns with the orientation of the strips.

The quantitative comparison that follows will support the theoretical expectations, through the analysis of simulated I/V curves, power production, and mismatch losses.

6.2.3 Result and comparison

The simulation results show a detailed comparison of four panel layouts: half-cell, full-cell, shingled with six vertical strips, and shingled with twelve horizontal strips, under various shade circumstances. To assess each configuration's performance, the analysis focuses on long-term power generation patterns and instantaneous I/V characteristics.

6.2.3.1 Instantaneous I/V Characteristic and Power Output Comparison

A brief comparison of the four topologies is performed under relatively homogeneous irradiance conditions (no shade), only to demonstrate that under ideal irradiated areas, shown in Fig. 6.5, the panels behave almost the same.

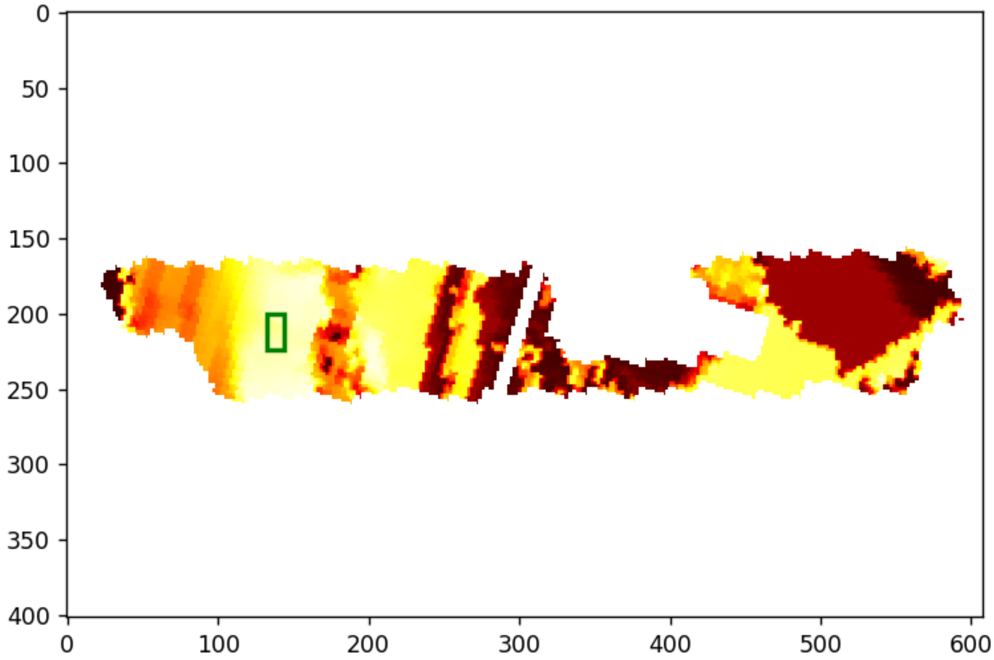


Figure 6.5: Selected panel profile with homogeneous radiance

All panel configurations generated almost the same power production, with values separated by short distances, perhaps due to calculation inaccuracies or differences in the matrix's radiation values. This shows that variations in performance are mostly caused by how interconnection architecture respond to shading effects rather than intrinsic efficiency differences.

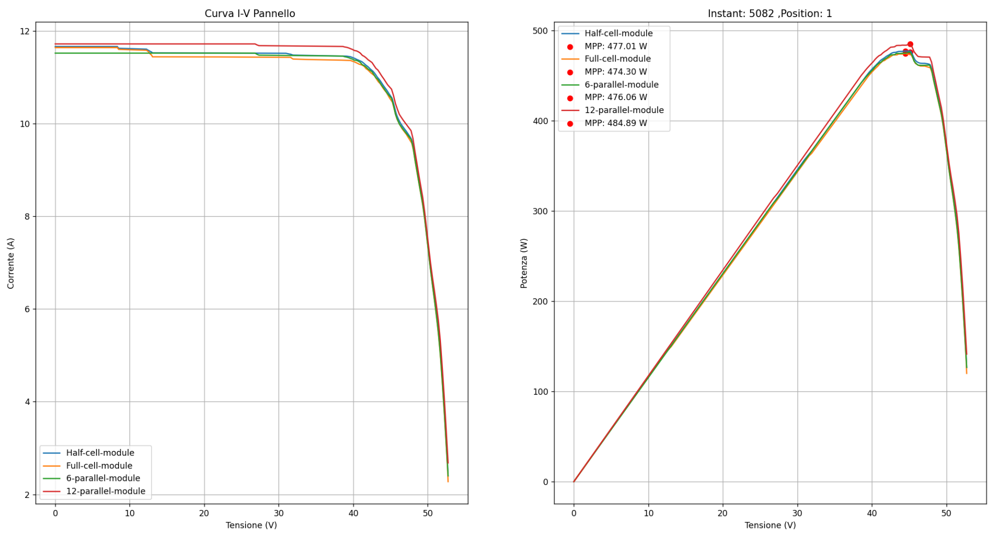
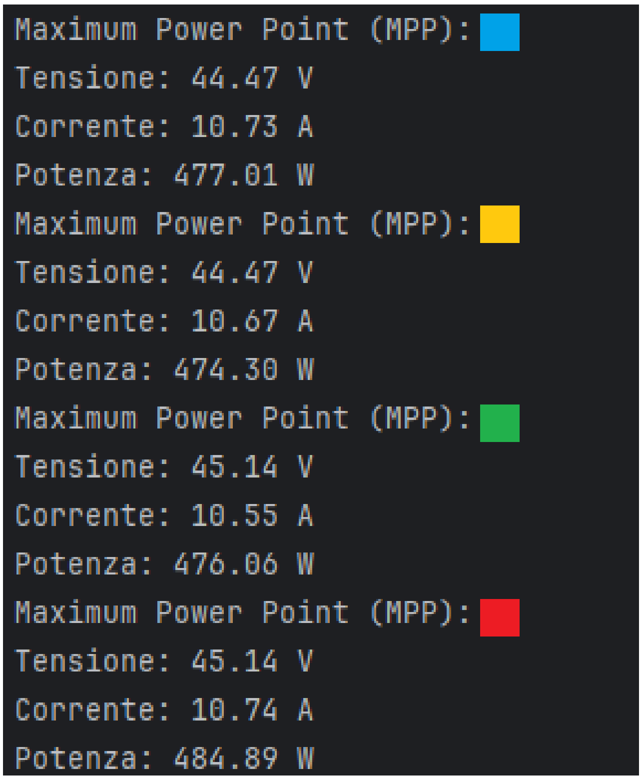


Figure 6.6: Comparison I/V graph under uniform radiance



```
Maximum Power Point (MPP):
Tensione: 44.47 V
Corrente: 10.73 A
Potenza: 477.01 W
Maximum Power Point (MPP):
Tensione: 44.47 V
Corrente: 10.67 A
Potenza: 474.30 W
Maximum Power Point (MPP):
Tensione: 45.14 V
Corrente: 10.55 A
Potenza: 476.06 W
Maximum Power Point (MPP):
Tensione: 45.14 V
Corrente: 10.74 A
Potenza: 484.89 W
```

Figure 6.7: Output data: Uniform radiance

Let's now examine the panel arrangement under various shading conditions:

- **Corner shadowing**

  The present test compares panel layouts under position 1 in Fig. 6.1, at instant 5080 of 3D irradiance matrix.

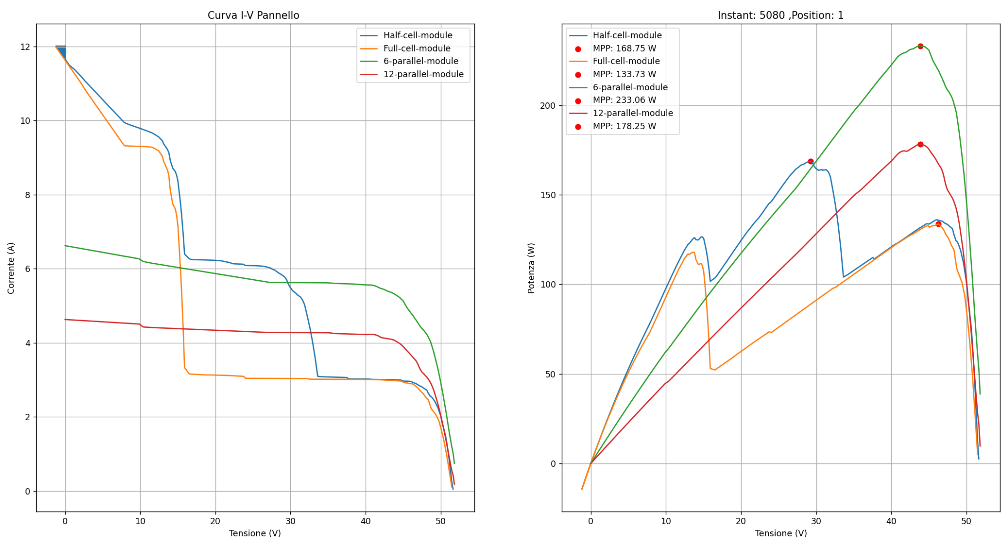


Figure 6.8: Comparison I/V graph: Corner shadowing

Figure 6.9: Output data: Corner shadowing

The voltage output at MPP point is the same for 3 of 4 panels. Half-cell one, due to bypass diode activation performing better under less voltage value.

The 6 vertical strip shingled cell panel provides a higher power output, followed by same level for half-cell and the other shingled. The full-cell panel performs the worst.

- **Short-side partial shadowing**

  This test compares panel layouts under position 1 in Fig. 6.1, at instant 5082 of 3D irradiance matrix.

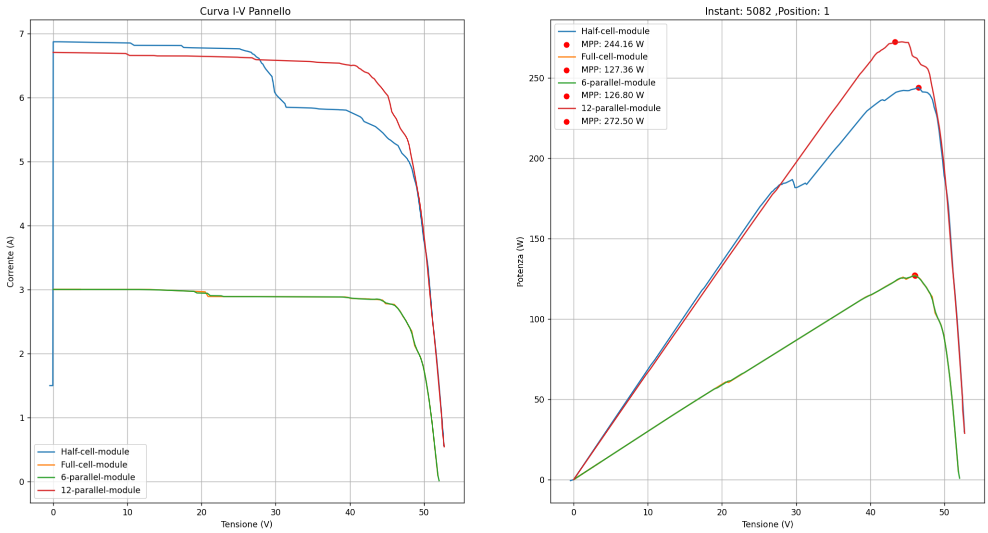


Figure 6.10: Comparison I/V graph: Short-side partial shadowing

```
Maximum Power Point (MPP):
Tensione: 46.51 V
Corrente: 5.25 A
Potenza: 244.16 W
Maximum Power Point (MPP):
Tensione: 46.00 V
Corrente: 2.77 A
Potenza: 127.36 W
Maximum Power Point (MPP):
Tensione: 46.06 V
Corrente: 2.75 A
Potenza: 126.80 W
Maximum Power Point (MPP):
Tensione: 43.31 V
Corrente: 6.29 A
Potenza: 272.50 W
```

Figure 6.11: Output data: Short-side partial shadowing

Due to horizontal strips for shingled panel, and independence of the halves for half-cell, these panels perform better under the present orientation of shadow. The others suffer because of the current cap detected on every string of the panel.

- **Long-side partial shadowing**

The present test compare panel layouts under position 2 in Fig. 6.1, at instant 5082 of 3D irradiance matrix.

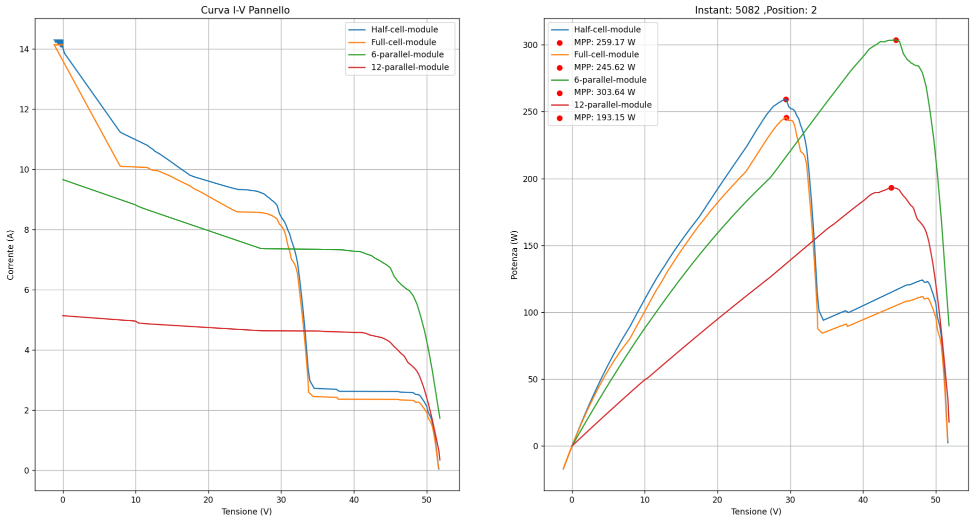


Figure 6.12: Comparison I/V graph: Long-side partial shadowing

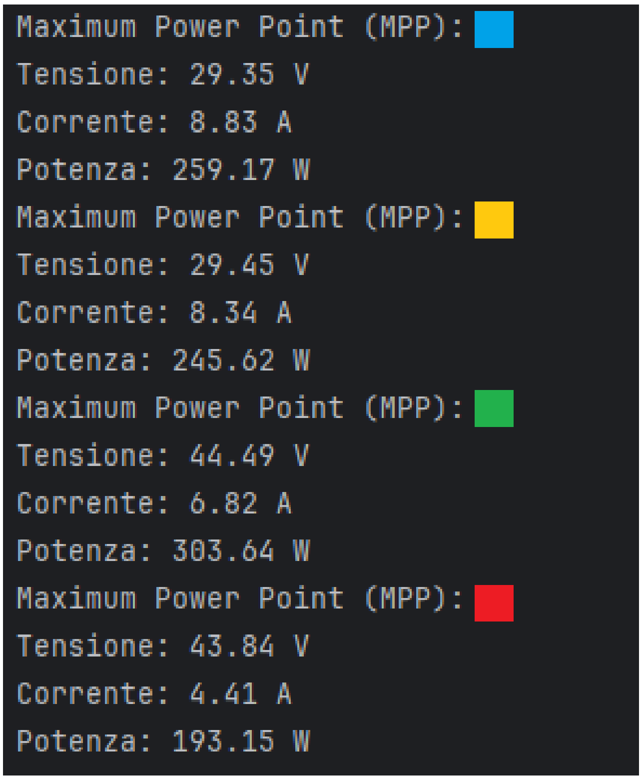


Figure 6.13: Output data: Long-side partial shadowing

About long-side's affecting shadow, half-cell and full-cell are aided by the activation of the bypass diodes, excluding the shadowed part of the panel. The shingled panel that outperforms the others is the one where strips are parallel to shadow pattern.

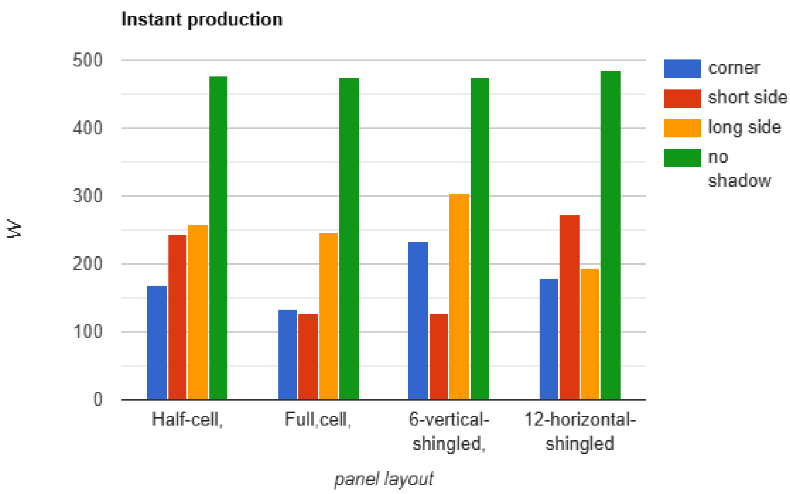


Figure 6.14: Bar graph instant power comparison

Here are the thoughts that can also be gleaned from the bar graph in Figure 6.14:

- As expected, the half-cell panel performed consistently well across cases, striking a balance between energy production and shading resilience.
- The shingled 6-strip panel performed best with long-side shadowing, because of its vertical segmentation. The shingled 12-strip panel excelled in short-side due to horizontal segmentation, and perform slightly better than the former in corner shadowing, probably because of the shadow discrepancy.
- Since shading on a single cell drastically decreases current throughout the entire string, the full-cell panel consistently performed the worst. Only for long-side shading, due to the bypass diodes' activation, the present layout performed slightly better than the 12 strips shingled module.

6.2.3.2 1500-Time-Step Power Production and MPP Trend Analysis

Long-term simulation is a great way to have a better understanding of the revenues that choosing one layout over another can bring in terms of production. A complete simulation took approximately 15 minutes, divided equally for each of the identified topologies.

The following are representative figures who help to evaluate each panel topology on the three previously discovered profiles.

The phases of the first case are analyzed in more depth.

- **Corner shadowing**

The following figure depicts the trend of the heat-map of the selected area over one day among those analyzed. It highlights the natural movement of the shadow which does not always influence the panel with the same intensity.

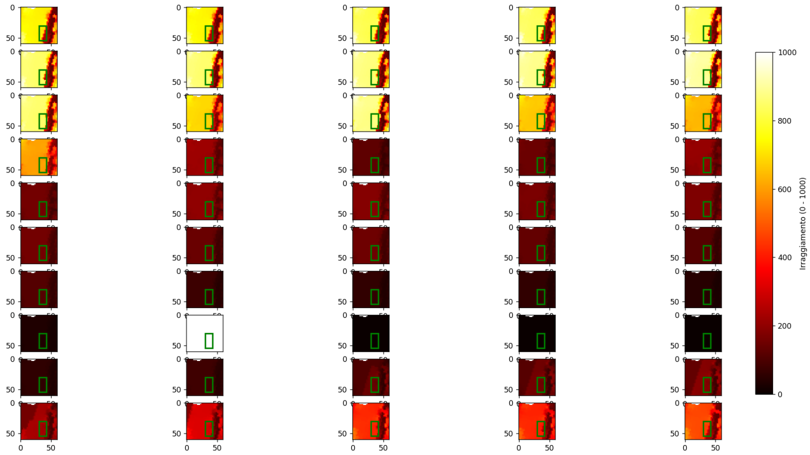


Figure 6.15: Heat-map panel profile over the first day of interest

Graphs for each panel topology are displayed to visually compare trends in MPP values over time.

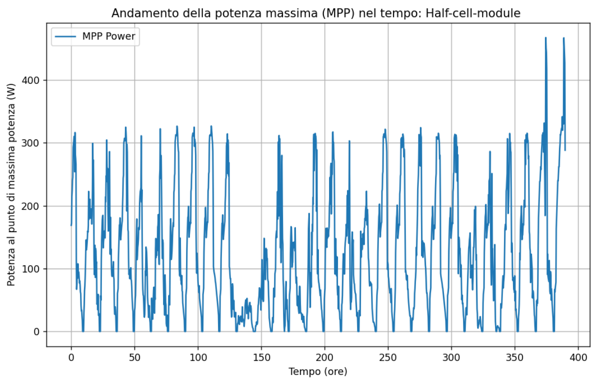


Figure 6.16: MPP trend graph: Half-cell

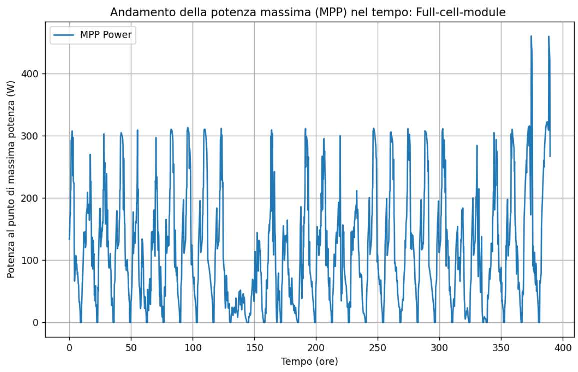


Figure 6.17: MPP trend graph: Full-cell

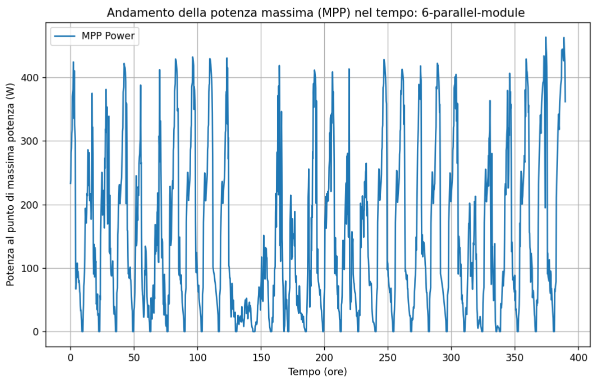


Figure 6.18: MPP trend graph: Shingled-cell 6 vertical strips

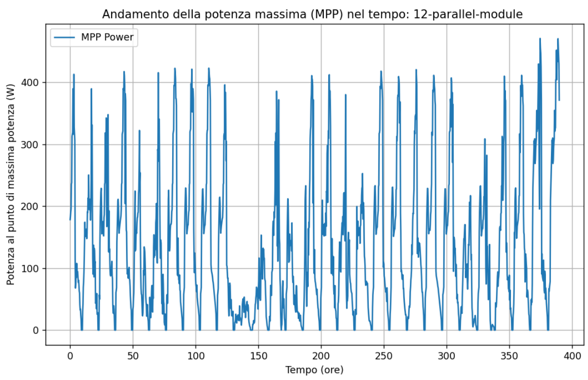


Figure 6.19: MPP trend graph: Shingled-cell 12 horizontal strips

In order to provide a quantitative measure for the comparison, a bar chart is used to compare difference in power output. The Wh produced is calculated by summing the values over time, multiplying the total by the minutes between samplings (15 minutes), and dividing by 60.

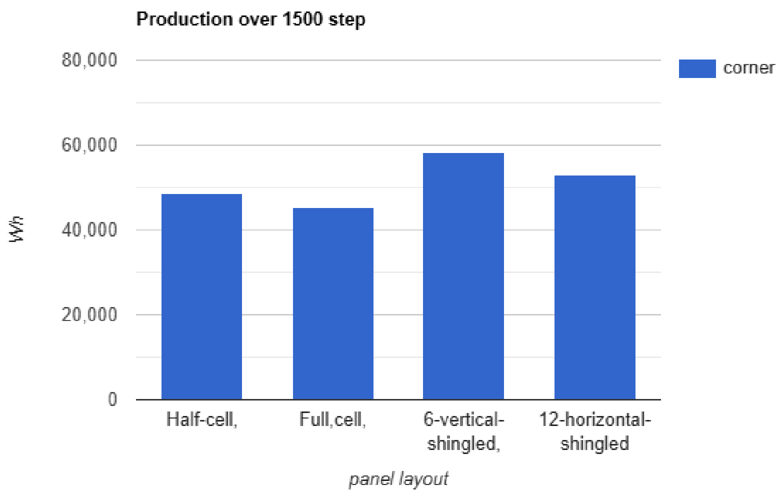


Figure 6.20: Panel production in Wh over 1500 steps (approximately 30 days)

Summarizing, the shingled layout perform overall better: 6-vertical-shingled layout has the highest energy production, followed by the 12-horizontal-shingled layout. The Half-cell and Full-cell layouts have lower production values, with the Full-cell performing the least. The percentage loss with the immediately least productive panel stands at 9%.

- **Short-side partial shadowing**

  The following image displays that the shadow affect the panel only for the first 2 steps.

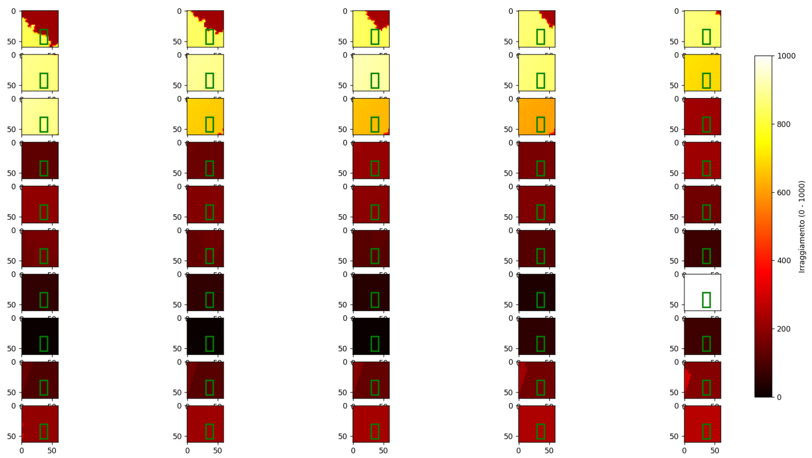


Figure 6.21: Heat-map panel profile over the first day of interest

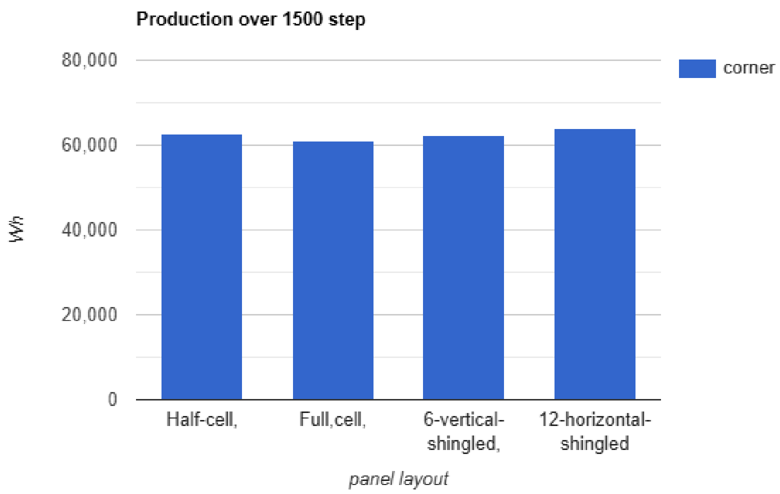


Figure 6.22: Panel production in Wh over 1500 steps (approximately 30 days)

Unlike the previous chart, in the corner shadowing category all four panel configurations show almost comparable energy production levels, with just minor differences. There aren't many variations between the panel layouts, however the 12-horizontal-shingled pattern seems to have a somewhat greater output. This suggests that panel layout has little to no significant affections on overall power output in this specific scenario.

- **Long-side partial shadowing**

  In that situation, the shadow is always a factor in energy production, because it moves throughout the panel position.

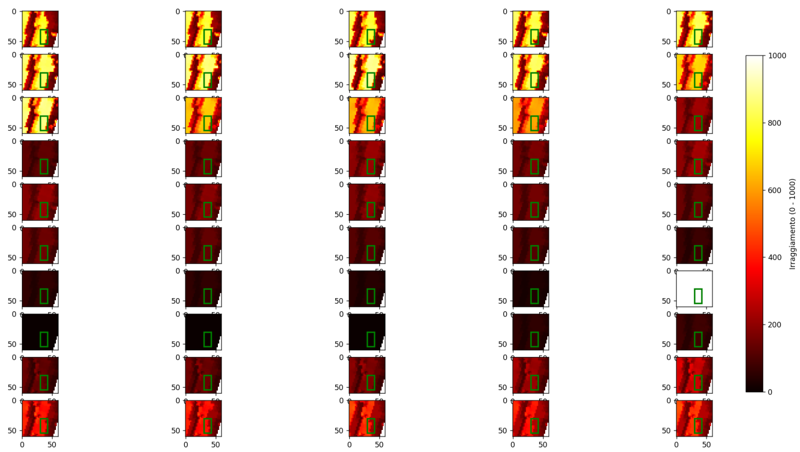


Figure 6.23: Heat-map panel profile over the first day of interest

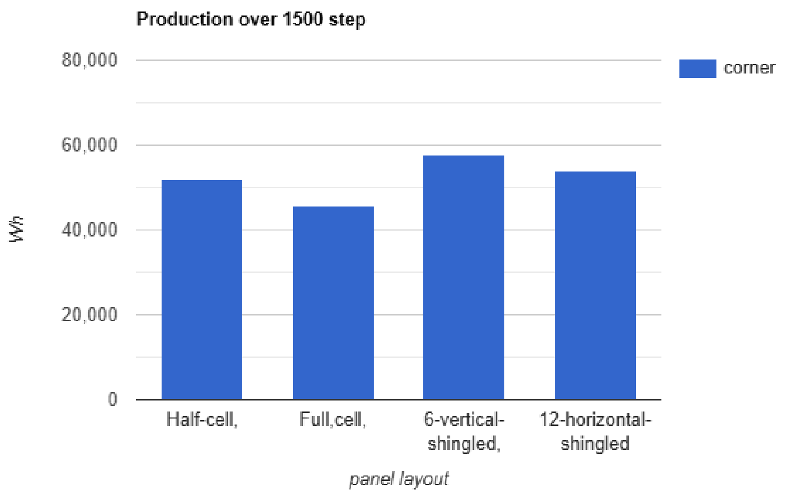


Figure 6.24: Panel production in Wh over 1500 steps (approximately 30 days)

This version of the chart follows the one relating to corner shading, where the 6-vertical-shingled layout perform the highest power output, followed closely by the 12-horizontal-shingled layout. The Half-cell panel performs better than the Full-cell, which has the lowest energy output. the percentage gap between panels production is always below 10%.

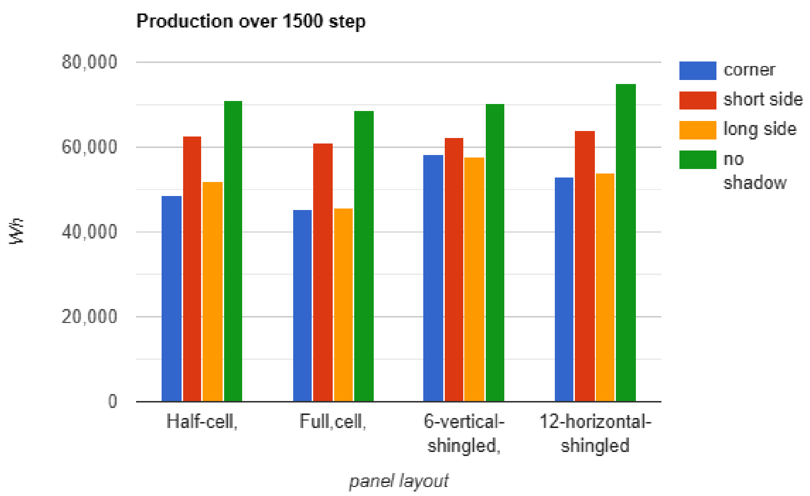


Figure 6.25: Bar graph long time energy production comparison

Figure 6.25 shows the production of the treated panels, additionally referring to the position without shading displayed in the preceding section. You can observe how, in contrast to instantaneous comparison, the long-term loss of productivity is significantly smaller for all layout types. In conclusion, the 6-strips-shingled panel is the most productive, followed by half-cell and 12-horizontal-shingled, with full-cell closing the quartet.

6.2.4 Outcomes

The findings support the expected impact of shading on various panel layouts.

Half-cell panels continuously demonstrated good performance, striking a balance between energy generation and shading resilience. The performance of shingled panels was layout-dependent like for the instantaneous comparison: the 6-strip variant performed better under long-side shading, whereas the 12-strip version performed better under corner and short-side shading. Full-cell panels performed the worst, losing substantial power due to shading-induced mismatch. However, bypass diode activation allowed them to perform marginally better in long-side shading conditions.

These results further support the benefits of half-cell and shingled designs in reducing shading losses, which makes them more appropriate for rooftop installations in situations of variable irradiance.

6.3 Evaluating Automated vs. Manual Panel Placement and Series Grouping

The positioning and electrical grouping of solar panels have a considerable impact on energy production efficiency, especially under shaded conditions. This experiment compares the outcomes of the automatic placement and series grouping method, suggested in Chapter 4, with manual (by-eye) placement, over three different rooftop scenarios.

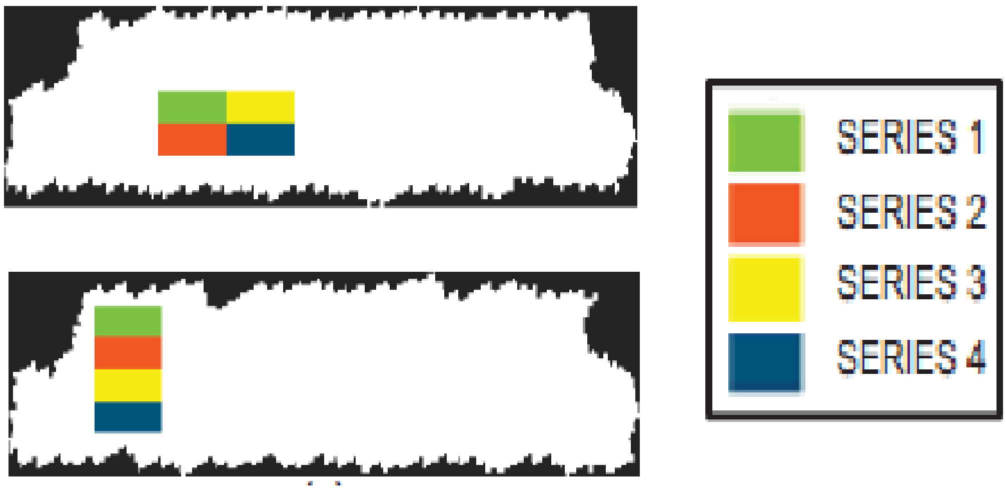


Figure 6.26: Example of manual placement standards

The manual placement is performed positioning the panels in a standard order, as evidenced in Fig. 6.26. The panels are positioned as attached as possible, in order to reduce the fragmentation of the empty space; grouping the closer panels in series. The area where the panels will be placed is selected by taking a look at the heat-map of the 75th percentile, trying to provide a more realistic evaluation of the algorithm. The purpose is to see if the algorithm can provide an efficient alternative way to increase energy yield, reduce shading losses, and improve series connections.

The assessed step phases involve:

- Evaluating whether the proposed k-means algorithm shows the highest irradiance areas for panel installation.
- Comparison of automatic and manual placement, over to grouping methodology, in order to evaluate the algorithmic effectiveness in minimizing losses due to shading and mismatch.
- Analyze power production across the selected scenarios for both approaches.

6.3.1 Scenario setup

6.3.1.1 Irradiance Data

We applied the algorithm on the roofs of three industrial buildings, representing three different real shading scenarios. They are lean-to roofs of approximately 49m×12m, facing S/S-W with inclination of 26°. The suitable area is then aligned to a 10cm grid, thus obtaining the irradiance matrices for the roofs.

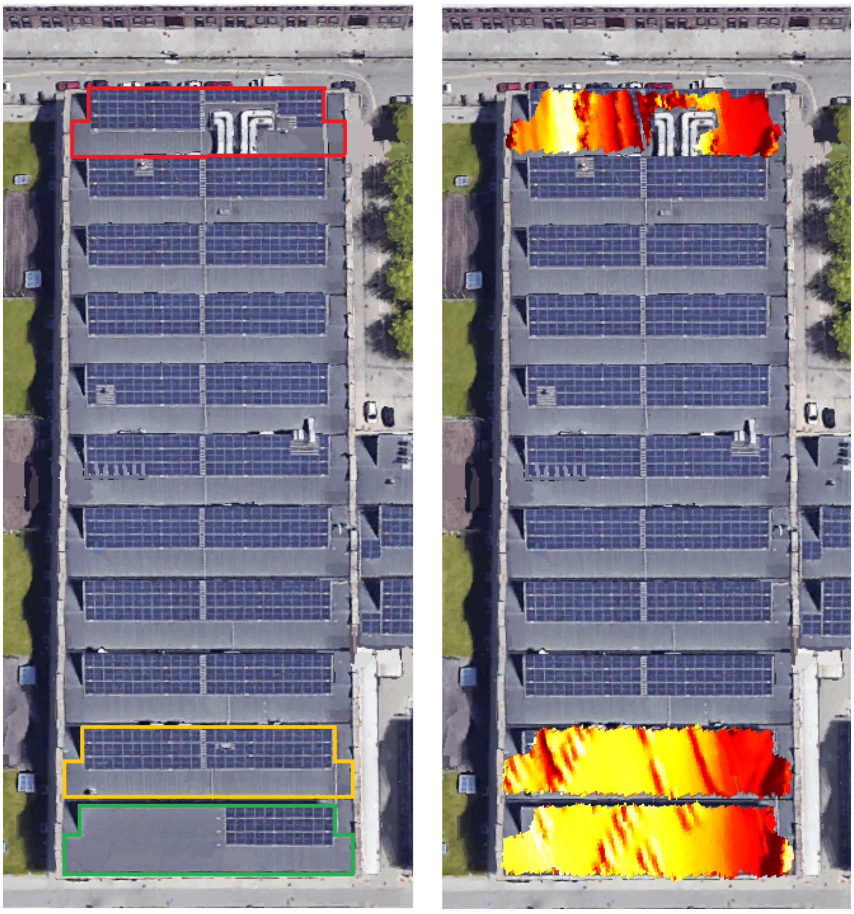


Figure 6.27: Rooftop location

For strictly technical reasons, the roof heatmaps are rotated relative to those presented in Figure 6.27.

- **Rooftop 1:** Outlined in green in Fig. 6.27, presents a large irradiated area, but not continuous, with shaded areas in the central part.

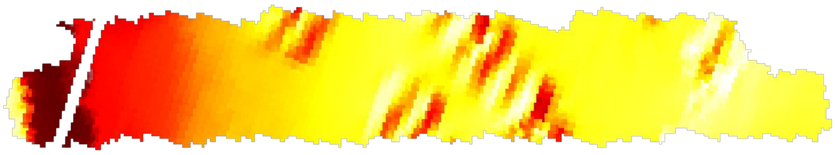


Figure 6.28: Rooftop 1 ,75th percentile heat-map

- **Rooftop 2:** The area immediately above has a large central irradiated area, with scattered shaded areas.

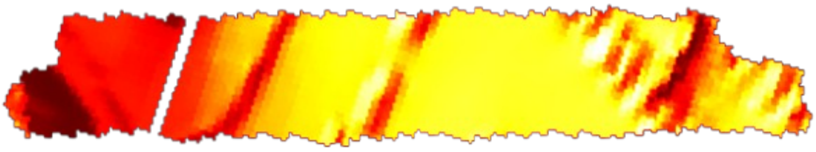


Figure 6.29: Rooftop 2 ,75th percentile heat-map

- **Rooftop 3:** The red one presents a rather heterogeneous area in terms of radiation with a central obstacle, namely the ventilation ducts. This scenario is also the one used for the previous simulation.

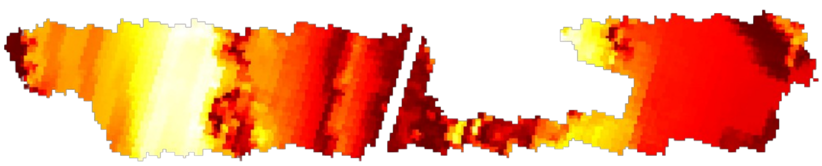


Figure 6.30: Rooftop 3 ,75th percentile heat-map

The simulations are performed using irradiance GIS-based matrices calculated with the processes described in the background section.

6.3.1.2 Panel Configuration

The purpose of this simulation is to assess how effective the algorithm outlined in Chapter 4 is. The chosen panel therefore has no bearing on the validity of the test because the step just attempts to assess the algorithm's efficiency.

In this example, a half-cell panel with 144 cells and standard configuration with three bypass diodes is chosen (like the one used in the previous test, Fig. 6.2). This is because it is the most suited panel to analyze the actual benefit of Pearson correlation with subareas, detailed in Section 4.3.2.3.

6.3.1.3 Simulation Procedure

The simulation is repeated for each roof examined, providing as input the data of the same panel, the matrices representing the roof data, the number of panels, the inverter constraint and the time duration of the energy calculation. Here follows the detailed pseudo-code with the step involved in the simulation:

1. Identify high-irradiance rooftop areas using K-Means clustering.
2. Selects the best panel positions accordingly with the greedy method described in Section 4.2.
3. Group panel into clusters following Pearson's correlation of sub-areas hints.
4. Simulates energy production of the whole system over time (separating for each cluster of panels in series).

```
FUNCTION:
    find_roof_power_top_irradiance_areas_k_means_clustering_greedy

INPUT:
    - image_path: Path to extract I/V curves from reference images.
    - rooftop_metrics_matrix_path: Rooftop irradiance-based metrics
   matrix.
    - rooftop_metrics_matrix_path_real_dimensions: Rooftop real-
   dimension irradiance data.
    - rooftop_matrix_path: 3D irradiance matrix representing rooftop
   shading over time.
    - num_panels: Number of panels to be placed.
    - num_total_cells: Total number of cells per panel.
    - num_columns: Number of columns per panel.
    - panel_data: Electrical characteristics of the selected panel
   type.
    - max_V, max_I, num_curves: Panel voltage, current limits, and I/V
    curve count.
    - instant, ran: Time range for the simulation.
    - folder: Storage path for intermediate outputs.
```

```
    - k_means_factor: Clustering factor for irradiance-based area selection.
    - vincolo_inverter: Inverter constraints for defining series grouping rules.
    - sampling_time_minutes: Time step resolution for energy yield calculations.

OUTPUT:
    - mpp_total: Maximum power point (MPP) values for each optimized panel cluster.

STEPS:
1. Load irradiance data:
   a. Load rooftop irradiance metric matrices (processed and real dimensions).
   b. Load 3D irradiance matrix for rooftop shading representation.
   c. Extract I/V curves for the selected panel type.

2. Identify high-irradiance rooftop areas using K-Means clustering:
   a. Extract 75th percentile irradiance values for all rooftop positions.
   b. Apply K-means clustering to segment rooftop into high-energy and low-energy areas.
   c. Select highest-ranked areas for potential panel placement.
   d. Display the identified high-irradiance zones on the rooftop.

3. Select best panel positions:
   a. Rank panel placement based on irradiance metrics.
   b. Memorize retrived positions in the array "selected_panels"
   c. Store selected panels positions in a file.

4. Group panels into series clusters:
   a. Compute optimal number of clusters.
   b. Apply series grouping optimization using Pearson's correlation.
   c. Save cluster configurations in a file.

5. Display panel placement and series grouping:
   a. Generate and display a heatmap of selected panel positions and their groupings.

6. Precompute interpolated I/V curves for all panels over time.
   a. Store precomputed panel curves in a file.

7. Simulate energy production over time (`t = instant -> instant + ran`):
   a. For each cluster:
      - Retrieve I/V curves of all panels.
      - Combine panels in series using `sum_series_module_without_diodes()`.
      - Compute the total I/V curve for the cluster.
      - Extract the Maximum Power Point (MPP).
      - Accumulate energy production over time.

```

```
8. Convert total power production into energy (kWh) based on sampling
    rate.

9. Print the final MPP values for each cluster.
```

On the other hand, the manual placement of the panels is performed by eye, providing the top-left corner for each panel to select. The data are saved in the "selected_panels" array, replacing those of the recursive algorithm that identifies the best positions. The grouping stage is performed according to standard procedures by selecting the closest panels.

6.3.2 Expected result

The automatic panel placement and series grouping method is generally going to outperform manual placement by variable degrees, depending on the peculiarity of the rooftops.

- Rooftops 1 and 2, which have large high-irradiance zones, could benefit from both approaches. However, by methodically choosing the highest irradiance places and creating better-matched series groups, the algorithm should still offer a minor edge by lowering mismatch losses.
- With restricted high-irradiance zones, the algorithm should perform noticeably better than manual placement for Rooftop 3. A normal manual approach may arrange panels too close together, resulting in some being positioned in low-irradiance locations. On the other hand, the algorithm performs placement by giving priority to areas with consistently high irradiation, and groups the connections in series to minimize energy losses.

Inverter restrictions are likely to have a noticeable influence on all rooftops. By ensuring that series groups preserve comparable I/V characteristics, the algorithm increases efficiency and lowers mismatch losses. In this regard, manual grouping is anticipated to perform poorly in the absence of a systematic irradiance correlation check.

Summarizing, the methodological approach should consistently result in higher energy output, especially in complex rooftop layouts. Even if the difference is small, the long-term reduction in mismatch losses improves system efficiency, making automated placement and grouping an option more dependable and effective.

6.3.3 Simulation Results

We used the PV placement algorithm on the three roofs, placing N = 32 panels. The panels are always grouped in series of 8.

The placement algorithm takes less than 120 seconds to execute on an Intel core i7-10710U notebook with 15,8 GB of RAM, a time that increases linearly as the number of valid grid elements and panels to be placed increases.

Despite their close proximity, the roof irradiance distributions varied significantly between roofs. Thus, the simulation's goal is to confirm that the methodology works by examining the intermediate output of each step, for each scenario.

1. K-Means Area Clustering.
2. Panel Placement in High-Irradiance Areas.
3. Grouping of Panels with Pearson's Correlation.

6.3.3.1 Rooftop 1

The first image shows the manual placement of the panels using the standard technique discussed previously. The placement is performed in the most irradiated areas of the roof and is based on accurate spatio-temporal irradiance data, which is typically unavailable to installers. We are comparing our solution to a "good" reference.

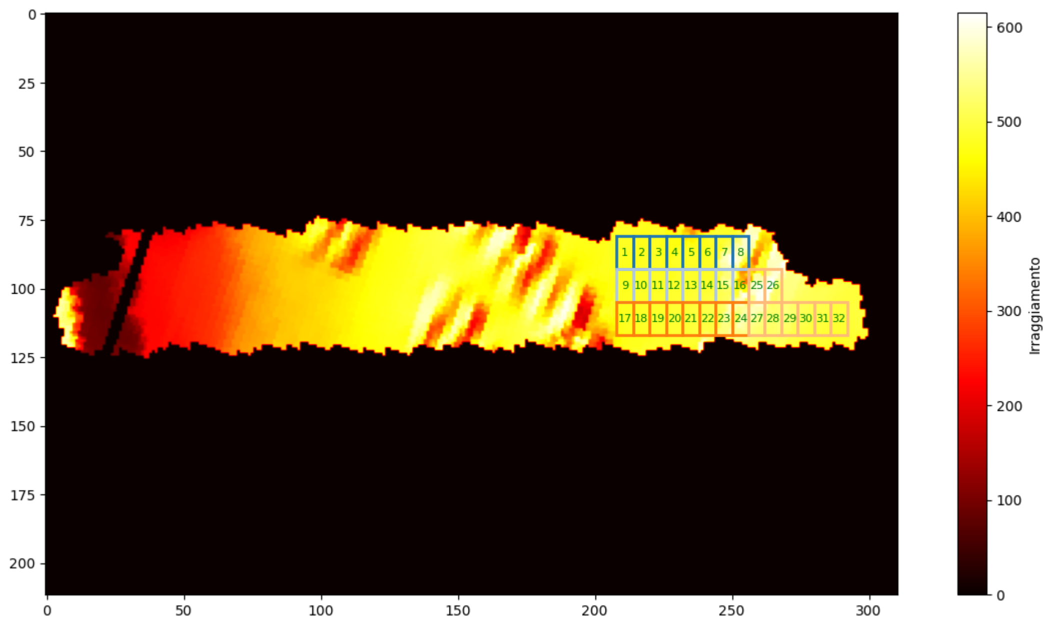


Figure 6.31: Rooftop 1: panel with manual positioning

The initial phase of the test technique involves clustering the 75th percentile matrix, from the best irradiated area to the worst irradiated area. The k-mean approach is assessed for identifying 50 locations, as shown in Fig. 6.31, colored with pigments taken from the *viridis* palette.

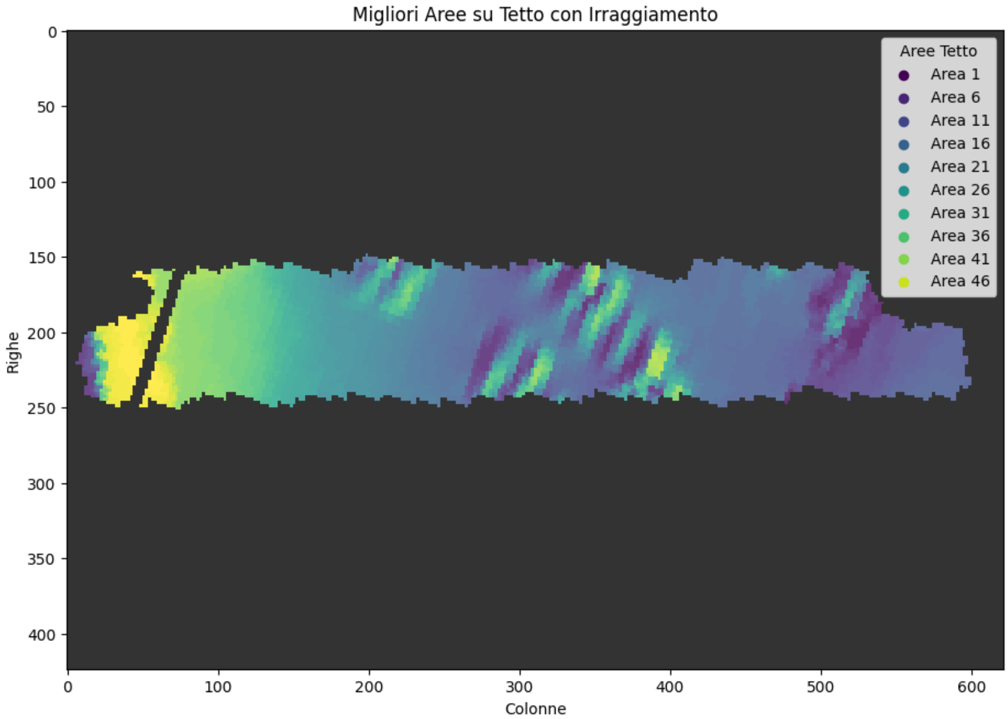


Figure 6.32: Rooftop 1: k-means with 50 areas heat-map

The brightest spots stand close to the darkened areas in the center of the roof, as shown in the Figure 6.32. The freer part of the roof, with the yellowest tint(in 75th percentile heatmap), is instead grouped into a large area.

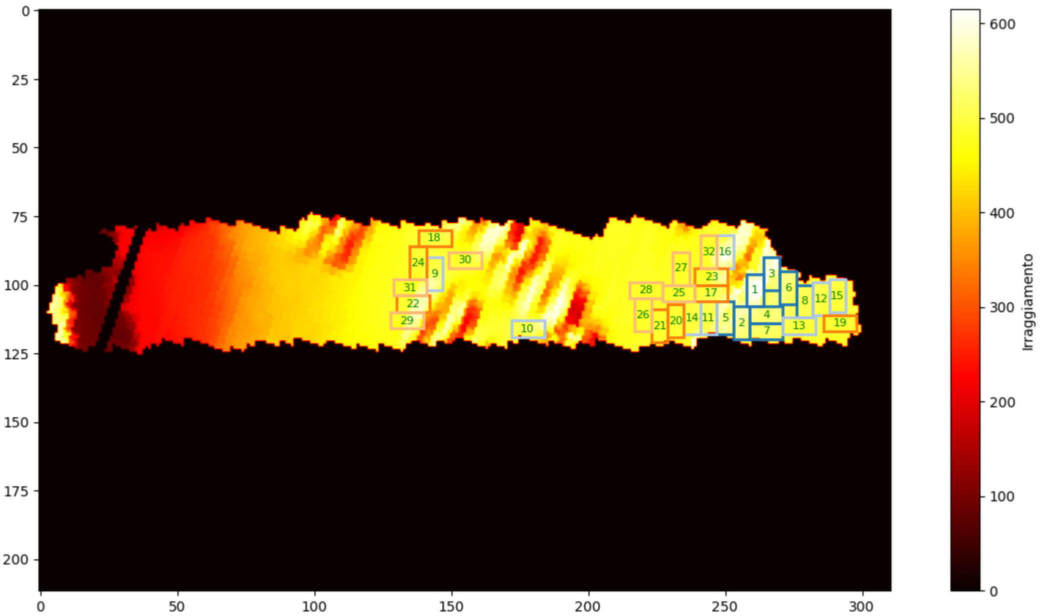


Figure 6.33: Rooftop 1: panels positioning without clustering

According to Section 4.2.2.4, panels are recursively placed in clusters from best to worst. Rectangles with colored edges represent panels, with the ones of the same color belonging to the same series string. At this point of the simulation panels are simply sorted by eight, from best to worst.

It is instantly apparent that the panels do not adhere to a normal arrangement: they attempt to cover more of the bright areas on the map and, as a result of the algorithm's greedy nature, there are vacant gaps in between the panels.

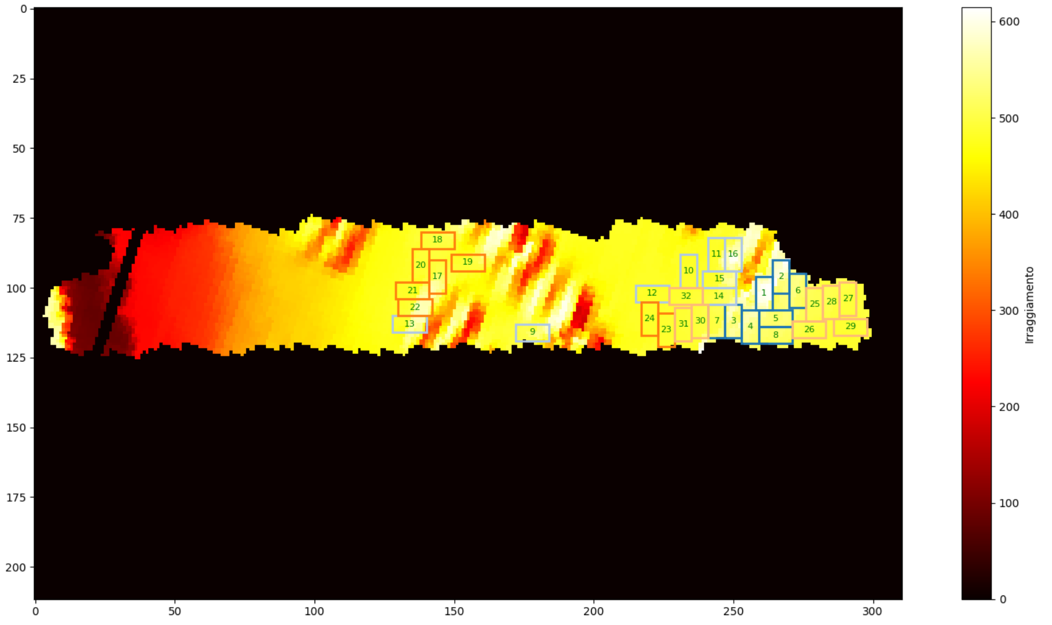


Figure 6.34: Rooftop 1: panels positioning with clustering

Once the definitive positions for the 32 panels are established, through processing on the original irradiation matrix discussed in detail earlier, the panels are grouped in the best way to prevent mismatch losses.

Except for a few exceptions, the grouping indicates how the nearest panels are often connected. This is most likely because, depending on the time of day, the sun's reflection off a sloping roof produces distinct radiation patterns. Despite that, the presence of isolated cases could highlight how some areas of the roof far from each other present a very similar radiation pattern over time.

6.3.3.2 Rooftop 2

We proceed straight to the comparison of the final arrangement as the considerations of the second case's intermediate steps are consistent with those of the first.

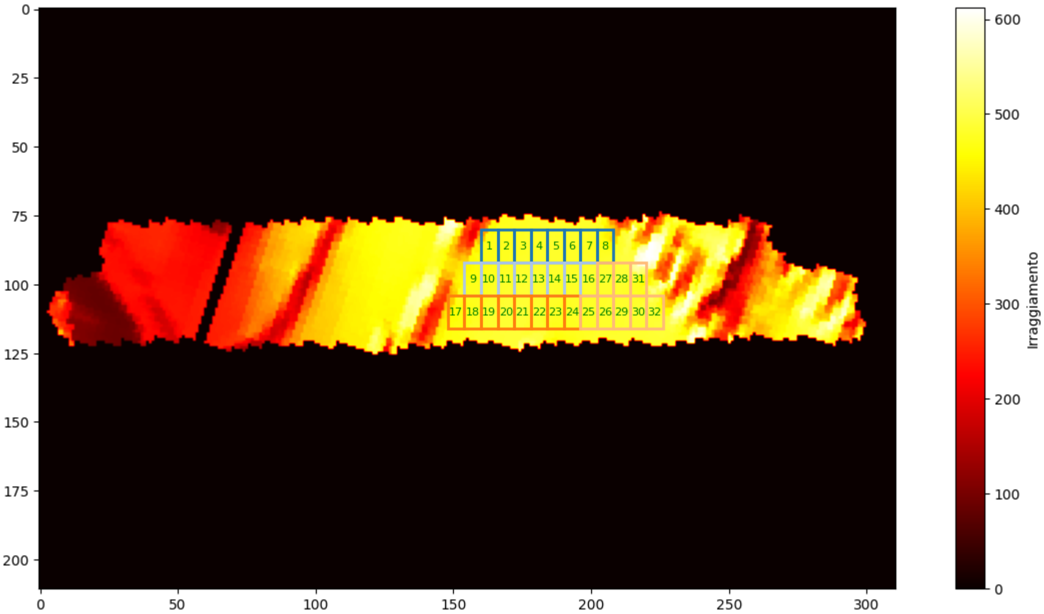


Figure 6.35: Rooftop 2: panels with manual positioning

Manual installation involves covering the most irradiated core part of the roof and grouping nearby panels in a succession.

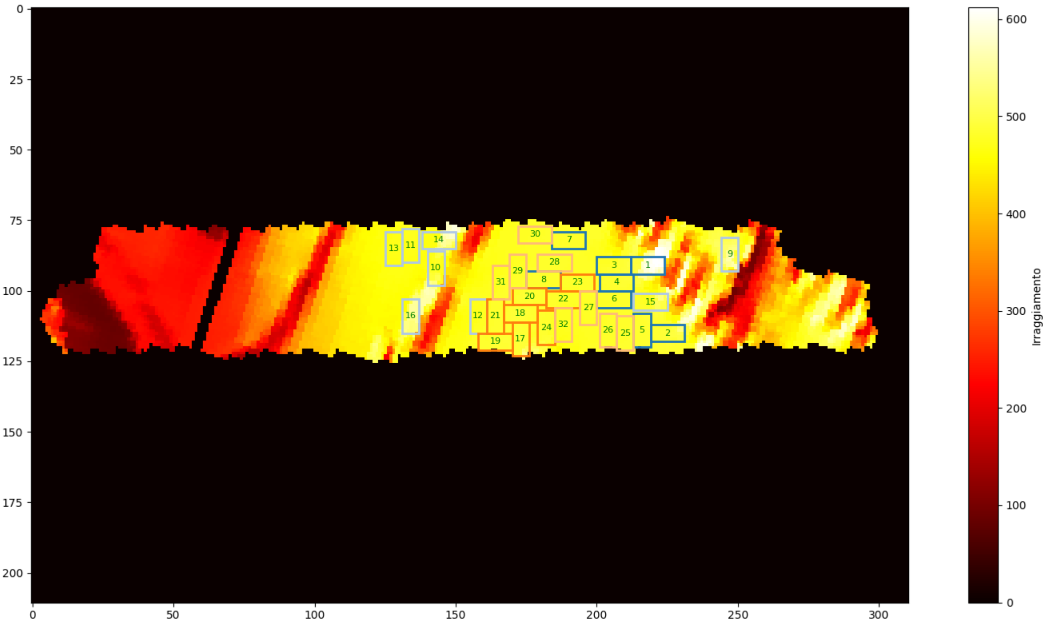


Figure 6.36: Rooftop 2: panels positioning with clustering

The output of the positioning algorithm also suggests an extensive coverage of the core area, as it has the highest values. However, it also covers areas beyond the shadow zones on the right and left that have heavily irradiated areas.

The grouping follows a method that may appear fairly random to the human eye but, according to the time series, will certainly lead to a reduction in mismatches.

6.3.3.3 Rooftop 3

The present roof offers an interesting scenario. The 75th percentile pattern suggests the presence of strong shading, with the highly irradiated area being very limited.

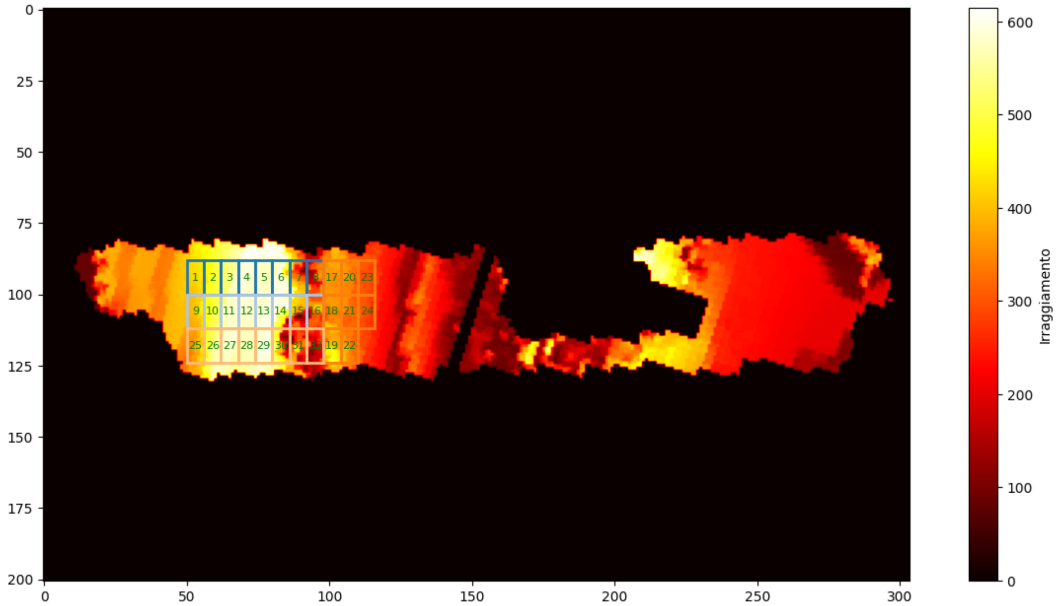


Figure 6.37: Rooftop 3: panels with manual positioning

According to the standards used so far, manual placement results in coverage of severely irradiated areas, as shown in Figure 6.37.

Furthermore, the series connection of panels in the yellow area with those in the red area will undoubtedly result in significant savings due to the effect of current cap.

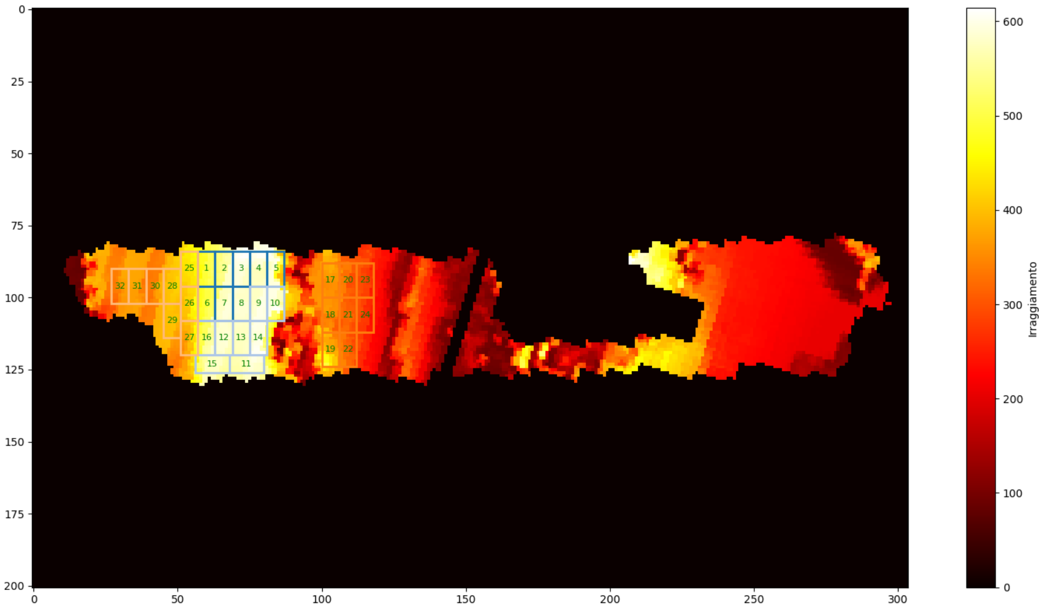


Figure 6.38: Rooftop 3: panels with ad hoc manual positioning

To reduce the disparity and more accurately evaluate the algorithm's actual benefit, we added an ad hoc manual setting.

The placement attempts to cover the most exposed area of the roof as effectively as possible. It is important to keep in mind that the following method is strongly influenced by the knowledge obtained during this thesis work, so it is not replicable by installers.

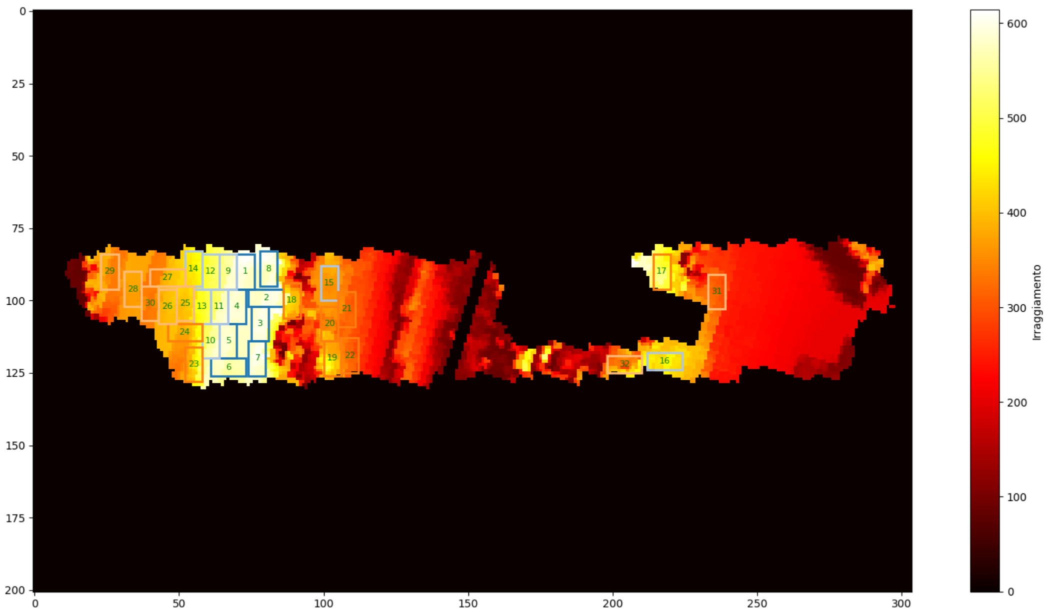


Figure 6.39: Rooftop 3: panels positioning with clustering

The result of the positioning function in fact offers a map fairly similar to the one defined ad hoc, even though, as a greedy methodology, it displays greater vacant spaces between the panels.

In this scenario, where there are several panels in places influenced by shade, the grouping technique could prove vital to provide good system production.

6.3.3.4 Considerations

The heat-maps of each rooftop placement state that the first step of the methodological approach correctly identifies the high irradiated areas, according to k-means' clustering. Panels are therefore positioned recursively from the best area onwards (until exhaustion), and grouped accordingly to the correlation between sub-areas.

The difference between the two approaches is evident: the highly irradiated positions indicated by the algorithm would hardly have been indicated by a classic positioning.

Although some irradiated areas remain uncovered, due to greedy nature, the algorithm generally behaves as expected.

6.3.4 Outcomes:

For the purpose of comparing the energy yield of systems, the simulation is performed on two consecutive days, analyzing the total energy production (Wh) of 32 panels grouped into four clusters of 8 panels each.

The results demonstrate the effectiveness of the optimization framework in improving energy production, due to the strategic placement of panels in high irradiance locations, as well as the reduction of mismatch losses through optimized series grouping.

6.3.4.1 Rooftop 1: Small performance difference, algorithm still outperforms

For Rooftop 1, which has a huge high-irradiance zone on the right of the heatmap (Figure 6.33), both manual and automated placement worked well. However, the algorithm still produced more energy, highlighting the advantages of a precise irradiance-driven strategy.

Method	**Total Energy**	**Best Cluster Performance**	**Lowest Cluster Performance**
Standard Manual Placement	16.126 MWh	4.278 MWh	3.784 MWh
Algorithmic Optimization Without panel grouping Algorithm	17.432 MWh	4.559 MWh	**4.235 MWh**
Algorithmic Optimization	**18.151 MWh**	**5.001 MWh**	4.140 MWh

Table 6.1: Rooftop 1: performance comparison

Key takeaways:

- The gain of 12% in favor of the methodological approach at the expense of manual placement derives from the predisposition to place the best panels in the most irradiated, albeit non-contiguous, area of the roof. It can also be deduced from the fact that some panels are located in the central area of the roof, close to the areas affected by partial shading.
- The algorithmic placement that neglects the optimal grouping with Pearson correlation yields 4% compared to the complete algorithmic one, demonstrating the actual effectiveness of this last step.
- As can also be seen from the section relating to the performance of the best cluster in the table, the grouping algorithm offers the best result connecting the most suitable panels to each other, avoiding current caps that could arise due to mismatches.

6.3.4.2 Rooftop 2: Significant gain from algorithmic placement

The distinction between algorithmic and manual placement is less evident with Rooftop 2. Both methods perform well, since the areas covered by the system are similar.

Method	Total Energy	Best Cluster Performance	Lowest Cluster Performance
Standard Manual Placement	17.683 MWh	4.700 MWh	**4.266 MWh**
Algorithmic Optimization Without panel grouping Algorithm	17.479 MWh	4.804 MWh	3.564 MWh
Algorithmic Optimization	**17.854 MWh**	**4.879 MWh**	3.443 MWh

Table 6.2: Rooftop 2: performance comparison

Key takeaways:

- In the present case, the difference in production between algorithmic and manual placement is closer to 1% in favor of the former. Since the roof has a highly irradiated area, large enough to accommodate the entire system, manual positioning was designed to entirely cover the affected area. This is sufficient to guarantee excellent productivity, which is not even achieved by the first step of the placement algorithm proposed in Chapter 4.
- Even if the placement method searches for the best panels, the areas between the panels that are not covered lead to a lower production yield of the system. However, the serial clustering algorithm manages to generate a production increase sufficient to fill the gap with manual positioning, managing to earn a little more.

6.3.4.3 Rooftop 3: Largest Difference Between Methods

For Rooftop 3, the algorithm demonstrated the most substantial improvement compared to a classic placement, since the available high irradiance areas were limited. The standard manual approach also involves heavily shaded areas, resulting in a drastic reduction in energy production.

Method	Total Energy	Best Cluster Performance	Lowest Cluster Performance
Standard Manual Placement	8.433 MWh	3.412 MWh	1.802 MWh
Manual "Ad Hoc" Placement	**15.540 MWh**	4.39 MWh	**3.41 MWh**

Method	**Total Energy**	**Best Cluster Performance**	**Lowest Cluster Performance**
Algorithmic Optimization Without panel grouping Algorithm	13.320 MWh	5.464 MWh	1.632 MWh
Algorithmic Optimization	14.008 MWh	**5.464 MWh**	2.196 MWh

Table 6.3: Rooftop 3: performance comparison

Key takeaways:

- As expected, algorithmic optimization produces approximately double the energy compared to the standard placement (Fig. 6.26) approach (~67% increase). The basic reason is that the form of the clearly apparent most irradiated area in the heat-map is insufficient to accommodate all of the panels in a normal layout, resulting in coverage of severely shaded portions.
- As the data demonstrate, a manual placement with important precautions can be much more effective in this particular situation. However, this was made possible by prior knowledge of the panels' behavior, which was only obtained after numerous experiments were conducted, and is thus challenging to adapt in real-world situations. This version was presented to demonstrate how the algorithmic version's creation is subpar (~10% less) but yet manages to stay somewhat close to the best one.
- Mismatch losses were significantly lower in the algorithmic approach, compared to the standard one, demonstrating the importance of data-driven positioning and clustering. Furthermore, in the case of the best 8-panel cluster, the algorithm also outperforms optimal positioning, stating that the temporal correlation-based grouping algorithm works very well.

6.3.4.4 Overall Insights and Conclusion

In summary, the most important outputs of the test are the following:

- Algorithmic optimization states excellently across all rooftops, outperforming standard manual approaches.
- Mismatch losses are always lower in algorithmic series grouping.
- The *best performing cluster* always provides the highest power in the algorithmic strategy, giving a clue for the evaluation output in the next ROI section.
- Manual configurations often resulted in unbalanced strings, leading to lower efficiency.

Automated panel placement and series grouping frequently resulted in increased energy output, with the greatest increases recorded on rooftops with the presence of small or non-homogeneous areas with higher exposure to the sun. The findings confirm that a data-driven, optimization-based strategy has significant advantages over manual PV system design.

6.4 Evaluating ROI: The Effect of System Size and Inverter Configuration

The economic viability of a solar system is determined not only by the increasing of the energy output, but also by optimizing the cost-to-benefit ratio of installed components. This section performs a Return on Investment (ROI) analysis using the methodology provided in Chapter 5 while taking into account various system designs and inverter strategies.

To maintain consistency, the three scenarios from Section 6.3 are used. These roofs provide the basis for a thorough assessment of the effects of panel clustering and total number on energy production and financial returns. This is because they represent a wide spectrum of scenarios with different irradiance distributions and shading.

6.4.1 Varying the Total Number of Panels in the System

One of the most important factors in designing a photovoltaic system is identifying the ideal number of panels to install, in order to balance both system costs and energy production. In this test, the total number of selected panels varies, but the series-grouping approach remains constant (8 panels per group) in such a way as to leave the inverter characteristic unchanged. The 32 panel positions are found with the same algorithm described above, whose heat-map is depicted in the figures in Section 6.3. Based on the number of panels selected for the experiment, the most productive series of panels that include them are chosen. The following configurations are investigated:

- **32 panels (4 groups of 8 panels each):** This configuration is the one adopted in the test of Section 6.3, now used as a reference point for comparisons.
- **24 panels (3 groups of 8 panels each):** A reduction of a quarter of the total number of panels, to verify how much the cost/production ratio decreases.
- **16 panels (2 group of 8 panels each):** Drastic reduction to add a further point to define the cost/benefit ratio trend curve; specific to better evaluate cases such as the third roof.

For each setup, the ROI formula given in Chapter 5 is used, taking into account the ratio between initial/maintenance costs and energy yield over a system expected lifetime.

$$\text{Cost for kWh} = \frac{C_{\text{initial}} + C_{\text{battery}} + C_{\text{maintenance and replacements}} + C_{\text{management}}}{P_{\text{total}}}$$

Let's define the costs per unit:

- **Half-cell panel unit cost :** €200
- **Inverter cost (10-15 years lifetime):** €900 for a 4 kW inverter
- **Battery cost (10-15 years lifetime):** €5,000 per unit for ~10-15 kWh storage.
- **Annual Maintenance Cost:** €200
- **Management Cost:** €0 (we assume self-management).

It is also important to consider the productive degradation of the system. We must sum up the decreasing production year by year. The formula that calculates total lifetime production (25 years) considering degradation is the following one:

$$P_{\text{total}} = P_{\text{annual}} \times \left(\frac{1 - (1 - 0.0045)^{24}}{0.0045} \right) \times (1 - 0.02) + P_{\text{annual}}$$

This accounts for:

- First-year degradation of 2
- Each subsequent year degrading by 0.45% of the previous year's output.

Reducing the number of panels is projected to reduce system costs, but at the price of overall energy production. However, in some cases, eliminating the least performing panels may result in a greater ROI for remaining panels, due to decreased mismatch effects and improved efficiency per panel.

The trade-off between early investment savings and long-term energy generation will be critical in determining the ideal arrangement.

6.4.1.1 Rooftop 1

Rooftop 1's cost-per-kWh ratio improves as the number of panels grows. This roof has large areas of high irradiance, which allows massive installations to be efficient. The 32-panel system turns out to be the most cost-effective option.

Num Panels	Production	Total Cost	Ratio
32 panels	423,686 kWh	60,600 €	**0,1430 €/kWh**
24 panels	327,045 kWh	47,200 €	0,1443 €/kWh
16 panels	225,787 kWh	33,800 €	0,1497 €/kWh

Table 6.4: Rooftop 1: System size performance comparison

Kew takeaways:

- It is more economical to deploy larger installations: The 32-panel configuration is the best investment to optimize the return on energy production since it has the lowest cost per kWh.
- Efficiency increases through panel distribution: The cost-to-performance ratio improves with more panels added, demonstrating that this rooftop can handle high-density installations without major losses.
- A negligible difference between 24 and 32 panels: Although 32 panels are the best option, a 24-panel system is still a good choice because it costs just 1.16% more per kWh.

6.4.1.2 Rooftop 2

For Rooftop 2, the most effective solution is the 24-panel one. 24 panels seem to be the most suitable number because, even if a larger size would lead to a greater overall production, in the tested cases, the cost per kWh for the 32-panel solution increases slightly

Num Panels	**Production**	**Total Cost**	**Ratio**
32 panels	416,750 kWh	60,600 €	0,1454 €/kWh
24 panels	336,382 kWh	47,200 €	**0,1403 €/kWh**
16 panels	227,351 kWh	33,800 €	0,1487 €/kWh

Table 6.5: Rooftop 2: System size performance comparison

Kew takeaways:

- 24 panels strike the ideal balance: Unlike Rooftop 1, where larger is better, 32 panels marginally raise the cost per kWh, making 24 panels the most efficient arrangement.
- Better efficiency is not necessarily correlated with higher energy output: In this case, the higher installation costs are not worth the benefits, despite the 32-panel system produces more energy.
- A scalable approach: If future extensions are envisaged, starting with 24 panels and then growing to 32 may be a preferable investment option.

6.4.1.3 Rooftop 3

For Rooftop 3, adding more panels leads to an increase in the cost per kWh, reversing the trend observed for the other two roofs with larger highly irradiated areas. This is due to the particular conditions of the roof, which has a relatively small area strongly more irradiated than the rest, demonstrating that smaller installations are more economically efficient. In conclusion, the system with 16 panels, grouped in two sets of 8, emerged as the best in terms of cost-production ratio.

Num Panels	**Production**	**Total Cost**	**Ratio**
32 panels	326,975 kWh	60,600 €	0,1853 €/kWh
24 panels	275,716 kWh	47,200 €	0,1712 €/kWh
16 panels	217,104 kWh	33,800 €	**0,1557 €/kWh**

Table 6.6: Rooftop 3: System size performance comparison

Key takeaways:

- Larger solutions are not always preferable: unlike roofs 1 and 2, adding additional panels negatively affects the cost-benefit ratio of this roof.
- 16 panels provide the highest return: With a cost per kWh of €0.1474, the 16-panel arrangement is the most cost-effective.
- Expanding beyond 16 panels is not recommended. The 32-panel arrangement production costs 18.3% more per kWh than the 16-panel system, making it a much less attractive option.

6.4.2 Varying the number of panels group

Selecting the best possible inverter configuration is another way to minimize the system's production cost per kWh. In this test, to simulate the characteristics of the inverter, the size of the cluster of panels to be connected in series is changed. In the case of micro-inverters, they are all considered in parallel. Since the size of the system does not affect this experiment, the total number of panels is left unchanged at 32.

The investigated configurations follow:

- **32 panels (4 groups of 8 panels each):** Same configuration used as reference for previous experiments.
- **32 panels (8 groups of 4 panels each):** The size of the inverters is reduced to support approximately 2KW, hence the series connection of 4 panels.
- **32 panels (Micro-inverter, 1 for each panel):** All panels have a micro-inverter, so we add up the power output of each individual panel.

The formula adopted to calculate the cost/production ratio is the same as that used for the experiment in Section 6.4.1.

Let's simply update the unit costs we consider for this test:

- **Half-cell panel unit cost :** €200
- **Inverter cost 8 panels (10-15 years lifetime):** €900 for a 4 kW inverter
- **Inverter cost 4 panels (10-15 years lifetime):** €400 for a 2 kW inverter
- **Micro-inverter unit cost :** €200

- **Battery cost DC (10-15 years lifetime):** €5,000 per unit for 10-15 kWh storage.
- **Battery cost AC (10-15 years lifetime):** €6,000 per unit for 10-15 kWh storage (used with Micro-inverters).
- **Annual Maintenance Cost:** €200
- **Management Cost:** €0 (we assume self-management).

In this experiment we also take into account the system's production degradation over a 25-year period, so that we can estimate and compare the unit cost per kWh over the entire life of a photovoltaic system.

By reducing the size of the cluster of panels connected in series, there will be a certain increase in power production, due to the reduction in mismatch losses. The growth in electronic components involved leads to an increase in the points of failure of the system and also to an increase in initial costs in the case of micro-inverters. However, in specific cases such as the third scenario, which presents a large disparity in radiation on the roof, it could also lead to a reduction in the cost per kWh.

The analysis of the outputs of this type of experiment could prove crucial in the moment of choosing the components of the photovoltaic system, especially knowing the current market prices.

6.4.2.1 Rooftop 1

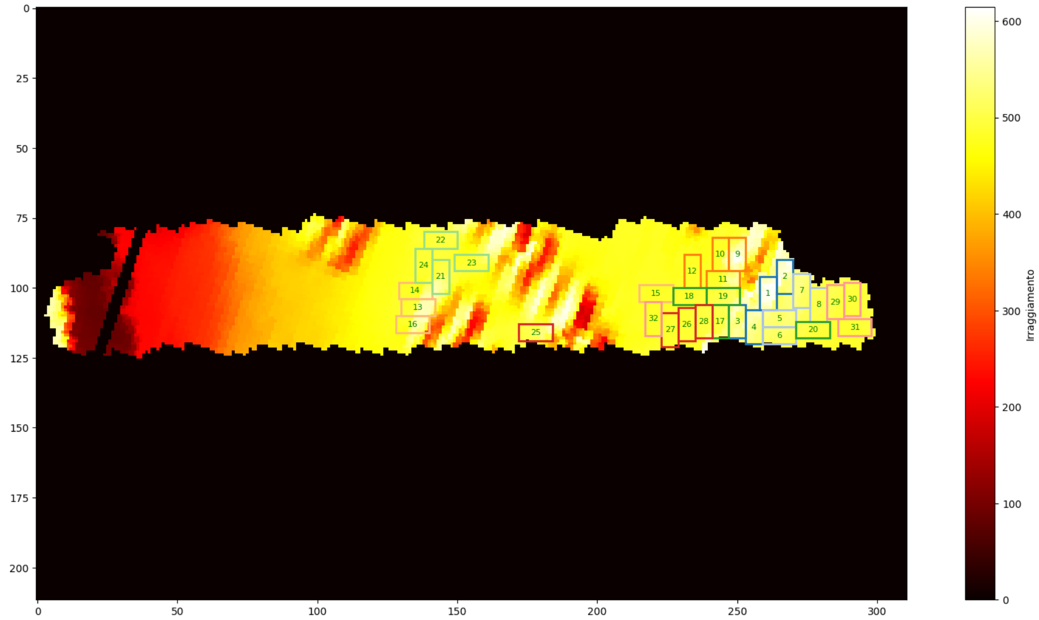


Figure 6.40: Rooftop 1: panel with automatic placement and grouping with 4 panels for group

There is a noticeable increase of about 4% in energy output for the rooftop 1, when the number of panels per inverter is reduced from eight to four. Micro-inverters tend to outperform the baseline in terms of production, but at a higher cost.

Panels for group	Production	Total Cost	Ratio
8 panels	423,686 kWh	60,600 €	0,1430 €/kWh
4 panels	441,875 kWh	59,800 €	**0,1353 €/kWh**
Micro-inverters	469,705 kWh	67,800 €	0,1443 €/kWh

Table 6.7: Rooftop 1: Inverter Characteristic performance comparison

Kew takeaways:

- The most economical option is four panels per inverter (€0,1353/kWh), which well balances production and expense.
- Although they cost a little more per kWh (€0.1443/kWh), micro-inverters generate the most energy (469,705 kWh).
- Keeping the inverter size to allow 8 panels in series remains the least competitive option (0.1430 €/kWh), compared to the other two.

6.4.2.2 Rooftop 2

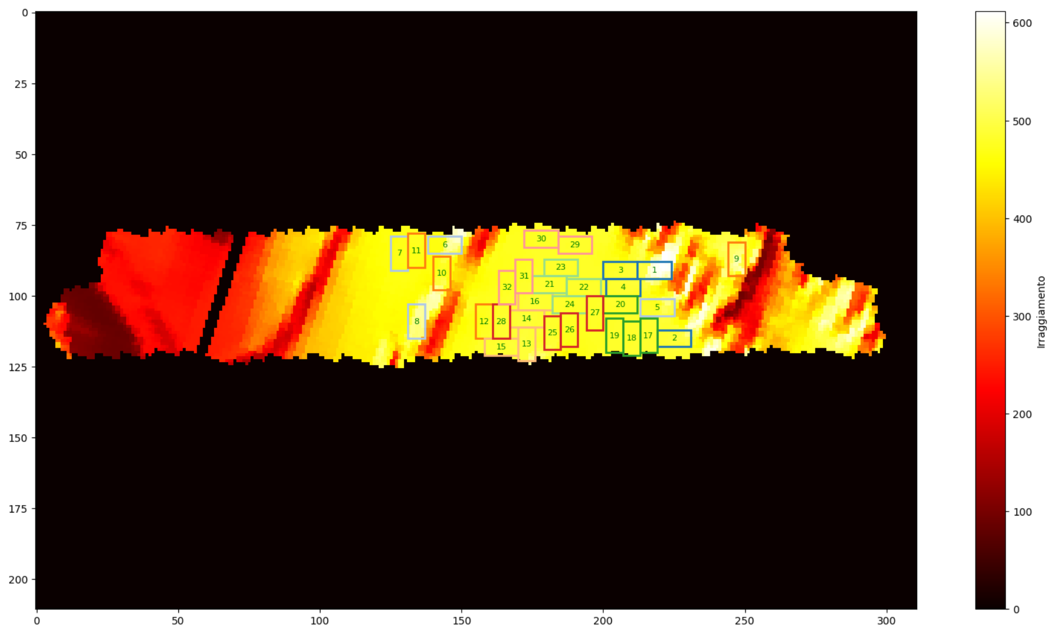


Figure 6.41: Rooftop 2: panel with automatic placement and grouping with 4 panels for group

Even for the rooftop 2, the configuration with 4 panels per inverter offers the best cost per kWh (0.1370 €/kWh), even if the difference compared to micro-inverters is less pronounced.

Panels for group	Production	Total Cost	Ratio
8 panels	416,750 kWh	60,600 €	0,1454 €/kWh
4 panels	436,462 kWh	59,800 €	**0,1370** €/kWh
Micro-inverters	460,068 kWh	67,800 €	0,1474 €/kWh

Table 6.8: Rooftop 2: Inverter Characteristic performance comparison

Kew takeaways:

- As for Rooftop 1, the optimal configuration (0.1370 €/kWh) is still the one with 4 panels per inverter, making it clearer how the parallel connection is generally preferable.
- Micro-inverters still offer the highest energy output (460,068 kWh), but their cost per kWh (0.1474 €/kWh) is now slightly worse than before.

- The least competitive configuration remains the one with 8 panels per inverter. Despite having a lower ratio than micro-inverters (0.1454 €/kWh), the difference of more than 10% in production makes them decidedly less advantageous.

6.4.2.3 Rooftop 3

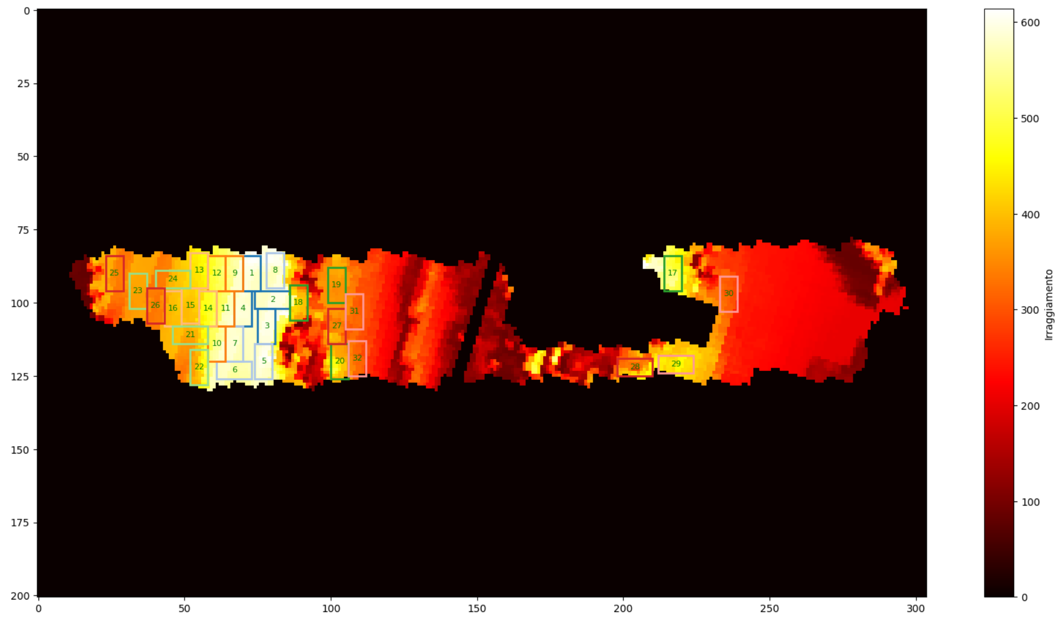


Figure 6.42: Rooftop 3: panel with automatic placement and grouping with 4 panels for group

For roof 3, where overall energy production is lower due to the low total irradiation, micro-inverters become the best option (0.1589 €/kWh). In this case, the configuration with 8 panels per inverter is worse in all comparative factors.

Panels for group	Production	Total Cost	Ratio
8 panels	326,980 kWh	60,600 €	0,1853 €/kWh
4 panels	373,277 kWh	59,800 €	0,1602 €/kWh
Micro-inverters	426,762 kWh	67,800 €	**0,1589 €/kWh**

Table 6.9: Rooftop 3: Inverter Characteristic performance comparison

Kew takeaways:

- Micro-inverters currently surpass all other installations (€0.1589/kWh), most likely owing to their capacity to maximize energy output under low-yield conditions.

- The efficiency of the 4-panel per inverter arrangement (€0.1602/kWh) is still acceptable, but micro-inverters are now superior.
- 8 panels per inverter also represent the worst choice in terms of cost/power ratio (0.1853 €/kWh), with a significant drop in performance.

6.4.3 Result and considerations

Comparing 16, 24, and 32-panel systems across three distinct scenarios reveals that larger installations generally reduce cost per kWh, although their utility depends on each scenario's individual roof energy yield.

The combined study of system size and inverter type demonstrates that the best configuration is determined by both site-specific factors: roof radiation heatmap with shading pattern, and budget restrictions.

With a low cost per kWh and little upfront expenses, a 32-panel system with 4-panel per inverter string configurations offers the highest return on investment for high-production settings. However, downsizing to 24 panels could be the more cost-effective option in situations when energy production efficiency is lower due to little high irradiated areas, since it strikes a balance between appropriate energy output and prices.

For inverters, 4-panel per inverter configurations consistently offer the lowest cost per kWh under high-yield circumstances(scenarios 1 and 2), while micro-inverters become the best option under low-yield conditions(scenario 3), due to their ability to optimize performance for each panel. 8-panel inverter installations should be avoided as they consistently offer the highest cost per kWh under all circumstances.

Ultimately, the optimal return on investment is attained by carefully balancing system size with inverter capacity, ensuring that the setup maximizes energy production while minimizing expenses.

6.5 Final Considerations on Approach Validation

The effectiveness and resilience of the simulation framework developed for the optimization of photovoltaic systems are demonstrated by the experimental study conducted in this chapter. An in-depth comparison across various shading patterns, panel layouts, and inverter settings is made possible by the framework's effective automation of the panel placement, electrical setup, and ROI evaluation processes.

Through a series of validation experiments, the framework was able to recreate real-world rooftop conditions and evaluate the influence of various design options on energy production and economic feasibility.

The important lessons from the chapter are summarized as follows:

- **Panel Layout Comparison (6.2):** Under shading conditions, the shingled panel design performed better than other layouts on a consistent basis, especially when the shade orientation matched the strip layout. Full-cells panels performed the worst due to higher mismatch losses, while half-cells panels showed superior overall adaptability and were also more cost-effective. In the long-term energy production analysis, half-cells modules and shingled panels produced the most energy.

- **Algorithmic vs. Manual Panel Placement (6.3):** The automated method for panel placement and clustering outperformed classical manual installation in all scenarios analyzed, with particular emphasis on the one representing challenging roofs with non-uniform irradiance distribution. The system was able to optimize panel placement by avoiding shadows, as well as aggregate panels using time series correlation, resulting in improved performance and reduced misalignment losses.

- **ROI Evaluation (6.4):** The cost-benefit study showed that cost efficiency does not always increase by adding more panels. Instead, the irradiance conditions of the roof should be used to find the most suitable system size.

  Furthermore, choosing the right inverter type is essential to optimize profitability. Micro-inverters proved most effective in low-yield situations, while 4-panel per inverter configurations produced the best cost-performance ratio on high-yield rooftops. All this can be summarized in the concept that it is important to find the right compromise between the increase in power due to the reduction of series connections and the induced costs.

Chapter 7

Conclusion and future developments

7.1 Key Findings Summary

This thesis presents a systematic and computationally efficient framework to improve the design of photovoltaic systems. It involves information systems that associate meteorological data with geographic locations such as GIS, processes the data with clustering and correlation algorithms, and simulates the electrical behavior of the PV system components.

Through diligent simulation-based evaluation, the framework has proved its capacity to improve panel location and connectivity schemes, with an eye to a targeted economic evaluation.

Among the research's main conclusions are:

- **PV Module's Schema Performance Comparison:** The experiment conducted and described in section 6.2 showed that half-cell and shingled modules perform better than full-cell modules under shading conditions, with shingled panels offering the highest resilience to partial shading under conditions where the shading follows the direction of the series cell strings.

- **Automated vs. Manual Placement:** Clustering-based best areas' selection increases placement efficiency by identifying the regions of the roof with the highest irradiation while reducing shade losses. This allowed us to define a systematic approach to find the best N panel locations on the roof, not constrained by the size and orientation of the panel.

- **Grouping Optimization for Inverter Compatibility:** Panel clustering ensures efficient electrical configurations, using the specific Pearson correlation explained in Section 4.3.2.3. Reduce mismatch effects due to different temporal irradiation patterns affecting the relevant areas of the module, increasing the overall output power.

- **ROI Trade-Offs:** The optimal combination of cost per kWh and expected production depends on the type of inverter, the layout of the photovoltaic module and the irradiance patterns on the roof, as the addition of more panels increases overall production in a non-linear way. According to the study, 4-panel string inverters offer the greatest economic trade-off under uniform irradiance circumstances, whereas micro inverters perform best under extremely variable irradiance situations.

The results demonstrate that data-driven, well-thought-out placement and electrical connectivity techniques can greatly increase energy output and financial feasibility, proving that the presented approach is a useful tool for optimizing photovoltaic systems.

7.2 Future Research

While the proposed methodology makes significant advances in PV system design, numerous areas require future study to enhance accuracy, scalability, and application.

1. **Dynamic Analysis**

   The current approach to optimizing panel placement is based on historical irradiance data, but including seasonal fluctuations in real time would increase precision. Future techniques could focus on dynamic placement, which involves minimal changes in panel locations and connections seasonally or even daily to improve energy production.

2. **Machine Learning for Placement Optimization and electrical grouping**

   Machine learning techniques, especially reinforcement learning or neural networks, could be used to update the layout of the panel placement seasonally using previous performance data. This could lead to self-adaptive photovoltaic systems that constantly modify the layout and connections for maximum efficiency.

3. **Enhanced Placement Algorithms for Improved Panel Density**

   The present greedy technique for panel placement efficiently chooses heavily irradiated places, however, it does not necessarily result in optimal panel density due to vacuum gaps between panels. Future research should focus on creating more advanced placement algorithms, such as constraint-based optimization or heuristic search approaches, to reduce wasted space in high irradiance zones while maintaining acceptable computational times. This would increase the energy yield per square meter while maintaining the effectiveness and flexibility of the existing automated technique.

4. **Improved Inverter Grouping Strategies**

   Although the study assesses several inverter topologies, more investigation is recommended to better improve inverter choices, taking into account hybrid systems that mix string and micro-inverters. Further research into adaptive MPPT algorithms and smart inverter technologies may improve overall system efficiency.

5. **Temperature Influence on Energy Production**

   The main element influencing PV efficiency is irradiance, however temperature variations can have a big effect on performance. Temperature modeling should be incorporated into future framework improvements to offer a more comprehensive optimization approach.

6. **Demand-Based Panel Sizing and Energy Storage Integration**

   The current strategy optimizes placement based only on available solar radiation on the roof, but a demand-driven methodology ensures optimal energy output based on customer usage patterns, also impacting panel count and inverter characteristics. Thus, integrating battery storage optimization into the framework can provide insight into appropriate storage sizing to ensure cost-effective energy management solutions.

7.3 Final Considerations

This thesis work has created a comprehensive and scalable strategy for optimizing photovoltaic systems, bridging the gap between theoretical efficiency and real-world feasibility. The developed framework is a useful tool for system designers and energy consultants as it combines spatiotemporal irradiance analysis, automated positioning, and economic evaluation.

Data-driven and AI-assisted approaches will become more and more important as solar energy usage grows to ensure maximum energy efficiency and financial sustainability of photovoltaic systems. The suggested framework's adaptability and scalability provide a solid basis for further developments in solar system intelligent design.

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Dedications

Dedicated to my family and to those who cherish values and knowledge.