



An-Najah National University
Faculty of Graduate Studies

**A NEW METHOD FOR OPTIMALLY
DESIGNING THE POWER DISTRIBUTION
NETWORK OF GRID-CONNECTED
PHOTOVOLTAIC POWER PLANT**

By
Hiba Bashar Assi

Supervisor
Prof. Tamer Khatib

**This Thesis is Submitted in Partial Fulfillment of the Requirements for The Degree
of Master of Electrical Power Engineering, Faculty of Graduate Studies, An Najah
National University, Nablus-Palestine.**

2024

A NEW METHOD FOR OPTIMALLY DESIGNING THE POWER DISTRIBUTION NETWORK OF GRID-CONNECTED PHOTOVOLTAIC POWER PLANT

**By
Hiba Bashar Assi**

This thesis was Defended successfully on 11/02/2024, and approved by:

Prof. Tamer Khatib
Supervisor


Signature

Dr. Jaser A Sa'ed
External Examiner


Signature

Dr. Aysar Yasin
Internal Examiner


Signature

Dedication

To my family, friends, especially Sura, and Dr. Tamer, who made all the moves, and let me then win the game in a one move.

Acknowledgement

I would like to thank Eng. Sura Malhis from Palestine Telecom Corporation for her extreme help in adjusting the data analysis methods. Authors would like to extend their thanks to Eng. Zaina Ruzzeh from An-Najah Company for Consultancy and Technical Studies for providing the real data of the actual photovoltaic system used in the comparison.

Declaration

I, the undersigned, declare that I submitted the thesis entitled:

A NEW METHOD FOR OPTIMALLY DESIGNING THE POWER DISTRIBUTION NETWORK OF GRID-CONNECTED PHOTOVOLTAIC POWER PLANT

Unless otherwise referenced, I declare that the work provided in this thesis is the researcher's work and has not been submitted elsewhere for any other degree or qualification.

Student's Name: Heba Bashar Assi

Signature: 

Date: 18-07-2024

List of Contents

Dedication	iii
Acknowledgement	iv
Declaration	v
List of Contents	vi
List of Tables	viii
List of Figures	ix
List of Appendices	x
Abstract	xi
Chapter One: Introduction and Literature Review	1
1.1 Brief introduction to photovoltaic systems	1
1.2 Significance of wiring configuration and inverter sizing in photovoltaic systems.....	1
1.3 Problem statement.....	4
1.4 Research goals and objectives	4
1.5 Research hypothesis.....	4
1.6 Research significance and relevance	5
Chapter Two: Photovoltaic System Power Distribution Network Design Consideration	6
2.1 Cable ampacity	6
2.2 Cable power losses.....	7
2.3 Cable voltage drop	8
2.4 Array and Inverter size	11
2.5 Earthing system.....	12
2.6 Photovoltaic system architectures	14
2.6.1 Centralized Connection Architecture.....	15
2.6.2 Distributed Connection Architecture	17
Chapter Three: Methodology	19
3.1 System's component sizing	19
3.2 Optimum inverters configuration and size.....	20
3.3 Photovoltaic panels' layout generation.....	22
3.4 Calculating and optimizing cable length for different inverter locations	23

3.4.1 DC cables length calculation methodology	23
3.4.2 AC cables length calculation methodology	24
3.4.3 Selecting the optimum inverter location	25
3.4.4 Minimizing dc cables length.....	25
3.4.5 Minimizing AC cables	26
Chapter Four: Results and Discussion	31
Chapter Five: Conclusions.....	44
5.1 Conclusion	44
5.2 Limitations	45
List of Abbreviations	46
References.....	47
Appendices.....	52
الملخص.....	ب

List of Tables

Table 2.1: Typical soil resistivity of various type of soil	14
Table 3.1: Example of generating inverter combination for three different sizes of inverters	22
Table 4.1: Latitude and longitude for selected site	31
Table 4.2: Specification of the adapted PV panel.....	37
Table 4.3: Specification of the adapted inverters	37
Table 4.4: Characteristics of the power distribution network of the actual PV system..	38
Table 4.5: Optimization results.....	40

List of Figures

Figure 2.1: Interactions of influences on photovoltaic system sizing.....	16
Figure 2.2: PV system architectures	18
Figure 3.1: Proposed optimizing approach flowchart.....	21
Figure 3.2: Calculating DC cables length.....	24
Figure 3.3: Flowchart for parallel Dijkstra algorithm.....	27
Figure 3.4: Connecting dc lines to different inverter locations	28
Figure 3.5: Connecting different inverter locations to the transformer room.....	29
Figure 4.1: Project's Land Contour (Case Study).....	33
Figure 4.2: Distribution of major load centers in the Palestinian Territories	34
Figure 4.3: Network Configuration of the case study PV project for land 1 and 2	35

List of Appendices

Appendix A: Open-source code of the proposed method.....	52
Appendix B: The datasheets of the adapted PV panel and inverters in this study	72
Appendix C: The PVsyst Simulation Report.....	76

A NEW METHOD FOR OPTIMALLY DESIGNING THE POWER DISTRIBUTION NETWORK OF GRID-CONNECTED PHOTOVOLTAIC POWER PLANT

By
Hiba Bashar Assi
Supervisor
Prof. Tamer Khatib

Abstract

Photovoltaic (PV) systems are attractive renewable energy source for rural electrification and distributed power generation. However, the capital cost of these systems as compared to non-renewable energy sources is still a challenging issue. Thus, many researchers have focused on enhancing the efficiency and the feasibility of photovoltaic systems. This research proposes an optimum methodology for designing the AC power distribution network for grid connected photovoltaic systems considering solar inverter size and location, as well as cable's size and configuration. The main aim of the proposed method is to offer the shortest cables length and path; achieving a higher efficiency and feasibility in the overall assessment. The suggested approach follows a heuristic method, starting by generating numerous inverter combinations for analysis. For each combination, the total length of cables is calculated considering all feasible inverter locations, aided by Python code to ensure precision. Ultimately, the method identifies the optimal inverter location that results in the shortest cable lengths. A 900 kWp grid connected photovoltaic system is chosen as a case study in this research. Results show that a 23% reduction in total cable length as compared to the conventional approach is achieved by the proposed method. Meanwhile the proposed method offered a better configuration of required solar inverters (size and location). Such a method is very useful for designing photovoltaic system AC and DC distribution networks and exceed and the conventional and intuitive methods.

Keywords: Cables sizing; Distribution systems; Inverters allocation; Photovoltaic system.

Chapter One

Introduction and Literature Review

1.1 Brief introduction to photovoltaic systems

Photovoltaic (PV) systems stand as one of the foremost renewable energy sources globally. Solar energy is forecasted to outpace new fossil fuel-based generation technologies, with a projected six-fold increase from 2018 to 2030 [1], maintaining an estimated sustained annual growth rate of 8.9% until 2050. It is anticipated that approximately 83 gigawatts (GW) of utility-scale PV solar energy installations will be added each year until 2025, with a predominant focus in China, the United States, and Europe [1]. While PV systems are acknowledged for their cleanliness, environmental friendliness, and energy security, their capital costs still remain relatively high compared to non-renewable energy sources. Hence, meticulous consideration is essential when designing a grid-connected PV system, encompassing factors such as determining the appropriate size of the PV array and inverter, optimizing the AC and DC distribution network in terms of length, size, and distribution, assessing shading impacts, ensuring compliance with local regulations and grid requirements, among other considerations [2].

The AC power distribution network within a PV system comprises three types of cables: DC, AC, and earthing cables. DC cables serve to connect the PV arrays to the inverter, while AC cables are employed to link the inverters to the electricity grid directly or via a power transformer. Meanwhile, earthing cables, categorized as AC cables, are utilized to ground all components of the PV system. Proper sizing of the PV system's power distribution network is crucial to bolster reliability and performance while concurrently mitigating costs [3].

1.2 Significance of wiring configuration and inverter sizing in photovoltaic systems

According to [4], more than half of the PV system costs are attributable to balance-of-system (BoS) components which include inverter and the wiring system. Therefore, it is necessary to reduce these costs to increase the feasibility of the PV system. The cost of system wiring depends on PV system layout's complexity, the length and gauge of the wires.

A significant portion of the system installation budget may be allocated to the wiring costs because cabling is necessary to link all of the components and to ensure efficient electrical flow. Thus, cutting back on wiring expenses can help in lowering PV system's overall cost and increase its economic viability [4].

Based on that, many authors focused on the importance of designing the cables to provide a higher efficiency for the overall PV system, whereas optimum power distribution network can decrease losses and increase the expected productivity of PV system [5].

The efforts of optimizing PV system power distribution network can be divided into two categories; which are the optimization of solar inverter size, and the optimal design of power distribution network (wire's length, configuration and size). For solar inverter size optimization, many authors have utilized meteorological data and PV system models in order to find the optimum solar inverter size that assures the maximum conversion efficiency. In [6] the authors proposed a method for optimal selection of solar inverter size considering specific locations. Similarly, in [7], a method was introduced to determine the most suitable inverter size, energy yield, and efficiency for grid-connected PV power plants in different geographical locations. The approach involves considering crucial factors that impact the performance of these power plants and employs a simple yet effective technique to select the appropriate inverter. In addition, in [8] an optimization method was proposed to select the optimum inverter's size for PV grid-connected power plants. The method considered various factors, including solar irradiance, temperature, wind speed, component specifications, and location characteristics.

In most of the previously mentioned researches, the authors have given the focus on the optimal sizing of solar inverter without considering AC and DC network. Although, according to [9], a saving of 50% may be achieved in photovoltaic system's Wp cost when optimally considering the design of "other system materials", including wiring configurations.

Based on that, some other researchers have given the focus on the optimal design approach of AC and DC wiring in photovoltaic systems. In [3] the author's used commercial software to simulate PV system to find the optimum value for cable cross-

sectional area by considering power losses, and economical operational factor. However, the authors didn't consider cables length and configuration in the study. On the other hand, in [9], a life cycle assessment (LCA) framework is introduced for selecting the most suitable rating for a DC cable in a photovoltaic system. The proposed method aims to find a trade-off between the investment cost and the cost of cable losses over the asset's operational life. According to this research the method can effectively meet both voltage drop and thermal limitations. Moreover, the authors concluded that oversizing the cable is advisable to minimize long-term losses effectively. However, the authors also reported that the proposed method is for small grid connected photovoltaic systems. [9] Meanwhile, it is crucial to emphasize that for large-scale solar PV farms, the distance between the PV array junction box and the inverter must be considered. Similarly, the author in [10] implemented a similar approach by presenting a method that considers the combined costs of losses and solar cable investment throughout the entire lifespan of the system.

The author of [11], proposed a method for optimally designing the power distribution network of a PV system that is located in agriculture area. The system has a special feature whereas all wires should be fixed at the land fence in order to save agriculture land. The proposed method took into account three factors; which are the distance from the fence to the AC electrical panel, the cost of inverters, and the geographic location. The results of this research indicated that micro-inverters outperformed in scenarios where the cross-over fence length is less than 30 meters or when the system had fewer than seven solar PV modules. On the other hand, for longer fences, string inverters are more suitable. In [12] a method was proposed for optimally sizing cable cross section area without considering cables optimal length. Similarly, the authors in [11, 13], used artificial intelligence (AI) based techniques for optimally sizing inverter and cable size without considering cables length and configuration. Finally, in [13], AI based algorithm is utilized for optimally designing the layout (source location and cable length) for large wind farm. This interesting research work considers the Net Present Value (NPV) metric as a combined objective function to represent a balance between source location and cable length. The proposed algorithm optimizes both parameters by reducing the distance between turbines in order to assure shortest required cables.

1.3 Problem statement

The problem addressed is the encountered inaccuracies when randomly placing the inverters, and designing the wiring configurations based on the engineering sense. Therefore, this research focuses on designing an optimal AC power distribution network for grid-connected photovoltaic systems, focusing on solar inverter placement, cable specifications, and configuration achieving an optimum design with shorter cables length, and a better wiring configuration.

1.4 Research goals and objectives

It is very clear that the optimal design of photovoltaic system AC and DC distribution power network (inverter size, location, and AC and DC wiring) is very important. Meanwhile, it can be concluded that most of the researchers focused on the optimal sizing of solar inverter and cable cross sectional area, without considering cables length and configuration. In addition to that, in most of the conducted research small PV system was considered, while the case of large PV plants still not addressed due to the complexity implied.

Based on these research gaps, this research offers the following significant contribution

- A novel method for calculating the shortest length of AC and DC power distribution network's wires.
- A full consideration of large photovoltaic plants which implies a very complex AC and DC power distribution network
- The method also suggests solar inverters size and location
- Open-source code for the proposed method for further possible enhancements and consideration.

1.5 Research hypothesis

This research proposes a streamlined method for optimizing the power distribution network in large PV power plants. The four-stage approach involves initial system component sizing, generating inverter sizes and configurations, creating PV panel distribution layouts, and applying an iterative methodology to minimize cable length for optimal inverter placement. The hypothesis states that when an effective method is

considered in designing the wiring configuration, a significant reduction in wires length will be achieved.

1.6 Research significance and relevance

The proposed method is expected to offer a better configuration of required solar inverters (size and location). Moreover, this research focuses on enhancing the wiring system and provide the optimal wire runs for AC and DC cables. Such a method is very useful for designing photovoltaic system AC and DC distribution networks and exceed and the conventional and intuitive methods.

Chapter Two

Photovoltaic System Power Distribution Network Design Consideration

In general, when designing a power distribution network for a PV system, there are some issues that should be considered. The following subsections are briefly discussing these issues and their impact on the power distribution network of PV system

2.1 Cable ampacity

When designing any power distribution network, it is vital to appropriately size the wires so that they can handle the current under operational temperatures without excessive losses. Additionally, it is recommended to down rate the current-carrying capacity of the cables when anticipating elevated operational temperatures [14].

The appropriate sizing of a cable is being done by estimating the maximum current that can flow in it. There are many tables and rules of thumb in the literature that associate cable's size with maximum current capacity considering weather conditions and system operating voltages. Moreover, short circuit current and voltage flicker rates are also considered when sizing cables [15]. Above all, the critical role of safeguarding the system components from substantial harm relies on the utilization of protective devices and accurately determining their size. To achieve this, it is recommended to employ fuses, switches, and circuit breakers to protect system's elements from excessive currents, ensuring that they are appropriately sized and able to handle the highest potential current load [15].

One of the primary elements safeguarding the DC block of a photovoltaic system is the fuse. Established guidelines offer suggestions for the specified current and the current at which the fuse blows in photovoltaic fuses. The rated current, typically indicated on the device, denotes the maximum current the fuse can consistently carry without breaking the circuit. Should the current surpass this rated value, the fuse will interrupt the circuit (blowing current) in accordance with its time-current curve[15].

The wiring methods and cables employed in photovoltaic systems must adhere to minimum safety standards. Ampacity requirements for photovoltaic cables are determined by considering two key factors; Overcurrent devices are typically rated for

continuous operation at 80% of their nameplate rating, as prolonged operation at 100% can cause overheating and loosening of terminals. Hence, cables in PV circuits should have their ampacity values derated by 20% to accommodate connected overcurrent devices. Additionally, the cable's ampacity requirement is determined by multiplying the rated short-circuit current of the PV module or array by 125%, denoted as 125% E (E for equipment limitation) [16].

Moreover, Single and polycrystalline PV modules exhibit a short-circuit current that rises with irradiance and temperature, especially on hot, clear days around solar noon. This current can surpass the rated standard test condition (STC). A multiplicative factor of 125% N (N for normal operation) is applied to account for these effects. Alternatively, if data on temperature and irradiance coefficients are available for a specific system, calculated maximum values of short-circuit current could be used instead of the fixed 125% N factor [16].

Based on the information provided, the wiring system should be designed such that 80% of the rated ampacity (125% E factor) is greater than or equal to 125% of the short-circuit current (125% N factor). In summary, the minimum ampacity of the wiring system should be equal to the rated short-circuit current multiplied by 1.56 (1.25×1.25) [16].

2.2 Cable power losses

The supply chain for components, particularly PV modules and Power Conditioning Units (PCUs), encountered significant delays, complicating the process of design and installation, which often had to be expedited. However, this urgency sometimes resulted in drawbacks. These included mismatches between optimal design specifications and actual installation scenarios, leading to potential issues such as current-voltage (I-V) mismatch within series-connected modules or partial shading on PV modules [17].

Additionally, there were challenges in aligning the peak power of the PV array with the rated power of the power conditioning unit, commonly known as an inverter, and occurrences of cracks in silicon solar cells due to mishandling during transportation and installation. Another complication stemmed from the use of components, such as PV modules and PCUs, which might not have been of the highest manufacturing quality and could exhibit underperformance, like electrical parameter mismatches in PV

modules, during outdoor operation. Despite these challenges, such components were readily available on the market at the time of installation, necessitating their use [17].

According to literature, the maximum cable losses for PV system shouldn't be higher than 3%, and this proportion shouldn't rise over time. The losses in the cables include corrosion and overheating [5]. For DC and AC cables in PV system, the time variant power losses can be given by equation (2.1).

$$P_{\text{cable,loss}}(t) = 2 \cdot \frac{r}{v^2} \cdot \left(\frac{N}{N_t}\right)^2 \cdot P(t)^2 \dots\dots\dots(2.1)$$

where v is the voltage applied by the inverter across the cable ends, r is the DC or AC resistance of the cable. N represents the number of strings connected to one dc cable, while N_t is the aggregate number of strings in the PV installation. Finally, $P(t)$ is the DC power as a function of time [5].

2.3 Cable voltage drop

Voltage drop refers to the reduction in voltage experienced along a cable while carrying current, typically due to the internal resistance of the cable and across cable contacts [1]. In small PV systems, where system components are more susceptible to damage, excessive voltage drop can pose significant risks [2]. Thus, it is advisable to minimize the length of cable runs to mitigate potential damage [3].

These cables serve the purpose of linking array combiner boxes to inverters and are essential for transmitting higher currents ranging from 200 to 600 A in utility-scale projects. They necessitate a larger cross-sectional area, ranging from 95 mm² to 400 mm². While DC cables, excluding those already connected to modules, constitute only about 2 percent of the overall solar project cost, their impact on power output is considerable. Inappropriately designed or poorly selected cables can give rise to safety risks, diminished power output, and other performance issues. The power loss in DC cables can reach up to 15 percent, but pinpointing and quantifying their role in poor performance is a time-consuming and challenging task. Additionally, an increased voltage drop often results in cable overheating and the potential for fire accidents. The measurement of power loss in DC cables is expressed in terms of voltage drop from the module to the inverter, where a higher voltage drop signifies a proportional loss of power [18].

Designers typically undertake the estimation of voltage drop levels as a fundamental aspect of their tasks, aiming to mitigate such drops through adjustments in sending end voltage and suitable system installation methods. Moreover, within the literature, numerous tables exist which correlate voltage drop with cable size and length, taking into account various factors such as weather conditions, levels of loading, and cable types [18]. These resources serve as valuable references for designers seeking to optimize system performance and minimize voltage drop-related issues.

The DC voltage typically fluctuates in accordance with the inverter's maximum power point tracking system, but this variation generally remains within a range of $\pm 5\%$ of the intended value, rendering it relatively stable [19]. This stability ensures that the DC voltage can be considered consistent for practical purposes, despite minor fluctuations dictated by the inverter's operational parameters.

The sizing of cables in accordance with standards is a critical aspect of photovoltaic system design and installation. In general, a photovoltaic system array consists of multiple strings, with these strings being interconnected in parallel through a junction box. Within each string, numerous PV modules are connected in series. As a result, the total voltage of a particular string within the PV array is the aggregate of the voltages across each individual module within that string. This arrangement necessitates careful consideration of cable sizing to ensure optimal performance and compliance with safety regulations.

Assuming that N_{module} is the number of modules connected in series in a string and V_{MPP} is the voltage of one module at maximum power point; The total voltage applied voltage at the junction box level can be represented by equation (2.2) [18]:

$$V = V_{MPP} * N_{module} \dots\dots\dots(2.2)$$

The current value of a string is identical to the current value of an individual module, as the modules in a string are connected in series. When multiple strings are connected in parallel to a junction box, the current at the junction box level is the total sum of the currents from each string connected to that junction box. This relationship can be mathematically expressed as follows [12]:

$$I = I_{MPP} * N_{string} \dots\dots\dots(2.3)$$

Where, I_{MPP} is the current of a string at maximum power point, and N_{string} is the number of strings per junction box [12].

In order to optimize the permissible current determined by equation (2.3), it is necessary to increase this current by a margin in accordance with installation standards, which can vary between countries [12]. In Malaysia, as per the Malaysian standards, this current should be augmented by a margin of 1.3. Additionally, a temperature correction must be applied to the current if the ambient temperature reaches 40 °C or exceeds it.

The maximum allowable voltage drop must adhere to installation standards. In Malaysia, the permissible voltage drop between the PV array and inverter should be below 5%. The outcome from equation (2.2) is multiplied by the maximum allowable percentage voltage drop to determine the voltage drop value (e). This voltage drop value is then employed in the subsequent equation (2.4):

$$A = L * \frac{I}{\gamma} * e \dots\dots\dots(2.4)$$

Where A is the cross-section area of the cable (mm^2), L is the length of the cable (m), I is the nominal current (Amp), γ is the conductivity of copper ($\text{m}/\Omega.\text{mm}^2$), and e is the maximum voltage drop (V) [20].

The outcome of equation (2.4) denotes the cross-sectional area (A) of the cable, determined based on the maximum allowed voltage drop in square millimeters (mm^2). It is crucial to emphasize that if the cable section, derived from the calculations of the maximum allowed current, is larger than the cable section derived from the calculations of the maximum allowed voltage drop, or vice versa, the larger cable section must be chosen. This selection is necessary because the resulting cable section must satisfy both the criteria of the maximum allowed current and the standards for maximum voltage drop [12].

2.4 Array and Inverter size

To ensure optimal performance from a photovoltaic system, it is imperative to ensure that the rated capacity of the PV array is in sync with that of the inverter. The correct sizing of both the PV array and the inverter hinges on several factors, including the local climate, orientation and tilt of the PV surface, inverter efficiency, and the cost ratio of PV to inverter components. Particularly in regions with low insolation levels, the PV array may operate at a fraction of its rated capacity, resulting in the inverter functioning under partial load conditions, thereby diminishing overall system efficiency [21].

Moreover, if the rated capacity of the inverter falls significantly short of that of the PV array, it operates under overload conditions, which can detrimentally impact PV efficiency. During instances of overloading, any surplus PV output beyond the inverter's rated capacity is essentially wasted, leading to increased PV energy costs. Hence, the utilization of an appropriately sized inverter is critical not only for optimizing the performance of the PV system but also for minimizing energy expenses [21].

Solar inverters convert the DC power produced by PV panels into AC power to feed the grid, appliances or any other end-user demand. Solar inverters also play a great role in maximizing the energy output of PV systems. To attain the maximum solar energy output from a system, it's crucial to ensure that the rated capacity of the inverter matches that of the PV array [21]. The nominal output power of inverters is usually sized 30% less than the PV array nominal power, with an initial efficiency of 95% to 97% at partial load, where it gradually declines at full load [22].

The optimum inverter size is described by the Inverter Loading Ratio (*ILR*), which is defined as the ratio between the DC and AC power as given in equation (2.5). Moreover, selecting the optimum *ILR* has a great impact on the overall efficiency of the PV system, *ILR* values differ depending on the solar energy and ambient temperature profile of the system [23], [24].

$$ILR(\%) = \frac{DC\ installed\ power\ kWp}{AC\ installed\ power\ kW} * 100\% \dots\dots\dots(2.5)$$

Figure 2.1 depicts all the main interrelationships between factors determining PV system sizing [25].

2.5 Earthing system

Photovoltaic systems are inherently susceptible to both lightning strikes and component malfunctions, factors that can subject the system to potentially harmful currents. Given this vulnerability, it is advisable to implement a robust earthing system as a safeguard to enhance the safety and reliability of the PV system. By establishing a low-resistance pathway, the earthing system facilitates the prompt discharge of current from the PV system directly into the ground, mitigating the risk of damage and ensuring operational integrity [15].

The establishment of a robust earthing system is essential for ensuring the safety and proper functioning of electrical installations. This is achieved by electrically bonding all metallic or conductive enclosures, structures, and exposed non-current carrying materials, thereby providing them with a pathway for current dissipation to the earth. These earthed components are then interconnected with the earth through an earthing electrode arrangement, which commonly involves the installation of conductive materials, such as rods or metallic grids, physically inserted into the earth. In the event of an electrical fault within the system, the earth serves as a crucial return path for fault currents to reach the neutral point of the system, effectively mitigating potential hazards. To maintain the effectiveness of the earthing system, it is imperative to ensure that the impedance in the return path remains sufficiently low to prevent the induction of dangerous voltages in the earthed equipment, thus safeguarding both personnel and equipment from electrical hazards [26].

In photovoltaic (PV) systems, it is essential to size earthing cables adequately, ensuring they can withstand the highest potential current encountered within the system. This requirement is crucial for maintaining safety and system integrity. Typically, earthing systems in PV setups comprise two distinct types: system grounding and equipment grounding. The former involves connecting one of the system conductors, whether positive or negative, to the ground. This measure serves to mitigate the risk of potential induced overvoltage, particularly during lightning strikes or faults, thereby safeguarding the system and its components [15]. Conversely, equipment grounding, the second type of earthing system, necessitates the connection of all metallic components within the system to the ground. This arrangement is vital for preventing these elements from

becoming electrified in the event of faults, thereby enhancing overall system safety and operational reliability.

The resistance of the earth grid in a grounding system is primarily influenced by two main factors: the size of the conductive materials that are embedded into the ground, and the resistivity of the soil (ρ) in the area where the grounding system is installed. Therefore, the resistivity of the soil is a crucial element in the design and effectiveness of grounding systems. Measuring soil resistivity is essential because it determines the soil's ability to impede or retard the conduction of an electric current. Soil resistivity values generally range from about 2 to 10,000 Ω -m, but it is not uncommon to encounter values that are even more extreme [27].

Table 2.1 provides a comprehensive overview of the soil resistivity range for different types of soil. The value of soil resistivity has a significant impact on the grid resistance, which is a measure of the effectiveness of the grounding system. This grid resistance, in turn, affects important factors such as the rise in earth potential and the transfer of voltage. Therefore, obtaining an accurate soil resistivity value is essential for designing a compliant and efficient grounding system [27].

To determine soil resistivity, several methods can be employed, each with its own advantages and specific applications. These methods include the Wenner method, the Schlumberger array, and the driven rod method. Each of these techniques can provide valuable data regarding soil resistivity, which is crucial for ensuring the effectiveness and safety of grounding systems. Accurate measurements of soil resistivity are indispensable for creating a grounding system that meets regulatory standards and performs reliably under various conditions [27].

Table 2.1*Typical soil resistivity of various type of soil [27]*

Type of Soil or water	ρ (Ω -m)
Sea Water	2
Clay	40
sGround well and spring water	50
Clay and Sand mix	100
Shale, Slates, Sandston	120
Peat, Loam and Mud	150
Lake and Brook Water	250
Sand	2,000
Morane Gravel	3,000
Ridge Gravel	15,000
Solid granite	25,000
Ice	100,000

In conclusion, a robust earthing system is crucial for the safety and reliability of photovoltaic (PV) systems. It protects against harmful currents from lightning strikes and malfunctions by providing a low-resistance path for current discharge into the ground. Proper earthing involves bonding all conductive materials and maintaining low impedance to prevent dangerous voltages. Accurate soil resistivity measurement, using methods like the Wenner method, is essential for effective grounding system design. This ensures compliance with standards and enhances the PV system's operational integrity and safety.

2.6 Photovoltaic system architectures

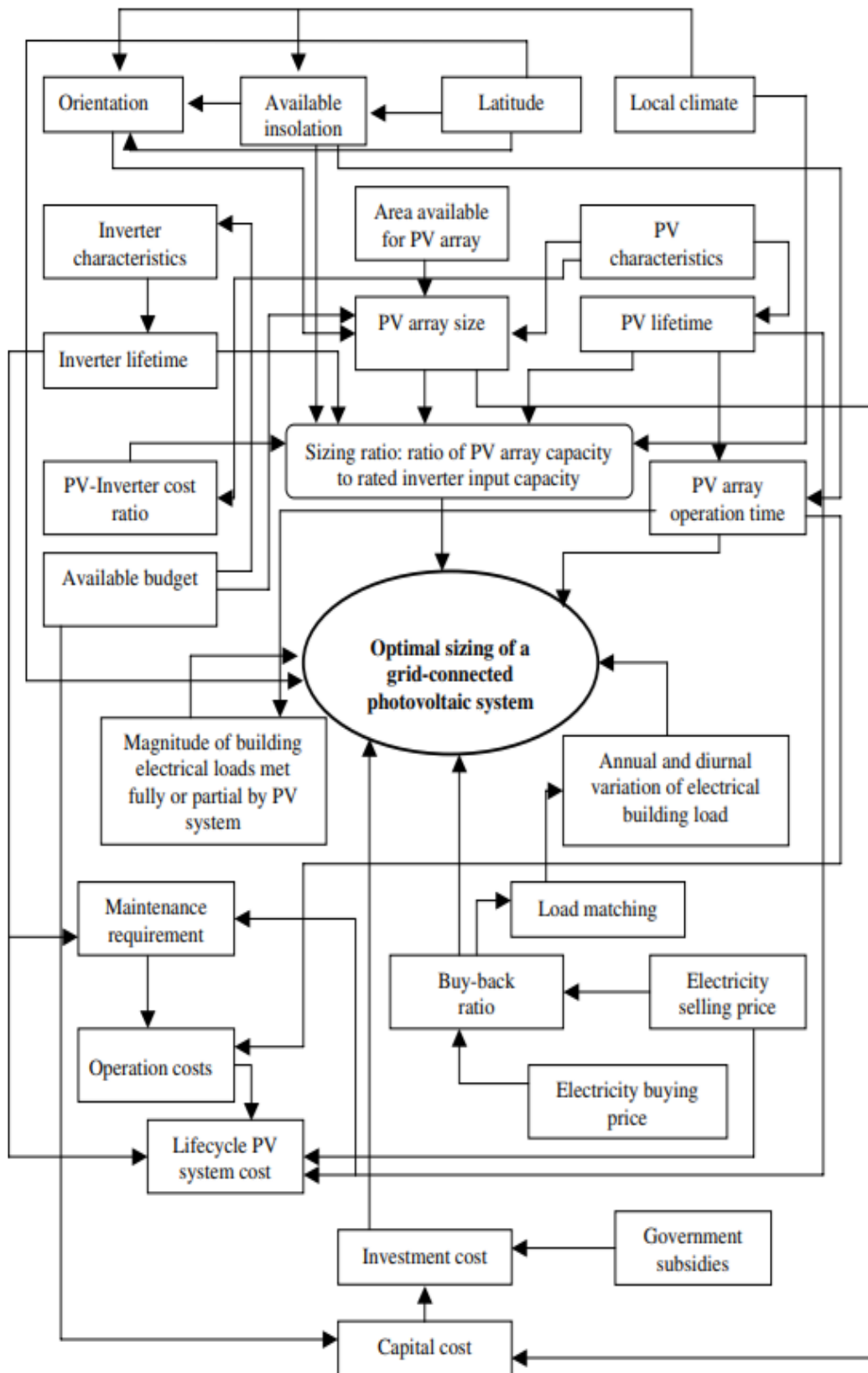
In the global deployment of photovoltaic systems, two prevalent connection designs are widely utilized: centralized and distributed. These architectures differ significantly in various aspects, including Maximum Power Point Tracking (MPPT) control, system complexity, and efficiency when subjected to non-uniform conditions. Depending on the chosen architecture, these factors undergo considerable variations [24].

2.6.1 Centralized Connection Architecture

The centralized layout, as illustrated in Figure 2.2(a), is often deemed the optimal choice for cost-effective and low-power PV solutions due to its inherent advantages. In this configuration, all PV modules are interconnected in parallel to a single high-efficiency converter. However, despite its benefits, this approach also presents certain drawbacks. Primarily, it exhibits lower Maximum Power Point Tracking (MPPT) efficiency compared to distributed PV systems, as it lacks the capability to independently track the Maximum Power Points (MPP) of each PV module. Additionally, centralized systems are more susceptible to mismatching losses, particularly in non-uniform conditions. Nonetheless, these systems stand out for their affordability and simplicity, as the entirety of the PV system's MPPT control can be managed by a single efficient converter [24].

Figure 2.1

Interactions of influences on photovoltaic system sizing [21]



2.6.2 Distributed Connection Architecture

Researchers have extensively explored distributed architecture PV systems as a viable solution to address the limitations inherent in centralized systems while enhancing the effectiveness of Maximum Power Point Tracking (MPPT) in non-uniform settings. Within these distributed systems, Module Integrated Converters (MIC) are employed for each PV module or set of PV cells. The implementation of distributed architecture encompasses various connection types, each offering distinct advantages and challenges [24]. These connection types include:

- **String Connection**

In Figure 2.2(b), it can be observed that photovoltaic (PV) modules are arranged into strings, interconnected in series, with each PV string linked to an individual power converter. This arrangement facilitates separate Maximum Power Point Tracking (MPPT) control for each PV string, thereby mitigating mismatches and enhancing the effectiveness of MPPT. This configuration is advantageous as it allows for optimized control over each PV string, minimizing any discrepancies in performance and maximizing overall energy generation efficiency [24].

- **MIC-Based Connections**

Parallel and series MIC connections offer advantages through their coupled MIC. They enable Maximum Power Point Tracking (MPPT) for each individual PV module, mitigating the impact of partial shading and mismatching effects, thereby enhancing MPPT effectiveness (as illustrated in Figure 2.2 (c & d)). Distributed Maximum Power Point Tracking (DMPPT) necessitates voltage and current information from each PV module within both parallel and series MIC connections, as referenced in. This approach ensures optimization across the entire PV array by utilizing data from individual modules to enhance overall performance [24].

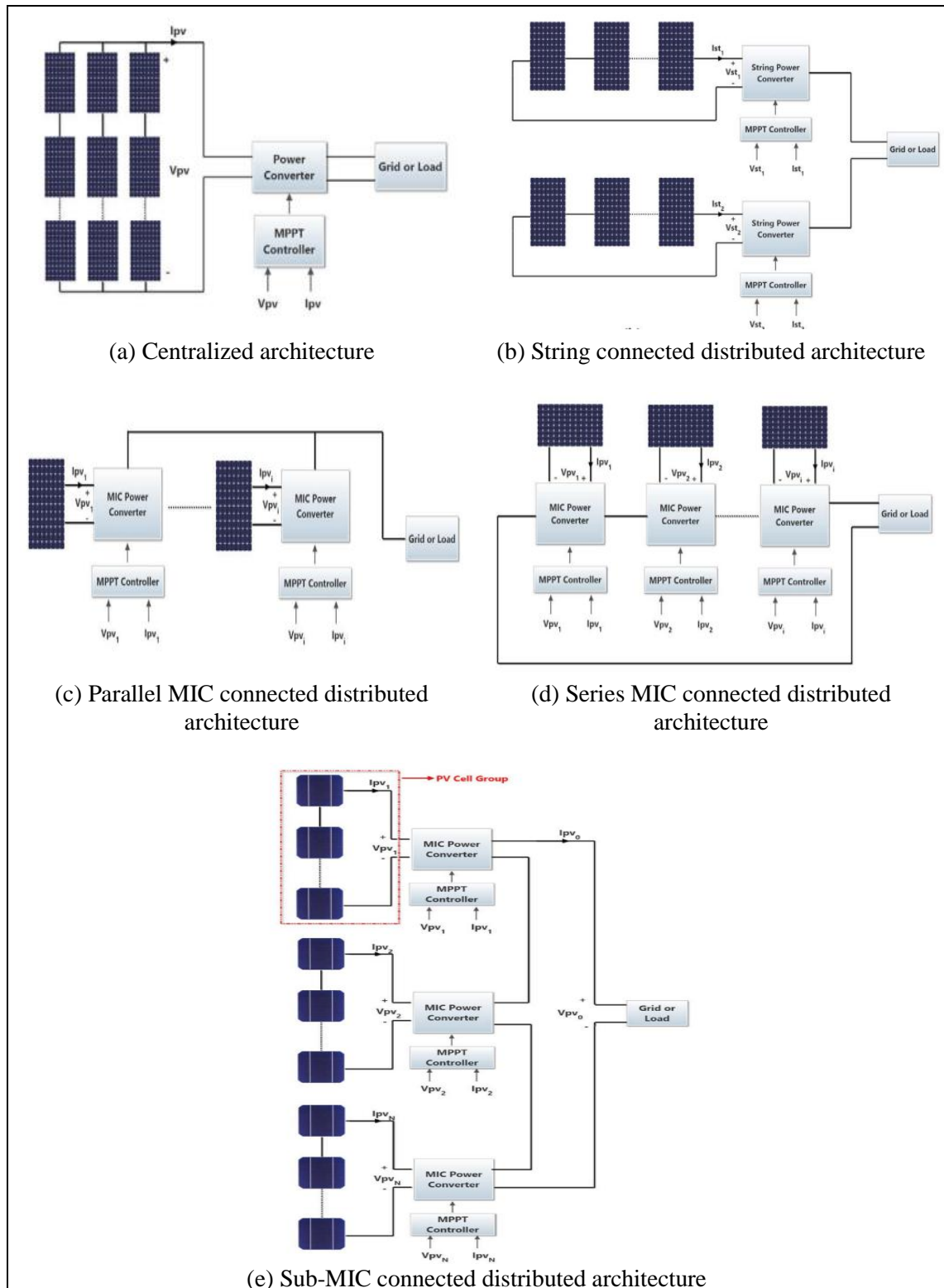
- **Sub-MIC Connection**

To address mismatch effects on PV cells within a module, the concept of sub-MIC connections is employed. This strategy involves linking individual PV cells or clusters of cells to high-efficiency sub-MICs, enabling maximum power point tracking (MPPT) at either the cell level or group cell level, as illustrated in Figure 2.2(e). The implementation of this approach requires the collection of voltage and current data from

each cell or group cell to enable dynamic maximum power point tracking (DMPPT) [24].

Figure 2.2

PV system architectures [24]



Chapter Three

Methodology

This study introduces a novel approach aimed at the optimal design of the power distribution network for expansive photovoltaic (PV) power plants. As depicted in Figure 3.1, the proposed methodology outlines a systematic process. It comprises four primary stages, each serving a distinct purpose in the overall optimization procedure. The initial stage, denoted as the "initial system's component sizing," sets the foundational parameters for subsequent optimization steps.

This phase is initiated utilizing user-provided input data, predominantly comprising system information encompassing the system's capacity, land dimensions, as well as data pertaining to PV panels and inverter units. Within this phase, it's noteworthy that the term "sizing of the inverter" pertains not to the individual size of each inverter unit, but rather to the cumulative requisite size.

Concurrently, a series of inverter sizes and configurations is formulated during the subsequent stage. Subsequently, in the third phase, a distribution layout for PV panels is generated for each scenario. Ultimately, in the fourth phase, an iterative approach is employed to compute the necessary length of cables for each potential inverter location, predicated on the design space crafted in the prior stages. The optimal location for the inverter is determined based on minimizing the length of cables, taking into account the minimal length of either AC or DC cables.

3.1 System's component sizing

The proposed method considers the following sizing parameters as inputs:

- System size in kWp
- Land dimensions in meters (land width, land length)
- Photovoltaic panels' data. (Panel size, panel dimensions (length * width), and panel optimum operating voltage (V_{mp}))
- Inverter's data such as inverter size, number of independent maximum power point (MPP) trackers ports, strings per MPP tracker, rated MPP input voltage, and number of PV panels per inverter. In the proposed method three different inverter sizes are

required as minimum input by user in order to provide optimum inverters' configuration.

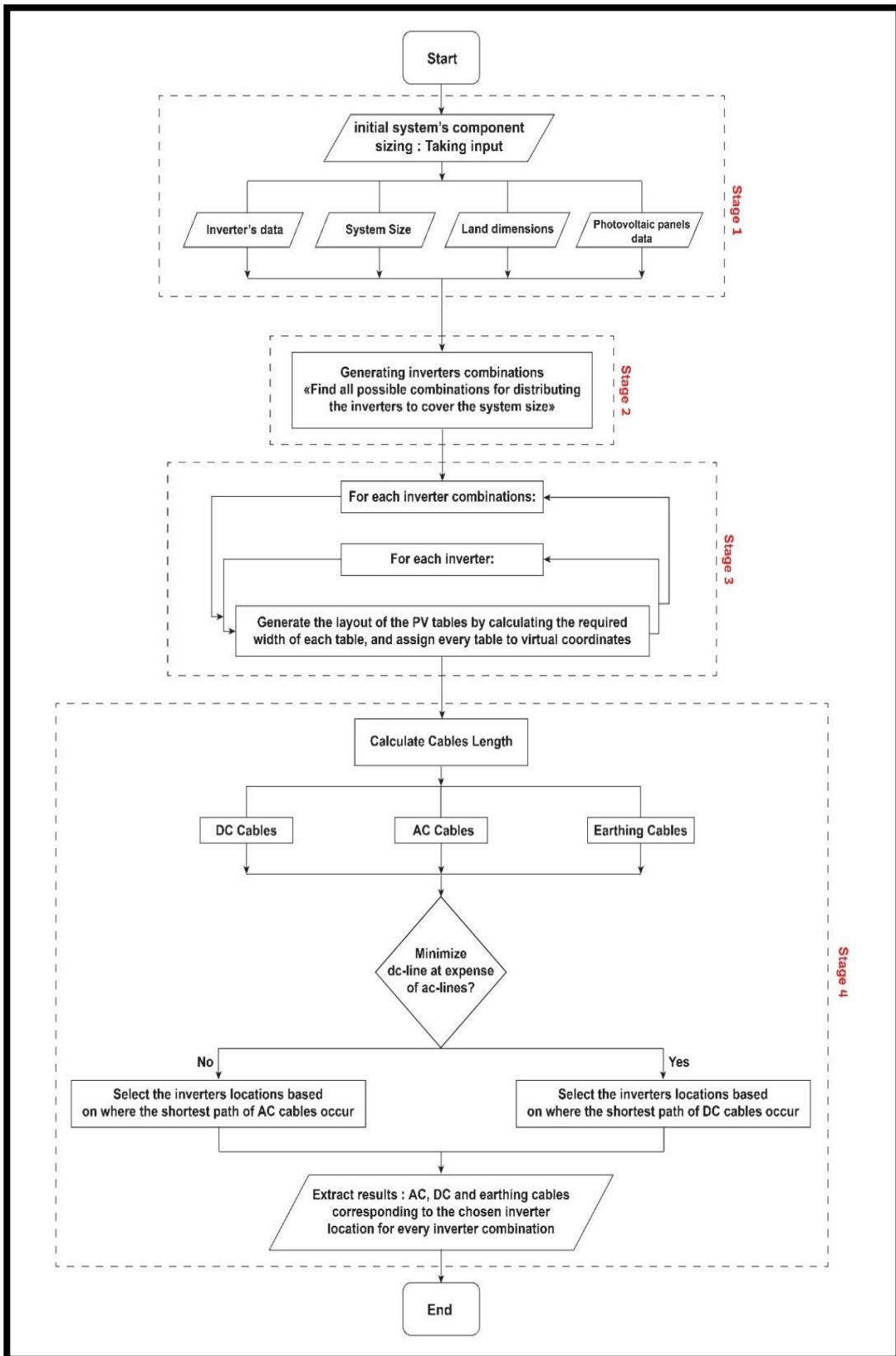
3.2 Optimum inverters configuration and size

Optimum inverters configuration and size play a pivotal role in the efficiency and effectiveness of solar energy systems. The selection of the right configuration and size directly impacts the system's overall performance, reliability, and economic viability. A well-optimized configuration ensures that the inverters are matched appropriately to the system's capacity and requirements, maximizing energy production while minimizing losses. Additionally, choosing the optimal size helps in achieving the desired balance between cost-effectiveness and performance, avoiding unnecessary expenses on oversized inverters or compromising system performance with undersized ones. Furthermore, an optimum configuration contributes to the system's resilience against various operational challenges, such as shading, temperature variations, and equipment failures, enhancing its long-term sustainability and return on investment.

In this research, the inverter's size and number of units has a direct effect on the required cables length. Therefore, all of the possible inverter combinations that could cover the system size are taken into consideration. This is achieved by considering different inverter choices through the input data, and the required number of PV panels for each inverter.

Figure 3.1

Proposed optimizing approach flowchart



To determine the optimal size and arrangement of inverters for a photovoltaic (PV) system, an iterative algorithm is employed. This algorithm systematically explores various combinations of inverters to meet the desired system size.

In our investigation, we explore the operational characteristics of three distinct sizes of inverters, identified as Size1, Size2, and Size3, with Size1 representing the largest capacity and Size3 the smallest ($\text{Size1} > \text{Size2} > \text{Size3}$). Within Table 3.1, we provide a detailed overview of various combinations of these inverters for further analysis and comparison.

Table 3.1

Example of generating inverter combination for three different sizes of inverters

Combination Number	1	2	3	4	5
	Size1	Size1	Size1	Size2	Size3
	Size1	Size1	Size2	Size2	Size3
Proposed inverter combination	Size1	Size2	Size3	Size2	Size3
		Size2	Size3	Size2	Size3
					Size3

3.3 Photovoltaic panels' layout generation

The layout of photovoltaic (PV) panels plays a pivotal role in harnessing solar energy efficiently and sustainably. Beyond mere placement, factors such as azimuth, tilt angle, and spacing between panels must be meticulously considered to ensure optimal energy production. Proper orientation towards the sun's path throughout the day maximizes exposure to sunlight, thereby enhancing energy yield. Moreover, the tilt angle of panels can be adjusted based on geographic location to account for seasonal variations in the sun's angle, further optimizing energy capture. Additionally, adequate spacing between panels is crucial to mitigate shading effects, ensuring uniform irradiance across the array and maximizing overall system performance.

Furthermore, an effective PV panel layout extends beyond immediate energy gains, contributing to the resilience and longevity of solar energy systems. Strategic placement and spacing can minimize the risk of damage from environmental stressors such as high

winds or heavy snow loads, safeguarding the structural integrity of the installation. Moreover, a well-designed layout facilitates ease of maintenance and monitoring, reducing downtime and operational costs over the system's lifecycle. By optimizing layout design, solar energy systems can not only maximize energy output but also enhance reliability, resilience, and cost-effectiveness, driving the adoption of renewable energy solutions for a sustainable future.

In this research, each distinct combination of inverters is treated as a separate case and thoroughly examined on an individual basis. This process starts by distributing the PV panels among tables and assigning each table specific coordinates. Subsequently, the necessary quantity of PV panels is accurately calculated, followed by their meticulous distribution across the designated tables. In order to facilitate subsequent calculations and analyses, the specific data pertaining to each inverter is stored together with its corresponding group of tables.

Once generating the layout of PV panels, every inverter is assumed to occupy one table based on the initial assumption that the land is continuous and has no vertical displacements. The width of the table is calculated by multiplying the number of PV panels assigned to each inverter with the PV panel width divided by the number of PV panel rows in each table. Depending on virtual coordinates, the first table is assigned to ([1,1], [table width, 1], [1, table length], [table width, table length]). if the table width is shorter than the land width, otherwise, the table will continue on the second row, and the procedure continues until assigning all tables to virtual coordinates.

3.4 Calculating and optimizing cable length for different inverter locations

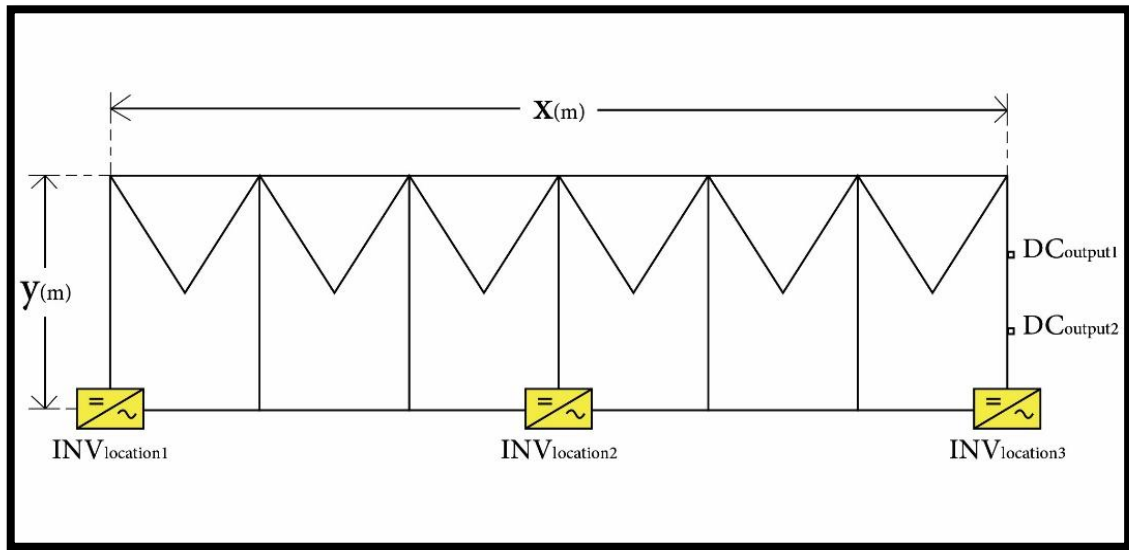
3.4.1 DC cables length calculation methodology

Figure 3.2 shows the proposed methodology for calculating the required DC cables length. The length of the required DC cable running from the DC output node to any inverter location is given in equation (3.1), where all inverter locations and DC outputs are given as coordinate pairs (x, y).

$$DC_{\text{cable,length}} = |DC_{\text{output1}(y)} - INV_{\text{location}(y)}| + |DC_{\text{output1}(x)} - INV_{\text{location}(x)}|. \quad (3.1)$$

Figure 3.2

Calculating DC cables length



3.4.2 AC cables length calculation methodology

Dijkstra's shortest path algorithm is a fundamental method used in graph theory to determine the shortest path between two nodes in a weighted graph. Named after Dutch computer scientist Edsger W. Dijkstra, this algorithm efficiently finds the shortest path from a single source node to all other nodes in the graph. It works by iteratively selecting the node with the lowest tentative distance from the source and updating the distances of its neighboring nodes accordingly. By iteratively exploring the graph, the algorithm gradually builds the shortest paths until the shortest path to each node is determined. Dijkstra's algorithm is widely utilized in various applications, including network routing protocols, GPS navigation systems, and optimization problems in transportation and logistics [23].

In this part, Dijkstra's shortest path algorithm is used to determine the best route for the ac cables from the inverter to the transformer room. The task of identifying the shortest path is a well-known problem, and Dijkstra's algorithm serves as a common solution for this purpose. Dijkstra algorithm, is illustrated in figure 3.3. The Dijkstra algorithm is a method for determining the shortest routes between nodes in a weighted graph, which could, for instance, be a network of connections for electrical cables [23].

When applying Dijkstra's shortest path algorithm to the photovoltaic project, the inverter is considered as the source node (v1), and the transformer room as the end node

(v2). The shortest path from v1 to v2 is to be determined. Then as usually implemented in PV project, cables run in horizontal and vertical trenches.

The Dijkstra shortest path algorithms offer the most efficient route from the source node to the destination node. This presents a superior solution for the intricacies of large-scale PV systems, where the number of potential path nodes is significantly higher compared to small-grid PV systems.

3.4.3 Selecting the optimum inverter location

In this research, the optimal location of inverters is achieved when having minimum required DC cables, minimum required AC cables, or when compromising the two parameters. In general, the cost and the length of DC cables are much more than the AC cables. Thus, the weight of the DC cables length factor is more dominant in this optimization process. However, it is also good to consider the minimum length of AC cables as AC cables length affect critically the voltage level at electricity grid integration point to consider these two factors, two approaches are adapted in this research as follows.

3.4.4 Minimizing dc cables length

In the case, the inverter location is chosen based on the length of connecting DC cables to every possible inverter location. Inverters are usually located near the bottom of PV-tables. Therefore, three locations are tested in each table (bottom-left, bottom-middle, and bottom-right) (see figure 3.4). Finally, the locations are compared based on the required DC cables length. Here once the optimum location is determined, the length of ac cables is located from the chosen coordinate regardless of its length.

In figure 3.4, the methodology employed to minimize the utilization of DC cables is illustrated. In Figure 3.4(a), the diagram represents the necessary DC cables when positioning one inverter on the bottom-middle side of the first table. Conversely, Figure 3.4(b) depicts the required DC cables for the same inverter when located on the bottom-left side of the second table. This process is applied to all potential locations of each inverter, and the optimal placement is determined by considering the shortest length of the DC cables.

3.4.5 Minimizing AC cables

In this case the inverter location is chosen based on the length of connecting AC-cables from every possible location to the transformer room. Finally, the locations are compared based minimum ac cables length. Once the optimum location is determined, the length of DC cables is located from this coordinate regardless of its length (See figure 3.5).

Figure 3.5 demonstrates a comparison between the necessary AC cables when positioning the inverter at two different locations; either at the bottom-left of the first table or at the bottom-middle of the second table. This method involves testing all potential locations for each inverter, as mentioned earlier, and selecting the optimal placement based on the shortest AC cables.

After selecting the best location of each inverter, the earthing cables lengths are calculated. The earthing cable can be connected to any point on the table; therefore, the point with the minimal cable length is chosen for earthing connections.

Figure 3.3

Flowchart for parallel Dijkstra algorithm [23]

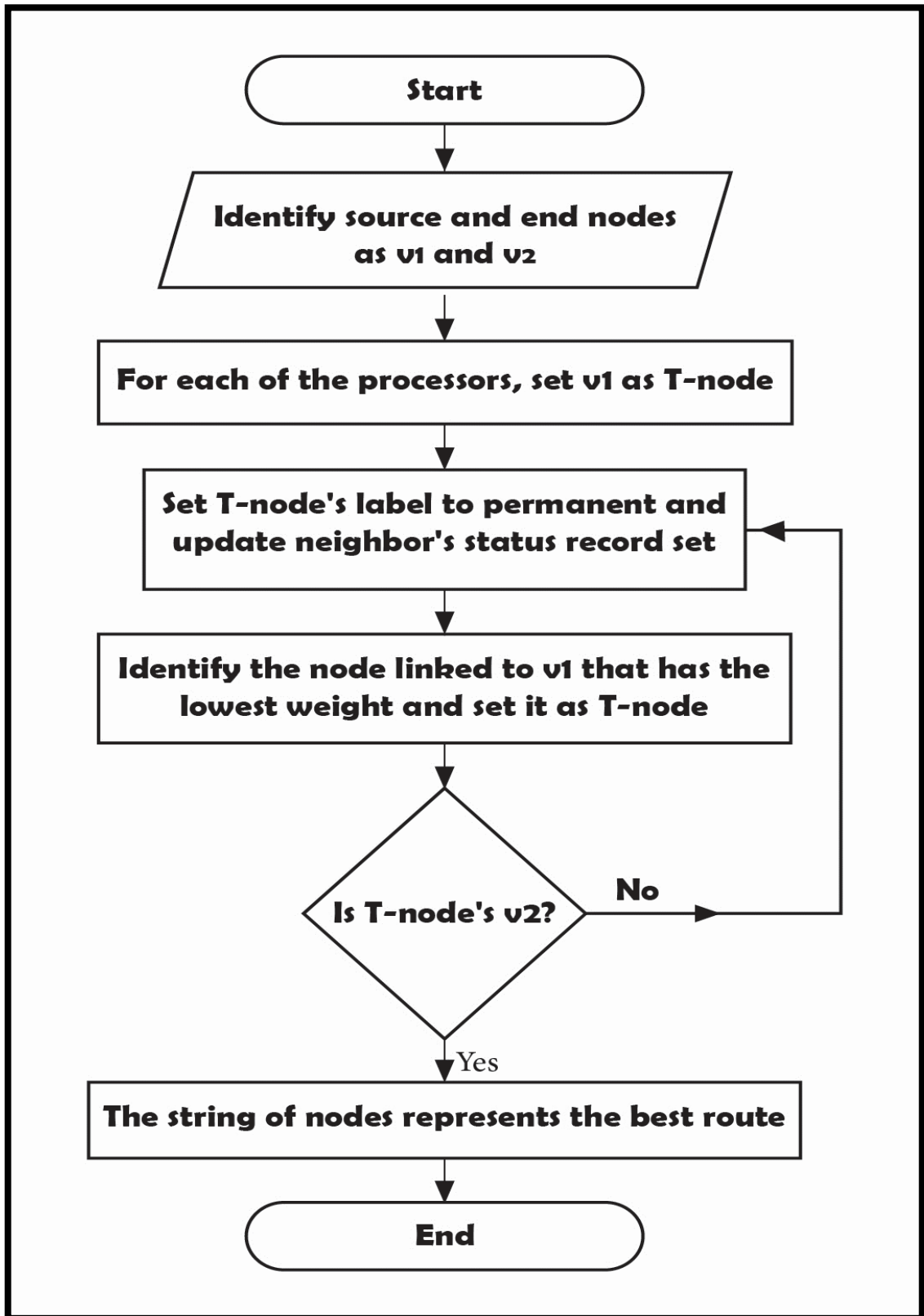


Figure 3.4

Connecting dc lines to different inverter locations

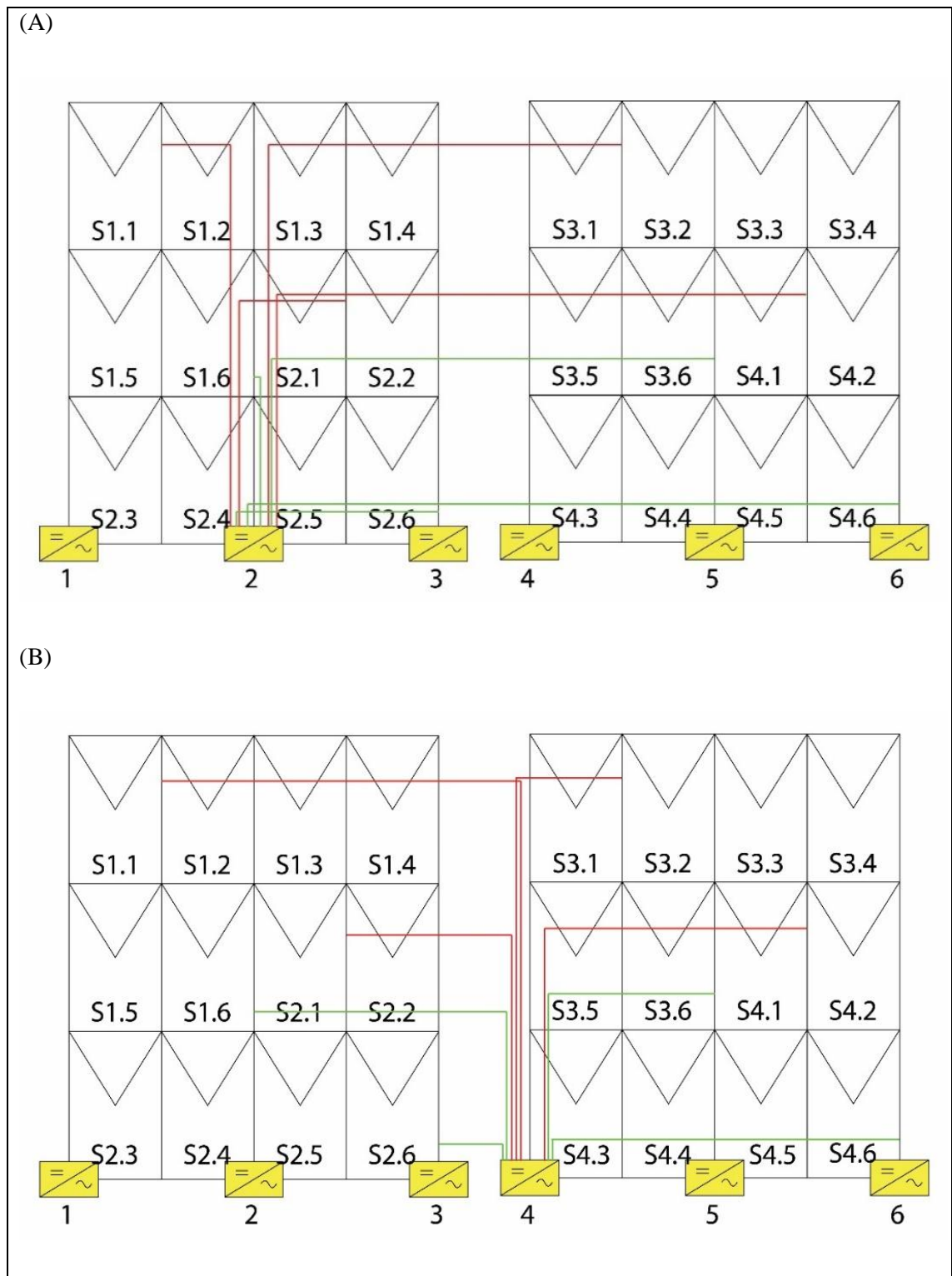
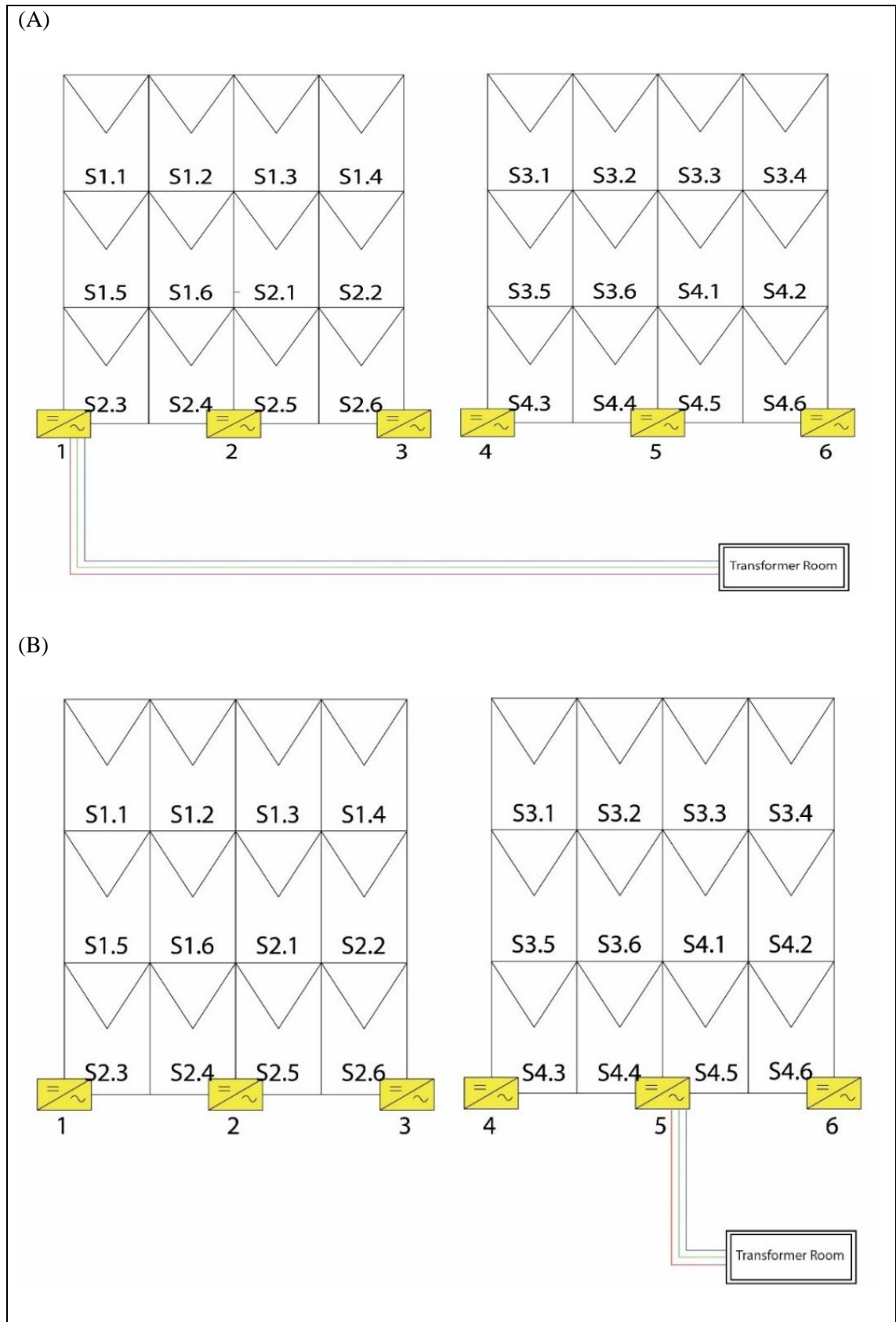


Figure 3.5

Connecting different inverter locations to the transformer room



Finally, results are extracted for the two approaches for minimal AC cables or minimal DC cables. Here, it's clearly noticed that the DC cables contribute to more than 75% of the total cables' length in the project. Thus, the approach of minimizing the DC cables at the expense of AC cables is preferable. Eventually, the output of this process are Ac cables lengths, dc cables lengths, and earthing cables lengths are the main outputs.

Chapter Four

Results and Discussion

In this research, the results of the proposed method are thoroughly validated by an actual photovoltaic (PV) system with a substantial capacity of 900 kilowatt-peak (kWp). This system is strategically located in Hebron city, situated in Palestine, and it occupies a considerable area of 10,000 square meters of land, as illustrated in Figure 4.1. The specific latitude and longitude coordinates of this given location are presented in Table 4.1 for precise reference.

Table 4.1

Latitude and longitude for selected site [28]

location	Latitude	Longitude
Hebron City	31.528 ° N	35.094 ° E

The primary load hubs in the Palestinian Territories encompass several significant cities, including Hebron, Gaza, Jerusalem, Nablus, and Ramallah. For a detailed understanding, refer to Figure 4.2, which illustrates the spatial distribution of these key load centers. In this figure, the size of each circle directly corresponds to the magnitude of the load, providing a clear visual representation of the load distribution across these critical locations [29].

The configuration of the PV panels applied in the photovoltaic (PV) project located in Hebron city was meticulously implemented using a total of 1656 PV panels, alongside 8 PV inverters each with a capacity of 110 kilowatts (kW). These components were strategically distributed across two separate parcels of land. The first parcel, which occupies an area of 6890 square meters, is illustrated in Figure 4.3(a). The second parcel, covering an area of 3110 square meters, is depicted in Figure 4.3(b). This distribution ensures optimal utilization of the available land and enhances the efficiency of the overall PV system.

To validate the results provided by the conventional approach described above, the system design is simulated using the PVsyst software. This simulation tool offers comprehensive analysis and detailed insights into the system's performance. The

resulting report, which includes all relevant data and findings from the simulation, is thoroughly documented and presented in Appendix C for further reference and verification.

The report initially provides the comprehensive electrical characteristics, encompassing detailed information on the electrical performance of the photovoltaic system. This includes crucial data such as direct current (DC) and alternating current (AC) power outputs, various losses, and efficiency metrics. Notably, the software recommended an optimized configuration involving the use of seven 110kW inverters instead of the initially proposed eight inverters, along with 1656 units of 545W PV panels. According to the recommendations, the distribution of the modules should be arranged into 92 strings, with each string consisting of 18 modules connected in series. This specific configuration yielded a power nominal ratio of 1.17, demonstrating the system's overall efficiency. Additionally, it resulted in a minimal loss fraction of 0.1% due to string mismatch losses and a 2.0% loss at the maximum power point (MPP) attributed to module mismatch losses, ensuring the system operates with high efficiency and reliability.

The PVsyst simulation also presented a detailed energy yield analysis, encompassing extensive data on the energy production capabilities of the system. This analysis accounted for various influential factors such as solar irradiance, shading losses, and temperature effects, which can significantly impact the overall energy yield. In this thorough simulation, a specific production output of 1778 kWh/kWp/year was obtained. Additionally, the system demonstrated a robust performance ratio of 82.85%, indicating a high level of efficiency and effectiveness in converting the available solar energy into usable electrical power.

Figure 4.1

Project's Land Contour (Case Study)

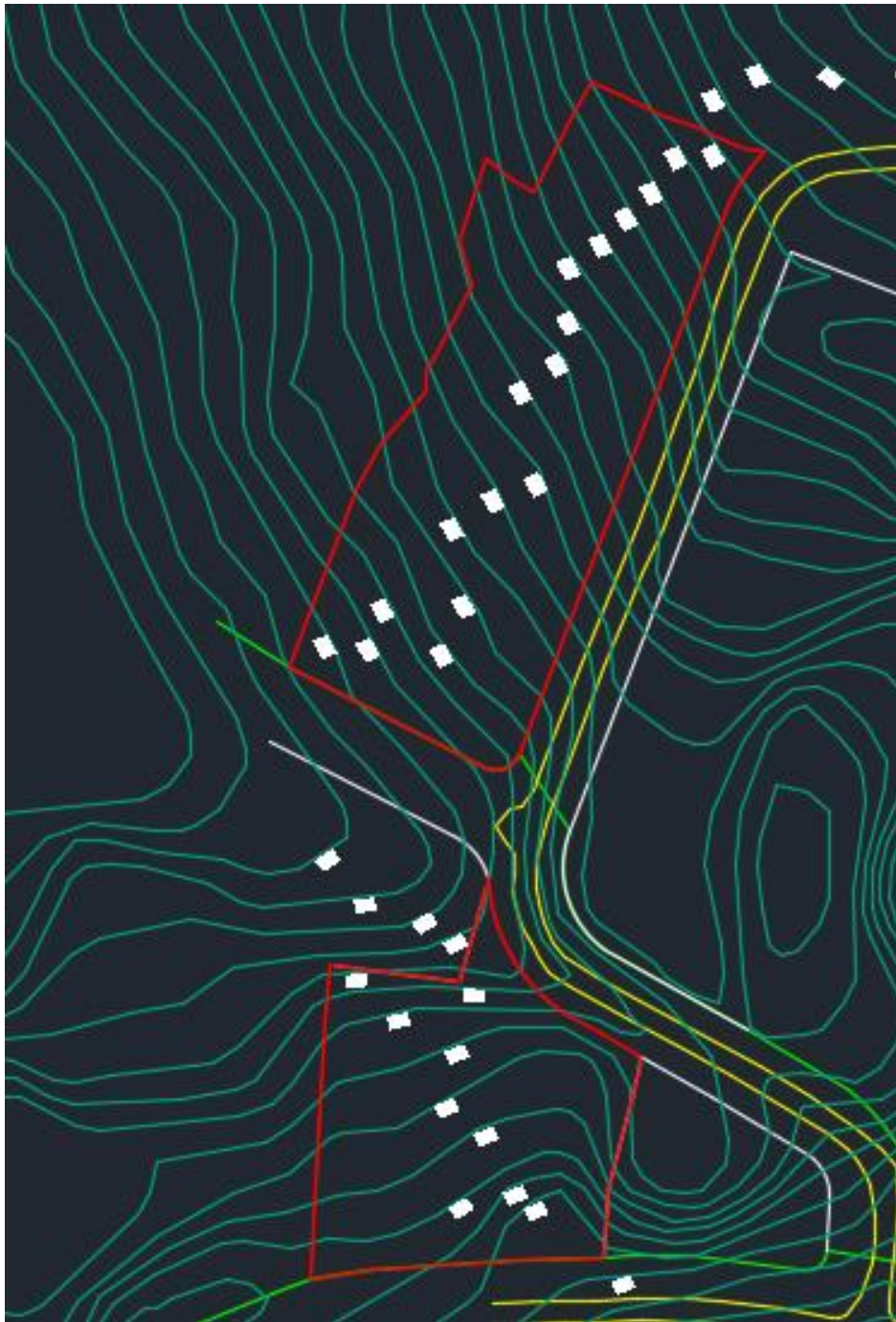


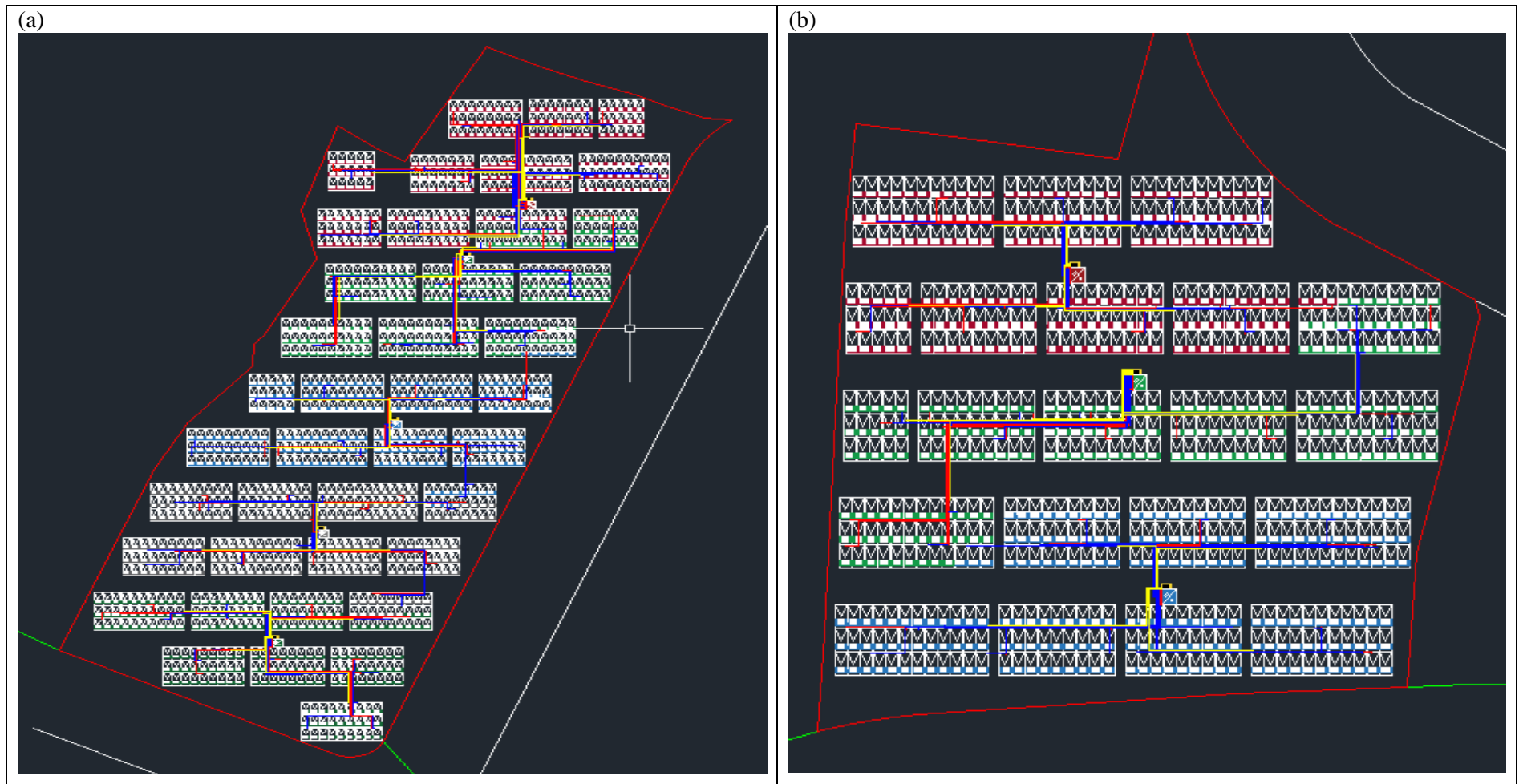
Figure 4.2

Distribution of major load centers in the Palestinian Territories [29]



Figure 4.3

Network Configuration of the case study PV project for land 1 and 2



Generally, PVsyst simulation reports offer a wealth of detailed information, encompassing various aspects of photovoltaic system performance and planning. These reports typically include comprehensive financial analysis, presenting crucial financial metrics such as the Levelized Cost of Energy (LCOE), payback period, and return on investment (ROI) calculations. Additionally, the reports provide detailed shading analysis, weather data, graphical representations of performance metrics, and sensitivity analysis, among other valuable insights. However, despite the extensive details, the output system configuration provided by the simulation does not address certain critical aspects such as the length and configuration of the cables and the impact of the inverter location on the overall system's cable lengths. This research makes a significant contribution by introducing a novel method that addresses these overlooked aspects in the simulation, thereby filling important gaps and enhancing the accuracy and reliability of the system design and analysis.

The results of the proposed method in this research are systematically compared to the results derived from the intuitive and conventional approach commonly employed in designing photovoltaic systems. This comparison focuses on several key aspects, including the configurations of different types of cables—specifically direct current (DC) cables, alternating current (AC) cables, and earthing cables. Additionally, the comparison examines the placement methodology of PV inverters within the system. By evaluating these critical components, the research aims to highlight the advantages and improvements offered by the proposed method over the traditional approaches, ensuring a more efficient and optimized system design.

For comparison purposes, this research utilizes the same type of photovoltaic (PV) panels throughout the analysis. However, to explore various scenarios comprehensively, three distinct types of inverters are considered. It's worth noting that the actual system employs only one type of inverter, which corresponds to Option 3. Detailed specifications of the adapted PV panels and inverters are provided in Tables 4.2 and 4.3, respectively. For further reference and in-depth analysis, the datasheets of the adapted PV panel and inverters are included in Appendix B, facilitating a thorough understanding of their technical characteristics and performance metrics.

Table 4.2*Specification of the adapted PV panel*

PV Panels	Hiku6 Mono Perc
Panel Size (W)	545
Panel Width (m)	1.134
Panel Length (m)	2.261
Panel Vmpp	38.9

Table 4.3*Specification of the adapted inverters*

Inverter Options	Option #1	Option #2	Option #3
	SUN-90K-G03	SG80KTL	STP 110-60
Inverter Size	70 Kw	80 Kw	110 Kw
Number of independent MPPT	4	1	12
Strings per MPP tracker	4	18	2
Rated MPP input voltage	Max = 1000V	(570 – 950) V	(500 V - 800) V

Based on the conventional method applied to the depicted land in Figure 8, the selection of the inverter's location relied heavily on engineering intuition. The designer opted for a location that intuitively appeared to minimize cable lengths, a practice commonly employed in such scenarios. Subsequently, this chosen location guided the cable connection process. The outcomes resulting from this conventional approach are presented in Table 4.4 below, offering insights into the implications of such design decisions on cable configurations and overall system performance.

Table 4.4*Characteristics of the power distribution network of the actual PV system*

System size	900 kWp
Land area	1000 m ²
# Of used inverters	8 (110 kWp each)
# Of used panels	1,656
Dc cables length	6,988m
Ac cables length	220m

In contrast, the proposed method is employed to design the power distribution network, taking into account the specific data of the adapted system. The process begins with rectifying the land area to a rectangular shape, measuring 50 by 182 meters, totaling 9100 square meters. Subsequently, utilizing the proposed methodology, eleven potential scenarios are systematically generated, each considering the same parameters as the adapted system but with variations in inverter types, now encompassing three options instead of one. The results obtained through this comprehensive approach are summarized in Table 4.5, providing a comparative analysis of the outcomes derived from each scenario facilitated by the proposed method.

From the data presented in Table 4.5, it is evident that in the first combination (combination #0), which involves the utilization of five inverters with a size of 110 kW each alongside one 80 kW inverter, notably shorter cable lengths are achieved compared to both the first and second approaches. Specifically, the total cable length for the first approach amounts to 5,558 meters, whereas for the second approach, it totals 8,450 meters. This substantial reduction in cable length underscores the efficiency and effectiveness of the proposed method in optimizing the power distribution network, resulting in tangible benefits such as minimized energy losses.

Indeed, a noticeable trend emerges as the number of inverters increases and their size decreases, resulting in a gradual escalation in the total cable length. This trend is clearly evident when examining Combination #1, where the total cable length amounts to 5,451 meters for the first approach and 8,173 meters for the second approach. Similarly, in Combination #2, the cable length increases to 5,898 meters for the first approach and

9,117 meters for the second approach. Furthermore, a more substantial increase in cable length is observed in the final combination (Combination #10), with the total cable length reaching 7,111 meters for the first approach and 10,682 meters for the second approach. This trend underscores the intricate interplay between the number and size of inverters and their impact on the overall cable length, highlighting the importance of optimization in designing the power distribution network to mitigate unnecessary energy losses and ensure optimal system performance.

Therefore, Scenario #1 emerges as the most favorable choice due to its achievement of the minimum length of cables. This scenario presents a compelling advantage, showcasing a remarkable 23% reduction in required cable length compared to the conventional methodology of designing, which yielded a total cable length of 7,208 meters. This substantial reduction not only signifies the efficiency and effectiveness of the proposed method but also underscores its capacity to optimize the power distribution network, leading to minimized energy losses.

The efficiency of converting direct current to alternating current in grid-connected photovoltaic inverters is influenced by a multitude of factors. These include climatic conditions, technical specifications of the inverters and PV modules, array orientation, the ratio of array peak power to inverter nominal power, and the DC input voltage supplied to the inverter. Consequently, selecting an optimal inverter size plays a crucial role in determining the total energy produced by the photovoltaic (PV) system [30]. Given the significance of this aspect, numerous researchers have directed their focus towards studying methods to optimally design PV inverters in photovoltaic systems. By considering these factors and employing advanced optimization techniques, researchers strive to enhance the efficiency and performance of PV systems, ultimately maximizing energy production and minimizing associated costs.

Table 4.5*Optimization results*

	# of inverters	# of panels	Inverters configuration	1 st Approach (Minimizing DC cables)			2 nd Approach (Minimizing AC cables)		
				Dc cables length (m)	Ac cables length (m)	Earthing cable length (m)	Dc cables length (m)	Ac cables length (m)	Earthing cable length (m)
Scenario #0	6	1656	1 (80 kWp), 5 (110 kWp)	5029	369	159	8101	190	159
Scenario #1	7	1656	3 (70 kWp), 1 (80 kWp), 3 (110 kWp)	4842	433	175	7763	234.5	175
Scenario #2	7	1680	2 (70 kWp), 2 (80 kWp), 3 (110 kWp)	5239	475	184	8606	327	184
Scenario #3	7	1704	1 (70 kWp), 3 (80 kWp), 3 (110 kWp)	5514	428	175	10375	224	175
Scenario #4	7	1656	5 (80 kWp), 2 (110 kWp)	5862	486	177	9923	306	177
Scenario #5	8	1680	6 (70 kWp), 1 (80 kWp), 1 (110 kWp)	4713	455	159	7547	268	159
Scenario #6	8	1680	5 (70 kWp), 2 (80 kWp), 1 (110 kWp)	5090	536	193	8601	356	193
Scenario #7	8	1704	4 (70 kWp), 3 (80 kWp), 1 (110 kWp)	5441	497	210	10164	270.5	210
Scenario #8	8	1656	3 (70 kWp), 5 (80 kWp)	5674	568.5	194	9651	392	194
Scenario #9	8	1680	2 (70 kWp), 6 (80 kWp)	6052	552	203	10187	326	203
Scenario #10	8	1704	1 (70 kWp), 7 (80 kWp)	6356	558	196	10132	354	196

Authors in [31] have applied a similar strategy in response to the increasing adoption of solar power in Finland, driven by the decreasing prices of PV system components. This paper proposes undersizing the inverters and identifying the optimum Inverter Loading Ratio (ILR) that balances the economic loss from clipped energy with the economic benefit from decreased system investment. The authors' findings indicate that undersizing the inverter effectively optimizes this ratio, leading to a more economically viable system design.

Similarly, in [32], a method was introduced to determine the optimum sizing ratio for photovoltaic systems across five sites in Malaysia. This method takes into account critical parameters such as solar irradiation and ambient temperature to accurately calculate the PV array output power. An iterative approach is employed by developing a MATLAB model, which aims to find the optimum inverter efficiency and sizing ratios. This model iteratively adjusts the parameters to achieve the most efficient and cost-effective system configuration, considering the local climatic conditions and the technical specifications of the components used.

Local solar radiation and ambient temperature play a critical role in determining the optimal size of inverters [33]. When solar radiation levels are low, which is the case for most days in many regions, the inverter's operating efficiency decreases because the photovoltaic (PV) arrays generate less power than their rated capacity [34]. This reduced power output leads to lower efficiency, as inverters are not operating at their optimal performance levels.

To mitigate this issue, many researchers have advocated for oversizing the solar arrays, resulting in a DC-to-AC ratio that exceeds 1. This strategy is advantageous because it facilitates greater energy capture during periods when the power production from the PV arrays is below the inverter's rating [35]. By oversizing the arrays, the system can capture more energy, even during times of low solar irradiation, which in turn enhances the overall energy yield and efficiency of the PV system.

Oversizing ensures that the inverter operates closer to its optimal performance range more frequently, thereby maximizing the energy output. This approach also helps in better utilizing the available solar resource, as the excess DC power can be effectively converted to AC power during periods of lower irradiation. Consequently, the system

becomes more efficient and economically viable, as it can generate more electricity and reduce the payback period.

Moreover, when a PV inverter is provided with more solar power than it can handle, inverter clipping occurs. In such cases, the daily production graph often exhibits a "flat-top" pattern, indicating that the inverters are operating at full capacity even though the panels could generate more energy. Interestingly, oversizing panels compared to inverters is a common industry practice, as highlighted in [31]. This approach reduces the portion of the total investment allocated to the PV inverter, without significantly decreasing the PV energy production due to the inverter's power limitations.

The goal of undersizing inverters is to determine the ideal ratio between the size of the array and the inverter, known as the Array-to-Inverter Sizing Ratio (AISR). This ratio aims to minimize the economic loss resulting from clipped energy against the economic benefit gained from reducing the investment in the PV system by using an undersized inverter. The rationale behind this strategy is to optimize the balance between the cost savings from a smaller inverter and the potential energy loss due to clipping. By carefully selecting the AISR, the system can achieve a cost-effective design that maximizes energy production and minimizes financial outlay [31].

In the first case examined, which previously demonstrated the shortest cable length achievement, a setup employing 1656 PV panels alongside three 110 kW inverters, one 80 kW inverter, and three 70 kW inverters yielded an Inverter Loading Ratio (ILR) of 146%. This indicates the adoption of the aforementioned approach of undersizing the PV inverter. This strategy was applied to a case study in Hebron, Palestine. Similarly, in [36], the authors introduced an iterative method to find the optimal inverter sizing ratio. Their analysis resulted in an optimum inverter sizing ratio of 166%, achieving a maximum efficiency of 95.16%. This highlights the effectiveness of carefully optimizing the inverter size to enhance system performance and efficiency.

After all, there are some minor errors in the proposed method due to several factors. Firstly, the proposed method assumes that the land is continuous and flat, whereas the actual case study involves land with varying vertical displacements. This discrepancy between the assumption and reality introduces inaccuracies in the calculations. Additionally, the proposed method approximates the land as a perfectly drawn

rectangle, which is not typically representative of real PV projects. Real-world PV projects often involve irregularly shaped plots of land, leading to further deviations from the idealized model used in the proposed method.

Consequently, this approximation process, which occurs during the pre-processing stage, leads to an accumulation of approximately 5% error in the cable length results. Moreover, due to the vertical displacements in the land, only 1656 panels could fit on the site, as more space was required between the tables. This is in contrast to the proposed theoretical analysis, which assumed a lower requirement for spacing between tables, allowing for greater flexibility in distributing the PV panels.

The idealized assumption of a perfectly flat and continuous land area in the theoretical model fails to account for the practical challenges posed by actual site conditions. These conditions include the need for additional space between tables to accommodate for variations in land elevation, which ultimately reduces the number of PV panels that can be installed. As a result, the theoretical model's predictions are slightly overestimated compared to the real-world scenario. This discrepancy not only affects the cable length calculations but also impacts the overall efficiency and layout of the PV system, demonstrating that the theoretical assumptions used during the pre-processing stage can lead to significant deviations from practical outcomes.

Additionally, this limitation highlights the need for more refined and accurate modeling techniques that account for real-world complexities, such as land irregularities and vertical displacements, to improve the precision of the proposed method. By addressing these factors, future analyses can better align theoretical predictions with actual project conditions, ultimately leading to more effective and reliable PV system designs.

Chapter Five

Conclusions

5.1 Conclusion

In this study, an optimal methodology was introduced to design the power distribution network for a grid-connected PV power plant, taking into consideration factors such as solar inverter size and location, as well as cable size and configuration. The approach involved an iterative method implemented through Python code, which systematically proposed various inverter combinations and tested different inverter locations. Through this iterative process, the methodology successfully identified the shortest cable lengths and optimal inverter locations.

To evaluate the effectiveness of the proposed methodology, both conventional and new approaches were applied to a 900-kWP grid-connected PV system for comparative analysis. The proposed method involved suggesting and analyzing ten different inverter combinations, providing flexibility in the choice between minimizing DC cables at the expense of AC cables or vice versa.

The results of the analysis indicated that DC cables accounted for more than 75% of the total cable length, supporting the initial approach of minimizing DC cable length. Furthermore, the findings revealed a gradual increase in total cable length when the number of used inverters increased with lower size.

A more detailed comparison was conducted under the best-case scenario, demonstrating that the proposed methodology resulted in a remarkable 23% decrease in total cable length compared to the conventional approach. This substantial reduction in cable length highlights the efficiency and optimization achieved by the proposed methodology.

In conclusion, the introduced methodology provides a valuable tool for enhancing the selection of inverter parameters in the design phase of a PV project. This, in turn, contributes to the development of more efficient and optimized PV systems by significantly reducing cable lengths, ultimately improving the overall feasibility and performance of grid-connected PV power plants.

5.2 Limitations

In this research, there were some challenges in translating the theoretical model and the algorithmic solution into a practical design, such as approximating the project's land into a rectangular area encountering a significant percentage of error. Moreover, the model deals with a single transformer room and does not adapt in the case of having multiple transformer rooms.

List of Abbreviations

Abbreviation	Meaning
AC	Alternating current
AI	Artificial intelligence
BoS	Balance-of-system
DC	Direct current
DMPPT	Distributed Maximum Power Point Tracking
GW	Gigawatt
ILR	Inverter Loading Ratio
kWp	Kilowatt 'peak' of a system
LCA	Life cycle assessment
MIC	Module integrated converters
MPPT	Maximum power point tracking
NPV	Net present value
PV	Photovoltaic
RMS	Root mean square
SB	Switchboard

References

- [1] A. Cagle, M. Shepherd, S. Grodsky, A. Armstrong, S. M. Jordaan, and R. Hernandez, "Standardized Metrics to Quantify Solar Energy-Land Relationships: A Global Systematic Review," *SSRN Electronic Journal*, 2022, doi: 10.2139/ssrn.4069060.
- [2] T. Khatib, I. A. Ibrahim, and A. Mohamed, "A review on sizing methodologies of photovoltaic array and storage battery in a standalone photovoltaic system," *Energy Convers Manag*, vol. 120, pp. 430–448, Jul. 2016, doi: 10.1016/j.enconman.2016.05.011.
- [3] S. Ekici and A. Kopru, "Investigation of PV System Cable Losses," 2017. [Online]. Available: <https://www.researchgate.net/publication/317701311>
- [4] S. Reichelstein and M. Yorston, "The Prospects for Cost Competitive Solar PV Power," *SSRN Electronic Journal*, 2012, doi: 10.2139/ssrn.2182828.
- [5] A. Narasimhan, "Qualitative Assessment of PV System Cable Loss and Practical Cost Optimization," in *2020 IEEE International Conference on Electronics, Computing and Communication Technologies (CONECCT)*, IEEE, Jul. 2020, pp. 1–6. doi: 10.1109/CONECCT50063.2020.9198671.
- [6] G. Notton, V. Lazarov, and L. Stoyanov, "Optimal sizing of a grid-connected PV system for various PV module technologies and inclinations, inverter efficiency characteristics and locations," *Renew Energy*, vol. 35, no. 2, pp. 541–554, Feb. 2010, doi: 10.1016/j.renene.2009.07.013.
- [7] C. Demoulias, "A new simple analytical method for calculating the optimum inverter size in grid-connected PV plants," *Electric Power Systems Research*, vol. 80, no. 10, pp. 1197–1204, Oct. 2010, doi: 10.1016/j.epsr.2010.04.005.
- [8] S. Chen, P. Li, D. Brady, and B. Lehman, "Determining the optimum grid-connected photovoltaic inverter size," *Solar Energy*, vol. 87, pp. 96–116, Jan. 2013, doi: 10.1016/j.solener.2012.09.012.

- [9] C. K. Gan, Y. M. Lee, D. Pudjianto, and G. Strbac, "Role of losses in design of DC cable for solar PV applications," in *2014 Australasian Universities Power Engineering Conference (AUPEC)*, IEEE, Sep. 2014, pp. 1–5. doi: 10.1109/AUPEC.2014.6966594.
- [10] S. I. Sulaiman, T. K. A. Rahman, I. Musirin, S. Shaari, and K. Sopian, "An intelligent method for sizing optimization in grid-connected photovoltaic system," *Solar Energy*, vol. 86, no. 7, pp. 2067–2082, Jul. 2012, doi: 10.1016/j.solener.2012.04.009.
- [11] K. S. Hayibo and J. M. Pearce, "Optimal inverter and wire selection for solar photovoltaic fencing applications," *Renewable Energy Focus*, vol. 42, pp. 115–128, Sep. 2022, doi: 10.1016/j.ref.2022.06.006.
- [12] A. D. Mosheer and C. K. Gan, "OPTIMAL SOLAR CABLE SELECTION FOR PHOTOVOLTAIC SYSTEMS," 2015.
- [13] D. Cazzaro, D. F. Koza, and D. Pisinger, "Combined layout and cable optimization of offshore wind farms," *Eur J Oper Res*, vol. 311, no. 1, pp. 301–315, Nov. 2023, doi: 10.1016/j.ejor.2023.04.046.
- [14] P. Mohanty and T. Muneer, "Smart Design of Stand-Alone Solar PV System for Off Grid Electrification Projects," 2014, pp. 63–93. doi: 10.1007/978-3-319-04816-1_4.
- [15] T. Khatib, "A Review of Designing, Installing and Evaluating Standalone Photovoltaic Power Systems," *Journal of Applied Sciences*, vol. 10, no. 13, pp. 1212–1228, Jun. 2010, doi: 10.3923/jas.2010.1212.1228.
- [16] H. Ziar, S. Farhangi, and B. Asaei, "Modification to Wiring and Protection Standards of Photovoltaic Systems," *IEEE J Photovolt*, vol. 4, no. 6, pp. 1603–1609, Nov. 2014, doi: 10.1109/JPHOTOV.2014.2344764.
- [17] F. Spertino *et al.*, "A power and energy procedure in operating photovoltaic systems to quantify the losses according to the causes," *Solar Energy*, vol. 118, pp. 313–326, Aug. 2015, doi: 10.1016/j.solener.2015.05.033.

- [18] A. Desai, V. Pandya, I. Mukhopadhyay, and A. Ray, “Temperature Effects on DC Cable Voltage Drop in Utility Scale Rooftop Solar PV Plant Based on Empirical Model,” in *2020 47th IEEE Photovoltaic Specialists Conference (PVSC)*, IEEE, Jun. 2020, pp. 2397–2402. doi: 10.1109/PVSC45281.2020.9300709.
- [19] K.-N. D. Malamaki and C. S. Demoulias, “Analytical Calculation of the Electrical Energy Losses on Fixed-Mounted PV Plants,” *IEEE Trans Sustain Energy*, vol. 5, no. 4, pp. 1080–1089, Oct. 2014, doi: 10.1109/TSTE.2014.2323694.
- [20] L. Recio Maillo, “APPLICATION NOTE ECONOMIC CABLE SIZING IN PV SYSTEMS: CASE STUDY,” 2017. [Online]. Available: www.leonardo-energy.org
- [21] J. D. Mondol, Y. G. Yohanis, and B. Norton, “Optimal sizing of array and inverter for grid-connected photovoltaic systems,” *Solar Energy*, vol. 80, no. 12, pp. 1517–1539, Dec. 2006, doi: 10.1016/j.solener.2006.01.006.
- [22] N. S. M. Hussin *et al.*, “Performance Factors of the Photovoltaic System: A Review,” *MATEC Web of Conferences*, vol. 225, p. 03020, Nov. 2018, doi: 10.1051/mateconf/201822503020.
- [23] M. Farhan, “Study of Parallel Algorithms for IP Switches,” *Land Forces Academy Review*, vol. 24, no. 2, pp. 158–163, Jun. 2019, doi: 10.2478/raft-2019-0019.
- [24] E. Kandemir, N. S. Cetin, and S. Borekci, “A comprehensive overview of maximum power extraction methods for PV systems,” *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 93–112, Oct. 2017, doi: 10.1016/j.rser.2017.04.090.
- [25] T. Khatib, “Optimization of a grid-connected renewable energy system for a case study in Nablus, Palestine,” *International Journal of Low-Carbon Technologies*, vol. 9, no. 4, pp. 311–318, Dec. 2014, doi: 10.1093/ijlct/ctt007.
- [26] R. Rüdénberg, “Grounding principles and practice I — Fundamental considerations on ground currents,” *Electrical Engineering*, vol. 64, no. 1, pp. 1–13, Jan. 1945, doi: 10.1109/EE.1945.6440813.

- [27] M. Nassereddine, K. Ali, and C. Nohra, "Photovoltaic solar farm; earthing system design for cost reduction and system compliance," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 3, p. 2884, Jun. 2020, doi: 10.11591/ijece.v10i3.pp2884-2893.
- [28] Y. F. Nassar, A. A. Hafez, and S. Y. Alsadi, "Multi-Factorial Comparison for 24 Distinct Transposition Models for Inclined Surface Solar Irradiance Computation in the State of Palestine: A Case Study," *Front Energy Res*, vol. 7, Feb. 2020, doi: 10.3389/fenrg.2019.00163.
- [29] S. R. Ersoy, J. Terrapon-Pfaff, and I. Brik, "SUSTAINABLE TRANSFORMATION OF PALESTINE'S ENERGY SYSTEM DEVELOPMENT OF A PHASE MODEL Study SUSTAINABLE TRANSFORMATION OF PALESTINE'S ENERGY SYSTEM DEVELOPMENT OF A PHASE MODEL," 2022.
- [30] T. Stetz *et al.*, "Cost optimal sizing of photovoltaic inverters-Influence of new grid codes and cost reductions", Accessed: Jul. 09, 2024. [Online]. Available: <http://www.sma.de>
- [31] J. Väisänen, A. Kosonen, J. Ahola, T. Sallinen, and T. Hannula, "Optimal sizing ratio of a solar PV inverter for minimizing the levelized cost of electricity in Finnish irradiation conditions," *Solar Energy*, vol. 185, pp. 350–362, Jun. 2019, doi: 10.1016/j.solener.2019.04.064.
- [32] M. Mahmoud, T. Khatib, A. Mohamed, and K. Sopian, "An Iterative Method for Calculating the Optimum Size of Inverter in PV Systems for Malaysia VL," *Przegląd Elektrotechniczny*, vol. 88, pp. 281–284, Jan. 2012.
- [33] M. Macagnan, *On the optimal size of inverters for grid connected pv systems*. 1992.
- [34] C. W, M. W, N. Y, D. G. L, and N. J, "Detailed comparison of the inverter operation of two grid-connected PV demonstration systems in Belgium.," *13th European Photovoltaic Solar Energy Conference, 1995, Vol.2*, pp. 1881–1884,

- 1995, Accessed: Jul. 09, 2024. [Online]. Available: https://jglobal.jst.go.jp/en/detail?JGLOBAL_ID=200902183981231928
- [35] P. M. Rodrigo, R. Velázquez, and E. F. Fernández, “DC/AC conversion efficiency of grid-connected photovoltaic inverters in central Mexico,” *Solar Energy*, vol. 139, pp. 650–665, Dec. 2016, doi: 10.1016/J.SOLENER.2016.10.042.
- [36] T. Khatib, A. Yasin, A. A. Mohammad, and I. A. Ibrahim, “On the effectiveness of optimally sizing an inverter in a grid-connected photovoltaic power system,” *2017 14th International Conference on Smart Cities: Improving Quality of Life Using ICT and IoT, HONET-ICT 2017*, vol. 2017-January, pp. 48–52, Nov. 2017, doi: 10.1109/HONET.2017.8102220.
- [37] “HiKu6 – Canadian Solar – Global.” Accessed: Jul. 09, 2024. [Online]. Available: <https://www.canadiansolar.com/hiku6/>
- [38] “SMA SUNNY TRIPOWER CORE2 Solar Inverter SMA STP 110-60 | mg-solar-shop.com.” Accessed: Jul. 09, 2024. [Online]. Available: <https://www.mg-solar-shop.com/sma-sunny-tripower-core2-solar-inverter-sma-stp-110-60>
- [39] “SUN-70/75/80/90/100/110K-G03 | 70-110kW | Three Phase | 6 MPPT Inverter Company, Supplier | Deye Inverter Technology.” Accessed: Jul. 09, 2024. [Online]. Available: <https://www.deyeinverter.com/product/three-phase-string-inverter/sun70-75-80-90-100-110kg03-70110kw-three-phase-6-mppt.html>
- [40] “SG80KTL String Inverter.” Accessed: Jul. 09, 2024. [Online]. Available: https://www.pvxchange.com/mediafiles/pvxchange/attachments/SG80KTL_Datasheet.pdf

Appendices

Appendix A

Open-source code of the proposed method

```
#Main.py  
  
# Import Other Files  
import data_entry  
import inv_table_coordinations  
import calculate_dc_lines_lengths  
import identify_nodes_edges_matrix  
import shortest_path_algorithm  
import pandas as pd  
  
# Import Project Data  
project_data = data_entry.automatic_data_entry()  
  
# Inverter Combinations  
inv_combinations = inv_table_coordinations.inverter_combinations(project_data)[0]  
string_per_inv = inv_table_coordinations.inverter_combinations(project_data)[1]  
panel_per_inv = inv_table_coordinations.inverter_combinations(project_data)[2]  
  
# Define and Draw Tables Coordination  
tables_coordinations = inv_table_coordinations.define_table_coordinations(project_data,  
inv_combinations,  
string_per_inv, panel_per_inv)  
  
#for combination in tables_coordinations:  
    #inv_table_coordinations.draw_tables(combination)  
  
# Identify the main nodes for each table -> [left_corner, middle, right corner, dc_output1,  
dc_output2]  
inv_coordinates = calculate_dc_lines_lengths.inv_coordinates(tables_coordinations)  
  
# Calculate dc_lines_lengths  
# Identify an array of dc_outputs per inverter, and possible inverter location per inverter  
dc_outputs_per_inverter =  
calculate_dc_lines_lengths.dc_output_and_inv_locations(inv_coordinates)[0]  
inverter_location_nodes =  
calculate_dc_lines_lengths.dc_output_and_inv_locations(inv_coordinates)[1]  
  
# Calculate the possible dc-lines lengths for each inverter location  
dc_lines_lengths = calculate_dc_lines_lengths.dc_lines_length(dc_outputs_per_inverter,  
inverter_location_nodes)  
  
# Calculating the shortest path from each inverter to the High-Pressure room  
  
# Identify a reference nodes matrix  
reference_nodes_matrix =
```

```

calculate_dc_lines_lengths.dc_output_and_inv_locations(inv_coordinates)[2]
# Identify land's right and left nodes arrays
land_edges_nodes =
identify_nodes_edges_matrix.land_left_and_right_nodes(inverter_location_nodes,
reference_nodes_matrix)
# Identify the nodes_edges_matrix, Number of nodes per combination
num_nodes_per_combination =
calculate_dc_lines_lengths.dc_output_and_inv_locations(inv_coordinates)[3]
nodes_edges_matrix =
identify_nodes_edges_matrix.define_nodes_edges_matrix(inverter_location_nodes,
reference_nodes_matrix,
land_edges_nodes[0],
land_edges_nodes[1],
num_nodes_per_combination)
# Calculating shortest distance for two cases
nodes_lists = calculate_dc_lines_lengths.dc_output_and_inv_locations(inv_coordinates)[4]
'Case#1: Based on the shortest AC-line of each inverter; Finding the minimum Lines-length'
dc_and_ac_lines_lengths1 = [[] for combination in reference_nodes_matrix]
summation_of_dc_and_ac1 = [[] for combination in reference_nodes_matrix]
lengths_per_combination =
shortest_path_algorithm.line_lengths_per_combination(inv_coordinates,
nodes_lists,
nodes_edges_matrix)
combination_idx = 0
for combination in reference_nodes_matrix:
    inv_idx = 0
    for inverter in combination:
        min_length = float('inf')
        table_idx = 0
        for table in inverter:
            node_idx = 0
            for node in table:
                if lengths_per_combination[combination_idx][node] < min_length:
                    min_dc_and_ac_length =
[dc_lines_lengths[combination_idx][inv_idx][table_idx][node_idx],
lengths_per_combination[combination_idx][node]]
                    min_length = lengths_per_combination[combination_idx][node]
                    sum = min_dc_and_ac_length[0] + min_dc_and_ac_length[1]
                node_idx += 1
            table_idx += 1
        inv_idx += 1
    # Results:
dc_and_ac_lines_lengths1[combination_idx].append(min_dc_and_ac_length)

```

```

        summation_of_dc_and_ac1[combination_idx].append(sum)
    combination_idx += 1
combination_idx = 0
total_lines_length_case1 = [[] for combination in inv_combinations]
for combination in summation_of_dc_and_ac1:
    final_lines_length = 0
    for inverter in combination:
        final_lines_length += inverter
    # Final Results:
total_lines_length_case1[combination_idx].append([final_lines_length])
    combination_idx += 1
'Case#2: Based on the shortest DC-line of each inverter; Finding the minimum Lines-length'
num_rows_per_inv = calculate_dc_lines_lengths.rows_per_inv(inverter_location_nodes)[0]
y_coordinate_of_each_row =
calculate_dc_lines_lengths.rows_per_inv(inverter_location_nodes)[1]
num_rows_per_inv_filled = calculate_dc_lines_lengths.lines_per_inverter(num_rows_per_inv,
inverter_location_nodes,
                                y_coordinate_of_each_row)
dc_and_ac_lines_lengths2 = [[] for combination in reference_nodes_matrix]
summation_of_dc_and_ac2 = [[] for combination in reference_nodes_matrix]
combination_idx = 0
best_inv_coordinates_matrix = [[] for combination in reference_nodes_matrix]
for combination in reference_nodes_matrix:
    inv_idx = 0
    for inverter in combination:
        min_length = float('inf')
        table_idx = 0
        for table in inverter:
            node_idx = 0
            for node in table:
                if dc_lines_lengths[combination_idx][inv_idx][table_idx][node_idx] < min_length:
                    min_dc_and_ac_length =
[dc_lines_lengths[combination_idx][inv_idx][table_idx][node_idx],
lengths_per_combination[combination_idx][node]]
                    min_length = dc_lines_lengths[combination_idx][inv_idx][table_idx][node_idx]
                    sum = min_dc_and_ac_length[0] + min_dc_and_ac_length[1]
                    # Best inverter location: [combination_idx, inv_idx, table_idx, node_idx]
                    best_inv_coordinates = [combination_idx, inv_idx, table_idx, node_idx]
            node_idx += 1
        table_idx += 1
    inv_idx += 1

```

```

dc_and_ac_lines_lengths2[combination_idx].append(min_dc_and_ac_length)
    summation_of_dc_and_ac2[combination_idx].append(sum)
best_inv_coordinates_matrix[combination_idx].append(best_inv_coordinates)
    combination_idx += 1
# Earthing cables:
earthing_cables_location = \
calculate_dc_lines_lengths.calculate_shortest_earthing_cables_for_all_inv(num_rows_per_inv,
best_inv_coordinates_matrix,
                                inverter_location_nodes)[0]
earthing_cables_lengths = \
calculate_dc_lines_lengths.calculate_shortest_earthing_cables_for_all_inv(num_rows_per_inv,
best_inv_coordinates_matrix,
                                inverter_location_nodes)[1]
total_earthing_cables_length = \
calculate_dc_lines_lengths.calculate_shortest_earthing_cables_for_all_inv(num_rows_per_inv,
best_inv_coordinates_matrix,
                                inverter_location_nodes)[2]

total_lines_length_case2 = [[] for combination in inv_combinations]
combination_idx = 0
for combination in summation_of_dc_and_ac2:
    final_lines_length = 0
    for inverter in combination:
        final_lines_length += inverter
    # Final Results:
    total_lines_length_case2[combination_idx].append([final_lines_length])
    combination_idx += 1
# Print out results
combination_idx = 0
for combination in dc_lines_lengths:
    # print('\nCombinations #{} \nInv_combinations: {}'.format(combination_idx,
    # inv_table_coordinations.inverter_combinations(project_data)[
    # combination_idx]))
    print('Nodes_edges_matrix = {}'.format(nodes_edges_matrix[combination_idx]))
    print('dc_and_ac_lines_lengths1 is: {}'.format(dc_and_ac_lines_lengths1[combination_idx]))
    print('dc_and_ac_lines_lengths2 is: {}'.format(dc_and_ac_lines_lengths2[combination_idx]))
    print('Total_lines_length_case1 is: {}'.format(total_lines_length_case1[combination_idx]))
    print('Total_lines_length_case2 is: {}'.format(total_lines_length_case2
                                                    [combination_idx]))
    print('Number of nodes = {}'.format(num_nodes_per_combination[combination_idx]))

```

```

inv_idx = 0
for inverter in combination:
    print('Inverter #{}'.format(inv_idx))
    # Tables coordination: nw_coordinates, sw_coordinates, ne_coordinates, se_coordinate
    print('Table
coordinates: {}'.format(inv_table_coordinations.define_table_coordinations(project_data,
inv_combinations,
string_per_inv,
panel_per_inv)[
combination_idx][inv_idx]))
    # Identify the main nodes for each table -> [left_corner, middle, right corner, dc_output1,
dc_output2]
    print('Critical nodes: {}'.format(inv_coordinates[combination_idx][inv_idx]))
    # Identify an array of possible inverter
    print('Possible inverter coordinates:
{}'.format(inverter_location_nodes[combination_idx][inv_idx]))
    # Identify a reference nodes matrix
    print('Reference node numbers:
{}'.format(reference_nodes_matrix[combination_idx][inv_idx]))
    table_idx = 1
    for table in inverter:
        # Calculate the possible dc-lines lengths for each inverter location
        print(
'Dc_lines length for Table #{} at [Left_corner] = {}, [Middle_node] = {},
[Right_corner] = {}'.format(
table_idx, table[0], table[1], table[2]))
        table_idx += 1
    inv_idx += 1
    combination_idx += 1
# Extracting data into DataFrames
inv_combinations = pd.DataFrame(inv_combinations)
inv_combinations.to_excel('inverter combinations.xlsx')
dc_and_ac_lines_lengths1 = pd.DataFrame(dc_and_ac_lines_lengths1)
dc_and_ac_lines_lengths2 = pd.DataFrame(dc_and_ac_lines_lengths2)
dc_and_ac_lines_lengths1.to_excel('dc_and_ac_lines_lengths1.xlsx')
dc_and_ac_lines_lengths2.to_excel('dc_and_ac_lines_lengths2.xlsx')
total_lines_length_case1 = pd.DataFrame(total_lines_length_case1)
total_lines_length_case2 = pd.DataFrame(total_lines_length_case2)
total_lines_length_case1.to_excel('Total_lines_length_case1.xlsx')
total_lines_length_case2.to_excel('Total_lines_length_case2.xlsx')
Table_coordinations = pd.DataFrame(tables_coordinations)

```

```

Table_coordinations.to_excel('Table_coordinations.xlsx')
dc_lines_lengths = pd.DataFrame(dc_lines_lengths)
dc_lines_lengths.to_excel('dc_lines_lengths.xlsx')
lengths_per_combination = pd.DataFrame(lengths_per_combination)
lengths_per_combination.to_excel('lengths_per_combination.xlsx')
earthing_cables_lengths = pd.DataFrame(earthing_cables_lengths)
earthing_cables_lengths.to_excel('earthing_cables_lengths.xlsx')
nodes_lists = pd.DataFrame(nodes_lists)
nodes_lists.to_excel('nodes_lists.xlsx')

```

#Data_entry.py

```
# Manual Data Entry
```

```
from typing import Any
```

```
def manual_data_entry():
```

```

    project_data = {
        'system_size': int(input('What is the required system capacity in kW? ')),
        'l_width': int(input('Land width')),
        'l_length': int(input('Land length')),
        'pv_data': {
            'panel_size': float(input('PV pannel size in Wp? ')),
            'panel_width': float(input('panel width')),
            'panel_length': float(input('panel length')),
            'panel_vmpp': float(input('Pannel data: vmpp')),
        },
        'inv_data': [],
        'continuous': bool(int(input('Insert 1 of the land is continuous, 0 if it is an earthquake land
    )))
    }
    n = 1
    while True:
        inv_size = int(input('Size of the inverter'))
        inv_num_mppt = int(input('The number of mppt in each inverter '))
        inv_vmpp = int(input('Inverter data1, voltage at each mppt in v '))
        inv_name = 'inv{}'.format(n)
        n += 1
        project_data['inv_data'].append({
            'inv_name': inv_name,
            'inv_size': inv_size,
            'inv_num_mppt': inv_num_mppt,
            'inv_vmpp': inv_vmpp,
            'panel_per_inv': (inv_vmpp / project_data['pv_data']['panel_vmpp']) *

```

```

inv_num_mppt,

    })
    if input('Do you have further inverter data? Yes or No') == "No":
        break
    return project_data
# Automatic Data Entry
def automatic_data_entry():
    project_data: dict[str, int | dict[str, int | float] | list[
        dict[str, int | str] | dict[str, int | str] | dict[str, int | str]] | bool | Any] = {
        'system_size': 900,
        'l_width': 50,
        'l_length': 182,
        'pv_data': {
            'panel_size': .545,
            'panel_width': 1.134,
            'panel_length': 2.261,
            'panel_vmpp': 38.9,
        },
        'inv_data': [{
            'inv_name': "inv1",
            'inv_size': 80,
            'inv_num_mppt': 1,
            'inv_vmpp': 650,
            'strings_per_inv': 18,
            'panel_per_inv': 162,
            'panel_per_string': 9,
            # panel_per_inv : (inv_vmpp/project_data['pv_data']['panel_vmpp'])*inv_num_mppt,
        }, {
            'inv_name': "inv2",
            'inv_size': 70,
            'inv_num_mppt': 4,
            'inv_vmpp': 850,
            'strings_per_inv': 16,
            'panel_per_inv': 144,
            'panel_per_string': 9,
        }, {
            'inv_name': "inv2",
            'inv_size': 110,
            'inv_num_mppt': 12,

```

```

        'inv_vmppt': 585,
        'strings_per_inv': 24,
        'panel_per_inv': 216,
        'panel_per_string': 9,
    }
],
'continuous': True
}
return project_data

```

#Inv_table_coordinations.py

```

def inverter_combinations(project_data):
    inv_capacities = []
    min_inv_capacity = float('inf')
    for inv in project_data['inv_data']:
        inv['actual_capacity'] = int(inv['panel_per_inv'] * project_data['pv_data']['panel_size'])
        min_inv_capacity = min(min_inv_capacity, inv['actual_capacity'])
        inv_capacities.append(inv['actual_capacity'])
    from itertools import combinations_with_replacement, combinations
    project_data['max_required_inv'] = project_data['system_size'] // min_inv_capacity
    inv_combinations = []
    for i in range(int(project_data['max_required_inv'])):
        temporary_combinations = list(combinations_with_replacement(inv_capacities, i + 1))
        for comb in temporary_combinations:
            if project_data['system_size'] + 37 > sum(comb) > project_data['system_size'] - 5:
                inv_combinations.append(comb)
    strings_per_inv = [[] for comb in inv_combinations]
    comb_idx = 0
    for comb in inv_combinations:
        for inv in comb:
            strings_per_inv[comb_idx] = [[] for inv in comb]
        comb_idx += 1
    comb_idx = 0
    for comb in inv_combinations:
        inv_idx = 0
        for inv in comb:
            if inv == 98:
                strings_per_inv[comb_idx][inv_idx].append(20)
            elif inv == 103:

```

```

        strings_per_inv[comb_idx][inv_idx].append(22)
    else:
        strings_per_inv[comb_idx][inv_idx].append(24)
    inv_idx += 1
    comb_idx += 1
panel_per_string = [[] for comb in inv_combinations]
comb_idx = 0
for comb in inv_combinations:
    for inv in comb:
        panel_per_string[comb_idx] = [[] for inv in comb]
        comb_idx += 1
comb_idx = 0
for comb in inv_combinations:
    inv_idx = 0
    for inv in comb:
        if inv == 98:
            panel_per_string[comb_idx][inv_idx].append(9)
        elif inv == 103:
            panel_per_string[comb_idx][inv_idx].append(9)
        else:
            panel_per_string[comb_idx][inv_idx].append(9)
        inv_idx += 1
    comb_idx += 1
return inv_combinations, strings_per_inv, panel_per_string
# Tables coordination: nw_coordinates, sw_coordinates, ne_coordinates, se_coordinate
def define_table_coordinations(project_data, inv_combinations, string_per_inv,
panel_per_string):
    if project_data['continuous']:
        tables_coordinations = [[] for combination in range(len(inv_combinations))]
        combination_index = 0
        for combination in inv_combinations:
            x_pointer, y_pointer = 1, 1
            covered_load = [False for inverter in combination]
            inv_idx = 0
            pannel_line = 0
            tables_coordinations[combination_index] = [[] for d in combination]
            while (inv_idx < len(covered_load)) and covered_load[inv_idx] == False:
                tables_coordinations[combination_index][inv_idx] = [[] for w in
range(string_per_inv[combination_index][inv_idx][0])]
                covered_tables = [False for i in

```

```

range(string_per_inv[combination_index][inv_idx][0])
    to_be_installed_table_width = project_data['pv_data']['panel_width'] *
(panel_per_string[combination_index][inv_idx][0] / 3)
    table_idx = 0
    while (table_idx < len(covered_tables)) and covered_tables[table_idx] == False:
        if table_idx == (len(covered_tables) - 1):
            x_displacement = 1
        else:
            x_displacement = 0
        if (panel_line % 2) == 0:
            if to_be_installed_table_width < (project_data['l_width'] - (x_pointer + 1)):
tables_coordinations[combination_index][inv_idx][table_idx].append([
                [x_pointer, y_pointer],
                [x_pointer, y_pointer + (project_data['pv_data']['panel_length'] * 3)],
                [x_pointer + to_be_installed_table_width, y_pointer],
                [x_pointer + to_be_installed_table_width,
                y_pointer + (project_data['pv_data']['panel_length'] * 3)]
            ])
            covered_tables[table_idx] = True
            table_idx += 1
            x_pointer += ((to_be_installed_table_width) + x_displacement)
            continue
        elif to_be_installed_table_width == (project_data['l_width'] - (x_pointer + 1)):
tables_coordinations[combination_index][inv_idx][table_idx].append([
                [x_pointer, y_pointer],
                [x_pointer, y_pointer + (project_data['pv_data']['panel_length'] * 3)],
                [x_pointer + to_be_installed_table_width, y_pointer],
                [x_pointer + to_be_installed_table_width,
                y_pointer + (project_data['pv_data']['panel_length'] * 3)]
            ])
            x_pointer = 49
            y_pointer += (project_data['pv_data']['panel_length'] * 3) + 2
            panel_line += 1
            covered_tables[table_idx] = True
            table_idx += 1
            continue
        elif to_be_installed_table_width > (project_data['l_width'] - x_pointer - 1):
            x_pointer = 49
            y_pointer += (project_data['pv_data']['panel_length'] * 3) + 2
            panel_line += 1

```

```

        continue
    else:
        if to_be_installed_table_width < (x_pointer - 1):
            tables_coordinations[combination_index][inv_idx][table_idx].append([
                [x_pointer, y_pointer],
                [x_pointer, y_pointer + (project_data['pv_data']['panel_length'] * 3)],
                [x_pointer - to_be_installed_table_width, y_pointer],
                [x_pointer - to_be_installed_table_width,
                 y_pointer + (project_data['pv_data']['panel_length'] * 3)]
            ])
            x_pointer -= ((to_be_installed_table_width) + x_displacement)
            covered_tables[table_idx] = True
            table_idx += 1
            continue
        elif to_be_installed_table_width == (x_pointer - 1):
            tables_coordinations[combination_index][inv_idx][table_idx].append([
                [x_pointer, y_pointer],
                [x_pointer, y_pointer + (project_data['pv_data']['panel_length'] * 3)],
                [x_pointer - to_be_installed_table_width, y_pointer],
                [x_pointer - to_be_installed_table_width,
                 y_pointer + (project_data['pv_data']['panel_length'] * 3)]
            ])
            covered_tables[table_idx] = True
            table_idx += 1
            x_pointer = 1
            y_pointer += (project_data['pv_data']['panel_length'] * 3) + 2
            pannel_line += 1
            continue
        elif to_be_installed_table_width > (x_pointer - 1):
            x_pointer = 1
            y_pointer += (project_data['pv_data']['panel_length'] * 3) + 2
            pannel_line += 1
            continue
    if inv_idx < len(inv_combinations[combination_index]):
        covered_load[inv_idx] = True
        inv_idx += 1
    if combination_index < len(inv_combinations):
        combination_index += 1
    return tables_coordinations
def draw_tables(table_coordinations, rect1=None):

```

```

# Tables coordination: nw_coordinates, sw_coordinates, ne_coordinates, se_coordinate
import pygame as pg
pg.init()
clock = pg.time.Clock()
running = True
window = pg.display.set_mode((1000, 800))
window.fill((255, 255, 255))
array = []
for combination in table_coordinations:
    for inverter in combination:
        for table in inverter:
            if table[2][0] > table[0][0]:
                array.append(pg.Rect(5*(table[0][0]), 5*(table[0][1]), 5*((table[2][0] - table[0][0])),
5*((table[1][1] - table[0][1])))
            elif table[2][0] < table[0][0]:
                array.append(pg.Rect(5*(table[2][0]), 5*(table[2][1]), 5*((table[0][0] - table[2][0])),
5*((table[1][1] - table[0][1])))
        while running:
            clock.tick(60)
            window.fill((255, 255, 255))
            for e in pg.event.get():
                if e.type == pg.MOUSEBUTTONDOWN:
                    (mouseX, mouseY) = pg.mouse.get_pos()
                    if (array.collidepoint((mouseX, mouseY))):
                        rect1.x = rect1.x + 1
                if e.type == pg.QUIT:
                    running = False
            # end event handling
            for i in array:
                pg.draw.rect(window, (255, 0, 255), i, 1)
            pg.display.flip()
        # end main loop
    pg.quit()

```

#calculate_dc_lines_length.py

```

import numpy as np

# Design of an empty array when needed
def define_empty_node_matrix(table_coordinations):
    inv_coordinates_matrix = [[] for combination in range(len(table_coordinations))]
    combination_index = 0

```

```

for combination in table_coordinations:
    inv_coordinates_matrix[combination_index] = [[] for inverter in combination]
    combination_index += 1
return inv_coordinates_matrix
# Identify the main nodes for each table -> [left_corner, middle, right corner, dc_output1,
dc_output2]
def inv_coordinates(table_coordinations):
    def middle_node_coordinate(sw, se):
        half_distance = abs(sw[0] - se[0]) / 2
        if sw[0] > se[0]:
            middle_node_coordinates = [(se[0] + half_distance), sw[1]]
        else:
            middle_node_coordinates = [(sw[0] + half_distance), sw[1]]
        return middle_node_coordinates
    def dc_output_coordinates(ne, se, sw):
        vertical_distance = abs(ne[1] - se[1])
        if se[0] > sw[0]:
            dc_output1 = [se[0], se[1] + .75 * vertical_distance]
            dc_output2 = [sw[0], se[1] + .25 * vertical_distance]
        else:
            dc_output1 = [sw[0], se[1] + .75 * vertical_distance]
            dc_output2 = [sw[0], se[1] + .25 * vertical_distance]
        return dc_output1, dc_output2
# Identifying_Inverter_Coordinates
inv_coordinates = define_empty_node_matrix(table_coordinations)
combination_index = 0
for combination in table_coordinations:
    inv_idx = 0
    for inverter in combination:
        table_idx = 0
        for t in inverter:
            for table in t:
                inv_coordinates[combination_index][inv_idx].append(
                    [table[1],
                    middle_node_coordinate(table[1], table[3]),
                    table[3],
                    dc_output_coordinates(table[2], table[3], table[1])[0],
                    dc_output_coordinates(table[2], table[3], table[1])[1]
                    ])
                table_idx += 1

```

```

    inv_idx += 1
    combination_index += 1
    return inv_coordinates
# Define an array of possible dc outputs and possible inverter locations per inverter
def dc_output_and_inv_locations(inv_coordinates):
    def define_empty_lengths_matrix(inv_coordinates):
        dc_outputs_per_inverter = [[] for combination in range(len(inv_coordinates))]
        inverter_location_nodes = [[] for combination in range(len(inv_coordinates))]
        combination_index = 0
        for combination in inv_coordinates:
            dc_outputs_per_inverter[combination_index] = [[] for inverter in combination]
            inverter_location_nodes[combination_index] = [[] for inverter in combination]
            combination_index += 1
        return dc_outputs_per_inverter, inverter_location_nodes
    reference_nodes_matrix = define_empty_lengths_matrix(inv_coordinates)[1]
    dc_outputs_per_inverter = define_empty_lengths_matrix(inv_coordinates)[0]
    inverter_location_nodes = define_empty_lengths_matrix(inv_coordinates)[1]
    nodes_lists = [[] for combination in reference_nodes_matrix]
    num_nodes_per_combination = []
    combination_idx = 0
    for combination in inv_coordinates:
        inv_idx = 0
        node_idx = 0
        for inverter in combination:
            table_idx = 0
            for table in inverter:
                dc_outputs_per_inverter[combination_idx][inv_idx].append(table[3])
                dc_outputs_per_inverter[combination_idx][inv_idx].append(table[4])
                inverter_location_nodes[combination_idx][inv_idx].insert(table_idx, [table[0], table[1],
                table[2]])
                reference_nodes_matrix[combination_idx][inv_idx].insert(table_idx,
                [node_idx, node_idx + 1, node_idx + 2])
                node_idx += 3
                table_idx += 1
            inv_idx += 1
        num_nodes_per_combination.append(node_idx)
        nodes_lists[combination_idx] = [i for i in
        range(num_nodes_per_combination[combination_idx] + 1)]
        combination_idx += 1
    return dc_outputs_per_inverter, inverter_location_nodes, reference_nodes_matrix,
    num_nodes_per_combination, nodes_lists

```

```

# Identify the number of rows for each inverter
def rows_per_inv(inverter_location_nodes):
    inv_rows = [[] for combination in inverter_location_nodes]
    num_rows_per_inv = [[] for combination in inverter_location_nodes]
    y_coordinate_of_each_row = [[] for combination in inverter_location_nodes]
    combination_idx = 0
    for combination in inverter_location_nodes:
        num_rows_per_inv[combination_idx] = [[] for inverter in combination]
        inv_rows[combination_idx] = [[] for inverter in combination]
        y_coordinate_of_each_row[combination_idx] = [[] for inverter in combination]
        inv_idx = 0
        for inverter in combination:
            for table in inverter:
                for location in table:
                    inv_rows[combination_idx][inv_idx].append(location[1])
                    unique_values_inv = len(np.unique(inv_rows[combination_idx][inv_idx]))
                    num_rows_per_inv[combination_idx][inv_idx] = [[] for i in range(unique_values_inv)]
                    y_coordinate_of_each_row[combination_idx][inv_idx] =
np.unique(inv_rows[combination_idx][inv_idx]).tolist()
                    inv_idx += 1
                combination_idx += 1
    return num_rows_per_inv, y_coordinate_of_each_row

# Put the coordinates of each row of the inverter in a separate array:
def lines_per_inverter(num_rows_per_inv, inverter_location_nodes,
y_coordinate_of_each_row):
    combination_idx = 0
    for combination in inverter_location_nodes:
        inv_idx = 0
        for inverter in combination:
            unique_value_idx = 0
            for table in inverter:
                for location in table:
                    if location[1] ==
y_coordinate_of_each_row[combination_idx][inv_idx][unique_value_idx]:

num_rows_per_inv[combination_idx][inv_idx][unique_value_idx].append(location)
                    else:
                        unique_value_idx += 1
                        if len(y_coordinate_of_each_row[combination_idx][inv_idx]) >

```

unique_value_idx:

```
num_rows_per_inv[combination_idx][inv_idx][unique_value_idx].append(location)
    inv_idx += 1
    combination_idx += 1
    return num_rows_per_inv
# Calculate the possible dc-lines lengths for each inverter location
def dc_lines_length(dc_outputs_per_inverter, inverter_location_nodes):
    def dc_output_to_inverter_distance(dc_output_coordinate, inv_location_coordinate):
        distance = (abs(dc_output_coordinate[0] - inv_location_coordinate[0]) +
                    abs(dc_output_coordinate[1] - inv_location_coordinate[1]))
        return distance
    def one_inverter_dc_lines_length(possible_dc_coordinates, inv_location_coordinate):
        dc_line_length = 0
        for dc_output in possible_dc_coordinates:
            dc_line_length += dc_output_to_inverter_distance(dc_output, inv_location_coordinate)
        return dc_line_length
    dc_lines_lengths = define_empty_node_matrix(inverter_location_nodes)
    combination_idx = 0
    for combination in inverter_location_nodes:
        inv_idx = 0
        for inverter in combination:
            table_idx = 0
            for table in inverter:
                dc_lines_lengths[combination_idx][inv_idx].insert(table_idx,
                    [(one_inverter_dc_lines_length(
                        dc_outputs_per_inverter[combination_idx][inv_idx],
                        table[0]), one_inverter_dc_lines_length(
                        dc_outputs_per_inverter[combination_idx][
                        inv_idx], table[1]), one_inverter_dc_lines_length(
                        dc_outputs_per_inverter[combination_idx][
                        inv_idx], table[2])])
                    table_idx += 1
            inv_idx += 1
        combination_idx += 1
    return dc_lines_lengths
def calculate_shortest_earthing_cables_for_all_inv(num_rows_per_inv,
best_inv_coordinates_matrix, inverter_location_nodes):
    total_earthing_cables_length = 0
    earthing_cables_lengths = [[] for combination in num_rows_per_inv]
```

```

earthing_cables_location = [[] for combination in num_rows_per_inv]
combination_idx = 0
for combination in num_rows_per_inv:
    inv_idx = 0
    earthing_cables_lengths[combination_idx] = [[] for inverter in combination]
    earthing_cables_location[combination_idx] = [[] for inverter in combination]
    for inverter in combination:
        best_combination_idx = best_inv_coordinates_matrix[combination_idx][inv_idx][0]
        best_inv_idx = best_inv_coordinates_matrix[combination_idx][inv_idx][1]
        best_table_idx = best_inv_coordinates_matrix[combination_idx][inv_idx][2]
        best_node_idx = best_inv_coordinates_matrix[combination_idx][inv_idx][3]
        for line in inverter:
            minimum_earthing_length = float('inf')
            for node in line:
                distance = (abs(node[0] -
inverter_location_nodes[best_combination_idx][best_inv_idx][best_table_idx][best_node_idx][
0]) +
                    abs(node[1] -
inverter_location_nodes[best_combination_idx][best_inv_idx][best_table_idx][best_node_idx][
1]))
                minimum_earthing_length = min(minimum_earthing_length, distance)
                minimum_earthing_location = [best_combination_idx, best_inv_idx,
best_table_idx, best_node_idx]

    earthing_cables_lengths[combination_idx][inv_idx].append(minimum_earthing_length)
    earthing_cables_location[combination_idx][inv_idx].append(minimum_earthing_location)
    total_earthing_cables_length += minimum_earthing_length
    inv_idx += 1
    combination_idx += 1
return earthing_cables_location, earthing_cables_lengths, total_earthing_cables_length

```

#Identify_nodes_edges_matrix.py

```

import calculate_dc_lines_lengths
# Finding the shortest path by creating a nodes edges matrix using a reference node array
# Identify land's right and left nodes arrays
def land_left_and_right_nodes(inverter_location_nodes, reference_nodes_matrix):
    land_left_nodes = [[] for combination in inverter_location_nodes]
    land_right_nodes = [[] for combination in inverter_location_nodes]
    combination_idx = 0
    for combination in inverter_location_nodes:

```

```

inv_idx = 0
for inverter in combination:
    table_idx = 0
    for table in inverter:
        node_idx = 0
        for node in table:
            if 1 < node[0] < 4:
                land_left_nodes[combination_idx].extend(
                    [[node,
reference_nodes_matrix[combination_idx][inv_idx][table_idx][node_idx]])
                if 46 < node[0] < 49:
                    land_right_nodes[combination_idx].extend(
                        [[node,
reference_nodes_matrix[combination_idx][inv_idx][table_idx][node_idx]])
                node_idx += 1
                table_idx += 1
                inv_idx += 1
                combination_idx += 1
    return land_right_nodes, land_left_nodes
# Identify the nodes_edges_matrix
def define_nodes_edges_matrix(inverter_location_nodes, reference_nodes_matrix,
land_right_nodes, land_left_nodes,
                            num_nodes_per_combination):
    nodes_edges_matrix = [[] for combination in inverter_location_nodes]
    combination_idx = 0
    for combination in inverter_location_nodes:
        inv_idx = 0
        for inverter in combination:
            table_idx = 0
            for table in inverter:
                nodes_edges_matrix[combination_idx].append(
[reference_nodes_matrix[combination_idx][inv_idx][table_idx][0],
reference_nodes_matrix[combination_idx][inv_idx][table_idx][1],
                abs(table[0][0] - table[1][0]))
                nodes_edges_matrix[combination_idx].append(
[reference_nodes_matrix[combination_idx][inv_idx][table_idx][1],
reference_nodes_matrix[combination_idx][inv_idx][table_idx][2],
                abs(table[1][0] - table[2][0]))
            if table_idx < (len(inverter) - 1):
                if table[2][1] == inverter_location_nodes[combination_idx][inv_idx][table_idx +

```

```

1][0][1]:
        nodes_edges_matrix[combination_idx].append(
        [reference_nodes_matrix[combination_idx][inv_idx][table_idx][2],
        reference_nodes_matrix[combination_idx][inv_idx][table_idx + 1][0],
        abs(table[2][0] -
inverter_location_nodes[combination_idx][inv_idx][table_idx + 1][0][0])
        )
        table_idx += 1
        if inv_idx < (len(combination) - 1):
            if inverter[len(inverter) - 1][2][1] ==
inverter_location_nodes[combination_idx][inv_idx + 1][0][0][1]:
                nodes_edges_matrix[combination_idx].append(
                [reference_nodes_matrix[combination_idx][inv_idx][len(inverter) - 1][2],
                reference_nodes_matrix[combination_idx][inv_idx + 1][0][0],
                abs((inverter[len(inverter) - 1][2][0]) -
(inverter_location_nodes[combination_idx][inv_idx + 1][0][0][0]))
                )
                inv_idx += 1
                combination_idx += 1
                combination_idx = 0
                for combination in land_left_nodes:
                    edge_idx = 0
                    while edge_idx < (len(combination) - 1):
nodes_edges_matrix[combination_idx].append([combination[edge_idx][1],
combination[edge_idx + 1][1],
abs(combination[edge_idx][0][1] - combination[edge_idx + 1][0][
1]))

                    edge_idx += 1
                    combination_idx += 1
                    combination_idx = 0
                    for combination in land_right_nodes:
                        edge_idx = 0
                        while edge_idx < (len(combination) - 1):
                            nodes_edges_matrix[combination_idx].append([combination[edge_idx][1],
combination[edge_idx + 1][1],
abs(combination[edge_idx][0][1] - combination[edge_idx + 1][0][
1]))

                            edge_idx += 1
# Inserting the distance between connection room and last land_right_node as 25 meters

```

```

nodes_edges_matrix[combination_idx].append([num_nodes_per_combination[combination_idx
],
                                             combination[edge_idx][1],
                                             5])
    combination_idx += 1
return nodes_edges_matrix

```

#Shortest_path_algorithm.py

```

def dijkstra(nodes, edges, source_index):
    path_lengths = {v: float('inf') for v in nodes}
    path_lengths[source_index] = 0
    adjacent_nodes = {v: {} for v in nodes}
    for [s, d, ds] in edges:
        # print(ds)
        adjacent_nodes[s][d] = ds
        adjacent_nodes[d][s] = ds
    # print(adjacent_nodes.items())
    temporary_nodes = [v for v in nodes]
    while len(temporary_nodes) > 0:
        upper_bounds = {v: path_lengths[v] for v in temporary_nodes}
        u = min(upper_bounds, key=upper_bounds.get)
        # print(u)
        temporary_nodes.remove(u)
        for v, w_uv in adjacent_nodes[u].items():
            path_lengths[v] = min(path_lengths[v], path_lengths[u] + w_uv)

    return path_lengths

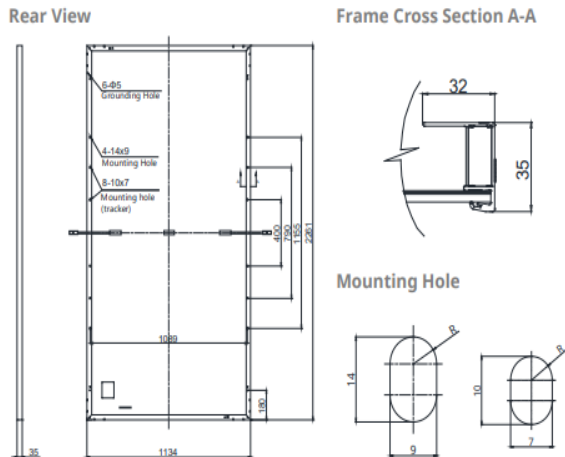
def line_lengths_per_combination(inv_coordinates, nodes_lists, nodes_edges_matrix):
    combination_idx = 0
    # lengths_per_combination = [[] for combination in inv_coordinates]
    lengths_per_combination = []
    for combination in inv_coordinates:
        lengths_per_combination.insert(combination_idx,
dijkstra(nodes_lists[combination_idx],
nodes_edges_matrix[combination_idx],
source_index=nodes_lists[combination_idx][int(len(nodes_lists[combination_idx])/2)])
        combination_idx += 1
    return lengths_per_combination

```

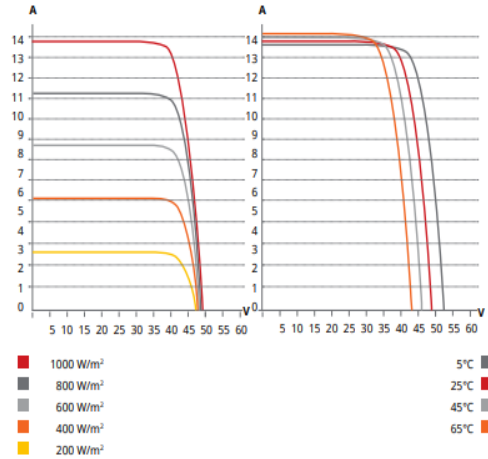
Appendix B

The datasheets of the adapted PV panel and inverters in this study

ENGINEERING DRAWING (mm)



CS6W-530MS / I-V CURVES



ELECTRICAL DATA | STC*

CS6W	530MS	535MS	540MS	545MS	550MS
Nominal Max. Power (Pmax)	530 W	535 W	540 W	545 W	550 W
Opt. Operating Voltage (Vmp)	40.9 V	41.1 V	41.3 V	41.5 V	41.7 V
Opt. Operating Current (Imp)	12.96 A	13.02 A	13.08 A	13.14 A	13.20 A
Open Circuit Voltage (Voc)	48.8 V	49.0 V	49.2 V	49.4 V	49.6 V
Short Circuit Current (Isc)	13.80 A	13.85 A	13.90 A	13.95 A	14.00 A
Module Efficiency	20.7%	20.9%	21.1%	21.3%	21.5%
Operating Temperature	-40°C ~ +85°C				
Max. System Voltage	1500V (IEC/UL) or 1000V (IEC/UL)				
Module Fire Performance	TYPE 1 (UL 61730 1500V) or TYPE 2 (UL 61730 1000V) or CLASS C (IEC 61730)				
Max. Series Fuse Rating	25 A				
Application Classification	Class A				
Power Tolerance	0 ~ + 10 W				

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C.

ELECTRICAL DATA | NMOT*

CS6W	530MS	535MS	540MS	545MS	550MS
Nominal Max. Power (Pmax)	397 W	401 W	405 W	409 W	412 W
Opt. Operating Voltage (Vmp)	38.3 V	38.5 V	38.7 V	38.9 V	39.1 V
Opt. Operating Current (Imp)	10.38 A	10.42 A	10.47 A	10.52 A	10.55 A
Open Circuit Voltage (Voc)	46.1 V	46.3 V	46.5 V	46.7 V	46.9 V
Short Circuit Current (Isc)	11.13 A	11.17 A	11.21 A	11.25 A	11.29 A

* Under Nominal Module Operating Temperature (NMOT), irradiance of 800 W/m² spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

MECHANICAL DATA

Specification	Data
Cell Type	Mono-crystalline
Cell Arrangement	144 [2 x (12 x 6)]
Dimensions	2261 × 1134 × 35 mm (89.0 × 44.6 × 1.38 in)
Weight	27.8 kg (61.3 lbs)
Front Cover	3.2 mm tempered glass
Frame	Anodized aluminium alloy
J-Box	IP68, 3 bypass diodes
Cable	4 mm ² (IEC), 12 AWG (UL)
Cable Length (Including Connector)	410 mm (16.1 in) (+) / 290 mm (11.4 in) (-) (supply additional jumper cable: 2 lines / Pallet) or customized length*
Connector	T4 series or MC4-EVO2
Per Pallet	30 pieces
Per Container (40' HQ)	600 pieces

* For detailed information, please contact your local Canadian Solar sales and technical representatives.

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.34 % / °C
Temperature Coefficient (Voc)	-0.26 % / °C
Temperature Coefficient (Isc)	0.05 % / °C
Nominal Module Operating Temperature	41 ± 3°C

PV panel datasheet [37].

Technical data	Sunny Tripower CORE2
Input (DC)	
Max. PV array power	165000 Wp STC
Max. input voltage	1100 V
MPP voltage range	500 V to 800 V
Rated input voltage	585 V
Min. input voltage / Start input voltage	200 V / 250 V
Max. input current per MPP tracker / Max. short-circuit current per MPP tracker	26 A / 40 A
Number of independent MPP trackers / Strings per MPP tracker	12 / 2
Output (AC)	
Rated power at nominal voltage	110000 W
Max. apparent AC power	110000 VA
Nominal AC voltage	400 V
AC voltage range	320 V to 460 V
AC grid frequency / range	50 Hz / 45 Hz to 55 Hz 60 Hz / 55 Hz to 65 Hz
Rated grid frequency	50 Hz
Max. output current	159 A
Power factor at rated power / displacement power factor adjustable	1 / 0.8 overexcited to 0.8 underexcited
Harmonic (THD)	< 3%
Feed-in phases / AC connection	3 / 3-PE
Efficiency	
Max. efficiency / European efficiency	98.6% / 98.4%
Protective devices	
Input-side disconnection device	●
Ground fault monitoring / grid monitoring / DC reverse polarity protection	● / ● / ●
AC short-circuit current capability / galvanically isolated	● / -
All-pole sensitive residual-current monitoring unit	●
Monitored surge arrester (type II) AC / DC	● / ●
Protection class (according to IEC 62109-1) / surge category (according to IEC 62109-1)	I / AC: III; DC: II
General data	
Dimensions (W / H / D)	1117 mm / 682 mm / 363 mm (44.0 in / 26.9 in / 14.3 in)
Weight	93.5 kg (206.1 lbs)
Operating temperature range	-30 °C to +60 °C (-22 °F to +140 °F)
Noise emission, typical	< 65 db(A)
Self-consumption (at night)	< 5 W
Topology / cooling concept	Transformerless / active cooling
Degree of protection (according to IEC 60529)	IP66
Max. permissible value for relative humidity (non-condensing)	100%
Features / functions / accessories	
DC connection / AC connection	Sunclix / terminal lug (up to 240 mm ²)
LED display (Status / Fault / Communication)	●
Ethernet interface	● (2 ports)
Data interface	Web Interface / Modbus SunSpec
Mounting type	Wall mounting / rack mounting
Warranty: 5 / 10 / 15 / 20 years	● / ○ / ○ / ○
Certificates and approvals (selection)	IEC 62109-1/-2, EN50549-1/-2:2018, VDE-AR-N 4105/4110/4120:2018, IEC 62116, IEC 61727, C10/C11 LV2/MV1:2018, CEI 0-16:2019, AS/NZS 4777.2, SI 4777, TOR Generator Typ A/B
● Standard features ○ Optional features – not available Data at nominal conditions Status 03/2020	
Type designation	STP 110-60

STP 110-60 Inverter datasheet [38]

Model	SUN-70K-G03	SUN-75K-G03	SUN-80K-G03	SUN-90K-G03	SUN-100K-G03	SUN-110K-G03
Input Side						
Max. DC Input Power (kW)	91	97.5	104	135	150	150
Max. DC Input Voltage (V)	1000					
Start-up DC Input Voltage (V)	250					
MPPT Operating Range (V)	200~850					
Max. DC Input Current (A)	40+40+40+40			40+40+40+40+40+40		
Max. Short Circuit Current (A)	60+60+60+60			60+60+60+60+60+60		
No.of MPP Trackers	4			6		
No.of Strings per MPP Tracker	4					
Output Side						
Rated Output Power (kW)	70	75	80	90	100	110
Max. Active Power (kW)	77	82.5	88	99	110	121
Nominal Output Voltage / Range (V)	3L/N/PE 220/380V, 230/400V					
Rated Grid Frequency (Hz)	50 / 60 (Optional)					
Operating Phase	Three phase					
Rated AC Grid Output Current (A)	106.1/101.5	113.6/108.7	121.2/115.9	136.4/130.4	151.5/144.9	166.7/159.4
Max. AC Output Current (A)	116.7/111.6	125/119.6	133.3/127.5	150/143.5	166.7/159.4	183.3/175.4
Output Power Factor	0.8 leading to 0.8 lagging					
Grid Current THD	<3%					
DC Injection Current (mA)	<0.5%					
Grid Frequency Range	47~52 or 57~62 (Optional)					
Efficiency						
Max. Efficiency	98.8%					
Euro Efficiency	98.3%					
MPPT Efficiency	>99%					
Protection						
DC Reverse-Polarity Protection	Yes					
AC Short Circuit Protection	Yes					
AC Output Overcurrent Protection	Yes					
Output Overvoltage Protection	Yes					
Insulation Resistance Protection	Yes					
Ground Fault Monitoring	Yes					
Anti-islanding Protection	Yes					
Temperature Protection	Yes					
Integrated DC Switch	Yes					
Remote software upload	Yes					
Remote change of operating parameters	Yes					
Surge protection	DC Type II / AC Type II					
General Data						
Size (mm)	838Wx568Hx324D					838Wx568Hx346D
Weight (kg)	81					
Topology	Transformerless					
Internal Consumption	<1W (Night)					
Running Temperature	-25~65°C, >45°C derating					
Ingress Protection	IP65					
Noise Emission (Typical)	<55 dB					
Cooling Concept	Smart cooling					
Max. Operating Altitude Without Derating	2000m					
Warranty	5 years					
Grid Connection Standard	VDE4105, IEC61727/62116, VDE0126, AS4777.2, CEI 0 21, EN50549-1, G98, G99, C10-11, UNE217002, NBR16149/NBR16150					
Operating Surroundings Humidity	0-100%					
Safety EMC / Standard	IEC/EN 61000-6-1/2/3/4, IEC/EN 62109-1, IEC/EN 62109-2					
Features						
DC Connection	MC-4 mateable					
AC Connection	IP65 rated plug					
Display	LCD 240 x 160					
Interface	RS485/RS232/Wifi/LAN					

SUN-90K-G03 Inverter Datasheet [39]

Input (DC)

Max. PV input voltage	1000 V
Startup voltage	620 V
MPP voltage range	570 - 950 V
MPP voltage range for nominal power	570 - 850 V
No. of MPPTs	1
Max. number of PV strings per MPPT	18
Max. PV input current	144 A
Max. current for input connector	12 A

Output (AC)

Nominal AC output power	80000 W
Max AC output power (PF=1)	80000 W
Max. AC output apparent power	80000 VA
Max. AC output current	116 A
Nominal AC voltage	3P + PE, 230 / 400 V
AC voltage range	310 - 480 V
Nominal grid frequency	50 Hz / 60 Hz
Grid frequency range	45 - 55 Hz / 55 - 65 Hz
THD	< 3 % (at nominal power)
DC current injection	< 0.5 % In
Power factor	> 0.99@default value at nominal power, (adj. 0.8 leading - 0.8 lagging)

Protections & Functions

Anti-islanding protection	Yes
LVRT	Yes
AC short circuit protection	Yes
Leakage current protection	Yes
DC switch	Yes
DC fuse	Yes
PV string current monitoring	Yes
DC overvoltage protection	DC Type II SPD (40 kA)
AC overvoltage protection	AC Type II SPD (40 kA)

System Data

Max. efficiency	99.00 %
Euro. efficiency	98.70 %
Isolation method	Transformerless
Ingress protection rating	IP65
Night power consumption	<1W
Operating ambient temperature range	-25 to 60 °C
Allowable relative humidity range	0 - 100 %
Cooling method	Smart forced air cooling
Max. operating altitude	4000 m (> 3000 m derating)
Display	Graphic LCD
Communication	RS485 / PLC (optional)
DC connection type	MC4
AC connection type	Screw clamp terminal
Certification	EN62109-1, EN62109-2, G59/3, BDEW

Mechanical Data

Dimensions (W*H*D)	634*959*267 mm
Mounting method	Wall bracket
Weight	60 kg

Note: this inverter only be used in industrial area

SG80KTL Inverter datasheet [40]

Appendix C

The PVsyst Simulation Report



Version 7.2.8

PVsyst - Simulation report

Grid-Connected System

Project: Beit Ula

Variant: New simulation variant

Sheds on ground

System power: 903 kWp

Beit Ula - Palestine, State Of

| Author

**PVsyst V7.2.8**

VC0. Simulation date:
02/04/23 13:18
with v7.2.8

Project: Beit Ula

Variant: New simulation variant

Project summary

Geographical Site	Situation	Project settings
Beit Ula	Latitude 31.36 °N	Albedo 0.20
Palestine, State Of	Longitude 34.59 °E	
	Altitude 98 m	
	Time zone UTC+2	
Meteo data		
Beit Ula		
Meteonorm 8.0 (1991-2010), Sat=31% - Synthetic		

System summary

Grid-Connected System	Sheds on ground	User's needs
PV Field Orientation	Near Shadings	Unlimited load (grid)
Fixed plane	Linear shadings	
Tilt/Azimuth 18 / 0 °		
System information		
PV Array	Inverters	
Nb. of modules 1656 units	Nb. of units 7 units	
Pnom total 903 kWp	Pnom total 770 kWac	
	Pnom ratio 1.172	

Results summary

Produced Energy 1605 MWh/year	Specific production 1778 kWh/kWp/year	Perf. Ratio PR 82.85 %
-------------------------------	---------------------------------------	------------------------

Table of contents

Project and results summary	2
General parameters, PV Array Characteristics, System losses	3
Near shading definition - Iso-shadings diagram	4
Main results	5
Loss diagram	6
Special graphs	7



Project: Beit Ula

Variant: New simulation variant

PVsyst V7.2.8

VC0, Simulation date:
02/04/23 13:18
with v7.2.8

General parameters

Grid-Connected System		Sheds on ground		Models used	
PV Field Orientation		Sheds configuration		Transposition Perez	
Orientation		Nb. of sheds 62 units		Diffuse Perez, Meteorom	
Fixed plane		Sizes		Circumsolar separate	
Tilt/Azimuth	18 / 0 °	Sheds spacing 10.0 m			
		Collector width 6.86 m			
		Ground Cov. Ratio (GCR) 68.6 %			
Horizon		Near Shadings		User's needs	
Free Horizon		Linear shadings		Unlimited load (grid)	

PV Array Characteristics

PV module		Inverter	
Manufacturer	CSI Solar	Manufacturer	SMA
Model	CS6W - 545MS	Model	Sunny Tripower STP110-60-Core2
(Custom parameters definition)		(Original PVsyst database)	
Unit Nom. Power	545 Wp	Unit Nom. Power	110 kWac
Number of PV modules	1656 units	Number of inverters	7 units
Nominal (STC)	903 kWp	Total power	770 kWac
Modules	92 Strings x 18 In series	Operating voltage	200-800 V
At operating cond. (50°C)		Pnom ratio (DC:AC)	1.17
Pmpp	815 kWp		
U mpp	675 V		
I mpp	1207 A		
Total PV power		Total inverter power	
Nominal (STC)	903 kWp	Total power	770 kWac
Total	1656 modules	Nb. of inverters	7 units
Module area	4237 m²	Pnom ratio	1.17

Array losses

Thermal Loss factor		DC wiring losses		Module Quality Loss				
Module temperature according to irradiance		Global array res.	9.2 mΩ	Loss Fraction -0.6 %				
Uc (const)	20.0 W/m²K	Loss Fraction	1.5 % at STC					
Uv (wind)	0.0 W/m²K/m/s							
Module mismatch losses		Strings Mismatch loss						
Loss Fraction	2.0 % at MPP	Loss Fraction	0.1 %					
IAM loss factor								
Incidence effect (IAM): User defined profile								
10°	20°	30°	40°	50°	60°	70°	80°	90°
1.000	0.998	0.995	0.995	0.986	0.970	0.917	0.763	0.000



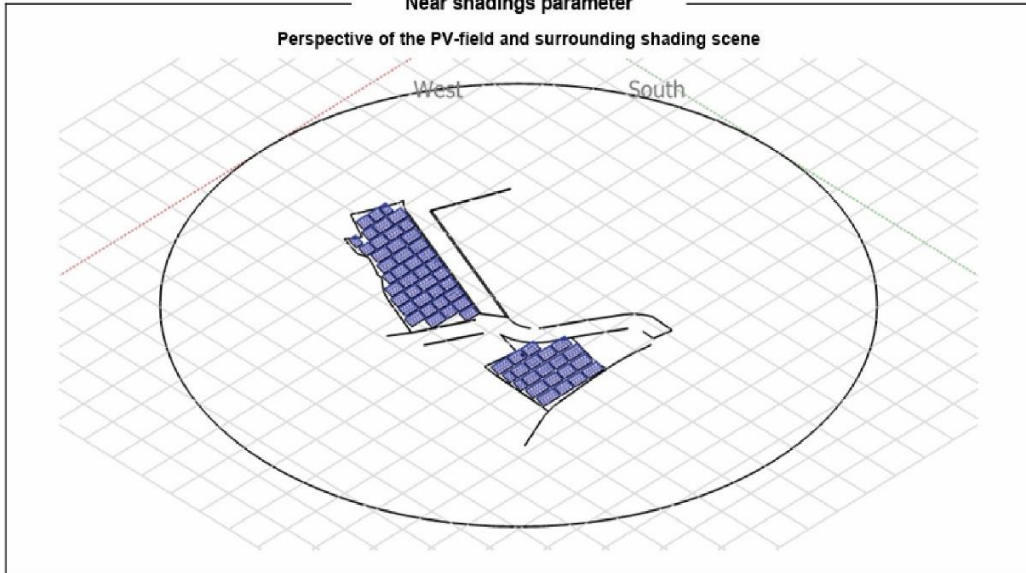
PVsyst V7.2.8

VCO, Simulation date:
02/04/23 13:18
with v7.2.8

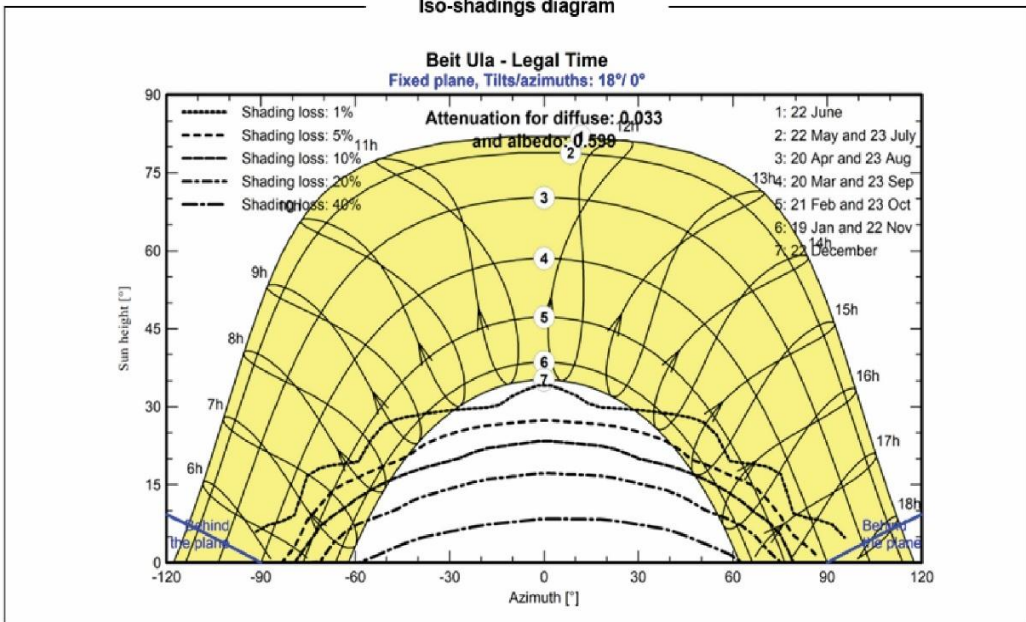
Project: Beit Ula

Variant: New simulation variant

Near shadings parameter



Iso-shadings diagram





Project: Beit Ula
Variant: New simulation variant

PVsyst V7.2.8
VC0, Simulation date:
02/04/23 13:18
with v7.2.8

Main results

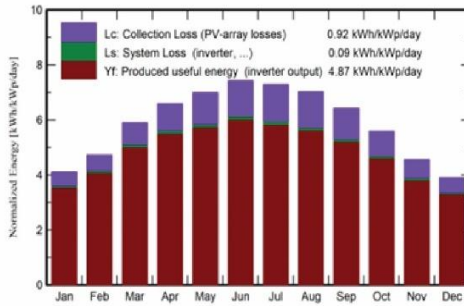
System Production

Produced Energy 1605 MWh/year

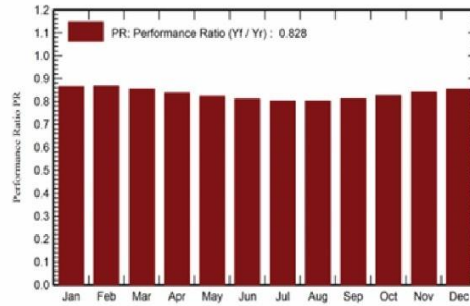
Specific production
Performance Ratio PR

1778 kWh/kWp/year
82.85 %

Normalized productions (per installed kWp)



Performance Ratio PR



Balances and main results

	GlobHor kWh/m ²	DiffHor kWh/m ²	T_Amb °C	GlobInc kWh/m ²	GlobEff kWh/m ²	EArray MWh	E_Grid MWh	PR ratio
January	96.8	38.10	12.65	127.4	121.8	101.4	99.4	0.865
February	108.9	46.88	13.73	132.3	128.3	105.5	103.6	0.868
March	161.5	63.48	16.50	182.5	178.0	143.2	140.5	0.853
April	187.8	70.45	19.18	197.8	192.8	152.4	149.6	0.838
May	218.8	81.86	22.90	216.9	211.1	163.9	161.0	0.823
June	231.1	72.01	25.61	222.7	216.9	166.0	163.0	0.811
July	232.2	70.64	28.26	226.1	220.3	166.4	163.4	0.801
August	212.1	72.44	28.76	217.9	212.4	160.5	157.7	0.802
September	174.8	58.50	26.65	192.7	188.1	143.7	141.2	0.812
October	144.8	50.41	23.81	173.2	168.5	131.5	129.2	0.826
November	104.9	35.15	18.70	136.3	131.4	105.5	103.6	0.842
December	89.7	34.95	14.69	120.6	114.5	94.6	92.8	0.853
Year	1963.5	694.88	21.00	2146.3	2084.1	1634.6	1604.8	0.828

Legends

GlobHor	Global horizontal irradiation	EArray	Effective energy at the output of the array
DiffHor	Horizontal diffuse irradiation	E_Grid	Energy injected into grid
T_Amb	Ambient Temperature	PR	Performance Ratio
GlobInc	Global incident in coll. plane		
GlobEff	Effective Global, corr. for IAM and shadings		



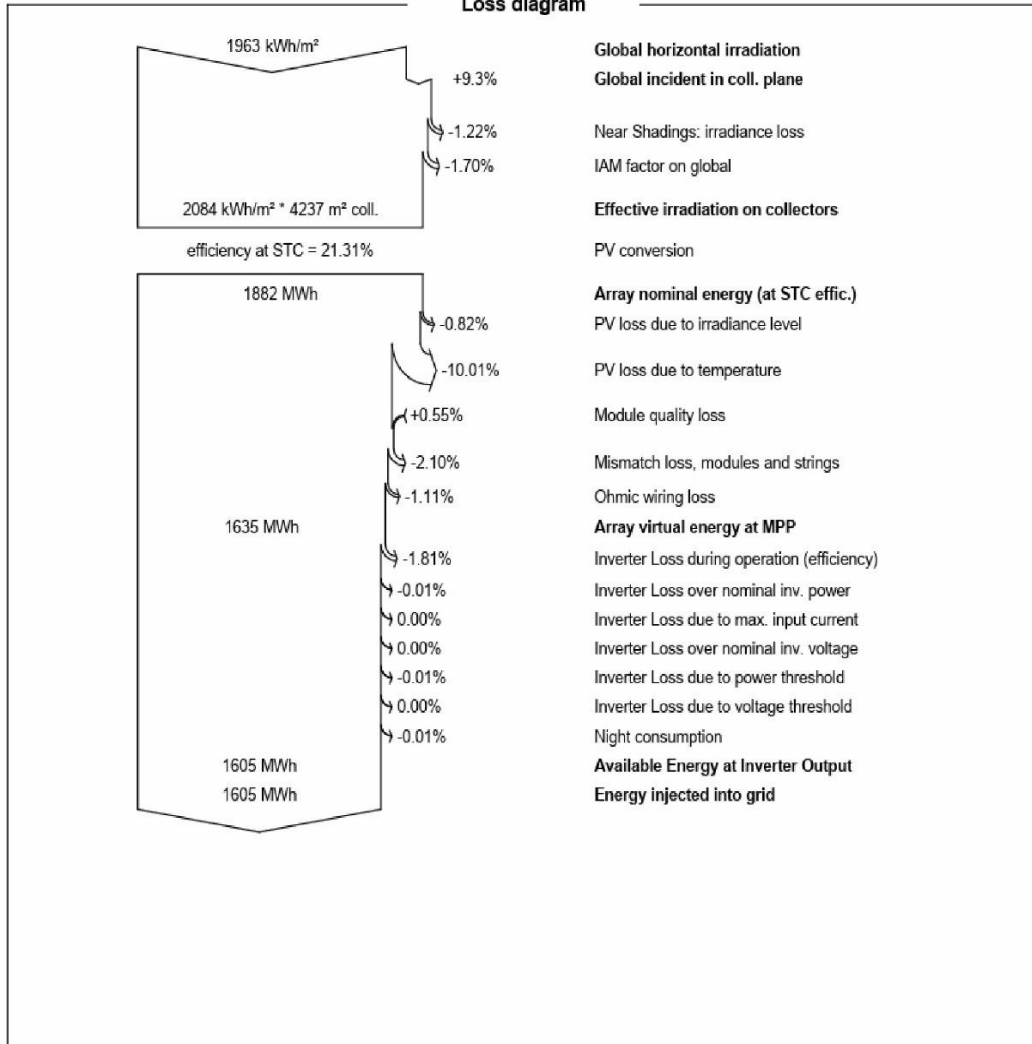
PVsyst V7.2.8

VC0, Simulation date:
02/04/23 13:18
with v7.2.8

Project: Beit Ula

Variant: New simulation variant

Loss diagram



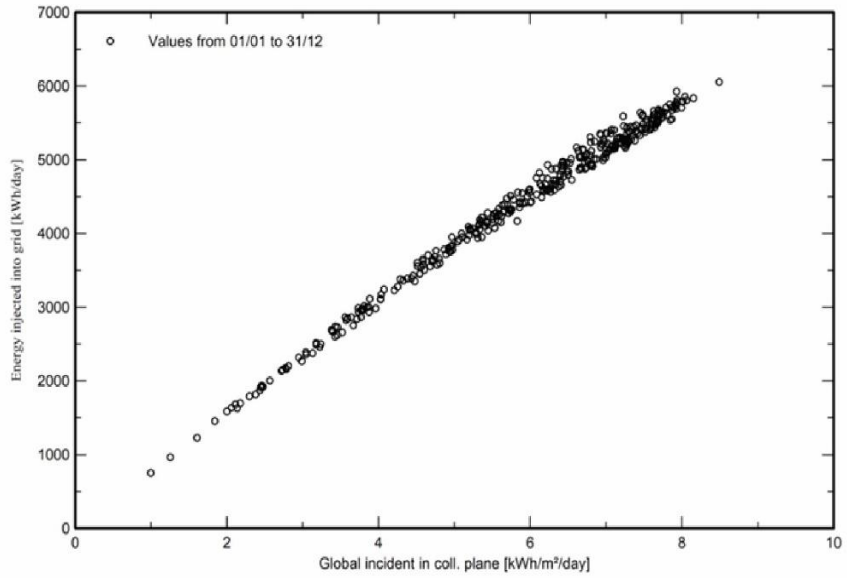


PVsyst V7.2.8
VC0, Simulation date:
02/04/23 13:18
with v7.2.8

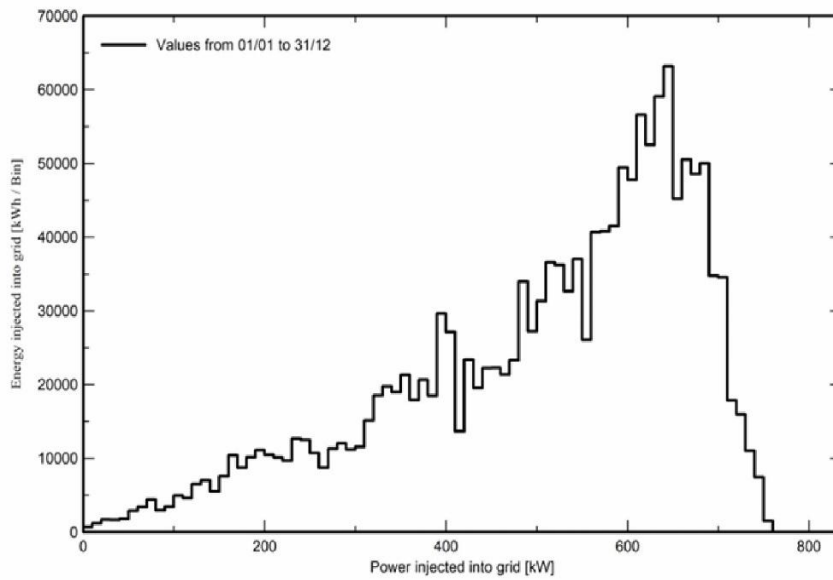
Project: Beit Ula
Variant: New simulation variant

Special graphs

Daily Input/Output diagram



System Output Power Distribution





جامعة النجاح الوطنية
كلية الدراسات العليا

تطوير طريقة جديدة لتصميم شبكات التوزيع الكهربائية الخاصة بأنظمة الطاقة الكهروضوئية بطريقة مثلى

إعداد

هبة بشار عبد الرزاق عاصي

إشراف

أ.د. تامر الخطيب

قدمت هذه الرسالة استكمالاً لمتطلبات الحصول على درجة الماجستير في هندسة القوى الكهربائية،
من كلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس - فلسطين.

2024

تطوير طريقة جديدة لتصميم شبكات التوزيع الكهربائية الخاصة بأنظمة الطاقة الكهروضوئية بطريقة مثلى

إعداد

هبة بشار عبد الرزاق عاصي

إشراف

أ. د. تامر الخطيب

الملخص

تعد أنظمة الطاقة الكهروضوئية خياراً جذاباً كمصدر للطاقة المتجددة لتزويد المناطق الريفية وتوليد الطاقة الموزعة. ومع ذلك، تظل تكلفة الاستثمار في هذه الأنظمة تحدياً صعباً مقارنة بمصادر الطاقة غير المتجددة. لذلك، تركز جهود العديد من الباحثين على زيادة كفاءة وجدوى أنظمة الطاقة الشمسية. تقدم هذه الدراسة منهجاً لتصميم شبكات توزيع الطاقة المترددة المتصلة بالشبكة لأنظمة الطاقة الشمسية الضوئية، مع مراعاة حجم وموقع قلابات القدرة، بالإضافة إلى حجم ومسار الكوابل. الهدف الرئيسي لهذا الأسلوب المقترح هو تقديم أقصر طول للكوابل وأقل مسار، مما يؤدي إلى زيادة كفاءة وجدوى هذه الأنظمة بشكل عام. يعتمد هذا الأسلوب على منهج ذكي يبدأ بإنشاء مجموعات متعددة من قلابات القدرة للطاقة للتحليل، حيث يتم حساب الطول الإجمالي للكوابل لكل مجموعة بمراعاة جميع المواقع الممكنة لقلابات القدرة، بحيث يتم استخدام لغة بايثون لدراسة كافة الاحتمالات و لضمان الدقة. في الختام، يتم تحديد الموقع الأمثل لقلابات القدرة التي تؤدي إلى أقصر طول للكوابل. تم اختيار أحد أنظمة الطاقة الكهروضوئية المتصلة بالشبكة بسعة 900 كيلوواط كدراسة حالة في هذا البحث. النتائج تظهر إنخفاضاً بنسبة 23% في الطول الإجمالي للكوابل مقارنة بالطريقة التقليدية للتوزيع، وفي الوقت نفسه، تقدم هذه الطريقة توزيعاً أفضل لقلابات القدرة في أنظمة الطاقة الكهروضوئية المطلوبة (الحجم والموقع). هذا الأسلوب يعد أداة مفيدة جداً لتصميم شبكات توزيع الطاقة المترددة والمستمرة لأنظمة الطاقة الشمسية، متفوقاً على الأساليب التقليدية والبدئية.

الكلمات المفتاحية: النظام الكهروضوئي؛ تخصيص العواكس؛ مقاسات الكابلات؛ أنظمة التوزيع.