COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCE

DEPARTMENT OF PHYSICS

OPTIMIZATION OF PHOTOVOLTAIC ENERGY PRODUCTION

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A PROJECT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF BACHILOR OF SCIENCE IN PHYSICS

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WOLKITE ETHIOPIA

WOLKITE UNIVERSITY

COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCE
DEPARTMENT OF PHYSICS

BACHELOR OF DEGREE SENIOR PROJECT ON OPTIMIZATION OF PHOTOVOLTAIC ENERGY PRODUCTION PROJECT SUBMITTED TO WOLKITE UNIVERSITY, COLLEGE OF NATURAL SCIENCES, DEPARTMENT OF PHYSICS IN PARTIAL FULFILLMENT OF REQUIREMENT OF BACHELOR OF SCIENCE IN PHYSICS

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Project title**:** OPTIMIZATION OF PHOTOVOLTAIC ENERGY PRODUCTION

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Acknowledgment

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Acronyms and Abbreviations

3D---Three dimensions

AC---Alternative current

BOS --Balance of System

CD-TE---Cadmium Telluride

C-SI--Crystalline silicon

DC---Direct current

EW--East-West

GA--Genetic Algorithm

LCOE --Levelized Cost of Energy

MPP--Maximum power point

MPPT---Maximum power point tracking

PSO--Particle swarm optimization

PV---Photovoltaic

PVsyst--- Photovoltaic system

PWM---Pulse width modulation

RES-- Renewable energy sources

Abstract

As a fundamental component of renewable energy, photovoltaic technology is still developing; thus, it is important to realize these factors for sustainable energy transitions. This project provides a thorough analysis of the present state of photovoltaic (PV) systems, their constraints, the major variables affecting productivity and efficiency, and strategies for improving energy production. A methodical evaluation of current photovoltaic energy production systems is carried out, examining performance indicators and investigative constraints. A review of the literature used to identify the key elements influencing the productivity and efficiency of PV systems. The project detailed the methodologies to enhance PV cell energy production that encompasses technological advancements. Therefore, the finding reveals current PV system performance, highlighting strengths and areas for improvement. Mainly, key factors influencing efficiency and productivity, including environmental conditions and technical parameters, are identified. Additionally, a range of enhancement methods, such as PV cell configurations and advanced tracking systems, are explored for their potential to supplement energy production. The study delivers valuable information into the multifaceted aspects of PV energy production and optimization of the output. It is also used to understand current performance, key influencing factors, and exploring enhancement methods PV electric energy production. Generally, it helps stakeholders plan effectively to advance the sustainability and efficiency of PV technologies, that vital for accelerating the adoption of renewable energy and mitigating the challenges of climate change.

Key words; Optimization, Photovoltaic cells, renewable energy, efficiency, photovoltaic technology

1. INTRODUCTION

1.1. Background of the Study

Photovoltaic, derived from the Greek word for light and Volta's name, involves using solar cells to convert sunlight into energy. Developed countries use clean energy in various sectors, but developing countries often lack reliable, insufficient, or absent electricity supply. The optimization of photovoltaic energy production encompasses a multifaceted approach, encompassing technological innovations, system design refinements, and advanced control strategies. Central to this endeavor is the pursuit of higher conversion efficiencies, aiming to extract maximum electricity from incident sunlight. Innovations targeting the enhancement of photovoltaic module performance, durability improvement, and reduction of manufacturing costs constitute focal points driving the evolution of PV technology. (Noghabi et al., 2021)

Furthermore, optimization extends beyond individual components to encompass entire PV systems and their integration into the broader energy landscape. This involves optimizing the orientation and tilt angle of solar panels, refining tracking systems to follow the sun's trajectory, and integrating energy storage solutions to mitigate intermittency and bolster grid stability. (IEA, 2020; Ghoneim & Elsayed, 2018) In the quest for sustainable energy solutions, developing nations such as Ethiopia are increasingly turning to renewable resources to meet their growing electricity demands while addressing environmental concerns. As Ethiopia envisions a future powered by clean and resilient energy sources, the optimization of photovoltaic energy production becomes a paramount undertaking with profound implications for both socio-economic development and environmental stewardship.(Tiruye et al., 2021)

As the world grapples with intensifying energy demands and the urgent need to combat climate change, the optimization of photovoltaic energy production assumes paramount importance. This study focuses on a critical exploration into the optimization of photovoltaic energy production, aiming to unlock new dimensions in efficiency, cost-effectiveness, and overall sustainability. This study delves into the investigation of the methods to enhance the efficiency and productivity of photovoltaic systems, aiming to reveal their full potential and significantly promote the transition towards a sustainable energy future.

1.2 Statement of Problem

This study aimed to identify that optimizing photovoltaic energy production is a critical endeavor facing multifaceted challenges that span technological, economic, and environmental dimensions. As we aim to harness solar energy efficiently and sustainably, the statement of the problem outlines key obstacles that underscore the necessity for targeted research and innovation in the field. With advancements in PV technology, there remains a persistent challenge in maximizing the efficiency and performance of solar cells. Issues such as energy conversion rates, material limitations, and degradation over time pose obstacles to achieving optimal energy output from photovoltaic systems.

This project aims to identify key challenges affecting in terms of PV system efficiency and productivity, such as technological constraints, solar irradiance, energy storage, environmental viability, policy ambiguities, environmental impact, and operational challenges, and contribute to solutions for enhancing PV system efficiency.

1.3 Objective

1.3.1 General Objective

To evaluate the optimization techniques and strategies to improve the efficiency and output of photovoltaic (PV) system

1.3.2 Specific Objective

1. To assess the current performance and limitations of existing PV energy production systems.
2. To identify key factors affecting the efficiency and productivity of PV systems.
3. To determine the methods to enhance the PV cell energy production.

1.4 Significance of the Study

The study of the optimization of PV energy production holds significant implications for various stakeholders and contributes to multiple aspects of societal, economic, and environmental development. In addition to this, it gives a basic understanding of how optimized photovoltaic energy can be used for public needs without having a negative impact on the environment. This project offers a long-term solution to significant challenges in the current economy. With increasing concerns about climate change and fluctuating fuel prices, people are questioning the sources of their power and how rising energy expenses might impact their businesses.

1.5 Research Questions

1.How can the current performance and limitations of existing (PV) energy production systems be comprehensively assessed, and what specific factors contribute to both the successes and constraints of these systems in their current operational context?

2. What factors influence the efficiency and productivity of existing (PV) systems?

3. how do these factors interplay to impact the overall performance of PV energy production?

1.6 The Scope of the Project

The scope of this project is the optimization of photovoltaic energy production, with a focus on maximizing energy output, efficiency, and cost-effectiveness. Using a sizing model, genetic algorithm, spacing factor and tilt, storage and Gid integration, real-time monitoring techniques and strategies to overcome the existing limitations on power consumption and cost, like site topography, shading, irradiation calculation method, electrical and mechanical layout, and economical evaluation procedures.

2. LITERATURE REVIEW

The major contributions of this review are to provide clear and detailed insight into the methods while directing attentive readers to other articles. “This review analyses the most recent literature on intelligent optimization methods in the field of solar energy PV applications.”

Technological Advancements

Several studies have focused on enhancing the efficiency and reliability of PV systems through technological innovations. Green (2019) presents comprehensive solar cell efficiency tables, highlighting the progress in PV technology. Luque and Hegedus (2011) provide an in-depth exploration of photovoltaic science and engineering, explaining fundamental principles and technological advancements. Albrecht et al. (2019) discuss advanced materials and concepts for improving PV performance, including novel semiconductor materials and device architectures.

System Design and Integration

Optimizing the design and integration of PV systems is crucial for maximizing energy production. Noghabi et al. (2021) review optimization techniques for photovoltaic arrays, covering both technical and economic aspects. Boukhriss and Boumedyen (2020) provide insights into optimizing PV systems, including considerations such as panel orientation, tilt angle, and tracking systems. Ghoneim and Elsayed (2018) discuss optimization techniques specifically for photovoltaic water pumping systems, highlighting the importance of system-level optimizations.

2.1 PV Overview

The solar cells, as photovoltaic (PV) devices, employ semiconductor materials to transform sunlight directly into electricity. When sunlight interacts with these materials, it prompts the movement of electrons, generating electric currents. Solar cells typically produce direct current (DC) electricity, which is the type of electrical current commonly used in batteries and many electronic devices.(SEIA, 2018) The PV effect occurs in solar cells, which consist of two types of semiconductors - a p-type and an n-type - that form a p-n junction. The junction formed between the p-type and n-type semiconductor materials creates an electric field, which drives electrons towards the positive p-side and holes towards the negative n-side. This electric field facilitates the movement of negatively charged particles in one direction and positively charged particles in the opposite direction. Photovoltaic cells can absorb photons, which are small packets of electromagnetic radiation. When light of an appropriate wavelength strikes these cells, the energy from the photon is transferred to an atom within the semiconductor material at the p-n junction. This energy transfer causes electrons to transition to a higher energy state, known as the conduction band. As a result of this transition, an electron-hole pair is created, consisting of a free electron and a positively charged hole.(Kaygusuz, 2001)

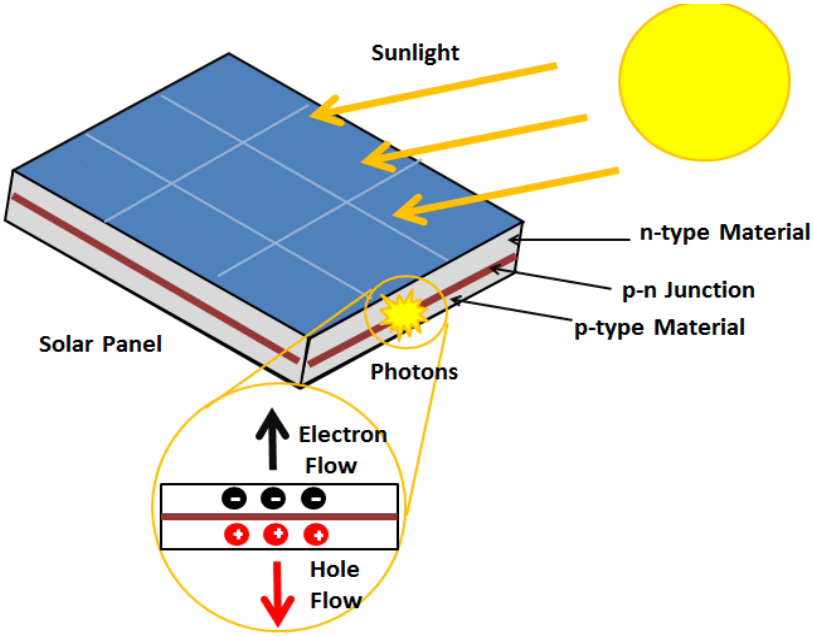

Figure 2.1: A diagram showing the photovoltaic effect (source(Fatma et al., 2020)).

In their unexcited state, electrons are bonded to surrounding atoms within the semiconducting material, thereby maintaining its structure. Consequently, they are immobile. However, when these electrons transition to the excited state in the conduction band, they gain the freedom to move throughout the material. Due to the electric field established by the p-n junction, electrons and holes move in unexpected directions. Instead of being attracted to the positively charged p-side, the liberated electrons tend to migrate towards the negatively charged n-side. This movement of electrons results in the generation of an electric current within the solar cell. As electrons move, they leave behind "holes" in the material, which also possess the ability to move, albeit in the opposite direction towards the p-side..(Bube & Fahrenbruch, 1981)

2.1.1 The Photovoltaic Power System

a. Off-grid connected PV Systems

Stand-alone (Off-grid) PV systems are engineered to function independently of the traditional electric utility grid and are typically sized to meet specific DC and AC electrical demands. Off-grid PV systems operate autonomously without any connection to the grid. A basic standalone PV system is an automated solar setup that generates electricity to charge battery banks during daylight hours, storing energy for use at night or when solar energy is unavailable. These standalone PV systems are particularly suitable for rural areas or remote offshore locations lacking grid connectivity or where extending power lines would be prohibitively expensive. In such scenarios, installing a standalone PV system is often more economically viable than extending power lines from local electricity providers directly to individual buildings. These standalone PV systems with battery storage can power both DC and AC loads.

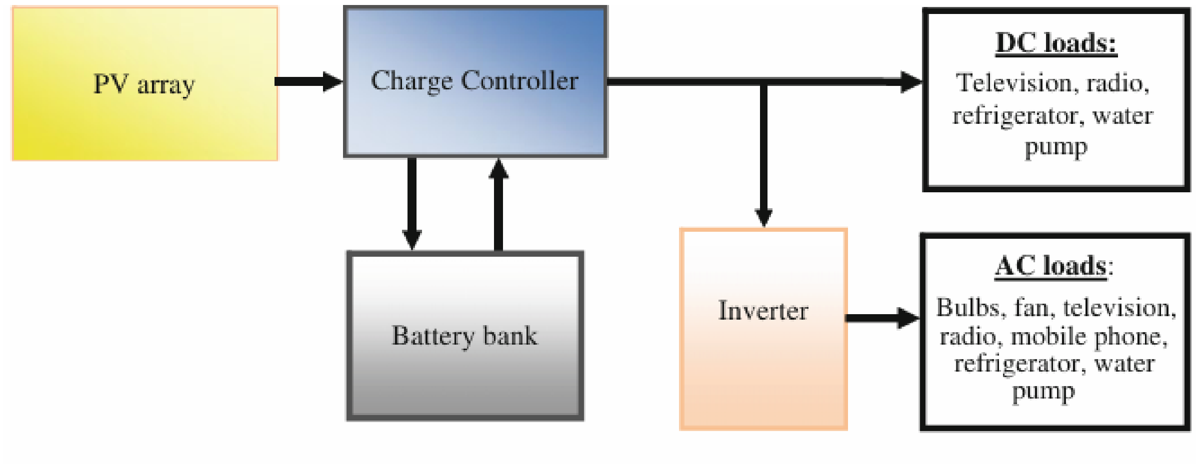

Figure 2.2: Stand-alone PV system with battery storage powering DC and AC loads (source,(“Green Energy Technol.,” 2006)).

b. Grid Connected PV Systems

Sunlight is a cheap, sustainable energy source that is both plentiful and free. All of Earth's yearly energy requirements are met in less than 30 minutes by the Sun, which offers abundant and sustainable energy. With no greenhouse gas emissions or hazardous waste, the sun is a clean, renewable energy source. (“Green Energy Technol.,” 2006)

A grid-connected PV system connects the PV array to an inverter without a storage battery, ensuring that electricity is only used when needed. If the system generates more power than needed, it is exported into the grid, turning the meter backwards. When the PV system isn't producing, the power grid supplies the building's demand, and the energy utility company provides credit based on solar production. This process, known as "Net Metering," ensures that energy goes in and out through a single meter.(Bhatia, 2022)

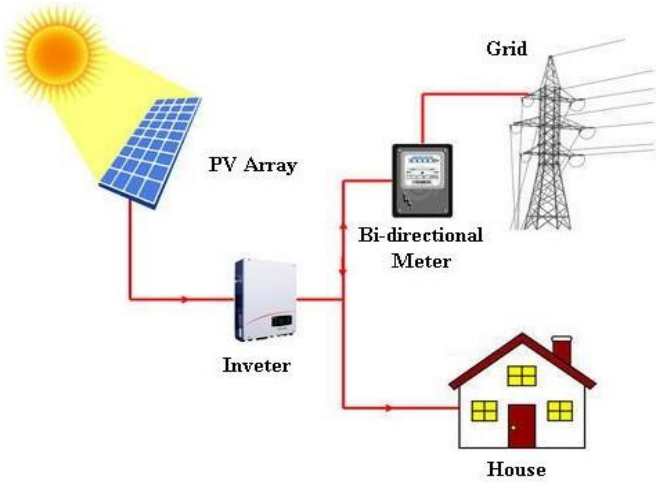

Figure 2.3: Schematic diagram of a grid-connected PV system (source,(Imam et al., 2020))

c. Hybrid-connected PV System

Hybrid Solar systems combine the technology of Solar Panels and Solar batteries to create a green energy solution that provides a back-up supply of energy. Although a hybrid PV system remains connected to the National Grid, any solar energy generated is first stored in a home battery solution before going to the grid.

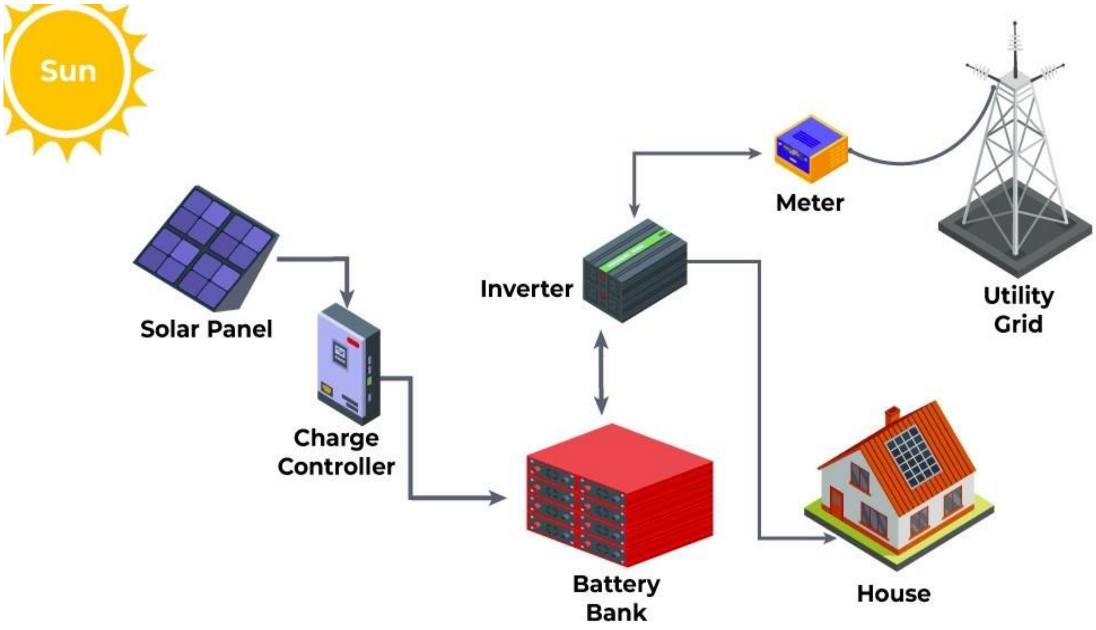

Figure 2.4: Hybrid solar system (source,(ENGINEERING DIGITAL NOTES ON, 2024)*)*.

The primary advantage of a hybrid solar system lies in its ability to store surplus energy in a battery. This stored energy can then be utilized to power your home during nighttime hours, reducing the need to export excess energy back to the grid. Additionally, unlike traditional on-grid systems, a hybrid system allows you to draw energy from your battery supply in the event of a grid outage, a phenomenon known as islanding. This feature is especially beneficial for property owners residing in areas susceptible to power outages, providing them with a reliable source of electricity even when the national grid is down. Hybrid solar panels offer flexibility and cost-effectiveness as an in-between solution for off-grid and on-grid energy use. They allow for battery storage expansion at any time and charging from the grid at cheap peak rates. However, due to the complexity of the system, they are less efficient compared to grid-tied systems. Hybrid solar systems are more budget-friendly than off-grid systems but more expensive than on-grid systems. They also allow for charging cheap peak rates, but they are more expensive than off-grid systems.(Amtsberg, n.d.)

2.1.2 Limitations and Constraints

2.1.2.1 Site Topography

PVsyst does not allow individual row distance correction according to the height difference. So, for large scale PV plant simulation the only possible option found was to use flat uniform design where module rows are located on the same altitude and are arranged with the same distance to each other. Therefore, it was assumed in PVsyst simulations the surface to be flat and rectangular, and the module arrangement to be uniform. For real design a calculation tool has been developed, which allows rearranging the row position based on height difference.(Fedorov, 2015)

2.1.2.2 Shadings

The shading effect on modules can be conditionally divided by three components: horizon shading, near shading and self-shading. Horizon shadings are caused by horizon line and far located objects. The horizon shading component in solar installation design involves making horizon angle measurements and creating a shading map in PVsyst. The horizon shading pattern is assumed to be the same for all locations of the site, with small buildings surrounding the field included in the horizon component. Near shadings are created by objects close to the solar installation, and PVsyst allows for the creation of a 3D model of the system and these objects, simulating the difference in shading profile during sun movements. In this thesis project, near shading is created by buildings of a recycling plant, and their dimensions and precise locations are included in the 3D model for detailed design. The self-shading component describes shading in multiple row systems caused by a row standing front. The electrical shading effect option is chosen for unlimited sheds profile in preliminary sizing. For detailed design, a 33% shading effect on electrical production is chosen, considering diffuse radiation's impact on module performance due to the large between row distance.(Fedorov, 2015)

2.1.2.3 Irradiation Calculation Method

While doing the optimization a substantial difference in results has been noticed depending on which anisotropic irradiation calculation model is used. PVsyst gives an opportunity to choose between Hay or Perez models. According to (Duffie and Beckman ,2013), The Hay and Davies method operates under the assumption that all diffuse radiation can be segmented into two components: isotropic and circumsolar. It estimates the circumsolar diffuse radiation as emanating from the same direction as the beam irradiation. On the other hand, the Perez et al. model provides a more intricate analysis, incorporating horizon brightening along with other factors. This model is notably more complex and relies on a more precise determination of diffuse irradiation, making it particularly sensitive to realistic conditions.

2.1.2.4 Electrical and Mechanical layout

When it comes to electrical and mechanical layout, the system was simplified to a great extent because of two reasons. Firstly, as mentioned before the site is not flat, so it was considered the final module arrangement to be done during the construction process. Secondly, none of the PV installation companies was willing to share the information about mounting details and costs. Consequently, the layout design is limited to module string sizing and numbering so that the array optimally fits an inverter. Unfortunately, this leads to one more limitation, that cables length, connections, junction boxes and other related components cannot be properly designed as well as detailed mounting system design cannot be covered in the project. Therefore, approximate assumptions were made for mounting and cable costs.(Fedorov, 2015).

2.1.2.5 Economical Evaluation Procedure

It is important to comment about limitations and constraints made in economical evaluation procedure, which assumption can affect the results to the greatest extent and may cause the major uncertainty part. The assumptions are following Engineering margin cost is assumed to be linearly dependent on system scale according to PV nominal power. Quotes for electrical components (wires, connections, junction boxes, etc.) Are assumed to be not affected by the between row distance difference. Chosen inverters require a special cabin to be installed in. The price of the cabin has not been included in the calculation procedure. The system requires a power transformer to be connected to 10kV power grid. The transformer costs were not considered. On a request of the company VAT tax and loans have not been included in the price.(Fedorov, 2015)

2.2 PV Techniques

2.2.1 System Sizing Models

The system is tailored to provide power for a remote island. Analysis of collected data reveals a close alignment between solar energy distribution and electricity consumption patterns, making PV modules the primary power source. Surplus energy beyond the load requirement is stored through pumped storage, a method that harnesses excess power from the solar PV system to elevate water from a lower reservoir to a higher one, storing potential energy. During periods when the PV system cannot meet the load demand, the stored water is released to flow downhill through a turbine, generating power. This pumped storage system offers flexibility and rapid response capabilities, enabling the provision of sustainable power for isolated locations.(" Optimization of Solar Power Generation Efficiency Using MINITAB Software ", 2019)

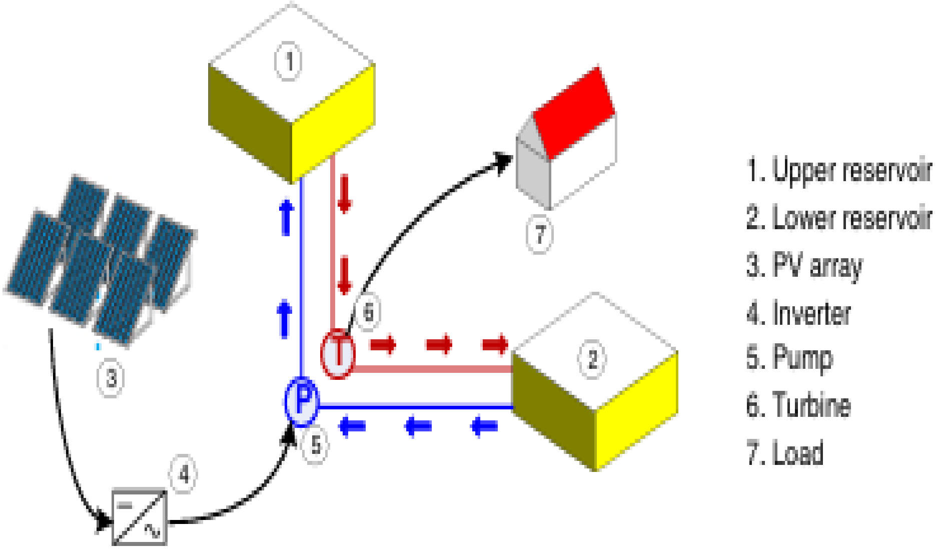

Figure 2.5: System Schematic (source,(Ma et al., 2014)).

2.2.2 Genetic Algorithms (GA)

Genetic algorithms (GA) are stochastic optimization algorithms inspired by natural selection and genetic principles. Their operation is straightforward: they begin with an initial population encoded to represent the problem model using various methods.

2.3 Overview of PV Optimization Methods

Solar radiation is a crucial factor for the proper functioning of solar energy systems. The energy produced by solar photovoltaic (PV) systems fluctuates with changes in solar irradiation throughout the day. Weather parameters significantly impact the reliability of solar energy systems. Therefore, optimization methods are essential for improving the reliability and effectiveness of these systems. Developing methods to address complex optimization problems specific to PV systems is crucial for achieving this goal. Solar energy system optimization, particularly in PV systems, is closely linked to weather factors like solar radiation, ambient temperature, and wind speed. Mathematical models have been used in previous studies to improve the performance of PV systems. The PSO algorithm has been proven to be an efficient and reliable technique for maximizing PV system performance, resulting in greater output power. The main objectives of optimization in solar energy systems include maximizing reliability, minimizing expected costs, optimizing scheduling operations, and assigning resources. Various optimization methods have varying convergence rates, accuracy performance, and computational complexity, making the selection of an appropriate approach based on user requirements and application type. Intelligent approaches are more robust and accurate than conventional methods due to their exploration and exploitation ability, precise calculation, and convergence speed. The objective functions of optimization often focus on maximizing system reliability, which can be achieved by controlling operational parameter efficiency. An active cooling system for PV panels has been implemented to enhance basic efficiency and improve electricity generation.(Al-shahri et al., 2021)

2.4 Types of PV Technologies

The two primary categories of solar cell technology are distinguished by the semiconductor material used: crystalline silicon in a wafer form and thin films of other materials.

2.4.1 Crystalline Technology

Crystalline silicon (c-Si) Crystalline silicon has been the predominant semiconductor material used in most solar cells, despite being a relatively an inefficient light absorber and requiring a significant thickness of material (several hundred microns). Nonetheless, it has been favored due to its ability to produce stable solar cells with good efficiencies and its utilization of process technology derived from the extensive industry knowledge base. There are two main types of crystalline silicon used in the industry:

1. **Monocrystalline silicon**: Produced by slicing wafers (up to 150mm in diameter and 350 microns thick) from a high-purity single crystal. Numerous factors constrain its efficiency. The highest efficiency achieved by silicon solar cells is around 23%, while other semiconductor materials can achieve efficiencies of up to 30%, depending on the wavelength and semiconductor material used.
2. **Polycrystalline silicon**: Manufactured by sawing a cast block of silicon into bars and then wafers. The prevailing trend in crystalline silicon cell production is moving towards polycrystalline technology.

2.4.2 Thin Film Technology

The selected materials for thin film solar cells are bright light absorbers and require only about 1 -micron thickness, resulting in significantly reduced materials costs. The most common materials used include amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIS or CIGS). These materials are suitable for large-area deposition onto substrates of approximately 1-meter dimensions, facilitating high-volume manufacturing.

Among these materials, **amorphous silicon** is the most mature technology in thin-film technologies. Achieving better stability requires thinner layers to enhance the electric field strength across the material. However, thinner layers reduce light absorption and consequently decrease cell efficiency.

Despite these advancements in thin film technologies, crystalline silicon technology remains preferred for solar PV projects due to its high solar conversion efficiency and area efficiency. Additionally, crystalline technology is widely adopted in the industry with numerous sources available for supply, further solidifying its position as the standard choice for solar PV projects.(" Optimization of Solar Power Generation Efficiency Using MINITAB Software ", 2019)

3. METHODOLOGY AND PROJECT DESIGN

This project used a comprehensive review of existing literature provides valuable insights into optimization techniques, challenges, and best practices in photovoltaic energy production. By synthesizing information from academic journals, and technical reports, the study can gain a thorough understanding of optimization strategies and their effectiveness.

3.1 Data Source

In this project the data was collected review of different books in the library and different ideas from the internet was be conducted. The source of information's is only second source of data collection like study article in other way source of information is the material that used to complete the proposal work by review article are gathered from searching from manuals, documentary, and related books from the library and some of them are taken from the internet.

3.2 Method of Data Analysis

PVsyst simulations and an economical evaluation process serve as the primary foundation for this project. As a result, the work process was planned according to following steps:

- ✓ The first step is to review the relevant literature and the prior design, then evaluate the outcomes.
- ✓ The next step was defining the case's boundary conditions, which included measurements of horizon shading. Identifying potential assumptions and limitations was a key aspect of the process.
- ✓ To analyze the site topography for potential shadings and determine the suitable area for photovoltaic (PV) installation.
- ✓ After this a preliminary system design has been done. This step covered the design and simulations of systems with different modules and the same inverter, which helped to define the optimal components for the case.
- ✓ Then, we varied the module tilt and the distance between panel arrays for South orientation. The objective was to analyze the results comprehensively and select the optimal combination based on the outcomes.

- ✓ During the preliminary sizing phase, a separate system with an alternative East-West module orientation was simulated to evaluate its feasibility and rationality.
- ✓ Too involved conducting two detailed system design simulations. The first simulation focused on optimizing a South-oriented system, while the second simulation centered on the East-West (EW) orientation. Each system underwent an economical evaluation based on the Levelized Cost of Energy (LCOE).
- ✓ Finally, to discuss the results and conclude.

Data analysis can be applied in a number of ways to weather data related to solar energy analysis:
a. Energy forecasting: this technique uses data analysis to forecast the amount of solar energy that will be produced at a specific place by utilizing information on weather variables, such as temperature, precipitation, and cloud cover.

b. Performance Evaluation: By contrasting actual energy output data with predictions derived from weather data, data analysis may be utilized to assess the performance of solar panels.
In order to optimize the effectiveness and output of the solar energy system, this might help to guarantee that solar panels are performing at their peak and that any problems are resolved quickly.

c. Maintenance: By using data analysis, maintenance schedules can be adjusted based on trends found in the correlation between weather data and solar panel performance. In order to optimize the effectiveness and output of the solar energy system, this might help to guarantee that solar panels are performing at their peak and that any problems are resolved quickly.

3.3 Equipment used for the Project

The various equipment’s used for this project are:

1. Solar plate
2. Infrared thermometer
3. Digital Multimeter
4. Battery
5. Inverter

6. Tong tester
7. Compass
8. Solar Power Meter
9. Clamp-on Power Meter
10. Battery Tester
11. Charge controller

3.4 Components Selection and System Sizing

High-quality components form the backbone of reliable and efficient PV systems.

Solar PV modules: High-quality solar modules incorporate materials with superior light absorption and conversion properties. Monocrystalline and polycrystalline silicon-based cells, as well as emerging technologies like perovskite solar cells, contribute to the efficiency and durability of solar modules. (Smith et al., 2021)

Inverter: High-quality inverters are a type of electrical equipment designed to convert direct current (DC) into alternating current (AC). Most inverters have conversion efficiencies of 90% or higher and incorporate important safety features such as ground fault circuit termination and anti-islanding protection. In the event of a power outage, inverters are programmed to shut down the PV system automatically.

These inverters not only optimize power output under varying conditions but also enhance the overall reliability and longevity of the PV system. Their efficiency and safety features contribute to the smooth operation of the system, ensuring maximum energy production while minimizing risks associated with electrical faults or disruptions.

Battery Bank: Premium batteries guarantee efficient energy utilization by storing the surplus energy generated by the photovoltaic (PV) array instead of instantly utilizing it. Consequently, they can supply power to your residence during nighttime or extremely cloudy conditions when sunlight is insufficient.

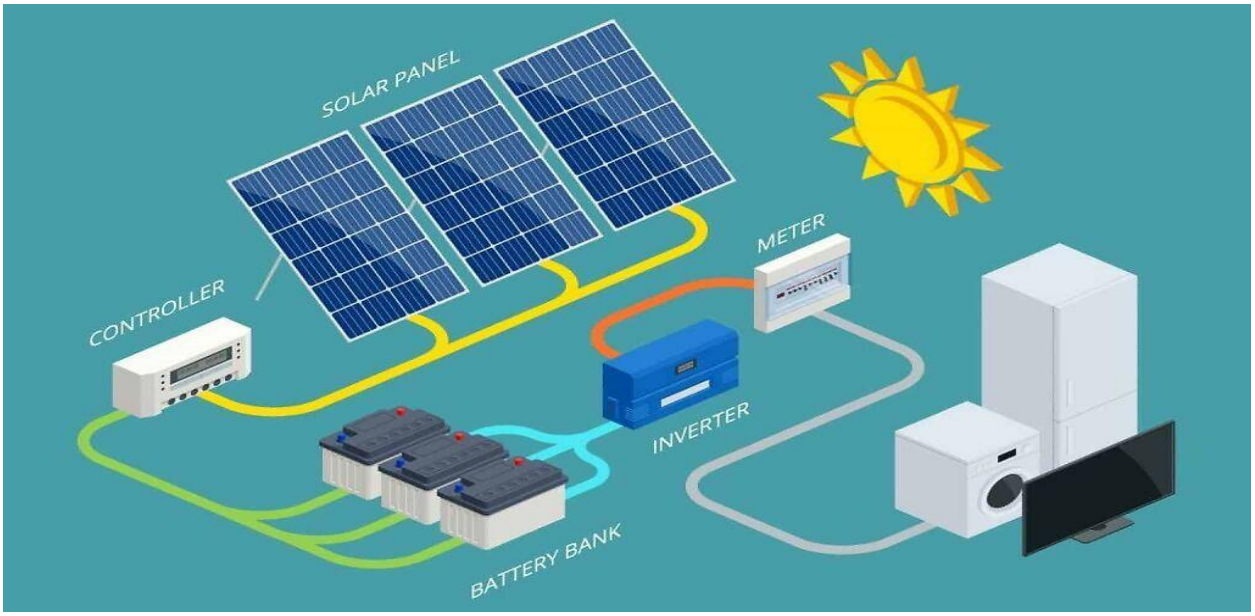

Figure 3.1: The Components of a Solar Photovoltaic System (source,(Solar, 2022)).

Charge Controller: high-quality charge controllers manage the direct current (DC) output from solar panels to prevent battery overcharging. These controllers are equipped to identify when batteries reach full capacity, thereby ceasing current flow to safeguard the batteries from potential damage(Solar, 2022).

3.5 Design and System Modeling

3.5.1 Preliminary Sizing

It was aimed to explore and evaluate the performance of different modules based on their bankability and to analyze the system performance with various tilts, row spacing factors and orientations. There are many variable parameters affecting final system performance and LCOE it was agreed to follow the next procedure. First, the system electrical layout should be designed, including string sizing and numbering. For doing this optimized row spacing factor and tilt were used, as suggested by PVsyst. Then several simulations were done by varying the row distance and finding the optimal tilt for each meter of the distance by defining the maximal system annual power production for each.

a String Sizing and Numbering

The first step in selecting the number of modules connected in series in a string was to define the lowest possible temperature for the absolute voltage limit, which constitutes -25°C. This temperature has been decided based on estimation made after studying the weather data for the location. The lowest ambient temperature can easily reach -30°, it is only possible during night, when there is no sunlight for module operation. Then according to this extreme temperature, it was possible to calculate maximum open circuit voltage for all modules for the location:

$$V_{MAX} = V_{OC} \cdot \left(1+\frac{((\mathrm{Tmod}-25°\mathrm{C}) \cdot K_T)}{100}\right) \qquad (1)$$

Where V_{MAX} is- Maximum photovoltaic module output voltage; V_{OC} is- Module open circuit voltage; T_{MOD} is - Lowest possible module temperature during day, (-25°C); K_T- Module temperature coefficient.

b. Row Spacing factor and tilt

One of the most important parameters to consider when designing a utility-scale photovoltaic system are module tilt and the distance between rows. Typically, in the Northern hemisphere it is recommended to install solar panels facing the South, being an optimal orientation solution. However, there are certain advantages of East-West orientation as well.

South Orientation The procedure started with finding the optimal tilt for a single module row for the site location using PVsyst preliminary design section. Figure 3.2 illustrates the dependence of global irradiation on collector plane and related losses on the plane tilt. It is observed from the graph that the irradiation curve reaches its peak of 1238 kWh/m^2 per year at 48° tilt. The graph gives also a good impression on how many losses due to not optimal orientation would take place with lower or higher tilts.

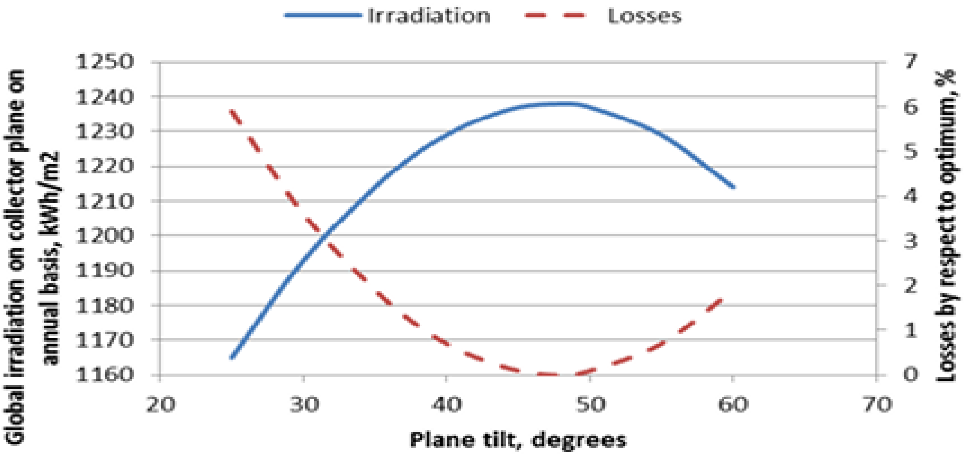

Figure 3.2: Graphical dependence of global irradiation on collector plane and related losses on plane tilt. South oriented system (source, (Fedorov, 2015)).

East-West orientation: EW solution has lower radiation on collector plane when it comes to East or West separately. In order to estimate the scale of losses due to not optimal orientation PVsyst preliminary section was used. In fact, high tilt for EW system causes undesirable shading, while extremely low angle prevents free rainwater and snow outflow. After studying already existing East-West systems it was decided to choose the tilt of 10° due to mechanical and shading reasons. For defining the optimal between row distance for East-West system it was assumed no self-shading. The only factor here was free access to panels for convenient installation and maintenance and availability for a person to pass through between rows. Therefore, the distances between rows are selected 100 mm and 500 mm as shown in Figure 3.3. Total distance between same oriented rows: $D = (1.16 \cdot \cos(10)) \cdot 2 + 0.5 + 0.1 = 2.88$ m Where 1.16m – the width of rows, equal to module length; 10° - array tilt.(Fedorov, 2015)

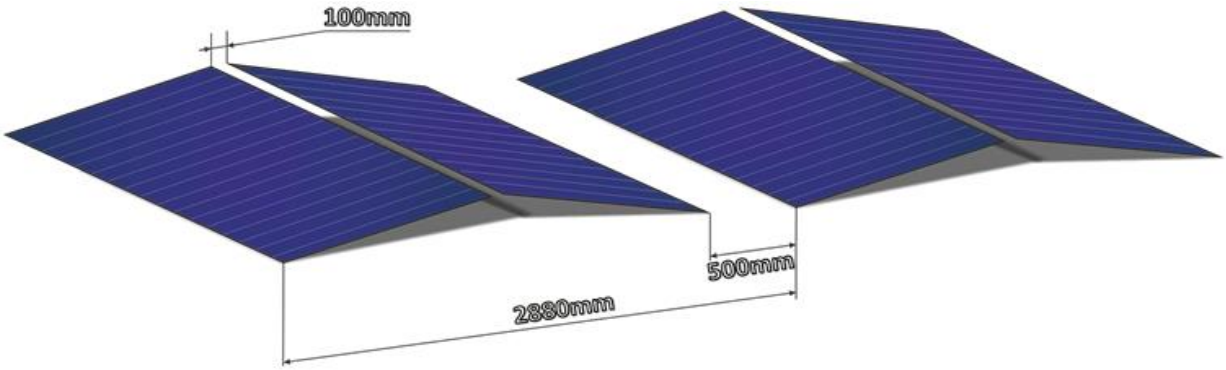

Figure 3.3: Distances between rows for East-West orientation (source,(Fedorov, 2015)).

Tilt

The tilt of solar panels defines the angle at which they face the sky during installation. For instance, if installed on a flat roof, the tilt would be 0°, while facing a wall would result in a tilt of 90°.

Determining the optimal tilt requires consideration of key factors such as seasonal variations and energy consumption patterns. In regions where energy demands peak during winter, when solar availability is lower, a more vertical tilt angle is preferable. This entails positioning solar panels at an angle equal to the latitude of the location plus 15°. This orientation maximizes exposure to the lower winter sun angle, thereby enhancing energy production.

Conversely, in areas where energy demands are primarily for cooling and refrigeration, a reduced tilt angle is recommended. In this scenario, solar panels should be angled equal to the latitude of the location minus 10°. This adjustment optimizes solar panel performance by aligning them more directly with the sun's rays during periods of higher solar availability.

Optimizing the tilt angle of your PV array can help maximize solar energy capture:

$$\beta = \varphi - \arctan\left[(\tan \delta \cos h) / \cos(\varphi - \delta)\right] \qquad (2)$$

Where:

β = Array tilt angle (degrees)

φ = Latitude of the location (degrees)

δ = Solar declination angle (degrees)

h = Hour angle (degrees)

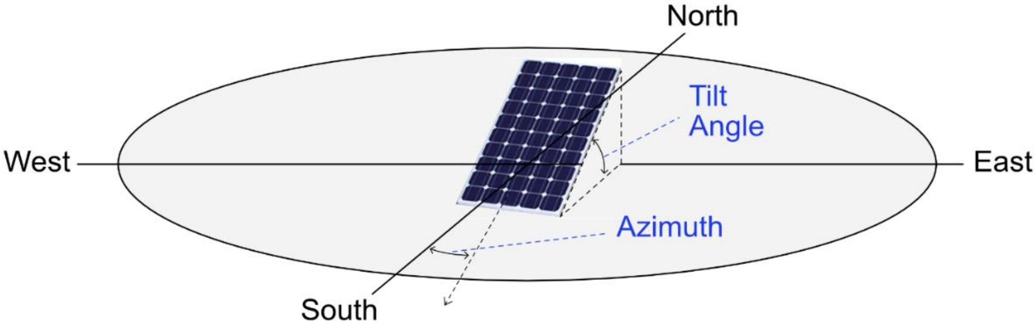

Figure 3.4: Azimuth refers to the compass direction your solar panels are facing (source,(Solar Design Guide, 2017)*)*.

Facing towards the equator generally yields the most electricity production from solar panels over the course of a day. This is because solar panels capture the most sunlight when they are perpendicular to the sun's rays, which occurs when facing towards the equator. In the northern hemisphere, facing solar panels southward maximizes their exposure to sunlight, while in the southern hemisphere, facing them northward achieves the same effect.

This principle is based on maximizing the exposure of solar panels to sunlight throughout the day, thus optimizing electricity generation. However, there can be exceptions and nuances depending on factors such as local geography, shading, and specific solar panel technologies. In some cases, adjustments may be made to panel orientation or tilt to account for these factors and further optimize energy production.

3.5.2 System Sizing

The available area for PV installation of 66000m^2 was considered as a rectangular shape field with 150 m width and 440 m length. The first step in sizing was to define the optimal number of modules in a string. It was necessary as in the detailed design other and more powerful inverters were selected. As the MPP voltage range of the inverter is lower (570-800 V), just two options of module numbers were suitable, 8 or 9. However, in the case of 8 modules in series the MPP voltage of the array at 60°C constituted 545 V and was slightly lower than inverter minimum MPP voltage.

System sizing in optimizing photovoltaic (PV) energy production involves determining the appropriate size and configuration of solar panels, inverters, and other components to maximize energy output while considering factors such as location, shading, orientation, tilt angle, and available budget. Here's a general approach to system sizing in optimizing PV energy production:

Energy Demand Analysis: Start by analyzing the energy demand of the location where the PV system will be installed. This includes understanding the average daily energy consumption, peak demand periods, and any specific requirements or constraints.

Site Assessment: Perform a comprehensive site assessment to analyze numerous factors influencing solar energy production, including potential shading from neighboring buildings or trees, prevailing local weather patterns, and the space available for solar panel installation. Utilize tools such as solar irradiance maps and shading analysis software to aid in this evaluation process.

Solar Resource Assessment: Determine the solar resource potential of the location by analyzing historical solar irradiance data and considering factors such as seasonal variations and weather patterns. This helps estimate the amount of solar energy that can be harvested throughout the year.

System Sizing and Design: System sizing and design are critical components in the successful implementation of PV energy production systems. Appropriate system design and component sizing is fundamental requirement for reliable operation, better performance, safety, and longevity of solar PV system. The sizing principles for grid connected and stand-alone PV systems are based on unique design and functional requirements. Sizing a photovoltaic system for photovoltaic power system involves a five-step process which will allow the photovoltaic system designer or user to accurately size a system based on users projected needs, goals and budget. These steps are: Estimating the Electric Load, Sizing and Specifying an Inverter, Sizing and Specifying Batteries, Sizing and Specifying an Array.

Estimating the Electric Load: The load determination is straightforward. Make a list of the electrical appliances and/or loads to be powered by the PV system. The power required by an appliance can be measured or obtained from the label on the back of appliance which lists the wattage.

Battery Sizing: Batteries for stand-alone systems are sized to store energy produced by the array for use by the system loads as required. The total amount of rated battery capacity required depends on the following: Desired days of storage to meet system loads with no recharge from PV, Maximum allowable depth-of-discharge, Temperature and discharge rates, System losses and efficiencies, The system voltage defines the number of series-connected battery cells required, the total capacity needed defines the number of parallel battery strings required. The formula provided offers a way to calculate the ideal battery size required for a specific setup. It determines the battery's capacity in ampere-hours (Ah) by considering the total watt-hours consumed by appliances per day and the desired number of days the battery should sustain power independently.

$$\text{Battery Capacity (Ah)} = \frac{\text{Total Watt}-\text{hours per day used by appliances}}{(0.85 \text{ x } 0.6 \text{ x nominal battery voltage})}\text{Days of autonomy} \qquad (4)$$

Days of autonomy signify the duration for which you aim to depend entirely on your battery bank for energy supply. It's worth noting that the 0.85 factor within the formula reflects the overall efficiency of the system. This encompasses various elements such as roundtrip efficiency, efficiency in converting DC to AC power, and losses in wiring.

Selecting an Inverter: An inverter is essential for converting direct current (DC) into alternating current (AC). Stand-alone inverters are typically voltage-specific, meaning they must match the nominal voltage of your battery. Inverter capacity is rated in Watts, and it's crucial that the input rating of the inverter exceeds the total wattage of connected appliances, ensuring proper functionality. For standalone systems, the size of the inverter is determined by its maximum continuous output in watts, which should exceed the total wattage of all connected AC loads.

Additionally, appliances like washing machines, dryers, and refrigerators, which utilize electric motors, have a higher power requirement during startup. This initial surge in power consumption can be more than double the normal consumption. Therefore, it's advisable for the input rating of the inverter to be ideally 25-30% larger than the rated wattage of these appliances to accommodate such power spikes effectively.

Sizing the Controller: A charge controller serves to regulate the flow of charge from your solar panel array into your battery bank, preventing overcharging and reverse current flow, particularly during nighttime. The most common charge controller types are Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT). The voltage at which a PV module produces its maximum power is termed the maximum power point (or peak power voltage), which varies with factors like solar radiation, ambient temperature, and solar cell temperature. MPPT solar charge controllers enable users to utilize PV modules with a higher voltage output than the operating voltage of the battery system. In the case of a series charge controller, the determination of its size hinges on two main factors: the total photovoltaic (PV) input current supplied to the controller and the configuration of the PV panels (whether they are arranged in series or parallel). Following standard practice, the sizing of a solar charge controller involves taking the short circuit current (Isc) of the PV array and multiplying it by 1.3. This calculation yields the rating required for the solar charge controller:

$$\text{Solar charge controller rating} = \text{Total short circuit current of PV array} \times 1.3 \qquad (5)$$

This approach ensures that the charge controller is appropriately sized to handle the expected current from the PV array, with a margin for variations and contingencies.

To effectively estimate the size and type of wire needed in various circuits, including the cable between PV modules and batteries, the cable between the battery bank and the inverter, and the cable between the inverter and the load, these steps are crucial. (Bhatia, 2022)

3.5.3 Energy Storage and Grid Integration

In optimizing PV energy production, energy storage and grid integration play crucial roles in maximizing the utilization of solar energy, improving grid stability, and enhancing the overall efficiency of the system. Here's how energy storage and grid integration are important components in PV optimization.

Energy Storage Systems (ESS)

Energy storage systems store excess energy generated by PV panels during periods of high sunlight and discharge it when demand is high or sunlight is low, thereby increasing self-consumption and reducing reliance on the grid. Common types of energy storage systems include battery storage (such as lithium-ion batteries).

Optimization: Integrating energy storage with PV systems allows excess solar energy to be stored for later use, which helps balance energy supply and demand. This reduces reliance on grid backup during times of low solar generation. Storing surplus energy ensures a more stable and reliable energy supply, even when solar output fluctuates. This integration enhances energy system resilience, efficiency, and sustainability. Moreover, it supports grid stability by providing flexibility in managing energy resources and meeting demand fluctuations. Overall, integrating energy storage with PV systems promotes greater energy independence and contributes to a cleaner and more resilient energy future.

Energy storage facilitates load shifting, a practice that involves storing excess energy generated during off-peak hours and utilizing it during periods of peak demand. This strategy helps decrease electricity expenses and peak demand charges by optimizing the use of stored energy when electricity rates are typically higher.

Grid Integration

Grid Connection: PV systems are typically connected to the electrical grid, allowing excess energy to be exported to the grid when production exceeds local demand and drawing power from the grid when solar generation is insufficient. Grid-integrated PV systems can provide ancillary services to the grid, such as reactive power support and voltage regulation, helping to maintain grid stability and reliability. Net metering policies allow PV system owners to receive credit for excess energy exported to the grid, effectively reducing their electricity bills and providing a financial incentive for PV adoption. Grid integration requires compliance with relevant grid codes and standards to ensure safe and reliable operation, including requirements for voltage and frequency regulation, power quality, and grid protection.

3.5.4 Real-time Monitoring System

System monitoring is critical for ensuring the performance of the PV system. The monitoring system is useful for collecting data and sending it to the control center, which allows users to conduct assessments and evaluations and control systems with the goal of lowering maintenance costs, viewing system performance, and detecting errors in the PV system.

Monitoring the PV system has several goals, including providing information about energy potential, fault detection, extracted energy, and energy losses. It is important to understand not only the description of system performance, but also how long a PV can work effectively in one day and other issues that can reduce energy production. This monitoring is also necessary because the level of solar radiation is always changing according to location, time of day and climatic conditions. All the monitoring data can be used as a guide for maintenance and preventative measures, as well as a warning for early detection and evaluation of changes in environmental conditions. For evaluating and optimizing system performance.

Performance Monitoring:

- **Solar Irradiance**: Real-time monitoring systems measure solar irradiance levels to assess the amount of sunlight available for PV energy generation. This data helps in predicting energy production and identifying deviations from expected performance due to changes in weather conditions.
- **PV System Output**: Monitoring the output of PV panels in real-time allows operators to track energy production levels and detect any anomalies or performance issues, such as shading, soiling, or equipment failures, which may affect system efficiency.

3.5.5 Economical Evaluation Procedure

One of the most common financial tools for evaluating renewable energy project's bankability and comparison of various generation options is Levelized Cost of Energy (LCOE). A low LCOE means that electricity is being produced at a lower price, with higher returns for the investor. It is an assessment of the economic feasibility of an energy source that incorporates costs over the project's lifetime. On a special request of Falu Energi & Vatten, simplified LCOE calculation method has been used. This method describes the sum of project initial costs and maintenance divided by system annual electricity production. Being less complex, this procedure has been used for preliminary sizing results evaluation and comparison. It can be calculated from:

$$\mathrm{LCOE_A} = \frac{\mathrm{IC} + \mathrm{TO}}{\mathrm{AEP}} \qquad (7)$$

Where $\mathrm{LCOE_A}$– levelized cost of energy on annual basis, kWh (or

SEK/annual kWh converted using exchanging rate of 1EUR=9.331 SEK);

IC – initial project costs;

TO– total operating and maintenance (O&M) costs over the project lifetime;

AEP – initial annual energy production, kWh.

Initial project costs represent the summary of total costs spent on PV modules, inverters, mounting, electrical components, installation work, shipping, engineering margin and project permission.

Here, LCOE was calculated by summing up all system costs over expected lifetime (including initial costs, engineering margin, maintenance, permissions and insurances), which are then divided by the system lifetime expected energy output.

$$LCOE = \frac{IC + \sum_1^n \frac{AO + I}{(1+IR)^n}}{\sum_1^n \frac{AEP \cdot (1-SDR)^n}{(1+IR)^n}} \qquad (8)$$

Where LCOE - levelized cost of energy;

AO – annual operating and maintenance (O&M) costs;

I – annual insurance;

SDR – system degradation rate, %;

IR – interest rate, %;

n– project lifetime, years.

System Scale Factor: In order to illustrate cost difference for various system size due to component wholesale prices the calculations were done assuming 1% cost reduction for PV modules, 10% for inverters, 10% for other electrical components, 5% for installation labor and 30% for engineering margin in scale of system size. In other words, these percentages represent how the price of components changes from the smallest to the largest considered system size. The dependence of the percentage share on the system size is assumed to be linear. These estimations were done for the particular case considered and cost sensitivity analysis for utility scale systems and prices got from component dealers. It was discovered that the prices for inverters are very dependent on the system size and for larger utility scale systems the cost per inverter Watt peak can be easily reduced by half. In contrast, the module price is not so flexible and may vary just up to 5%.

3.6 Implementations

3.6.1 Maintenance and Monitoring

Maintaining solar panels requires qualified experts to prevent electrocution or fatal accidents. Proper maintenance contracts are crucial for maximizing panel lifespan and cleaning. After installation, the contract should cover electrical connections, structure condition, and inverter operation, ensuring the system's longevity. At Energy Con, our dedicated team of analysts specializes in remote monitoring and maintenance of installed solar panels. Through continuous monitoring, we gather real-time data on energy production, enabling us to promptly detect malfunctions, system errors, and assess module performance. This proactive approach ensures maximum efficiency in harnessing solar energy.

Our expertise in maintenance and monitoring extends throughout the entire lifecycle of solar panels. From initial installation to ongoing maintenance, we provide integrated sales and after-sales services. This comprehensive approach ensures that our customers receive top-notch support and assistance, optimizing the performance and longevity of their solar panel systems.

Panels Cleaning: Regular cleaning of PV panels is essential, particularly when there is a noticeable buildup of soiling deposits. In desert areas prone to dust accumulation, more frequent cleaning is necessary. Typically, ambient-temperature de-mineralized cleaning solutions are used to prevent glass-shock or hard-water spots. In addition to panels, it's important to clean dust and dirt from the electrical combiner box and DC-to-AC inverters to maintain optimal performance.

Verification of Supports: Periodic verification of the entire system, including its supports, is crucial to ensure structural integrity and stability. It's important to verify if the system's performance remains consistent with previous benchmarks to detect any deviations that may indicate issues.

Regular Maintenance of Batteries: Battery maintenance involves checking for imperfections such as corrosion or leakage. If necessary, electrolyte levels should be monitored and replenished, and equalizing charging may be required to maintain battery health and performance.

Inverters Control: Verify that the inverter is correctly matched to the panels to ensure optimal energy conversion. Regular checks should be conducted to ensure the inverter's proper functioning and to address any issues promptly.

4. RESULT AND DISCUSSION

4.1 Optimization Due to Inverter Oversizing

The initial optimization focused on determining the most cost-effective ratio between the nominal power of the PV array and the inverter power. The findings are illustrated in Figure 4.1, which depicts a line graph showing the relationship between the Levelized Cost of Energy (LCOE) on an annual basis and the system losses attributed to inverter under-sizing, relative to the ratio of the module to inverter nominal power. This analysis was conducted for a South-oriented system using thin-film modules, with a row distance of 10 meters and a tilt angle of 34°.

The dispersion of data points on the graph can be attributed to the nonlinearity inherent in the PVsyst system's energy output, which varies depending on the selected number of strings. Despite this variability, a discernible trend is evident in the graph, allowing for observation of the primary relationship.

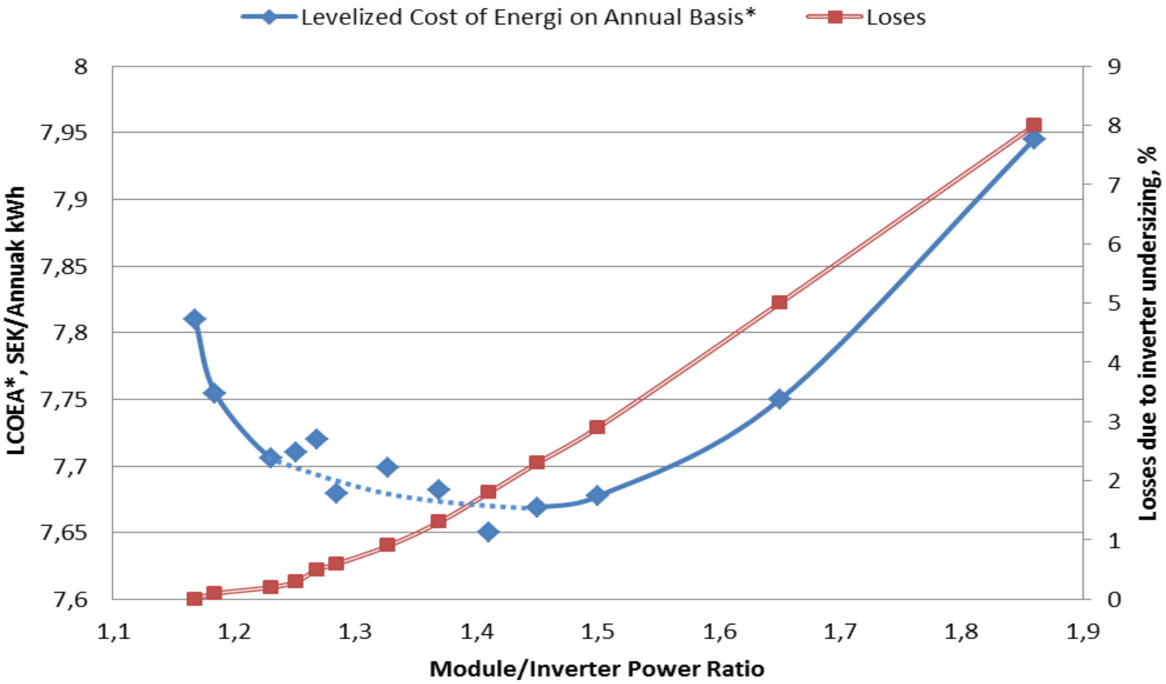

Figure 4.1: Graphical dependence of Levelized Cost of Energy on annual basis and system losses due to inverter under-sizing on module to inverter nominal power ratio for South oriented system.

4.2 System Performance

The East-West (EW) orientation of solar panels offers advantages over traditional south-facing systems by providing a more balanced energy production profile throughout the day. This results in increased energy delivery to the grid during morning and evening peaks, aligning better with typical energy consumption patterns. EW designs also improve self-consumption, reduce midday peaks, perform well in variable weather conditions, and make efficient use of available roof space. Overall, EW orientation offers a compelling option for maximizing energy production and matching it with consumption patterns.

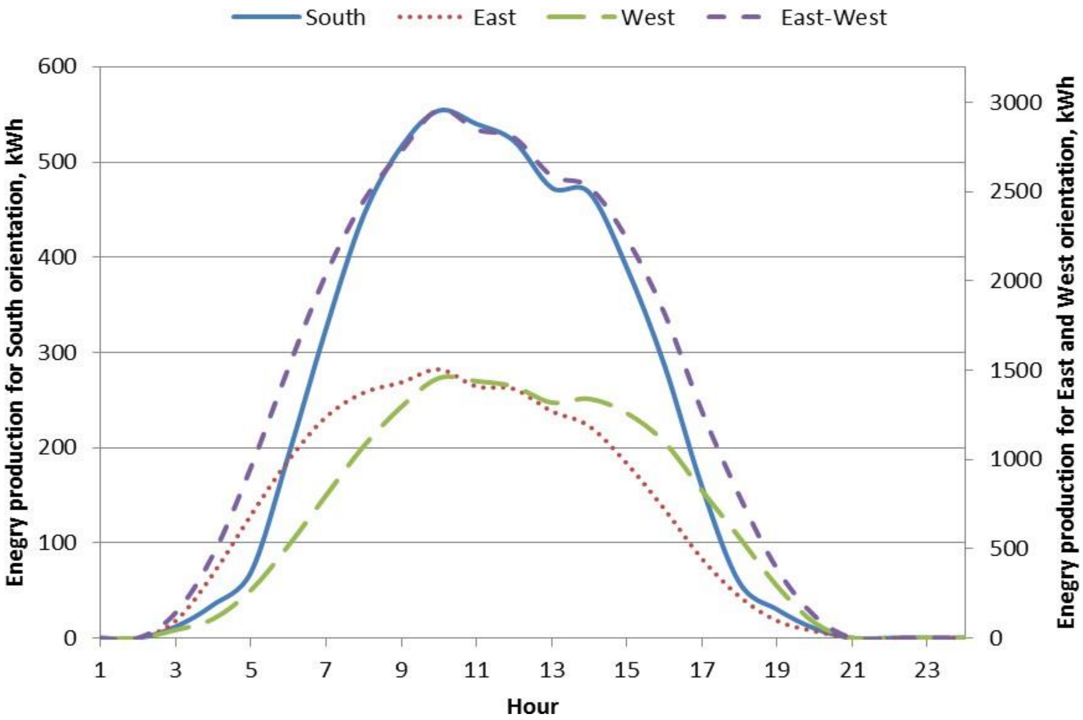

Figure 4.2: Monthly hourly average energy production for June for South, East, West and East-West oriented system.

4.3 Using Advanced Cell Technologies

Invest in high-efficiency PV cell technologies such as monocrystalline or polycrystalline silicon cells, thin-film solar cells (like CIGS or Cd-Te), or emerging technologies such as perovskite solar cells. These technologies offer higher conversion efficiencies compared to traditional silicon cells.

The electricity demand varies across seasons, with the highest daily total energy consumption occurring in winter at 436 kWh, and the peak demand reaching 23 kW during this season. In contrast, summer sees lower consumption, with the highest daily total energy consumption dropping to 278.5 kWh. The yearly average daily total electricity consumption for the school is 334 kWh, with a peak demand of 17 kW.

Regarding the variation of generated electricity in a unit area of Mono-Si, Multi-Si, and Cd-Te PV panels during the day, the hourly average solar radiation data is utilized for the calculation of PV-generated electricity. The results indicate that for a yearly mean day:

- Mono-Si panels generate approximately 0.94 kWh/m² of electricity.
- Multi-Si panels generate approximately 0.77 kWh/m² of electricity.
- CdTe panels generate approximately 0.72 kWh/m² of electricity.

These figures provide insights into the potential electricity output for each type of PV panel technology based on the average solar radiation received during the day.

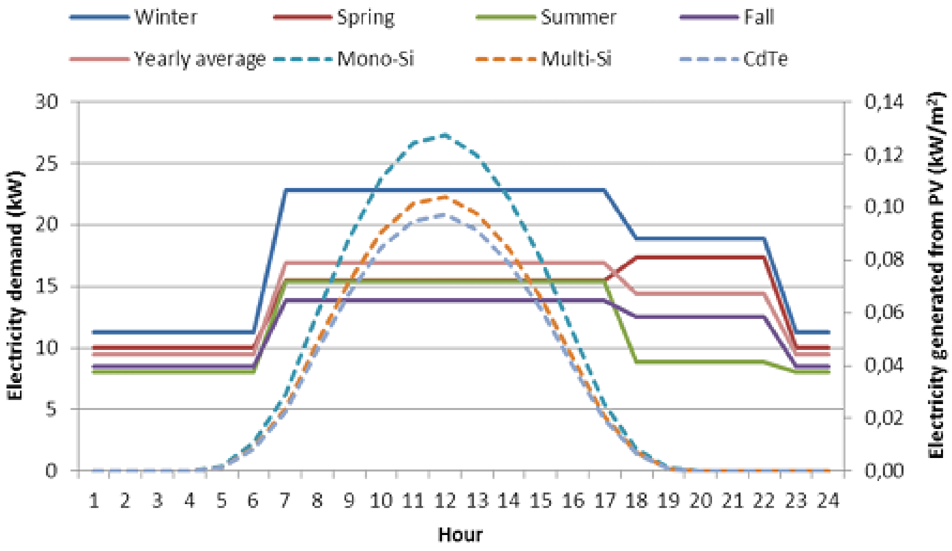

Figure 4.3: Hourly variation of the seasonal electricity consumption and the electricity generation per unit area of three different PV technologies.

The graph illustrates the variations in self-sufficiency and self-consumption of three different PV technologies concerning panel area, with the average daily peak electricity demand of 17 kW as a determining factor. For instance, considering the utilization of CdTe (assuming 1 kWp PV panel requires 5.4 m² surface area) for PV installation, it suggests that approximately 400 kW of installed

PV could be accommodated on the campus roof. However, it's essential to determine the optimal capacity of PV installation based on the campus's electricity demand.

Solar PV performance and efficiency vary based on cell types. Mono-crystalline cells have high efficiency but are complex manufacturing process. Multi-crystalline cells are cost-effective but low efficiency. Multi-junction cells with different bandgaps enhance efficiency but are complex and expensive. Figure 5.4 shows that thin-film module technology requires the largest area for a 2MW system due to low efficiency and energy yield. To achieve the same power output, more area is needed, with 34020-meter squares requiring almost 8.406 acres, which is twice as much as other technology.

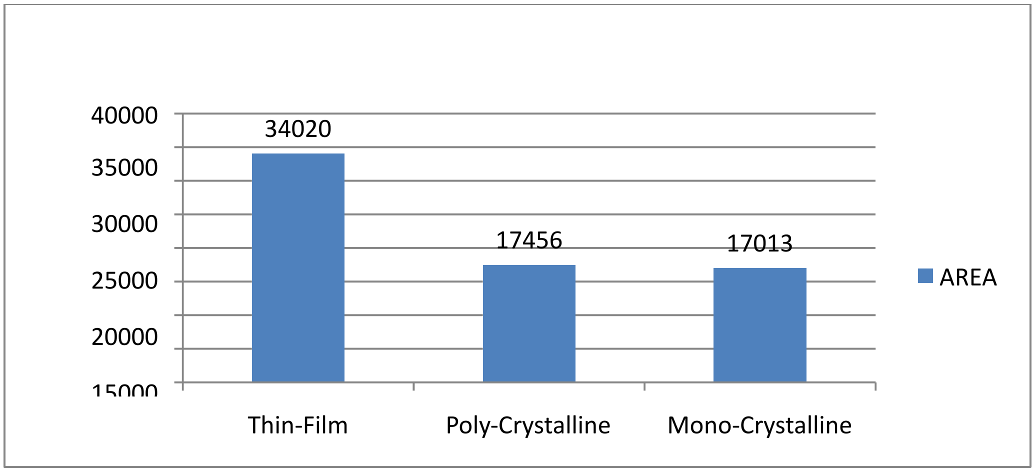

Figure 4.4: Area Comparison of Different Technologies

The figure below displays the price of a 2 MW photovoltaic system using various technologies. It is demonstrated that mono-crystalline module type has the highest cost, while thin-film technology has the lowest. The area cost must be disclosed as it was not part of the system cost. The explanation for why, in rich nations, area-related costs account for a sizeable portion of total costs, yet in developing nations, government-provided areas are free and serve as an incentive for PV investment. Thin-film technology would be more expensive and, in some cases, more expensive than other technologies if the needed system's area cost were large enough to meet the largest area requirement.

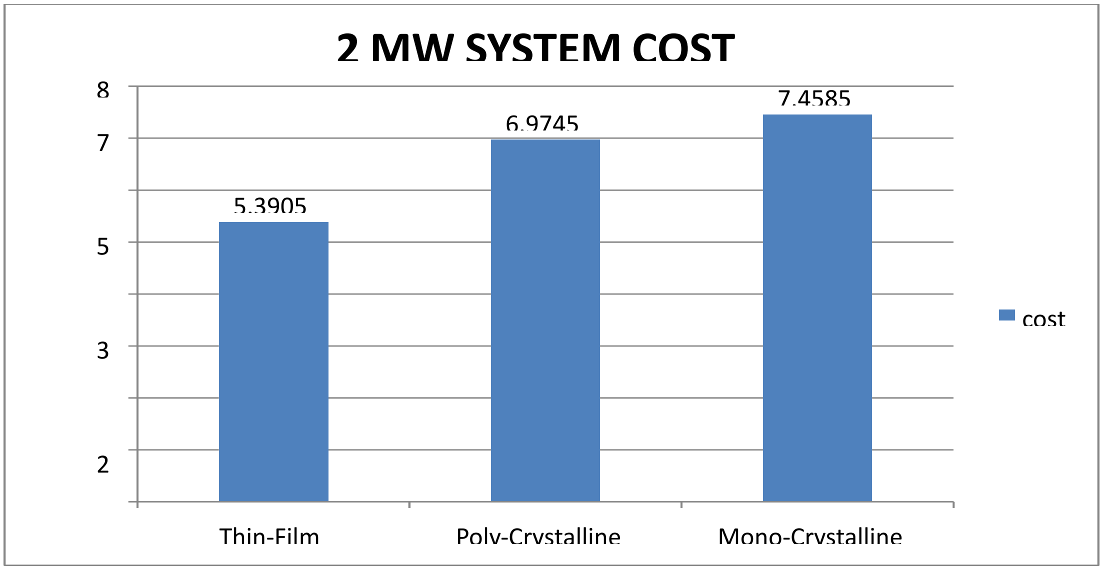

Figure 4.5. Cost Comparison

The general goal of solar energy optimization is to identify the best options in terms of price, size, load, demand, power, and efficiency. Finding the best options in terms of cost, size, load, demand, power, and efficiency is typically the goal of solar energy optimization.

Cost: Deciding which options are most economical, taking into account possible long-term savings in comparison to traditional energy sources as well as the initial installation and maintenance costs.

Size: Choosing the ideal solar energy system size based on the amount of space available, the amount of energy needed, and financial restrictions.

Load and demand: Determining if the solar energy system can effectively meet the demand by analyzing the location's or facility's energy requirements.

Power: Making the most of the solar energy system's power production in order to provide enough electricity to fulfill the needed demand.

Efficiency: Increasing the solar panels' and other components' efficiency to make sure they convert sunlight.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 conclusion

Accordingly, the result of the project depicts selecting better optimization methods is more suitable than conventional ones due to their ability, performance, and appropriate speed of energy production. They help reduce operational costs and power losses and improve integration and controllability of peak power. The review discusses key challenges in solar PV optimization, including complex computation, objective function problems, algorithm integration, cost, sizing, design, placement, power quality, and reduction of energy loss. It also explores the MPPT approach, energy conversion, maintenance, and monitoring.

The review provides future opportunities for designing robust and efficient as well as best optimization procedures for advanced solar PV energy systems, it provides suggestions for the determination of solar cell material, hybridization, execution complexity, MPPT, multi-objective formulation, and energy conversion. The main benefit of these findings is cost reduction due to the sizing factor and lower prices of inverters, mounting, and annual maintenance.

In addition, the East-West system has a better daily profile with a lower midday peak and higher performance in the mornings and evenings. So, to enhance the energy production of photovoltaic (PV) cells, as mentioned before, various methods must be implemented. These include improving cell efficiency through advanced materials and design, optimizing system installation to minimize shading and maximize sunlight exposure, utilizing tracking systems to follow the sun's path, exploring advanced PV cell concepts, integrating energy storage solutions, and optimizing electrical components such as inverters. By employing these strategies, solar energy systems can give higher efficiency output, and contribute to overall energy production.

5.2 Recommendations

This project examined various advanced optimization strategies that take into account the improvement of the PV systems' output compared with actual operating conditions. It makes it clear that the stakeholders who work on solar energy can improve solar technology installation, production, and applications. In addition, it find out that a greater effort is needed to advance research on renewable energy, including PV energy systems, which might assist in lowering global emissions and support the expansion of the energy industry as well as the nation's well-being and economy as a whole.

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