UNIVERSITY OF PRINCE MUGRIN

DESIGN AND IMPLEMENTATION OF A FLOATING PV POWER PLANT FOR MADINAH REGION

by

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A Report
submitted in partial fulfillment of the requirements
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We have made efforts in this project; however, it would not have been possible without Allah's blessings and guidance.

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Thank you all for your invaluable contributions to our journey.

ABSTRACT

This report proposes the implementation of a floating photovoltaic (PV) power plant on Al-Aqoul Lake in the Madinah Region, to generate clean, sustainable electricity while minimizing water evaporation. Through electrical study and design, prototype construction, and financial analysis, the project seeks to develop renewable energy sources, enhance energy efficiency, and foster economic development. This initiative has the potential to become one of Saudi Arabia's leading sources of affordable, clean electricity, aligning with the nation's efforts to diminish environmental pollution and its commitment to clean, sustainable energy, as outlined in Vision 2030. By leveraging advanced engineering techniques and academic knowledge, the project represents a significant step towards a greener future.

Index Terms – FPV, Al-Aqoul Lake, PV panel, design, implementation, simulation

ETHICAL STATEMENT

This thesis/report embodies the ethical principles and guidelines fundamental to responsible research practices. Ethical considerations were meticulously integrated into every phase of this study, ensuring the utmost respect for participants, integrity in data handling, and compliance with ethical standards.

Research Design and Participants: The research design prioritized the well-being and rights of participants. Informed consent was obtained from all participants before their involvement in the study, emphasizing their voluntary participation. Measures were taken to guarantee confidentiality and anonymity, and steps were implemented to ensure data protection throughout the research process.

Data Collection and Analysis: The data collection process adhered strictly to ethical protocols, maintaining respect for individual autonomy and privacy. Participants' identities were protected through coding and anonymization of sensitive information. During data analysis, efforts were made to ensure transparency and rigor, preventing any potential biases or misinterpretations.

Compliance and Approvals: This research was conducted in compliance with the ethical guidelines of the University of Prince Mugrin.

Acknowledgement of Sources: Academic integrity was maintained by acknowledging and citing all sources accurately. No form of plagiarism or academic misconduct was tolerated throughout this research endeavor.

In conclusion, this thesis reflects the commitment to ethical conduct in research. The ethical principles observed throughout this study aim to uphold the dignity, rights, and well-being of all participants involved.

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EQUATIONS

ABBREVIATIONS

PV: Photovoltaic

FPV: Floating Photovoltaic

HDPE: High-Density Polyethylene

FRP: Fiber-Reinforced Plastics

MDPE: Medium-Density Polyethylene

CdTe: Cadmium Telluride

a-Si: Amorphous Silicon

CIGS: Copper Indium Gallium Selenide

kWp: Kilowatt 'peak' power output

UV: Ultraviolet

kg: kilo gram

cm: centi meter

IoT: Internet of Things

PVsyst: Photovoltaic Systems software

DC: Direct Current

AC: Alternating Current

kVA: kilo Volt Ampere

IC: Integrated Circuit

IEC: International Electrotechnical Commission

UL: Underwriters Laboratories

Voc: open-circuit voltage

PNomPV(ac): AC Nominal power of PV

STC: Standard Testing Conditions

I-V: I: electrical current. V: electrical voltage.

Rsh: Shunt Resistance

Rs: Series Resistance

I_0: Diode Saturation Current

µA: micro-Ampere

Isc: short-circuit current

Mpp: Maximum power point

ºC: Celsius

Pmpp: power at maximum power point

Vmpp: maximum power voltage

MWp: Megawatt 'peak' power output

Inv. Max DC: inverter maximum DC voltage

Inv. Ph.max DC incl. overload: inverter peak DC voltage including overload

BOM: Bill of Materials

3D: three dimensional

mm: milli meter

CHAPTER 1

INTRODUCTION

In the face of a rapidly changing global energy landscape, the Kingdom of Saudi Arabia has taken a proactive stance in embracing renewable energy, aligning with the nation's Vision 2030 environmental objectives [1]. This shift is critical not only for energy diversification but also for ecological sustainability. In this context, the FPV Power Plant project in the Madinah Region stands as a pioneering initiative. This project was selected due to its innovative approach to addressing two critical challenges: the growing demand for renewable energy and the efficient utilization of space, particularly in geographically constrained areas.

The FPV Power Plant is more than an engineering feat; it is a testament to the potential of combining technology and nature for a sustainable future. The primary goal is to develop an advanced FPV system that efficiently harnesses solar energy in Madinah. This project will generate clean energy while simultaneously reducing water evaporation from Al-Aqoul Lake, showcasing an inventive use of water bodies to combat land scarcity.

Integral to the project's success is the application of knowledge and skills honed through the Electrical Engineering program at the University of Prince Mugrin. It synthesizes core principles from courses like Renewable Energy (EE 459) and Solar Cells & Photovoltaic Systems (EE 404), along with advanced engineering techniques from other key courses in the curriculum. This academic foundation ensures a robust and informed approach to the design and execution of the plant.

By focusing on renewable energy, especially solar power, this capstone project not only aligns with Saudi Arabia's strategic energy goals but also serves as a beacon for sustainable development in arid regions worldwide. It embodies the practical application of electrical engineering in solving real-world problems, marking a significant stride towards a greener and more sustainable future.

1.1. Objectives

- Develop Renewable Energy Sources.
- Innovative Utilization of Water Surfaces.
- Enhance Energy Efficiency.
- Reduce Water Evaporation.
- Implement Advanced Solar Technologies.
- Economic Development.

1.2. Deliverables

- Study, simulate, design, and analyze the real mega FPV Power Plant.
- Build a functional, creative, and representative prototype.
- Conduct financial study: Prove floating PV's cost-effectiveness over land-based systems.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a focused literature review on PV systems, a cornerstone of renewable energy innovation. It synthesizes key findings from academic research, industry developments, and case studies, providing a critical foundation for understanding the technological, environmental, and practical aspects of FPV systems.

2.1. FPV Systems

Elshafei et al. [2] FPV technology involves placing solar modules over water bodies, categorized by their supportive structures: permanent tilt panels on rigid pontoons, tracking patterns with optional pontoons, and lightweight flexibility matrices without pontoons. These systems vary in scale and structural design, including cooled, permanent, and tracking FPVs, with tracking systems offering higher power output despite greater costs. FPVs address space constraints and deforestation risks by utilizing water surfaces, leading to improved efficiency due to reduced shadow effects and lower panel temperatures. Key components include pontoons, mooring devices, photovoltaic modules, and electrical connectors. Innovations in this field include flexible modules adaptable to water movements and bifacial components that capture reflected solar radiation, potentially increasing energy exposure significantly. This diverse range of FPV technologies is pivotal in enhancing solar energy utilization.

Also, Refaai et al. [3] note that there is a wide categorization of the different floating photovoltaics that have been documented in the research, as shown in Figure 1.

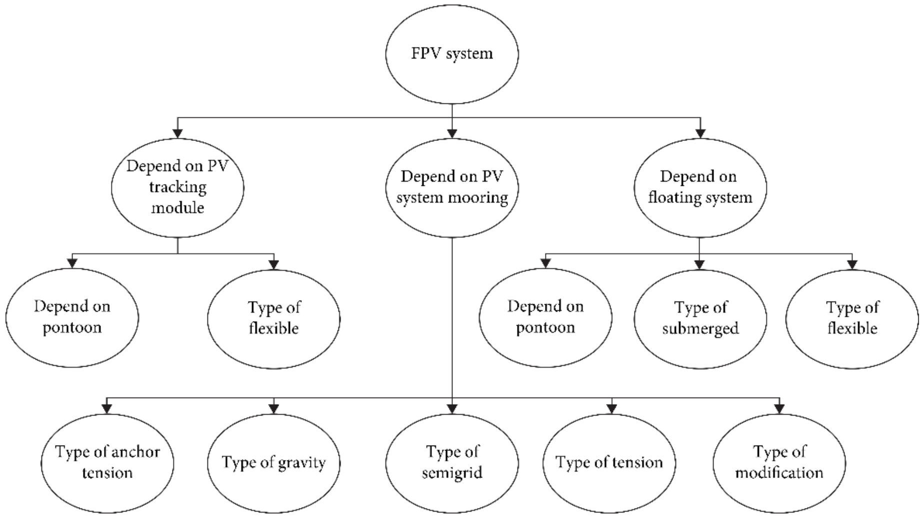


Figure 1. FPV Systems, Different Types of FPV Systems.

2.2. Structural Design of FPV System

The floating structure comprises components like pontoons, floaters, and racks for mounting PV panels. It also includes a mooring subsystem, which consists of a mooring line and an anchor, to stabilize the platform and adjust to water level changes. The mooring line connects the floating structure to an anchor at the lake's bottom, and considering the floats' size is crucial for the platform's design to ensure the buoyant force can counterbalance the platform's total weight under various operating and environmental conditions. Structural design is paramount, focusing on the types and materials of floating platforms, which are primarily divided into two categories: frame arrays and independent floating, Elshafei et al. [2].

The choice of materials for these floating platforms is crucial, with HDPE being the most commonly used material in the majority of FPV power plants worldwide. However, other materials like FRP, MDPE, and ferro-cement are also being utilized, each offering unique benefits and challenges. The design of these floating platforms is vital as it not only supports all necessary components, such as solar PV panels, but also ensures stability and efficiency throughout the project's lifespan, Sachin et al. [4].

According to Edwards et al. [5], floating photovoltaic systems are supported on water by pontoons, which are essentially interconnected floats that bear the weight of the structure. Jiang et al. [6] also highlight this design aspect. The majority of these floats are made from HDPE, as noted by Natarajan et al. [7]. HDPE is chosen for its low maintenance needs, resistance to UV rays, recyclability, corrosion resistance, and strong tensile strength. Another material sometimes used for floats is fiberglass-reinforced plastic, though this is less common, as pointed out by Abdurohman and Adhitya [8]. These floating systems usually have fixed panel angles, which are hard to modify post-installation. Rosa-Clot [9] suggests that one advantage of these floating structures is their relative ease of decommissioning compared to ground-mounted PV systems. Cazzaniga [10] adds that there are additional design options for floating structures, such as single or dual-axis tracking platforms and galvanized steel stands.

2.3. System Cable and PV Module

Cables play a vital role in FPV systems by connecting solar panels to the power inverter located on the platform. Kumar et al. [11] highlight that these cables, often positioned above water, are responsible for transmitting electricity, sometimes extending to an onshore substation. Given the demanding conditions of the marine environment, including constant exposure to saltwater, waves, and wind, the construction of these cables in FPV systems requires meticulous attention to ensure durability and reliability. Moreover, it's essential that the cables are adaptable to fluctuating water and wind levels, as they not only transfer power but also facilitate the movement of the platforms and the transmission of data to monitoring stations. To meet these needs, materials like aluminum, copper, or their combinations are commonly employed in the cables' manufacture, Amer et al. [12].

Luo et al. [13] note that crystalline silicon is the predominant module type used in FPV systems. While these modules are effective in freshwater environments, the industry's shift towards marine environments necessitates modules that can withstand saltwater conditions. This shift requires a move away from traditional metal frames to alternative materials. According to Amer et al. [12], second-generation solar panel technologies like CdTe, a-Si, and CIGS are suitable alternatives for FPV systems, particularly in marine settings.

CdTe solar panels use a slender cadmium telluride coating as their key light-absorbing element. These panels, highlighted by Kaliyannan et al. [14], are preferred in extensive installations due to their superior efficiency in energy conversion and the affordability of their production. Furthermore, compared to various other solar technologies, CdTe panels demonstrate greater resilience to elevated temperatures and maintain effectiveness in conditions of diminished light.

Solar panels made from non-crystalline silicon, also known as a-Si, are characterized by their flexible and lightweight nature. Despite their lower energy conversion efficiencies compared to other technologies, a-Si panels excel in diffuse lighting situations like cloudy days or in shaded areas. Mayville et al. [15] suggest that this feature could be particularly advantageous for FPV systems, where varying light conditions are common due to reflections and ripples on the water's surface.

CIGS solar panels are composed of thin films of copper, selenide, gallium, and indium. These panels are recognized for their high conversion efficiencies and their effective performance in low-light environments. Wijewardena and Kazmerski [16] highlight the notable flexibility of CIGS panels, which allows them to conform to curved or irregular surfaces. This adaptability makes them particularly suitable for FPV systems, where conforming to the contours of the water body may be necessary.

2.4. Coverage Ratio Of Water Bodies In FPV Projects

It's suggested that for natural water bodies or those containing natural habitats, only 50% of the area should be covered by FPVs to limit their impact on aquatic culture. In general, the maximum coverage ratio of water bodies is around 65% on average [17].

The National Renewable Energy Laboratory (NREL) conducted a study on the potential of FPV in the United States, focusing on human-made bodies of water, which are more likely to be managed and have infrastructure in place. This study found that if 27% of the surface area of the identified water bodies were to be covered with FPV systems, they could generate approximately 10% of the nation's energy needs. This percentage was chosen considering various factors including ease of installation and environmental concerns [18].

2.5. FPV Power Plants Review

[19] stated that FPV plants can be classified into three categories based on their size and capacity:

1) Small Size Power Plants (up to 500 kWp): These are typically installed on small water bodies, such as ponds or pools, for local or residential use. An example of

a small size FPV plant is the Far Niente Winery in California, USA, [20] which has a 175 kWp system, shown in Figure 2.

2) Medium Size Power Plants (500 to 1500 kWp): These are usually installed on larger water bodies, such as reservoirs or lakes, for commercial or industrial use. An example of a medium size FPV plant is the Inami town in Japan, [21] which has a 1428 kWp system, shown in Figure 3.

3) Large Size Power Plants (above 1500 kWp): These are the most ambitious and complex FPV projects, which aim to generate large amounts of electricity for the grid or for specific purposes. An example of a large size FPV plant is the Walton-on-Thames in the UK, [22] which has a 6338 kWp system, shown in Figure 4. The area of the floating pontoon is 57,500 square meters [23].

Figure 2. Small Size Power Plant: Far Niente, California, USA, 175 kWp

Figure 3. Medium Size Power Plant: Inami town, Japan, 1428 kWp

Figure 4. Large Size Power Plants: Walton-on-Thames, UK, 6338 kWp

2.6. FPV Advantages and Disadvantages

FPV technology is a relatively new innovation. Nevertheless, they have several benefits and drawbacks compared to land-based solar power systems. Some of the benefits are that they reduce water evaporation, save land space, and improve the efficiency of solar panels by cooling them due to their location on the surface of water body. Some of the drawbacks are that the PV panels are bulky and not easy to move. They also face challenges in securing them against the forces of the water body [24].

CHAPTER 3

LITERATURE ANALYSIS

In this chapter, we will review the top references to provide the important aspects that we want to discuss about FPV Power Plants. This section will help us to identify the current state of the art, the existing gaps, and the potential opportunities for our project.

3.1. FPV System

In this section, we embark on a comprehensive exploration of FPV system design, a pivotal innovation in renewable energy. We will cover the design parameters and constraints, including panel efficiency, flotation system design, and electrical integration.

3.1.1. Design Parameters and Constraints

This section provides an in-depth analysis of the critical design parameters and constraints that govern the development of FPV systems, highlighting the considerations necessary to maximize their efficiency and effectiveness in harnessing solar energy.

3.1.1.1. Panel Type and Efficiency

The choice of solar panels is a fundamental aspect of the design process. Different types of panels, such as monocrystalline, polycrystalline, or thin-film, offer varying levels of efficiency, cost, and physical characteristics. Monocrystalline panels, known for their high efficiency and durability, might be preferable in scenarios where space is limited. Polycrystalline panels, offering a balance between efficiency and cost, are suitable for larger installations. Thin-film panels, although less efficient, can be advantageous due to their flexibility and lower weight, which could be beneficial for floating structures [12].

3.1.1.2. Floating System Design

The floating structure that supports the PV panels is a critical component in the design of FPV systems. It must provide sufficient buoyancy to carry the weight of the panels and associated equipment. Materials such as HDPE are commonly preferred due to their inherent buoyancy, resistance to UV radiation, and robust durability against harsh weather conditions. Furthermore, the design of these structures must prioritize stability, ensuring minimal tilting or rocking which can significantly affect the efficiency of the solar panels [10].

In the realm of FPV systems, there are two primary design classes for the platforms: frame arrays and independent floating systems. Frame arrays involve a connected framework that holds multiple panels, offering a consolidated structure that can be easier to install and maintain. On the other hand, independent floating systems consist of individual units for each panel, providing greater flexibility and adaptability to varying water levels and conditions. Both approaches have their unique advantages and challenges, and the choice between them often depends on the specific environmental conditions, available space, and scalability requirements of the installation site. Integrating these design considerations is essential for creating an efficient, durable, and environmentally harmonious FPV system [2].

3.1.1.3. Mooring and Anchoring Systems

Mooring and anchoring are essential for maintaining the position and stability of the FPV system. The design of these systems must consider local water depth, tide variations, currents, and wind forces. The use of dynamic mooring lines, anchors, and shock absorbers helps in accommodating movements due to waves and wind while ensuring the structure remains in its designated location [2].

3.1.1.4. Tilt Angle and Orientation

The tilt angle and orientation of the solar panels are crucial for maximizing solar energy absorption. This involves calculating the optimal tilt angle that corresponds to the geographic latitude and considering any seasonal variations. Additionally, the orientation of the panels typically faces the equator to ensure maximum sunlight exposure throughout the year [4].

3.1.1.5. Electrical Layout

Electrical design encompasses the integration of solar panels with cables, inverters, batteries (if used for storage), and the electrical grid. This involves configuring the voltage levels, current flow, and safety mechanisms like circuit breakers and grounding systems. The design must ensure minimal energy loss during transmission and adherence to local electrical codes and standards.

In the realm of FPV systems, the choice of inverters is crucial, encompassing types like string inverters, microinverters, central inverters, and hybrid inverters, each tailored to specific system needs and scales. In choosing an inverter, not only the type but also the manufacturer plays a pivotal role. Companies like Fronius, SMA, and Enphase are notable in this sector, each bringing unique strengths. Fronius is renowned for its reliable and efficient string inverters; SMA excels with its robust central inverters, often preferred for large-scale installations; and Enphase is a leader in microinverter technology, offering enhanced performance for systems with shading issues or complex layouts. This diverse landscape of inverter types and manufacturers reflects the varied and evolving demands of PV systems, necessitating a tailored approach to maximize efficiency, reliability, and overall system performance [4].

Cable design and routing for FPV plants require careful planning. In contrast to ground-based solar PV systems, floating solar PV plants have variable cable lengths due to the movement of the floating platform on the water's surface. The wind load and changes in water level are what cause the floating platform to move. To accommodate the floating platform's movement, extra length in the form of slack must be provided. If this is neglected, inadequate cable length could cause cables to break and snap under tension. The cable's voltage, current, and losses are the other factors that determine the type of cable stability for the system, according to Pandey et al. [13]

3.1.1.6. Maintenance and Accessibility

Proper maintenance is essential for the longevity and efficiency of the system. The design should facilitate easy access for routine inspections and repairs. This includes considerations for safe and efficient movement of maintenance personnel and equipment around the floating structure [4].

3.1.1.7. Environmental Regulations

Adherence to local and international environmental regulations can impose constraints on the design. These regulations might dictate permissible materials, the impact on local wildlife, and emissions standards [2].

3.1.1.8. Weather and Climate Conditions

Local weather patterns and climate conditions significantly influence the design. Areas with high wind speeds, frequent storms, or extreme temperatures require robust designs that can withstand these conditions [2].

3.1.1.9. Structural Load Limitations

The floating structure has a maximum load capacity, which limits the weight of the solar panels and associated equipment. This requires a careful balance between system size and structural integrity [10].

3.1.1.10. Budgetary Limitations

Budget constraints often impact the choice of materials, the scale of the installation, and the technology used. Cost-effective solutions must be sought without compromising on efficiency and durability [4].

3.2. FPV Opportunities

In this section, we will discuss the opportunities of floating solar (FPV) in the green energy sector. FPV has many advantages over land-based or rooftop solar systems, such as higher efficiency, lower land use, and environmental benefits. It is important to explore the potential and the prospects of FPV in the current and future energy scenario. Some of the opportunities of FPV are [24]:

- Increasing investments in renewable energy, driven by global investor interest, and enabling regulations in many countries which have made the project tenders more competitive and attractive.
- Improving performance, risk management, and governance of the leading developers, who have overcome the challenges of supply, mobility, and labor.
- Freeing up the equity capital of the developers for further growth, by attracting global funds that are looking for green investments.
- Expanding the global deployment of FPV, which has a potential of 1000 GW, equivalent to the capacity of all photovoltaic solar panels installed worldwide by 2020.
- Utilizing the unused space on water bodies, especially where land use is limited, such as reservoirs and hydropower plants.
- Promoting and encouraging the adoption of FPV many governments, which has provided various subsidies schemes and minimal paperwork.
- Providing professional engagement and livelihood opportunities for various youths, who can work in the installation, service, and repair of the FPV system.

3.3. FPV Challenges

[24] discussed in detail FPV challenges. They can be summarized as follows:

- ❖ The floats are made of UV-resistant HDPE materials, which are bulky and difficult to transport to the site.

- The floats need to be securely attached and moored to withstand harsh weather conditions. This may be challenging if the water depth is deep, or the water body is too large.
- There are no FSPV-specific standards or technical guidelines available, which may affect the quality and safety of the system.
- The data on the water body, such as bathymetry and water tests, may be inaccessible or limited, which may affect the design and performance of the system.
- There is a lack of national production and development of FPV, which may limit the availability and affordability of the system.
- The protection and durability of the FPV plant components may be compromised by the exposure to water, corrosion, or biofouling.
- The installation, service, and repair of the FPV system may be challenging due to the remote and floating nature of the system.
- The social and environmental factors, such as legal, regulatory, stakeholder, and ecological issues, may pose barriers or risks to the FPV system.

CHAPTER 4

PROJECT DESIGN

This section will present the design of our floating solar (FPV) power plant project. The design is based on the problem definition that we stated in the previous chapters, which is to design, install, and operate a FPV system on Al-Aqoul Lake in Madinah, by a simulation and a prototype. We will provide more details on the problem definition, such as the site analysis and components selection. We will also show the related design and diagrams, hence the project specifications, such as the type, size, and number of solar panels, floats, inverters, cables, and moorings, will be detailed. In addition, we will discuss the limitations, restrictions, and conditions of operation of our FPV system.

4.1. Problem Formulation

This project aims to provide a sustainable renewable energy power plant in an innovative approach to solve the problem of water evaporation, land acquisition, and energy efficiency. As a result, we need to construct an accurate and functional design, so, we are required to have a proper and comprehensive analysis. In the previous chapter, we had performed the needed analysis. Therefore, this chapter will detail all specifications related to our design, including selecting the best components and performing an adequate site study.

4.1.1. Location and Climate Analysis

Al-Aqoul Lake, located in the Medina region of Saudi Arabia, is a prominent geographical feature with significant environmental and topographical characteristics. Spanning an area of approximately 3,609,849.04 m2 and encompassing a perimeter of 15,772.53 m by Google Earth, as shown in Figure 5, this lake is a key component of the Al-Aqoul area. By using PVsyst software, we found the geographic coordinates of Lake Al-Aqoul, which are 24.5232°N latitude and 39.747°E longitude, with an altitude of 628 meters, as shown in Figure 6. The local time zone for this location is UTC+3.

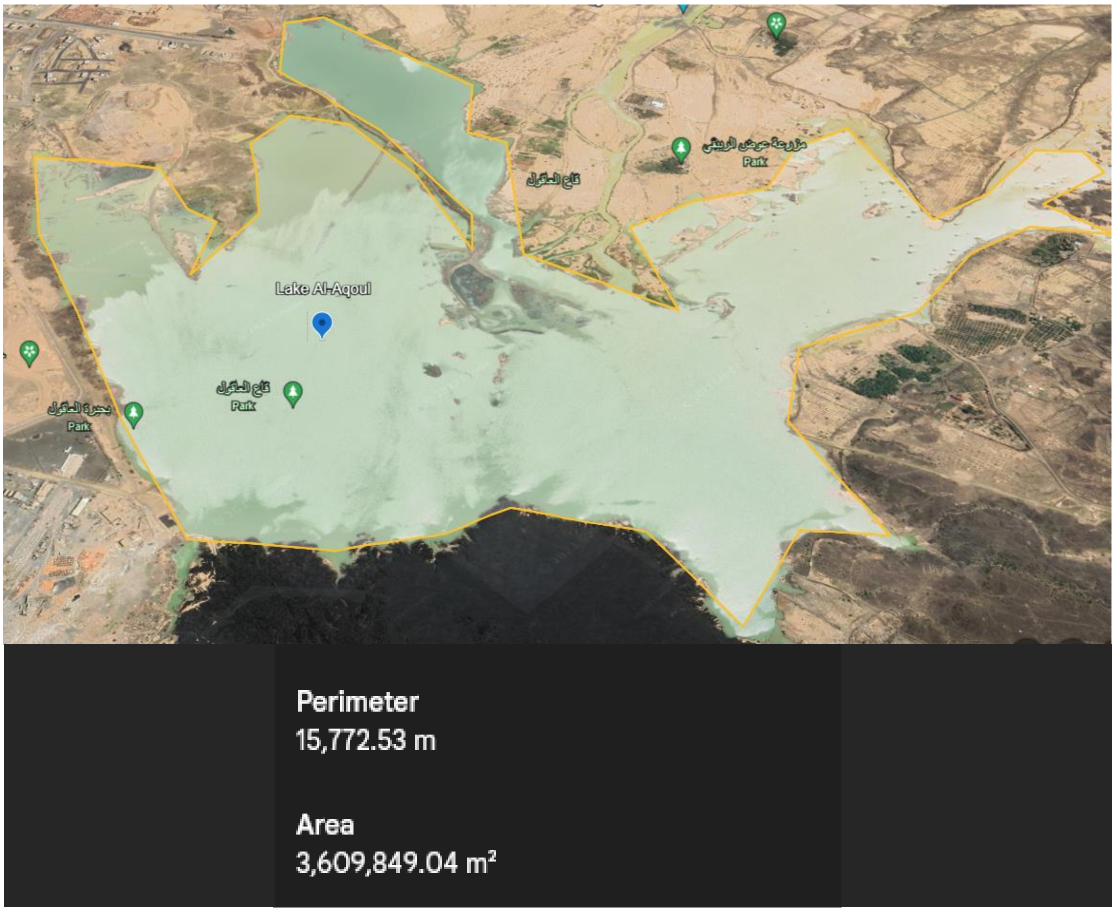


Figure 5: Site Data by Google Earth

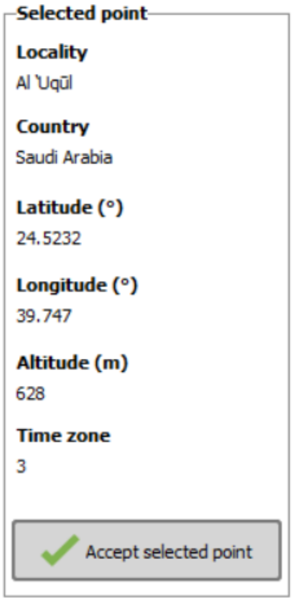


Figure 6: The Geographic Coordinate by PVsyst Software

During our 5 visits to Al-Aqoul Lake in the Medina region, we captured several photographs that reflect the lake's expansive and serene environment, in different seasons of the year. These images complement our geographical analysis and offer a visual insight into the site's natural beauty, as shown in Figure 7.

Figure 7. Al-Aqoul Lake Photo.

We have an issue that may rise in the futre, from the lake's images and inspections, water level varies a little around the year. Although we did not find any areas inside of the lake that are epmty (with 0 water lever), it might happen in the future. Therefore, we have developed a simple and sophisticated electronic scheme to solve this issue, it is provided in Chapter 4.

4.1.1.1. Clouds

In Medina, the seasonal variation in cloud cover significantly impacts solar panel efficiency. The period of least cloud cover, from around May 16 to July 3, with June being the clearest month, provides optimal conditions for solar power generation. During this time, clear, mostly clear, or partly cloudy skies about 89% of the time allow for maximum sunlight exposure, greatly benefiting solar panel output, especially those designed for high efficiency in direct sunlight. Conversely, from July 3 to around May 16, the increase in cloud cover, peaking in December with overcast or mostly cloudy skies about 26% of the time, reduces the efficiency of solar panels. This is due to the decreased direct sunlight reaching the panels. However, panels optimized for low-light conditions, such as thin-film solar panels, might still perform relatively well. Figure 8 and Table 1 in the provided data detail the average cloud cover in Medina and the percentage of time spent in each cloud cover band, respectively, further illustrating the impact of these seasonal changes on solar energy generation [25].

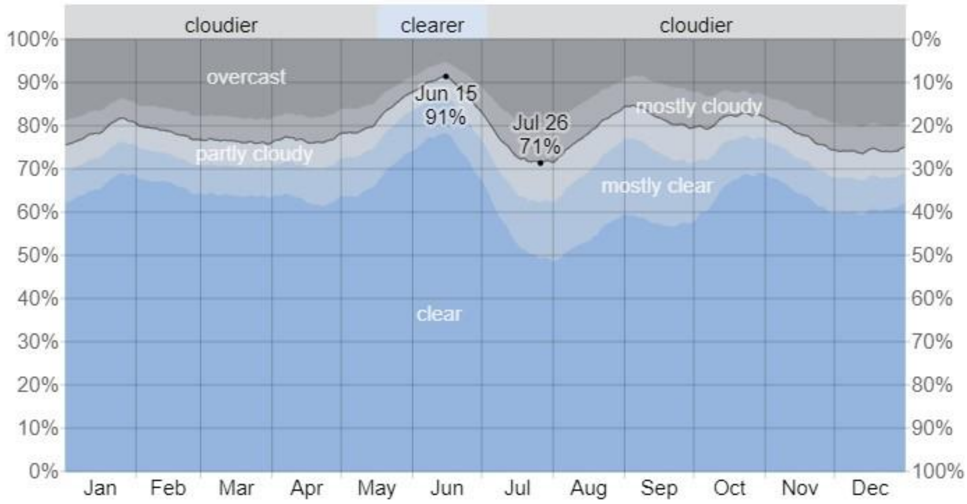


Figure 8: Average Cloud Cover In Medina

Table 1: The Percentage of Time Spent In Each Cloud Cover Band

Fraction	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cloudier	21%	22%	24%	23%	18%	11%	26%	21%	18%	18%	22%	26%
Clearer	79%	78%	76%	77%	82%	89%	74%	79%	82%	82%	78%	74%

4.1.1.2. Precipitation

Precipitation in Madinah is extremely scarce, aligning with its desert climate. Depending on last year, the annual mean of rainfall is about 85.96 mm as shown in Figure 9. The very low rainfall implies that most days are without significant precipitation, which is beneficial for solar energy collection but may necessitate the occasional cleaning of solar panels to remove dust and debris [26].

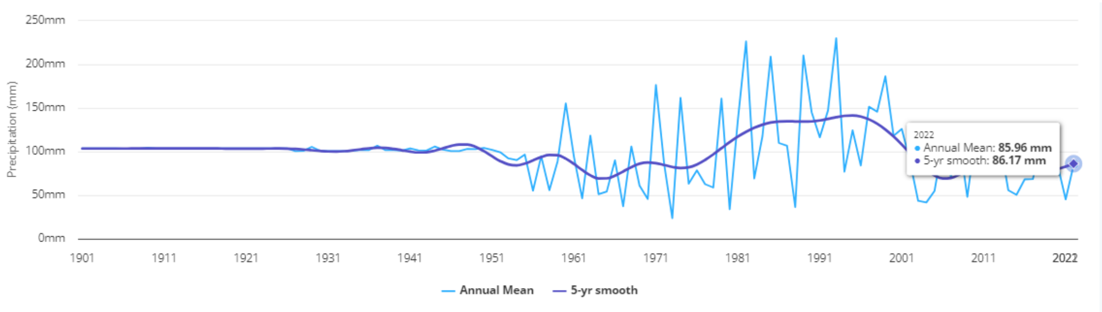


Figure 9: Observed Annual Precipitation of Madinah, Saudi Arabia for 1901-2022

4.1.1.3. Wind

In Medina, the hourly average wind speed and direction at 10 meters above ground level exhibit mild seasonal changes, significantly influenced by local topography and other factors. Wind speeds and directions can vary more than hourly averages suggest. The year is divided into windier and calmer periods. From November 19 to August 26, the average wind speed is typically above 9.0 miles per hour, with July being the windiest month, averaging 10.2 miles per hour. A less windy period lasts from August 26 to November 19, with October being the calmest month, having an average wind speed of 7.9 miles per hour. Regarding wind direction, for 8.1 months, from January 28 to September 30, winds predominantly came from the west, peaking at 68% on July 22. From September 30 to January 28, winds mostly blow from the east, with the highest frequency (44%) on January 1 [25].

The impact of wind on solar panels, particularly in bodies of water like floating photovoltaic systems, is notable. Wind over water bodies tends to be stronger and more consistent, potentially increasing the cooling effect on solar panels, which can enhance their efficiency [24]. However, this also means that solar panel installations need to be robustly engineered to withstand these higher wind forces, ensuring the stability and longevity of the system. This data, illustrated in Figure 10 and Figure 11, underscores the importance of considering wind patterns in the design and placement of solar panels in Medina, especially for floating installation.

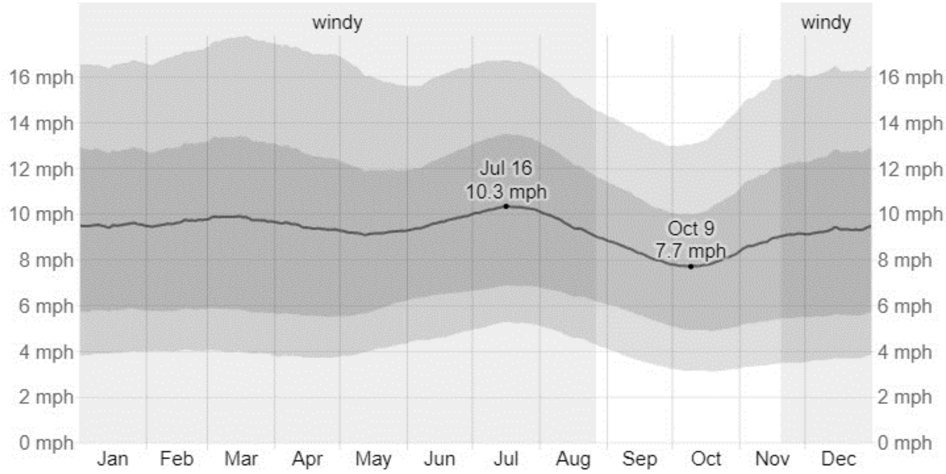


Figure 10: Average Wind Speed in Medina

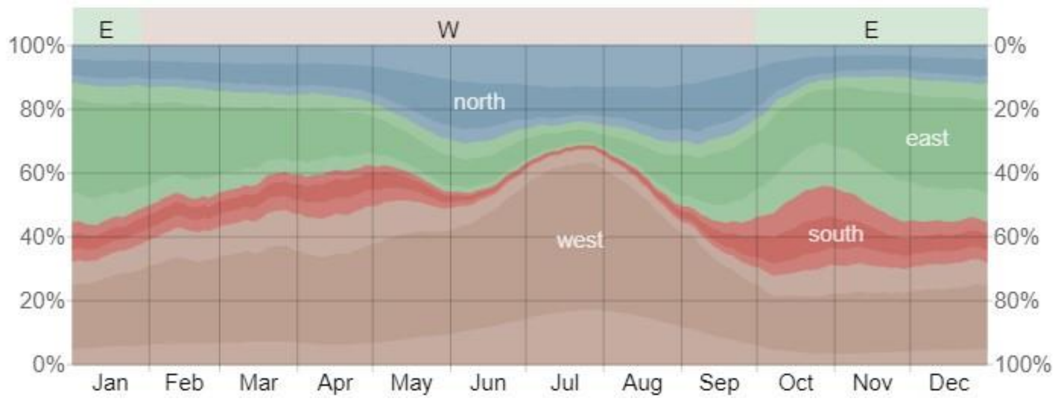


Figure 11: Wind Direction in Medina

4.1.1.4. Temperature

In Medina, the hot season extends for 4.6 months, from May 17 to October 3, with average daily high temperatures exceeding about 39.4°C. The warmest month is August, featuring average highs around 42.8°C and lows near 30.6°C. Conversely, the cool season spans 2.9 months, from November 29 to February 25, with daily high temperatures typically below 27.8°C. January is the coldest month, with average lows around 12.8°C and highs near 24.4°C. Figure 12 shows the average temperature in Medina [24]. So, one advantage of FPV panels, particularly relevant in these conditions, is their interaction with the body of water's temperature. This interaction helps prevent the panels from overheating, which is especially beneficial during Medina's hot season. By maintaining a cooler operational temperature, FPV panels can operate more efficiently, avoiding the efficiency losses typically associated with elevated temperatures in traditional land-based solar panels [2].

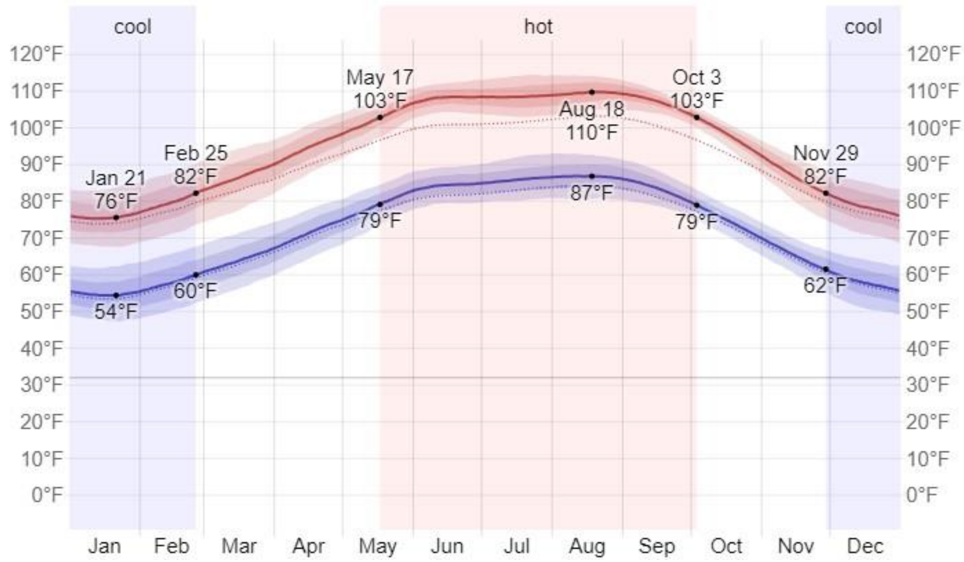


Figure 12: Average High and Low Temperature in Medina

4.1.1.5. Sun Light & Solar Energy

The duration of daylight in Medina changes throughout the year. In 2023, the year's shortest day falls on December 22, offering 10 hours and 37 minutes of daylight, while the longest day is on June 21, providing 13 hours and 39 minutes of daylight. Sunrise timings also vary, with the earliest at 5:32 AM on June 9 and the latest at 7:07

AM on January 14. Similarly, sunset times range, with the earliest at 5:32 PM on November 29 and the latest at 7:14 PM on July 3 [25]. These variations in daylight length and sunrise/sunset times have a direct impact on solar panel performance. Longer daylight hours during the summer months, especially on the longest day, mean more available sunlight for solar panels to convert into energy. Conversely, shorter winter days result in less sunlight and, consequently, reduced solar energy production. This seasonal fluctuation in solar irradiance needs to be considered for effective solar energy system planning and management in Medina, as illustrated in Figures 13 and 14.

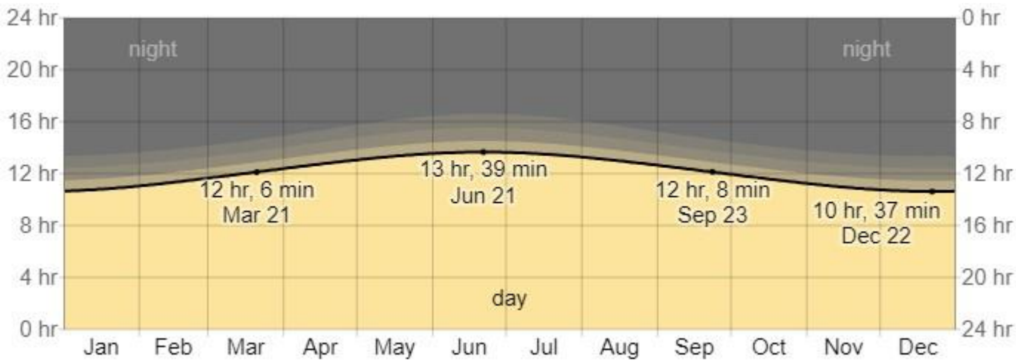


Figure 13: Hours of Daylight and Twilight in Medina

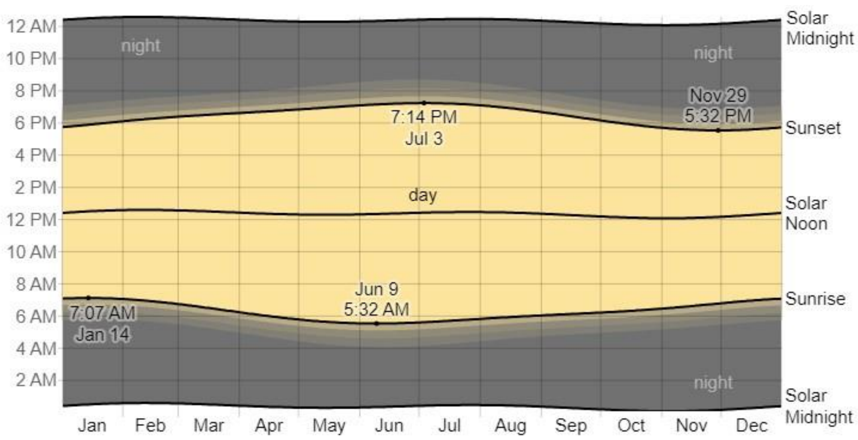


Figure 14: Sunrise & Sunset with Twilight in Medina

Figure 15 offers a concise depiction of the sun's position throughout the reporting period, measured in terms of solar elevation (the angle of the sun above the horizon) and azimuth (its direction relative to a compass bearing). Days of the year are plotted along the horizontal axis, while hours of the day are on the vertical axis. The background color for each specific day and hour combination represents the sun's azimuth at that time. Additionally, black contour lines are drawn to indicate constant levels of solar elevation [25].

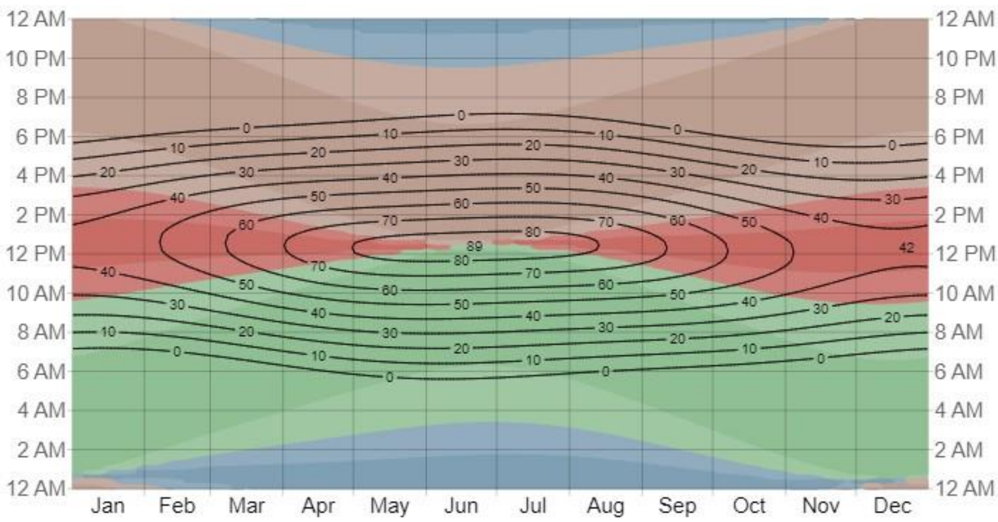


Figure 15: Solar Elevation and Azimuth in Medina

This section examines the total daily shortwave solar energy, which includes both visible light and ultraviolet radiation, reaching the ground over a broad area. It accounts for factors like day length, sun elevation, and atmospheric absorption. There's a significant seasonal variation in this energy throughout the year. The brighter part of the year in Medina spans 3.4 months, from May 5 to August 18, with daily shortwave energy averaging over 7.6 kWh per square meter. June is the brightest month, averaging 8.4 kWh.

Conversely, the darker period extends for 2.9 months, from November 4 to January 31, with energy falling below 5.2 kWh per square meter, and December is the darkest month, averaging 4.4 kWh as shown in 16 [25].

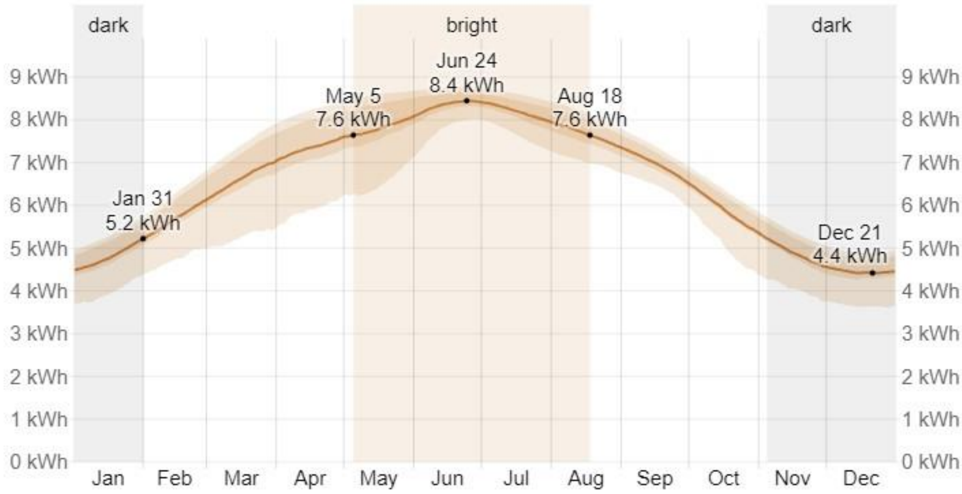


Figure 16: Average Daily Incident Shortwave Solar Energy in Medina

4.1.2. Floater and Moorings Selection

Based on PV Panel analysis in chapter 3, in floater, they usually use frame arrays, which are often employed in larger installations over 1 MW and consist of rows of cylindrical or rectangular floats, as shown in Figure 17. On the other hand, there is another type, which is independent floating modular units made from HDPE, linked together to create surface pontoons, as shown in Figure 18 (a-b). Overall, we recommend using frame arrays in real projects because these floats support the PV panel frames arranged in arrays, offering benefits such as ease of maintenance, improved ventilation, and enhanced PV generation due to the cooling effect of water. [2].

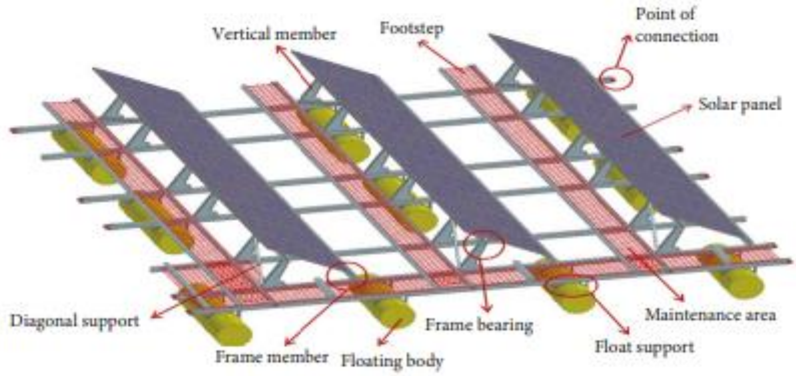


Figure 17: Frame array design of FPV floating platform

Figure 18: (a) Float module. (b) Connected modules forming pontoon.

For moorings there are two main types: Chain moorings, primarily made of galvanized steel, are commonly used in shallow waters up to 100 meters deep for long-term mooring, thanks to their low elasticity and high resistance to force, which minimizes vessel movement and enhances anchor performance. However, they are heavy and prone to corrosion. Rope moorings, on the other hand, are made from synthetic fibers like nylon, offering high elasticity and buoyancy, making them suitable for deep water applications. They are lighter than chains but require more maintenance and are more expensive, with a need for regular inspections to avoid damage [27]. However, we recommend using chain moorings because of their advantages and stability for the system.

The mathematical calculations for the related parameter:

- The submerged pipe cross-sectional area, As, is given by:

$$A_s = \theta * \left(\frac{D}{2}\right)^2 - L_1 * L_2. \qquad (1)$$

- The buoyant force is given by:

$$F_B = g * \rho_w * L_p * A_s, \qquad (2)$$

where L_p is the total HDPE pipe length and ρ_w is the density of the water.

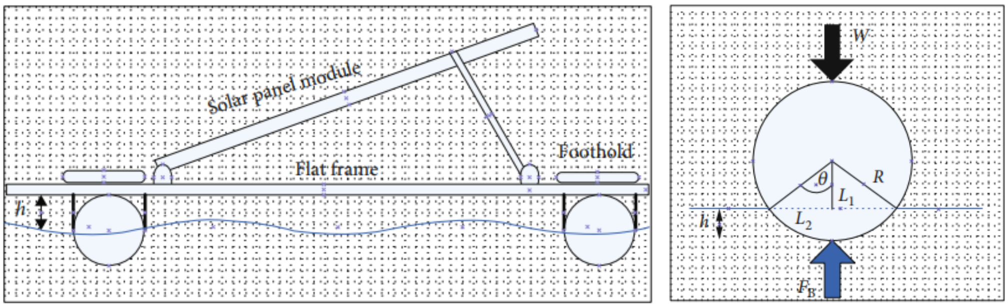


Figure 19. (a) Illustration of Mounting Racks Carried by Pipe Pontoons. (b) Parameters Used in The Calculations

4.1.3. PV Panel Selection

Based on PV Panel analysis in chapter 3, the JA Solar 545W Mono panels shown in Figure 20, known for their monocrystalline silicon technology, present a compelling option. Their balance of high efficiency, resilience to harsh conditions, competitive pricing, and proven performance in FPV systems makes them a noteworthy choice for the real project. Let's delve into the specifics of these panels to understand their suitability for our needs:

- Efficiency and Technology: JA Solar panels generally offer an efficiency between 20% and 21%, which is above average in the market. The company employs modern solar technologies such as half-cut cell construction, PERC cell technology, and busbars, enhancing the performance and quality of their panels [28].

- Cost-Effectiveness: JA Solar panels are priced competitively, with a cost per watt between $0.55–$0.65. This makes them a more affordable option compared to some other brands, while still maintaining high efficiency, especially for their price range [28].
- Durability and Warranty: The panels exhibit good mechanical loading tolerance, able to withstand substantial wind speeds, which is crucial for floating systems that might face harsh weather conditions. JA Solar typically offers a 12-year warranty for the product and a 25-year warranty for performance, with some models like bifacial panels having extended warranties and better degradation rates [28].
- Specific Use in Floating PV Systems: JA Solar has already successfully supplied modules for floating PV systems, such as Spain's first grid-connected floating solar plant and a 10MW project in Malaysia. The use of mono-facial and bifacial modules in these projects, which can be installed in various orientations and inclination angles on different floating systems, demonstrates their adaptability and effectiveness in such applications. Additionally, the water environment of floating systems helps in controlling the surface temperature of the modules, thereby enhancing power generation [29].

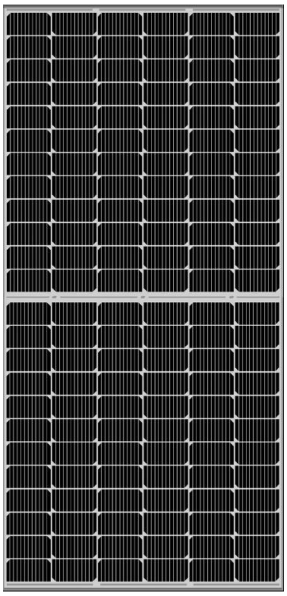


Figure 20: JA Solar 545W Mono Panel

4.1.4. Inverter Selection

In the specialized field of FPV systems, various inverter types like string inverters, microinverters, central inverters, and hybrid inverters are considered, each with distinct advantages for different system scales and requirements. Among these, string inverters are particularly notable for their alignment with the unique needs of FPV systems. Delving into the choice of string inverters, it's essential to look beyond just the type to the manufacturer, where Fronius emerges as a standout choice. The integration of Fronius’s reputable string inverters into FPV systems encapsulates a holistic approach, combining the technological strengths of string inverters with Fronius's innovation, reliability, and efficiency. This combination makes Fronius string inverters an exemplary selection, addressing the specific challenges and maximizing the potential of FPV installations.

Fronius is renowned for its innovation and quality in the solar energy sector. Their string inverters are particularly noted for their reliability and efficiency, which is a critical factor for FPV systems exposed to unique environmental challenges. The proven track record of Fronius in advancing string inverter technology, with a focus on efficiency and power density, ensures that their products are at the forefront of solar energy technology. This continual development is vital for maintaining high performance in the dynamic conditions faced by FPV systems [30].

In terms of power management, Fronius string inverters excel in enabling effective grid integration and control. This capability is essential for FPV systems, which need to manage the dynamics of power distribution and quality effectively. Fronius inverters facilitate active participation in feed-in power management, contributing to grid stability and operational efficiency, crucial aspects in the context of floating installations [30].

Fronius string inverters also stand out in environmental performance and analytics. They can provide comprehensive environmental data analytics, integrating inputs like irradiation and module temperature, which is highly beneficial for FPV systems where environmental factors significantly impact performance. This feature helps optimize the performance and efficiency of the PV system, an aspect where Fronius inverters show their strength [30].

Safety features in Fronius string inverters, such as series arc detection and AFCI, are paramount for FPV systems. These safety functions minimize fire hazards and ensure operational safety, a critical consideration given the unique installation environment of FPV systems [30].

Cost-effectiveness is another domain where Fronius string inverters shine. Compared to alternatives like microinverters, Fronius inverters are more economical in both initial installation and long-term operation, a crucial factor for budget-conscious FPV projects [31].

4.1.5. Cable Selection

Based on PV Panel analysis in chapter 3 for the cable of the FPV Panel System, we have suggested the MC4 WiLEADER® floating solar cable, as shown in Figure 21, which presents a comprehensive solution tailored to the unique requirements of solar power systems, including FPVs, also considered the voltage, current, and losses in the system, as shown in Table 2.

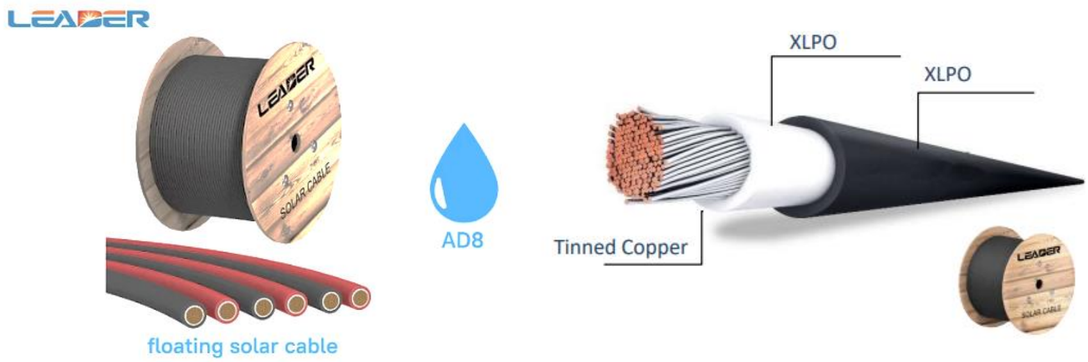


Figure 21: MC4 WiLEADER® Floating Solar Cable

The rationale behind this choice encompasses several key factors:

- Specialized Design for Solar Systems: The MC4 WiLEADER® cable is specifically designed for photovoltaic solar systems, ensuring optimal compatibility and performance with solar panels and related equipment.
- International Certifications: This cable has earned multiple international certifications, including TUV, UL, IEC, CE, and RETIE. These certifications attest to its quality and reliability, ensuring that it meets global standards such

as UL4703, IEC62930, and EN50618/CPR.

- Versatility: The cable is suitable for a wide range of solar power applications, from large-scale solar power stations to rooftop and water-surface floating power stations. This versatility makes it an ideal choice for diverse project requirements.
- Durability in Harsh Environments: It is engineered to withstand harsh environmental conditions prevalent in solar installations, such as high temperatures, humidity, and salt content. This resilience is crucial for FPV systems, especially those located in challenging environments like lakes, sea sides, and deserts.
- Long-Term Performance: The cable's design emphasizes stable and secure connections, which are essential for the long-term safety and efficiency of photovoltaic systems.
- Safety and Efficiency: Ensuring the safe and efficient operation of PV installations, the MC4 WiLEADER® cable aligns with our goal of achieving sustainable and profitable photovoltaic operations.

Table 2: Specifications of Photovoltaic Power Transmission Cable

Conductor	Class 5 (flexible) tinned copper, based on EN 60228 and IEC 60228	Smoke Emission	Based on UNE-EN 60754-2 and IEC 60754-2.
Insulation & Sheath Jacket	Polyolefin Copolymer electron-beam cross-linked	European CPR	Cca, according to EN 50575
Rated voltage	1000/1500VDC,Uo/U=600V/1000VAC	Water performance	AD8
Test voltage	6500V,50Hz,10Min	Minimum bend radius	5D (D:cable diameter)
Temperature Rating	-40^{o}C-120^{o}C	Optional features	Meter by meter marking, rodent-proof and termite-proof
Fire Performance	Flame non-propagation based on UNE-EN 60332-1 and IEC 60332-1	Certification	TUV/UL/RETIE/IEC/CE/RoHS

4.2. System Designs and Diagrams

After preparing all data from the previous sections, we are ready to start the designs and diagrams that distinguish all aspects of our project. However, since we aimed to provide a simulation for the real FPV system, and a prototype for a scaled down system, some designs will be for the simulation, while others will be for the prototype.

Figure 22 shows the Flow Chart of our project. It states:

- The start.
- The end.
- Data (input / output).
- The Processes.
- The Decision.

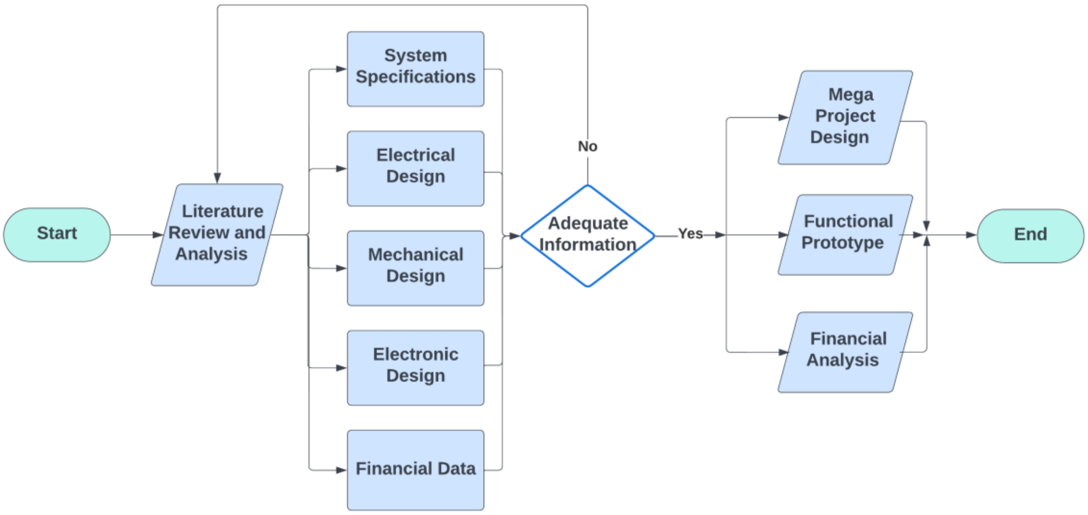


Figure 22. Project Flow Chart.

4.2.1. Mechanical Design

The first design, as shown in Figure 23, that we will provide is a mechanical design for the prototype. This design includes the floating structure, the mooring system, panels' holding structure, and the electric system (Motors and PV panels). For the electric system, it is mainly just the PV panels, however, we will suggest later an electronic system to be integrated with this system, therefore, we are including the motors to indicate that.

There is another mechanical design for the prototype. This design includes the floating structure, panels' holding structure, and a control unit (battery and electronic devices) to operate the water level sensor, as shown in Figure 24.

The mechanical structure is done by Autodesk Fusion 360 and is shown in the next figure.

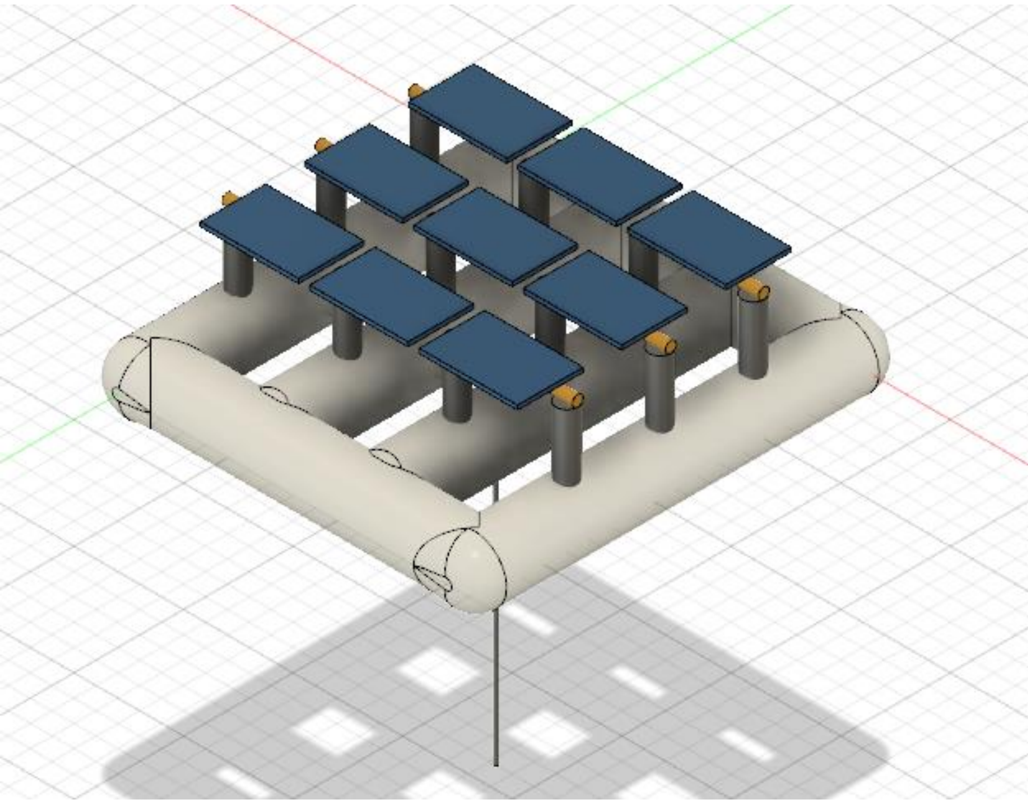


Figure 23. Fisrt Alternative Design.

We can see PV panels in blue, the white structure illustrates the white plastic pipes that we will use. These pipes are 30 cm in diameter, and they are very light. The objects in yellow are the motors. The grey pipes indicate the plastic pipes that will hold the PV panels. They are 5 cm in diameter and lightweight. Finally, the thin rod that is going down from the structure is an indication of the mooring system. The mooring system will be mostly an iron chain connected to a 10 kg weight at the end (that will be at the bottom of the lake).

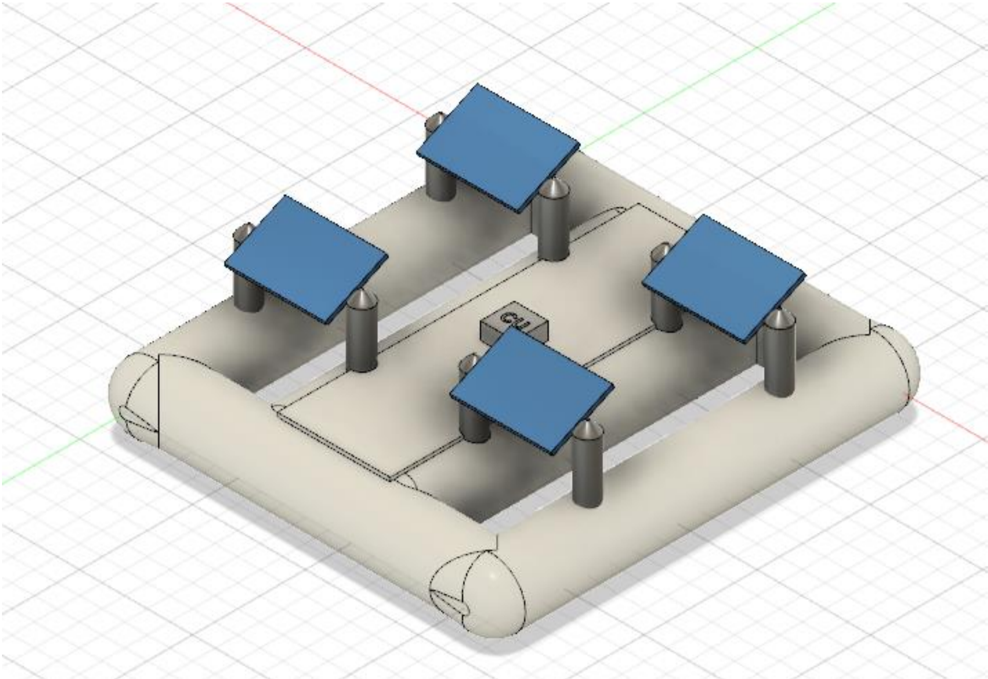


Figure 24. Second Alternative Design.

The second mechanical design, as shown in Fig.24, features a floating structure made of 30 cm diameter white plastic pipes for buoyancy, with 5 cm diameter grey pipes holding the blue PV panels. At the center, a control unit houses the battery and electronic devices to operate the water level sensor. This alternative is selected for its simplicity, enhanced monitoring capabilities, and budget-friendliness.

We identified the standards for the detailed design of the selected alternative based on a literature review and real project implementation.

We will select the second alternative design for the following reasons:

- Simplicity and Maintenance: The second design is simpler and easier to maintain. The absence of the mooring system and motors reduces mechanical complexity and potential points of failure.

- Control and Monitoring: The integration of a control unit with a battery and electronic devices for the water level sensor provides better monitoring and control capabilities, ensuring the system's efficiency and responsiveness.
- Budget: The second design is more cost-effective. By eliminating the motors and mooring system, the overall cost of materials and assembly is reduced, making it a more budget-friendly option.

Detailed Design of the Selected Alternative

- ✓ Floating Structure: The floating structure employs 30 cm diameter white plastic pipes to ensure buoyancy and stability for the entire system. These pipes are chosen for their light weight and durability, making the structure easy to deploy and maintain.
- ✓ Panels' Holding Structure: The PV panels are supported by a holding structure made of 5 cm diameter grey pipes. These pipes are lightweight yet robust, providing secure mounting and optimal positioning for the panels to maximize solar energy capture.
- ✓ Control Unit (Battery and Electronic Devices): The control unit features lithium-ion batteries, selected for their high energy density and long cycle life, tailored to meet the power requirements of the water level sensor and other electronic components. Integration of the water level sensor and electronics is achieved using an Arduino system, equipped with a buzzer and sensor, ensuring efficient monitoring and control of the water level and overall system performance.

In floating photovoltaic platform design, the size of the floats plays a vital role. The floats must generate a buoyant force that is equal to the weight of the fluid they displace. This buoyant force must be capable of supporting the entire weight of the platform, including all components and additional loads, across a range of operating and environmental conditions. Ensuring this balance is key to maintaining the platform's stability and effectiveness. The floats are represented by the white plastic that we discussed in the previous paragraph.

4.2.2. Electrical Design

This design represents the circuitry used in the real FPV system; it is taken from the simulation of the system by PVsyst. The following figure shows the design.

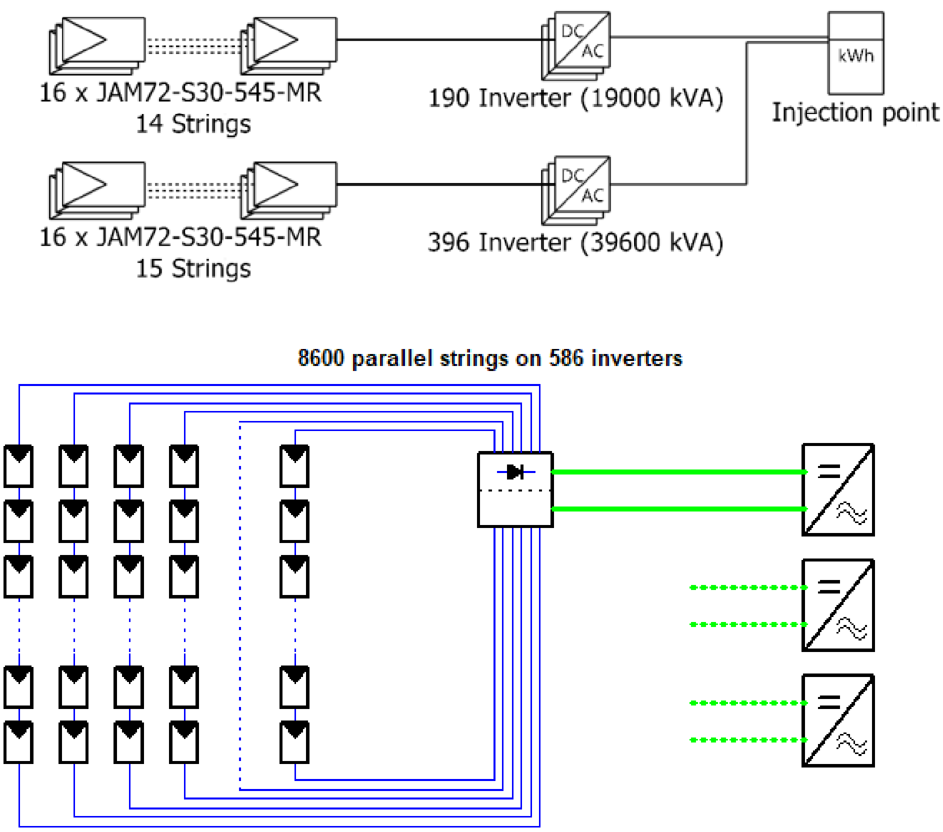


Figure 25. PVsyst Electrical Design

This design is a one-line diagram of the system. It shows the connection of the panels with itself, and with the inverter, then, the connection of inverters with the injection point, because it is a grid-connected system. A grid-connected system is a solar PV system that is connected to the electricity grid, which means that its DC output is converted to AC, then injected to the grid.

The PV panels connection is as follows:

- The whole system is represented by one array.
- The array has 16 panels in series and 8600 strings in parallel, the 16 panels represent a single string, so they are 137,600 panels. Then they are connected to 586 inverters.

The number of solar panels is determined by PVsyst based on the available space for the solar system. We have chosen the space of the solar park to be 360,985 square meters, which is 10% of the lake's surface area. The reasons of this are:

1- Available water area: since the lake is not deep that much.
2- System design: since our floating park does not prioritize much spacing for water flow.
3- Lake topography: the lake has a fluctuation in its topography during the year, because the water level depends on the rain mainly, so it is safer to choose a lower area for the panels, and this area is selected to be on the places that surely would have water in all of the year's seasons.

In addition, before choosing the 10% area, we have studied the specification of 3

Floating Solar System projects:

- FPV of Queen Elizabeth II reservoir [50]:

- Location: The UK's largest floating solar farm is situated on the Queen Elizabeth II reservoir near Walton-on-Thames, Surrey.
- Number of Panels: It comprises more than 23,000 solar photovoltaic panels.
- Capacity: The total capacity of this floating solar farm is 6.3 megawatts (MW).
- Panels area = 57,500 m^2
- lake area = 1 279 000 m^2
- % of solar system = 4.50%

Figure 26. FPV Project 1

- Sirindhorn Dam Floating Solar Farm [51]:

- Location: Sirindhorn, Thailand.
- Number of Panels: 145,000 solar photovoltaic panels.
- Capacity: The total capacity of this floating solar farm is 45 megawatts (MW).
- Panels area = 121,000 m^2

- lake area = 2 000 000 m^2 (area taken manually, not available on internet)
- % of solar system = less than 1%

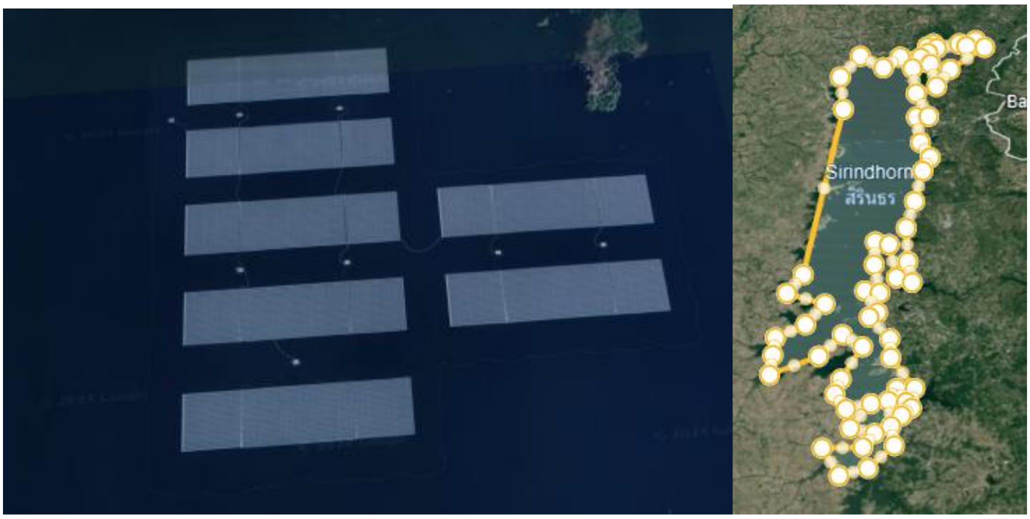


Figure 27. FPV Project 2

- Sembcorp FPV Farm [52]:

- Location: Singapore.
- Number of Panels: 122,000 solar photovoltaic panels.
- Capacity: The total capacity of this floating solar farm is 60 megawatts (MW).
- Panels area = 450,000 m^2
- lake area = 1 235 737 m^2 (area taken manually, not available on internet)
- % of solar system = 36.42%

Figure 28. FPV Project 3

4.2.3. Electronic Designs

This subsection will provide the implemented electronic design, and a suggested electronic system design.

4.2.3.1. Depth Warning System

In this part demonstrates a simple system that solves enormous problem, it is depth warning system!

Al-Aqoul Lake's fluctuating water levels pose potential challenges, particularly in areas with varying depths. Although instances of low water levels are rare, we've developed a simple yet sophisticated solution to prevent any risks. Our Depth Warning System, depicted in the following illustration, serves as a proactive measure to ensure the safety and efficiency of our floating PV power plant, alerting us to any deviations in water levels and allowing for timely adjustments.

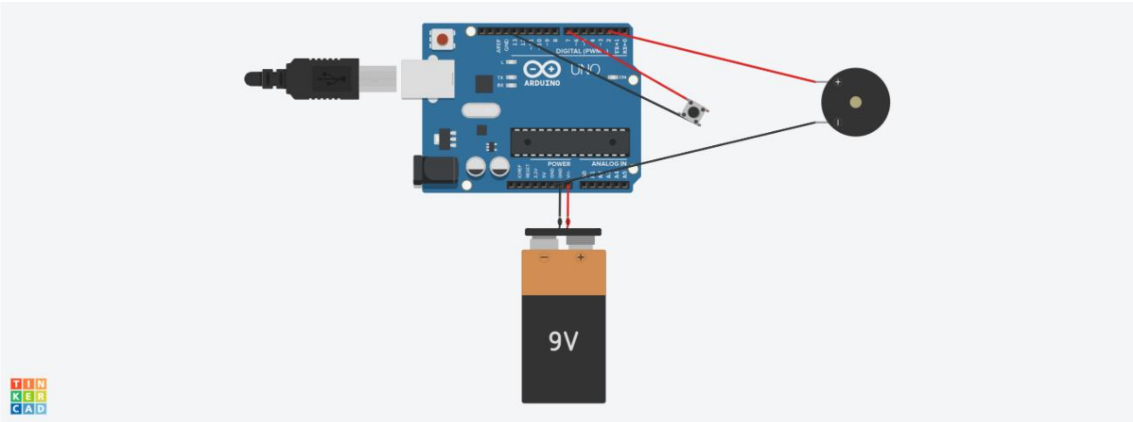


Figure 29. Depth Warning System

This schematic is done by Tinkercad. It has a 9V battery to power the Arduino. Despite the fact that we already have our battery that will be charged by the panels and can be used for the Arduino, we used an independent battery because this is the professional practice of separating the systems in case any damage happens. In addition, it has a simple passive buzzer, and a push button. The mechanism is that when the button is pressed, the buzzer will activate. The button is put in the bottom of a specific rod, to represent a simple depth sensor, when it will be pressed, the buzzer will activate. Therefore, the buzzer is like the alarm of the system. The Arduino is like the simple microcontroller of the system, and it has the code of that process, the code is provided in Appendix 1. The implemented mechanical design is supplied in the Implementation Chapter.

This system can be upgraded to provide better performance. We can put an IoT Raspberry Pi that supports Wi-Fi signals instead of the Arduino, to support wireless and wide-range signals to the operator. Also, we need to have a signals transmitter instead of the buzzer. Finally, for the push button below, we can add a real depth sensor that has better functionality and accuracy.

4.2.3.2. Suggested Tracking System

This design is for a solar tracking system that could be applied in the prototype in the next semester.

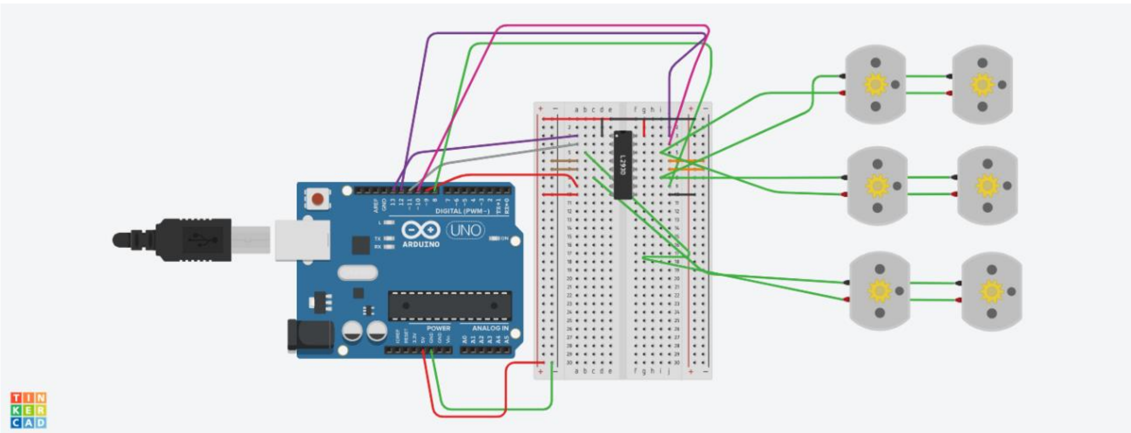


Figure 30. Suggested Electronic Design.

This schematic is done by Tinkercad. It shows 6 DC motors that will rotate the PV panels. An IC, which is H-bridge motor driver, to control the motors rotation. A microcontroller, which is the Arduino Uno R3. It can be programed to rotate the motors in a specific time. Nevertheless, we can use any other tracking mechanism. The preliminary code for motors' rotation using the Arduino is provided in Appendix 1.

The design and implementation of the electronic system is a large amount of work for a team of two. However, the purpose here is just to present the design that could be applied if there are no problems in the execution of the prototype and the simulation.

4.3. System Specifications

In this section, we will determine and analyze the parameters, conditions of operation, and limitations of our simulation.

First, we will start with the site parameters and general parameters, shown in the next figure.

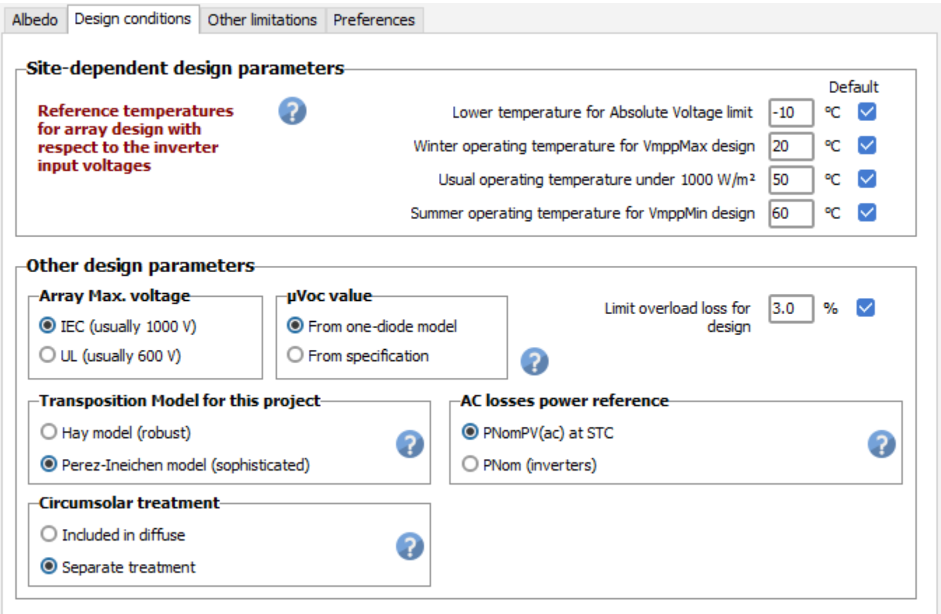


Figure 31. Main Parameters.

- Site-dependent design parameters: Reference temperatures for array design with respect to the inverter input voltages: This would typically include a lower temperature for the absolute voltage limit and standard operating temperatures for both summer and winter, which would affect the voltage output of the PV panels.
- Other design parameters: Array Maximum voltage: Standards like IEC (International Electrotechnical Commission) may specify a usual voltage (1000 V is mentioned, which is common for large-scale installations), and another standard is listed as UL (Underwriters Laboratories), usually 600 V, which is more typical for residential systems in the United States.
- Voc value: Options to choose the Voc (open-circuit voltage) value from either a one-diode model or from specification. This parameter is essential for ensuring the PV system does not exceed the inverter's maximum voltage limit.
- Limit overload loss for design: Expressed as a percentage (3.0% is listed), this refers to the acceptable level of power loss due to inverter overload. This needs to be minimized to ensure system efficiency.
- Transposition Model for this project: Options between the Hay model, which is robust, and the Perez-Ineichen model, which is more sophisticated. These models are used to calculate the solar irradiance on tilted surfaces, which is critical for determining the expected energy production of the PV system.
- AC losses power reference: PNomPV(ac) at STC: This likely refers to the nominal power of the PV system at standard test conditions, related to AC power.
- PNom (inverters): This could specify that the reference for AC losses should be based on the nominal power rating of the inverters.

- Circumsolar treatment: This involves options for including circumsolar radiation (the solar radiation from the vicinity of the sun) in diffuse radiation calculations or treating it separately. The treatment of circumsolar radiation can affect the accuracy of the energy yield prediction for the solar PV system.

Second, the panel parameters are discussed after the following figure.

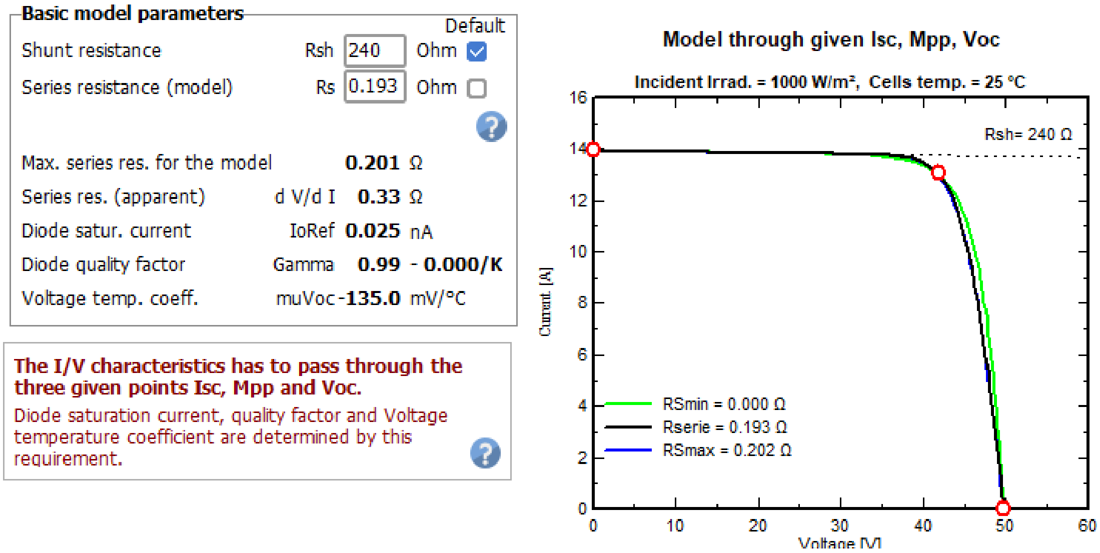


Figure 32. PV Panel Parameters.

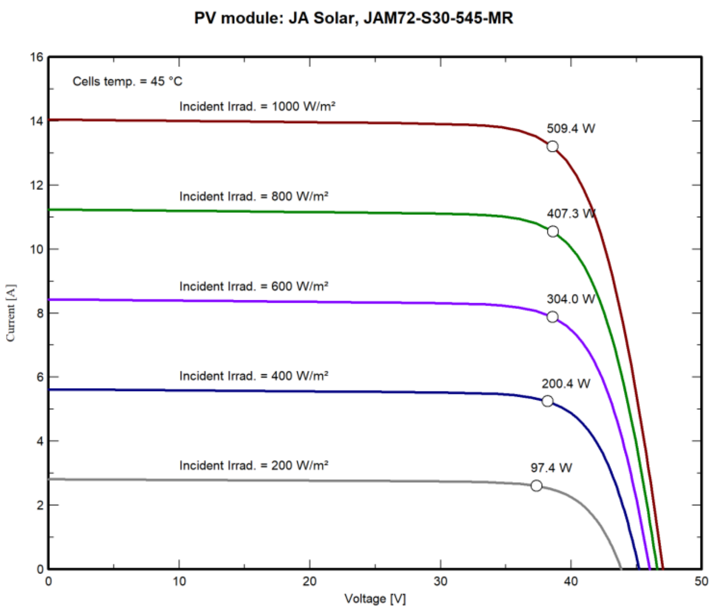


Figure 33. PV Panel V-I Curve with Varying Irradiance

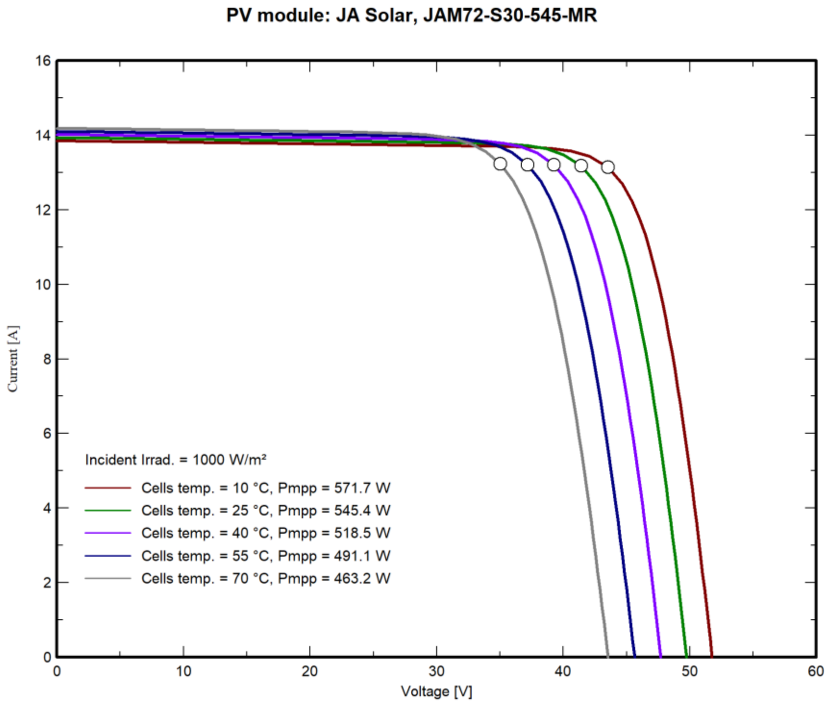


Figure 34. PV Panel V-I Curve with Varying Temperature

- Basic Model Parameters and I-V Curve:
  - Shunt Resistance (Rsh): 240 Ohms indicates how well the cell can divert current within itself. A higher shunt resistance is generally better.
  - Series Resistance (Rs): 0.193 Ohms represents internal electrical resistance to the current flow. Lower series resistance is preferred for better efficiency.
  - Maximum Series Resistance for the Model: 0.201 Ohms, is likely the threshold beyond which the panel efficiency drops significantly.
  - Diode Saturation Current (I0Ref): 0.025 nA, a parameter that impacts the diode equation describing the I-V curve of the solar cell.

- Diode Quality Factor (Gamma): 0.99–0.000/K relates to the ideality of the diode. A factor of 1 is ideal, meaning the diode behaves perfectly according to the diode equation.
- Voltage Temperature Coefficient (muVoc): -135.0 mV/°C, shows how the open-circuit voltage (Voc) changes with temperature.
- The note states that the I/V characteristics must pass through the three given points, Isc, Mpp, and Voc, which are the short-circuit current, maximum power point, and open-circuit voltage, respectively.
- The graph shows the I-V curve with the specified series resistances and shunt resistances. The red circles represent the points through which the curve must pass: Isc, Mpp, and Voc.

• I-V Curves at Different Irradiances:

This graph shows I-V curves for a solar panel model named JA Solar, JAM72-S30-545-MR, at a cell temperature of 45°C and under different incident irradiances (from 200 W/m² to 1000 W/m²):

- As the irradiance decreases, the curves drop, indicating lower current and power output.
- The open-circuit voltage (Voc) does not change significantly with irradiance, which is typical for PV cells.
- The maximum power point (indicated by circles on the curves) also drops with irradiance. This is the point where the product of current and voltage (power) is at its maximum.

- I-V Curves at Different Temperatures:

  This graph shows I-V curves at a constant irradiance of 1000 W/m² for various cell temperatures (from 10°C to 70°C):

  - As the temperature increases, the curves shift downward, indicating a decrease in voltage, which is typical due to the negative voltage temperature coefficient of the cells.
  - The maximum power point (Pmpp) decreases with temperature, showing that higher temperatures reduce the efficiency of the solar panel.
  - Voc decreases with temperature, which is consistent with the negative temperature coefficient mentioned in the first image.

- Limitations and Conditions of Operation of the PV module:

  - The performance of the PV module is highly dependent on temperature and irradiance, as seen in the second and third images.
  - The series and shunt resistances can cause significant power losses if not optimized.
  - The actual performance in the field will depend on matching these model parameters with real-world conditions.

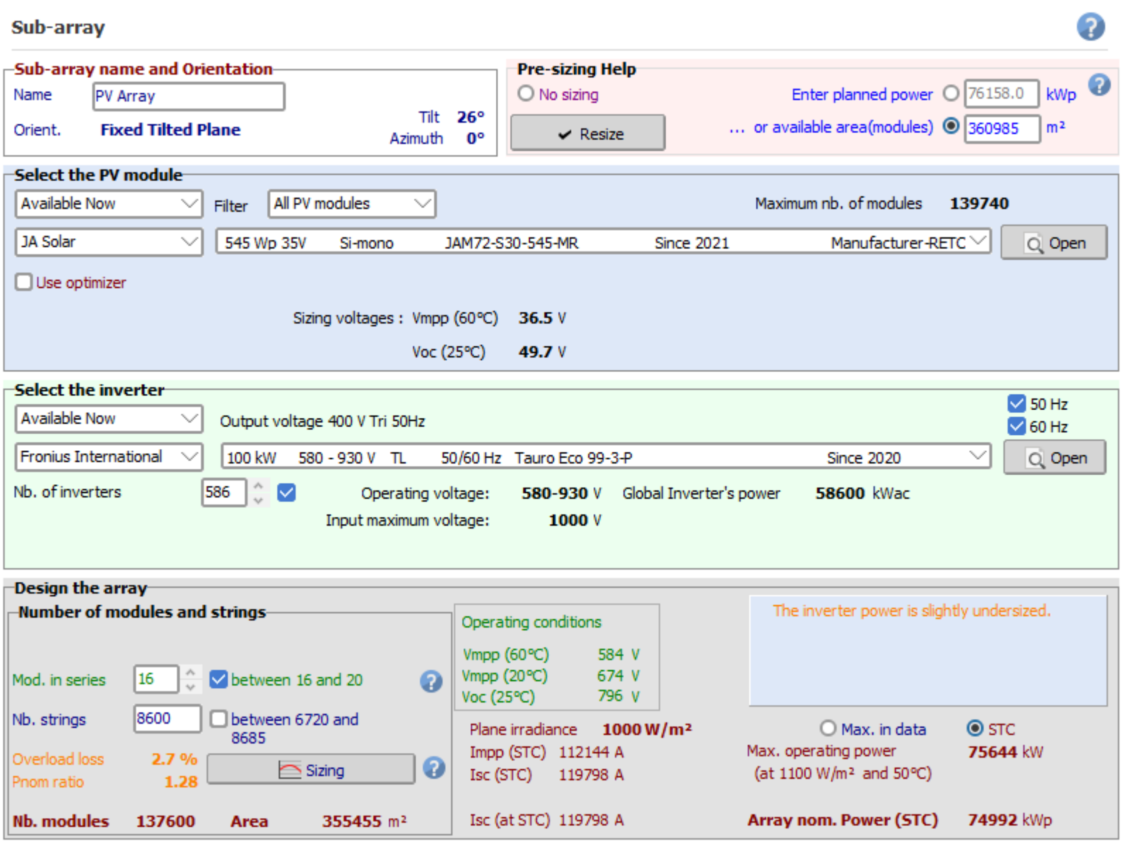


Figure 35. System Parameters.

Third, system parameters are shown in Figure 35. The specifications are:

- Sub-array Section

This section is describing a sub-array within a larger PV system, which is set up on a fixed tilted plane at an angle of 26 degrees from horizontal, facing true north (an azimuth of 0°).

- Pre-sizing Help

This provides assistance in pre-sizing the solar array. The user has an intended design power output of approximately 76.185 MWp and has an available area of about 360,985 m^2 to install around 137,600 solar modules.

- Select the PV Module

The selected solar module is a 545 Wp model from JA Solar, suitable for the specified conditions with a maximum power voltage (Vmpp) at 60°C | 36.5 V and an open-circuit voltage (Voc) at 25°C | 49.7 V.

- Select the Inverter

The system uses Fronius inverters, each with a capacity of 100 kW. A total of 3133 inverters are required to match the PV array's power output, with an input voltage range that the inverters can handle, up to a maximum of 1000 V.

- Design the Array

This section outlines the configuration of the solar panels within the array. There will be 16 modules connected in series per string, with a total of 8,600 strings. Overload loss is minimal at 2.7%, indicating a well-designed system. The Pnom ratio, which could indicate the nominal power ratio, is set at 1.28. The total number of modules slightly exceeds the approximate needed modules, ensuring the planned power output can be met. The area matches the available area given in the pre-sizing help section.

- Operating Conditions Box

This box lists the voltage conditions at various temperatures and the current conditions at Standard Test Conditions (STC). The voltage drops with temperature increase, and the current is substantial, as expected for a large array:

  - Vmpp (60°C): 584 V
  - Vmp (20°C): 674 V
  - Voc (25°C): 796 V
  - Plane Irradiance: 1000 W/m²
  - Imp (STC): 112144 A

- Isc (STC): 119798 A

- Power and Efficiency Indicators

  The system is capable of a maximum operating power of 75.644 MW under specific conditions (high irradiance and temperature), while the nominal power at STC is approximately 74.992 MWp.

- Limitations and Conditions of Operation:

  - The solar array's performance is optimized for specific environmental conditions, like temperature and irradiance.
  - There is a maximum input voltage limitation for the inverter (1000 V), dictating the maximum number of modules that can be connected in series.
  - The design suggests that the array is large, spread over an area of approximately 360985 m², which requires careful planning for physical installation and maintenance.

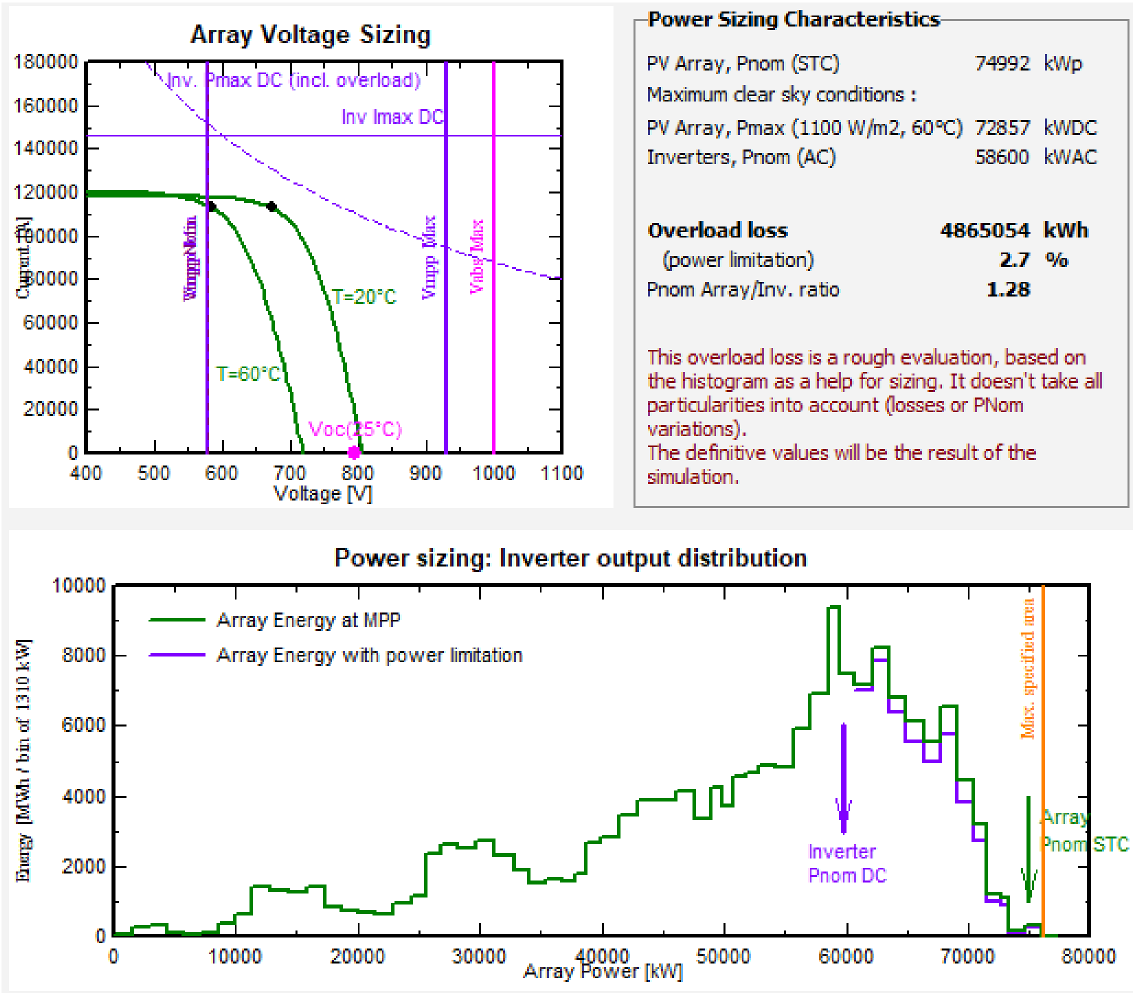


Figure 36. Array/Inverter Sizing Parameters

Fourth, inverter and sizing parameters are shown in Figure 36. The specifications are:

- Array Voltage Sizing
    - The graph shows the current (in amperes) versus the voltage (in volts) of the solar array at two different temperatures: 20°C and 60°C.
    - It illustrates the maximum power voltage (Vmpp) at 20°C and 60°C, and the open-circuit voltage (Voc) at 25°C.

- The purple vertical lines represent the inverter's maximum DC voltage (Inv. Max DC) and the inverter's peak DC voltage including overload (Inv. Ph.max DC incl. overload).

The graph helps to ensure that the array's voltage at various temperatures stays within the inverter's voltage limitations to avoid damaging the equipment or reducing efficiency.

- Power Sizing Characteristics
    - PV Array, Pnom (STC): 74992 kWp — This is the nominal power of the PV array at Standard Test Conditions.
    - Maximum clear sky conditions: Maximum power that the array can produce under ideal (clear sky) conditions at 1100 W/m² irradiance and 60°C temperature is 72857 kWDC.
    - Inverters, Pnom (AC): 58600 kWAC — This is the nominal power of the inverter set in alternating current.
    - Overload Loss: 4865054 kWh — The total energy loss due to inverter overload over a given period (typically a year).
    - Power Limitation (power limitation): 2.7% — This indicates the percentage of power loss due to inverter limitations compared to the total power output of the array.
    - Pnom Array/Inv. ratio: 1.28 — This ratio could indicate the sizing ratio between the array's nominal power and the inverter's nominal power.

The note suggests that the overload loss is a rough estimate and the definitive values for sizing will be the result of the simulation, implying that these numbers are preliminary and subject to change upon further analysis.

- Power Sizing: Inverter Output Distribution
    - Array Energy at MPP: This is the energy that the array would produce if it always operated at its maximum power point (MPP), which is the most efficient operating point.
    - Array Energy with power limitation: This line shows the actual energy output of the array when considering the inverter's power limitations. This value is typically lower than the energy at MPP due to these limitations.

The histogram likely shows the frequency or duration that the array operates at different power levels.

- Limitations and Conditions of Operation:
    - The PV array's voltage must not exceed the inverter's maximum DC input voltage to prevent damage or inefficiency.
    - Power losses due to inverter limitations must be considered, as they can significantly affect the overall performance and energy yield of the PV system.
    - The histogram indicates that the array will not always operate at the maximum power point due to real-world conditions and limitations, impacting the total energy output.
- Results Interpretation

    The results shown in the figure, particularly the overload loss and power distribution histogram, will be discussed in the results chapter or section of the analysis. This would involve a deeper analysis of how often the PV system operates at different power levels and the implications of these operations on the system's energy yield and efficiency. It will also involve looking at how the system performs under real-world conditions, not just under STC.

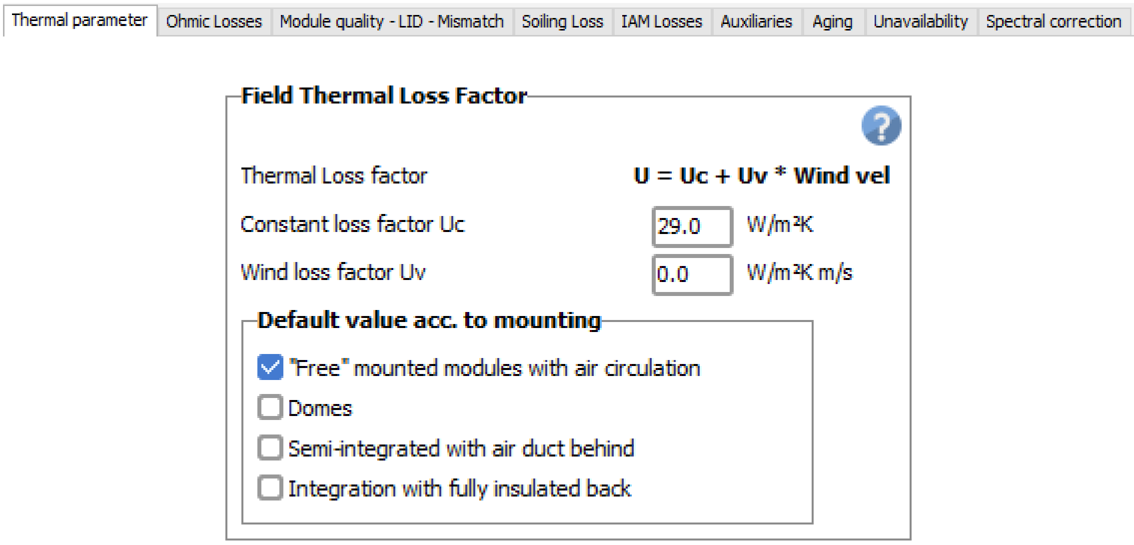


Figure 37. Losses settings

Finally, the losses section that is shown has many parameters that have been changed to emulate the top-water-body environment. Here are the details:

1- The thermal losses have decreased by increasing Uc as instructed in [32].

2- Ohmic losses, Model quality, Model Mismatch losses, String Voltage mismatch, IAM losses, Unavailability of the system, and Spectral correction are defined as default values, as instructed by PVsyst tutorials in their website and inside the program help menu.

3- Soiling losses are set to 2% instead of 3% (the default value) because of the natural cleaning of the panels in that environment.

4- No auxiliaries' settings: there is no loads management system inside because there are no loads.

CHAPTER 5

EXPERIMENTATION & IMPLEMENTATION

This chapter is an outline of our planned steps for the forthcoming semester. We will explain how we selected the best ideas, software, and hardware for our project, based on logical reasoning and criteria. Also, we will provide the project plan, which includes the project deliverables, budget, milestones, roadmap, and division of work. The project plan is designed to be realistic and feasible, considering that the project has to finish within the one-year timeframe that is dedicated to this project. We will also include any time that is needed for the learning/training required to master new skills or acquire new knowledge during the academic year.

5.1. Idea Selection

This section will describe how we generated and evaluated different ideas for our FPV project, and how we selected the best one based on logical reasoning and criteria.

In the Literature Review chapter, it can be seen that there are plenty of ideas around the FPV project, and there are many ways to implement it. However, we had many meetings and have done much research about what is the optimal way of doing this. As a result, the chosen ideas that we came up with are:

- For the hardware structure, we will have a 3*3 array; it has 9 PV panels, 3 in series making a single string, then, 3 strings in parallel. It was the proper and logical way of representing a scaled down FPV power plant.

- For simulation, we could use another software. Nevertheless, we used PVsyst because it is the most common, accurate and practical PV program that we know. Additionally, our supervisor has suggested it.

However, in the second semester, due to budget limitation, and prototype presentation, we changed the structure. It has become a 2*2 array, and all panels connected to a battery to charge it, and we have added a control unit for having a working electronic system that solves important problems. Also, we have removed the anchoring system as it is not necessary for our prototype purposes, we just success by making the structure float, and the electronic scheme and solar panels working. Nevertheless, the whole prototype building and presentation will be shown in the coming sections.

5.2. Software Selection

In selecting the best software for simulating and analyzing our FPV plant project, we have chosen PVsyst as mentioned earlier. For the solar energy industry, PVsyst is a software package that can design, simulate, and analyze different kinds of solar energy systems.

For the 3D mechanical design, we have used Autodesk Fusion 360. It is a cloud-based 3D modeling computer aided software. We do know the basics of it, and it is well-known for its capabilities in the 3D industry. Therefore, it was the right option.

5.3. Hardware Selection

The selection of the best hardware components for our FPV prototype, such as the solar panels, the floats, the cables, and the moorings, is described as follows:

- **PVC Elbows and Connectors**: These were essential for creating a sturdy, water-resistant framework for the solar panels. PVC (Polyvinyl Chloride) is chosen for its durability, resistance to corrosion from water exposure, and its ability to withstand the lake's environmental conditions. The variety of elbow angles and connectors allowed for flexibility in design and assembly as shown below:

- **PVC Pipes**: Long, straight sections of PVC piping were used to form the primary structure of the floating base. These pipes provide buoyancy and structural integrity, forming the backbone of the floating platform as shown below:

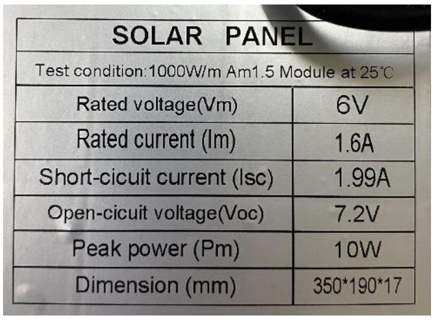
- **CPVC Adhesive:** A specific type of adhesive designed for bonding CPVC and PVC components. This heavy-bodied, medium set adhesive was crucial for ensuring that all joints and connections between the PVC parts were watertight and secure as shown below:

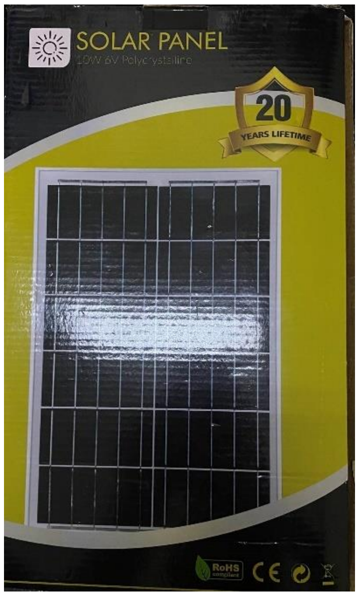
- **Hacksaw:** Essential for cutting the PVC pipes and other materials to the required sizes during the initial construction phase as shown below:

- **Digital Multimeter:** Used for electrical testing and troubleshooting during the installation of solar panels. It ensured that all electrical components were functioning correctly and safely before the platform was deployed on the lake as shown below:

- **Measuring Tape:** Used to ensure precise measurements of materials, which is critical for maintaining the balance and symmetry of the floating structure, impacting its stability on the water.

- **10W 6V Polycrystalline Solar Panel:** Polycrystalline, known for balance between cost and efficiency, with a focus on durability and reliability as shown below:





5.4. Budget

Table 3 provides a comprehensive financial outline, encompassing the estimated costs for materials and components required for the prototype's assembly. This budget serves as a financial compass, guiding our purchasing decisions and highlighting the economic considerations critical to the project's successful execution.

Table 3. BOM

No.	Item	Quantity	Cost (SAR)	Total Cost (SAR)
1	Waterproof Glue	1	25	25
2	Plastic Rods (for the bottom)	4	-	56.67
3	Plastic Joints	4	-	92
4	Plastic Rods (for holding panels)	4	-	22.02
5	PV Solar Panels (10W each)	4	40 each	160
6	Control Unit Plastic Box	1	5	5
7	Cork Plate (70*150)	2	10 each	20
8	A3 Cover Paper	1	10	10
9	Reflecting Tape	1	5	5

10	Black Color Spray	7	-	68
11	Arduino Uno	1	45	45
12	Buzzer	1	5	5
13	Push Button	1	5	5
14	9V Battery	1	4	4
	Total Cost			**522.69**

5.5. Prototype Building Process

The Prototype Building Process section details the systematic development of the floating solar panel prototype, specifically tailored for Al-Aqoul Lake. Spanning the entirety of Ramadan, the construction was segmented into five distinct stages. This structured approach not only facilitated meticulous planning and execution but also ensured that each phase contributed effectively towards building a robust and efficient prototype.

- **Stage 1: Frame Construction**

  The initial stage of building the floating solar panel prototype focused on constructing the frame, which serves as the foundation of the entire structure. This phase involved the assembly of PVC pipes into a square frame (each side of this square turned to be 144cm) , ensuring that the structure was both lightweight and buoyant, essential characteristics for stability on the water as shown below:

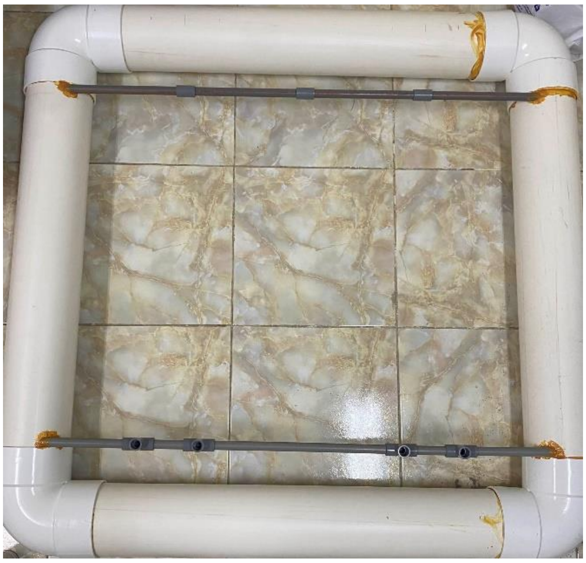
Key Steps in Frame Construction:

1. Cutting and Measuring: PVC pipes were carefully measured and cut to precise dimensions to ensure that the entire frame was symmetrical and balanced. This step was crucial to maintaining the structure's integrity and effectiveness in water.
2. Assembly: The cutting pipes were assembled using PVC elbows and connectors to form a square base. Each joint was meticulously cemented to enhance the rigidity and durability of the frame, preventing disassembly or leakage under the dynamic conditions of the lake.
3. Sealing and Waterproofing: All joints were sealed with a special waterproof adhesive to ensure that no water could infiltrate the frame. This step was critical in maintaining the buoyancy and overall performance of the prototype.

This stage laid the groundwork for the subsequent installation of solar panels and other components, setting the stage for a successful deployment of the prototype on Al-Aqoul Lake. The robustness of this foundational frame is instrumental in supporting the weight of the solar panels and withstanding environmental stresses, ensuring the long-term sustainability of the solar energy project.

- **Stage 2: Structural Reinforcement for Solar Panel Installation**

  The second stage of the prototype construction focused on reinforcing the PVC frame, preparing it for the critical task of supporting solar panels. This reinforcement was essential to ensure that the structure could withstand the additional weight and environmental pressures such as wind and water currents at Al-Aqoul Lake, the figure below shows the structural:



Key Enhancements for Solar Panel Installation:

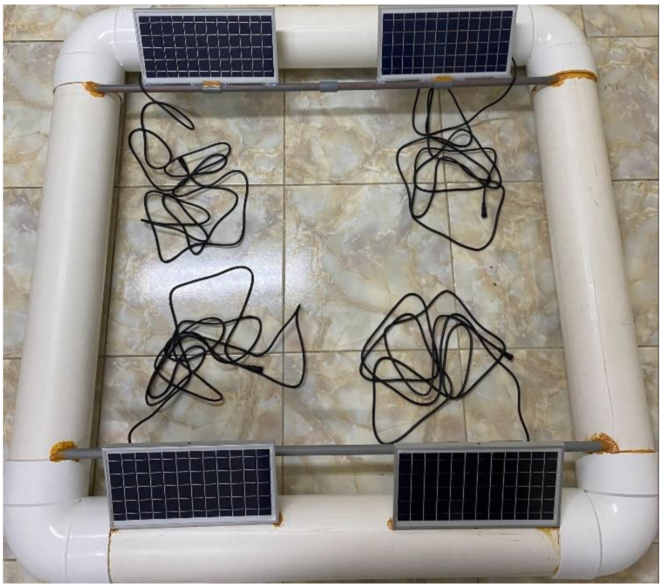
1. Installation of Support Rods: To prepare for solar panel mounting, support rods were integrated across the width of the frame. These rods are designed to provide additional structural support and distribute the weight of the solar panels evenly across the frame, minimizing any sagging or bending.
2. Securing the Rods: Each rod was securely fastened to the PVC pipes using robust clamps and fittings. This firm attachment is crucial to ensure the frame's stability and durability, especially once the solar panels are installed and exposed to dynamic weather conditions.

3. Load Testing: With the support rods in place, the frame underwent a series of load tests to simulate the weight of the solar panels and assess the frame's ability to maintain integrity under pressure. These tests help verify that the frame would hold up without any structural failures when deployed in the lake.

The goal of this stage was to create a robust and reliable base for the solar panels, ensuring that the prototype would function optimally under the operational conditions of Al-Aqoul Lake. This careful preparation is key to the successful implementation and sustainability of the floating solar panel system.

- **Stage 3: Solar Panel Installation**

  The third stage in the construction of the floating solar panel prototype marked a significant milestone: the installation of the solar panels themselves. This phase was crucial for transforming the reinforced structure into a functional energy-generating unit as shown below:



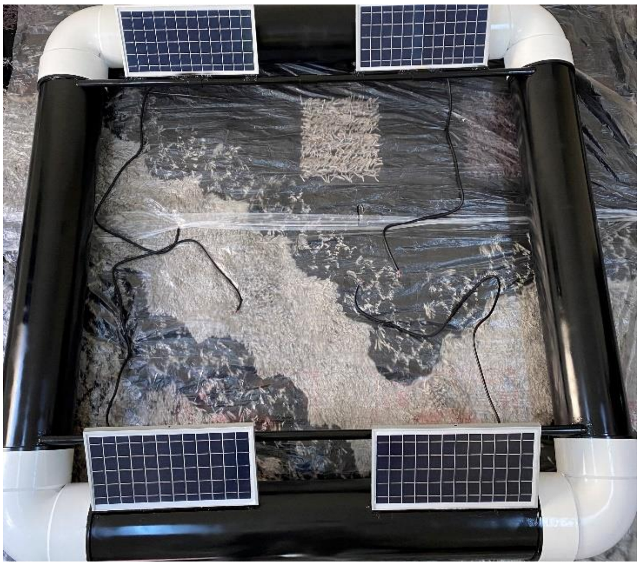
Key Steps in Solar Panel Installation:

1. Mounting the Solar Panels: The solar panels were securely mounted onto the reinforced support rods using durable mounting brackets. These brackets ensure that the panels are held firmly in place while allowing for optimal orientation toward the sun for maximum energy absorption.
2. Ensuring Durability: Additional measures were taken to protect the panels and their connections from environmental factors. This included applying protective coatings and securing all loose ends to withstand wind, rain, and constant water exposure.

This stage was pivotal in the prototype's development, as it directly impacted the project's core objective of generating renewable energy. By successfully installing and securing the solar panels, the prototype was prepared for real-world testing and evaluation on Al-Aqoul Lake.

- **Stage 4: Aesthetic Enhancement and Wiring Preparation**

  The fourth stage of the floating solar panel prototype involved aesthetic enhancements and preparatory work for final electrical connections, focusing on ensuring that the prototype was not only functional but also visually appealing and ready for seamless integration as shown below:



Key Components of Stage 4:

1. Color Change of PVC Frame: To improve the visual appeal and increase the durability of the PVC frame, a special waterproof and UV-resistant paint was applied. This not only enhanced the appearance of the frame but also added an extra layer of protection against the elements, ensuring longevity and resistance to sun and water exposure.
2. Preparing for Final Connections: The wires from the solar panels were arranged to ensure that they could be easily connected to the energy storage or management systems in the final stage. This preparation was essential to streamline the installation process, minimizing potential errors and ensuring a smooth final setup.

- **Final Stage: Installation of Control Unit and Final Assembly**

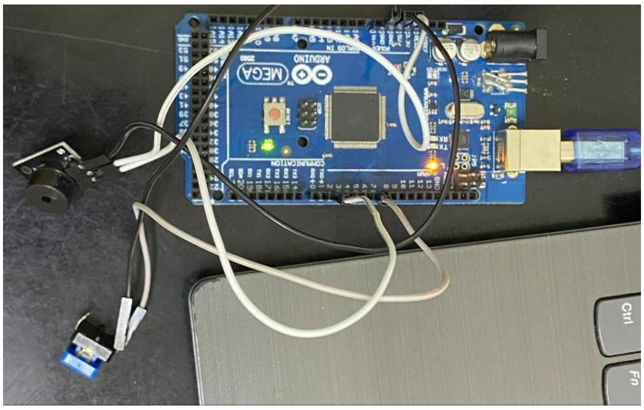
  The final stage of the floating solar panel prototype involved crucial steps to complete the assembly, ensuring that the prototype was fully operational and ready for deployment. This phase focused on installing the central control unit, securing the platform, and making all necessary electrical connections as shown below:

Key Components of the Final Stage:

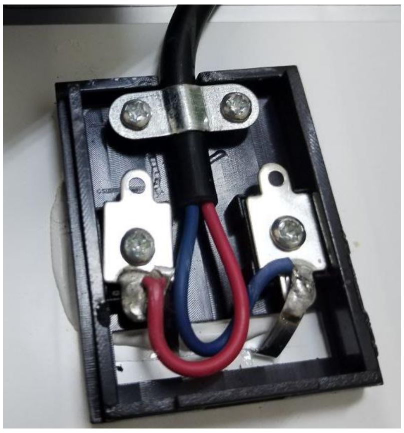
1. Installation of the Cork Base: A cork base was placed in the center space of the frame to serve dual purposes: housing the control unit and providing a stable, non-conductive surface that could also be used as a walkway during maintenance. Cork was chosen for its buoyancy, durability, and resistance to water, making it an ideal material for this application. Also, adding a reflecting yellow type for safety purposes.
2. Building the Control Unit: Integration of Arduino and Sensor System, In the construction of the control unit for our floating solar panel prototype, we incorporated an Arduino board equipped with a battery for power supply. This setup is essential for managing and monitoring the operational status of the prototype efficiently. In addition, the battery is charged by the solar panels, achieving a self-contained system.

   Key Features and Functionalities:

- Arduino Setup: The Arduino Uno board is used as the central processing unit for our control system. It is powered by a battery, ensuring continuous operation even in the absence of direct solar power. This microcontroller board is chosen for its reliability and ample input/output pins, which are necessary for handling various sensors and output devices as shown below:



- Control System Box: The Arduino, the wires, and a 6V battery are placed inside a control unit box in the middle of the module. The 6V battery is the battery connected to the PV Panels, to be charged. The battery is connected with the panels in parallel, because the panels have 6 Vm rating, i.e. the positive terminal of all panels is connected to the positive terminal of the battery, same with negative terminals. In addition, the box has the buzzer above it, also, it has a switch to turn on\off the whole electronic circuit. The following photos show the control unit and the blue and red wires of the panels (the two terminals).



- Water Level Sensor: A crucial component of the control unit is the water level sensor, designed to extend from the control unit down towards the lakebed. This sensor helps in monitoring the water level; if the water level drops to a point where the sensor touches the ground, it triggers an alarm. The sensor is connected to the Arduino, which is programmed to react to changes in water level. A significant drop that causes the sensor to contact the lakebed results in the Arduino activating a buzzer. This buzzer serves as an audible alert to notify maintenance personnel of potential issues that could affect the stability or efficiency of the solar panels as shown below:

This sophisticated control unit is integral to ensuring the operational safety and efficiency of the floating solar panel system. By automating responses to critical changes in environmental conditions, such as significant water level fluctuations, we enhance the system's reliability and maintain continuous energy production. This careful integration of technology ensures that our prototype can operate autonomously while providing real-time data and alerts to support ongoing maintenance and operational decisions. Finally, below are photos for the final setup with the whole circuit components:

5.6. Field Visits and Depth Measurement Process

This section discusses the field visits and depth measurement processes conducted at Al-Aqoul Lake for the floating solar panel project. These activities were critical in assessing the lake's geographical and environmental features, essential for the project's success. The data collected on the lake's depth variations informed the design of a robust floating structure capable of adapting to different water levels. This overview emphasizes the role of these preliminary investigations in the strategic planning and effective execution of the project.

- **Field Visits:**

During the development of the floating solar panel project, 5 field visits were conducted at Al-Aqoul Lake under various conditions to confirm the site's suitability for the project and to ensure that there were no significant risks associated with its implementation. These visits were essential in providing a comprehensive understanding of the lake’s dynamics throughout different times and environmental states.

Additionally, it was discovered that there is a dam connecting the lake to another valley. However, during our observations, the dam was found to be closed, and there was no water flow as shown below.

- **Lake Depth Measurement Process:**

In one of our visits to the lake, we measured the depth of water for the real implementation of the mooring system, so the data can be ready. At one of the lake's points, we connected a rope to a heavy wight and threw it to a distance of 2 m forward to the lake's side (it can be considered as the base of a right triangle), when we were standing at the final spot at lake's beach. Then we measured the wet part of the rope (and it can be considered as the hypotenuse of the right triangle) and it was 6.8 m. Therefore, the depth is measured by Pythagorean theorem, considering it as the altitude of the right triangle, and it was 6.48 m. The following images capture the process.

Figure 38. Depth Measurment

5.7. Project Plan

As we review the progress made in our capstone project during this semester, we can confidently affirm that the comprehensive plan outlined in our Gantt Chart as shown in Figure 39 has been diligently followed. This adherence to the structured timeline has enabled us to effectively manage our tasks and adhere to our projected milestones. By closely aligning each phase of the project with our overarching objectives, we have maintained a strategic approach, ensuring that every step contributes positively toward achieving our project goals.

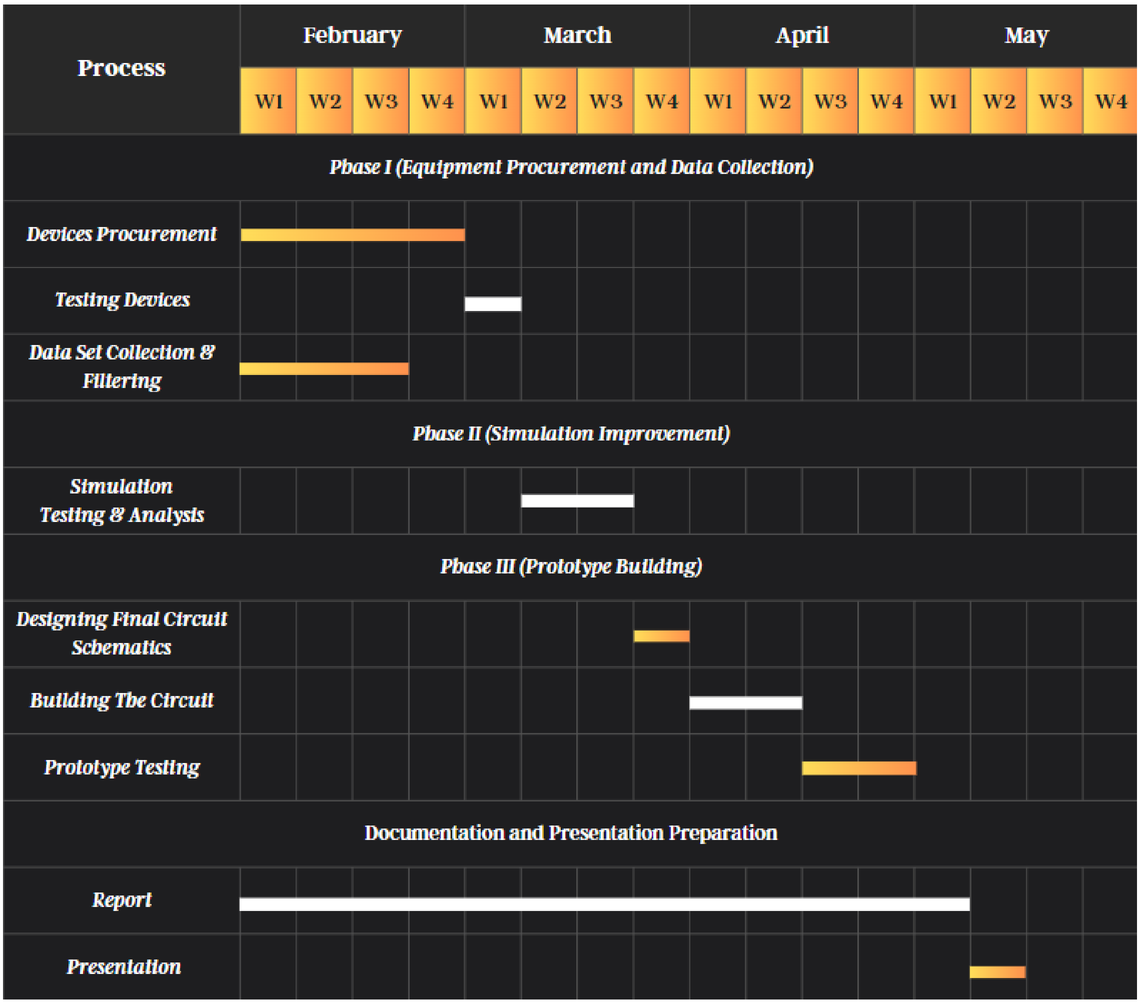


Figure 39: Followed Gantt Chart

5.8. Learning/Training Plan

The time that is needed for the learning/training required to master new skills or acquire new knowledge during the academic year is shown in this section. The learning/training plan will specify the topics, the sources, the methods, and the outcomes of the learning/training activities. However, these are the new skills/knowledge:

1- PV and FPV knowledge: learning about the theoretical side of our project topics is a must. Therefore, the phases of literature review and literature analysis were essential. It took around 3 weeks to understand the fundamentals of these systems, and we are continuing to learn more and more in our project journey.

2- PVsyst: to dive more into the details of this program we had to learn from the tutorials provided by PVsyst channel on YouTube. They were very beneficial and informative.

3- Fusion 360: making a detailed and clear 3D design for our mechanical structure made us learn more about Fusion 360 features. Even though it did not take much time to learn this feature, it took time in applying them in the designing phase.

5.9. Division of Work

The working nature of our team is collaborative and comprehensive. For instance, in the report writing, there were many parts when someone starts writing a chapter and another completes it. However, regarding meeting attending and instructions commitment, both of us were obligated to that.

The following table shows an approximate division of tasks.

Table 4. Tasks Division

Task	**Person**
Literature Review	*Most Literature: Hamza*
Mechanical Design	*3D Design: Marwan*
PVsyst Design and Analysis	*Hamza and Marwan (Marwan Most)*
Report Writing	*Hamza and Marwan (equal tasks)*
Presentation Slides Preparation	*Design: Hamza. Content: Marwan.*
Financial Study	*Hamza and Marwan (Hamza Most)*
Prototype Building Components	*Marwan*
Work Instruments	*Hamza*

If there is any other task that is not mentioned, it means that it is not so significant.

CHAPTER 6

RESULTS & DISCUSSION

This chapter covers the final results of our floating solar (FPV) power plant project. Mainly, the simulation final results. Therefore, we will delve into the results and discussion of our FPV Power Plant project. This section presents a comprehensive analysis of the outcomes we achieved and a reflective discussion on the journey, challenges, and learnings.

6.1. PVsyst Results

The main results obtained in our project were regarding the simulation.

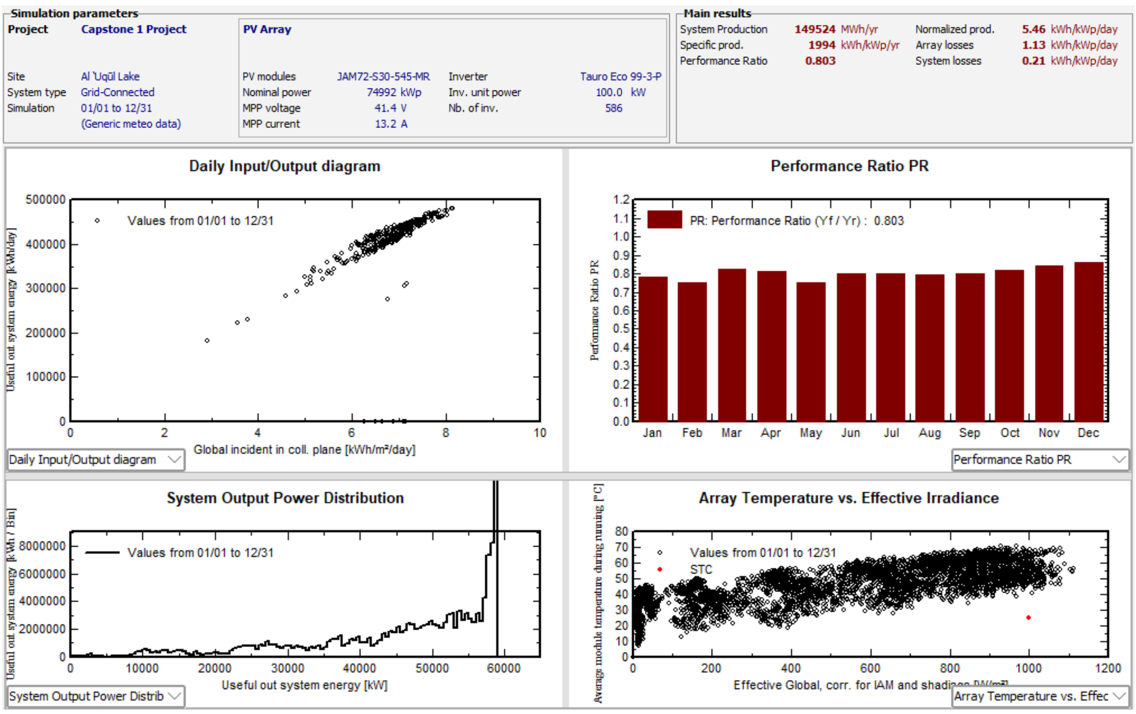


Figure 40. PVsyst Results

Figure 40 shows the results of our PVsyst simulation, that we have defined its parameters in the design chapter. The results can be explained as:

- Simulation Parameters

    - System type: Grid-Connected
    - Simulation Period: 01/01 to 12/31 (a full year)
    - PV Array: Model JAM72-S30-545-MR with a nominal power of 74992 kWp, MPP voltage of 41.4 V, and MPP current of 13.2 A.
    - Inverter: Tauro Eco 99-3P with an inverter unit power of 100.0 kW and a total number of inverters at 586 units.

- Main Results

    - System Production: 149524 MWh/yr
    - Specific Production: 1994 kWh/kWp/yr
    - Performance Ratio (PR): 0.803
    - Normalized prod.: 5.46 kWh/kWp/day
    - Array losses: 1.13 kWh/kWp/day
    - System losses: 0.21 kWh/kWp/day

The system has produced 149,524 MWh over the year, with a performance ratio of 0.803, which is a measure of the system's efficiency relative to its theoretical maximum under ideal conditions. The specific production value provides insight into the average energy produced per kWp of installed capacity.

- Daily Input/Output Diagram
  - The scatter plot shows the relationship between daily global incident irradiation in the collector plane (horizontal axis) and daily energy output (vertical axis).
  - This graph is used to assess how well the system converts sunlight into electricity on a daily basis throughout the year.
- Performance Ratio PR

  The bar graph shows the performance ratio for each month of the year.

It indicates that the performance ratio is relatively stable throughout the year, slightly fluctuating but remaining around the annual average of 0.803.

- System Output Power Distribution

  The histogram shows the distribution of the system's output energy throughout the year. It provides insight into how often the system operates at different energy output levels, which is useful for understanding the system's behavior under varying solar irradiance and temperature conditions.
- Array Temperature vs. Effective Irradiance
  - The scatter plot relates the array temperature to the effective global irradiation on the PV module plane.
  - This graph helps to analyze the impact of temperature on the PV module's performance, as higher temperatures generally reduce the efficiency of solar cells.

- Limitations and Conditions of Operation
    - The performance ratio indicates that the system is operating at 80.3% of its theoretical optimal performance, which is quite good but suggests there may be some room for improvement.
    - Array and system losses are relatively low, indicating a well-designed system.
    - The scatter plot of daily input/output may indicate some days with high irradiance where the output is not as high as might be expected, which could be due to temperature effects or other system inefficiencies.

The simulation results give a comprehensive overview of the system's expected performance over a year and are crucial for validating the design, planning maintenance, and forecasting the financial returns of the solar power project. The results chapter would likely delve deeper into these graphs, providing a detailed analysis of the factors affecting performance and identifying any potential issues or areas for optimization.

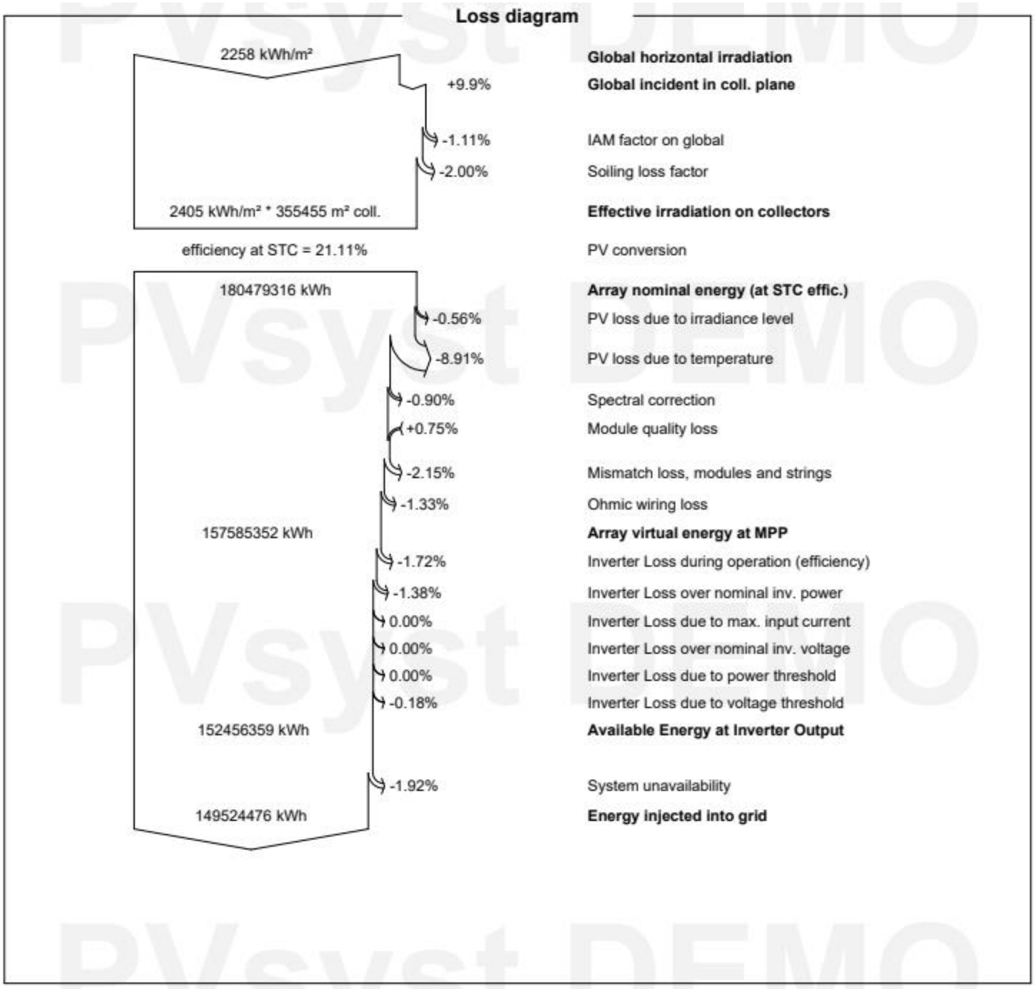


Figure 41. Losses Results.

The losses diagram elements can be illustrated as the following:

- Loss Diagram Overview:
  - Global Horizontal Irradiation: The starting point is the total solar irradiation received on a horizontal plane, which is increased by 9.9% to account for the global incident in the collector plane.
  - IAM Factor on Global: The Incidence Angle Modifier (IAM) factor adjusts the incident energy based on the angle of sunlight, which can reduce the energy reaching the collector.

- Effective Irradiation on Collectors: The total irradiation that is effectively available for the PV system after considering the IAM factor.
- PV Conversion: The process of converting solar irradiation into electrical energy.
- Array Nominal Energy (at STC Efficiency): This is the theoretical energy output of the array calculated at Standard Test Conditions (STC) efficiency.
- PV Losses due to Irradiance Level/Temperature: These are losses due to variations in irradiance and temperature from the STC, which affect the efficiency of PV panels.
- Module Quality Loss, Mismatch Loss, Ohmic Wiring Loss: These categories represent energy losses due to the quality of the PV modules, mismatch between modules and strings, and resistance in the wiring.
- Array Virtual Energy at MPP: This represents the energy that the array would produce if it operated continuously at its maximum power point (MPP), which is the optimal point for energy production.

- Inverter Losses:
  - Inverter Loss during operation (efficiency): Losses due to the inverter's efficiency, which does not convert 100% of the DC power into AC power.
  - Inverter Loss over nominal input power/current/voltage: These losses occur when the inverter operates over its nominal specifications for power, current, and voltage.
  - Inverter Loss due to power/voltage threshold: Losses that occur when the power or voltage falls below a certain threshold, which might prevent the inverter from operating.

- Final Energy Output:
    - Available Energy at Inverter Output: The total energy available after all the above losses have been accounted for.
    - Energy Injected into Grid: The net energy that is actually delivered into the power grid for use, which should be the same as the available energy at the inverter output in the absence of further losses or storage.
- Interpretation:
    - The diagram shows a step-by-step reduction of energy from the initial solar irradiation to the final grid-injected electricity.
    - The efficiency at STC is 21.11%, which is relatively high for PV modules.
    - The total system production is 149524476 kWh, with a series of losses amounting to approximately 5.02% of the virtual energy at MPP.
    - The largest single loss is due to temperature, which reduces output by 8.91%.
    - Overall, the losses are relatively small compared to the initial irradiation, indicating a well-designed system.
    - This loss diagram is an essential tool for understanding where improvements can be made to increase the efficiency and output of the PV system.

The values and percentages in the loss diagram are critical for optimizing the design and performance of the solar PV system. They help in identifying the most significant sources of efficiency losses, which can then be targeted for improvement through better system design, component selection, or operational adjustments.

✓ Please note that there is a full detailed report of the PVsyst simulation provided in Appendix 2.

6.2. Financial Study

The Financial Study section of our report provides a detailed analysis of the economic viability of the floating solar panel project at Al-Aqoul Lake. This section meticulously evaluates the initial investment, operational costs, expected returns, and the overall financial sustainability of the project. By incorporating data-driven projections and real-world cost considerations, we aim to present a clear picture of the financial implications and potential profitability.

Through comprehensive cost-benefit analyses, break-even assessments, and sensitivity analyses, this study aims to underpin the project's feasibility with robust financial metrics. This evaluation will not only inform our strategic decisions but also serve as a critical resource for stakeholders to assess the financial health and potential return on investment of the project.

6.2.1. Market Analysis

The Market Analysis section explores the viability and competitiveness of the floating solar panel project at Al-Aqoul Lake. It includes a Demand Analysis that assesses the growing demand for solar energy in Saudi Arabia, underscoring the project's market relevance. Additionally, the Competitive Landscape review identifies other renewable energy initiatives and floating PV installations in the region, helping us gauge market competition and formulate effective pricing strategies.

6.2.1.1. Demand Analysis

- **Saudi Arabia's Renewable Energy Goals**: Saudi Arabia has set ambitious renewable energy targets under Vision 2030, aiming to generate 50% of its energy from renewables by 2030. This target is expected to drive significant demand for renewable energy sources like solar power.

- **Solar Energy Potential**: The country receives abundant sunlight throughout the year, making solar energy a particularly attractive renewable energy source. The demand for solar energy is expected to grow as the cost of solar technology decreases and environmental awareness increases.
- **Government Initiatives:** The Saudi government has launched several initiatives to promote renewable energy, including the National Renewable Energy Program (NREP), which aims to add 58.7 GW of renewable energy capacity by 2030.
- **Industrial and Commercial Demand**: There is a growing trend among industries and commercial entities in Saudi Arabia to adopt renewable energy solutions to reduce costs and demonstrate environmental responsibility.
- **Residential Demand**: The residential sector is also expected to contribute to the demand for solar energy as homeowners seek to reduce their electricity bills and carbon footprints.

6.2.1.2. Competitive Landscape

- **Existing Renewable Energy Projects:**

  a. **Sakaka Solar Project**: Developed by ACWA Power, this 300 MW photovoltaic (PV) solar power plant in Al-Jouf is Saudi Arabia's first utility-scale solar project. It is a key milestone in the country's renewable energy journey [33].

  b. **Dumat Al-Jandal Wind Farm**: While not a solar project, it is another significant renewable energy initiative in Saudi Arabia. Located in Al-Jouf, it boasts a capacity of 400 MW and contributes to the nation's renewable energy goals [34].

c. **NEOM Solar Projects**: NEOM, a futuristic city development, has plans for several renewable energy projects, including solar power plants. These projects underline NEOM's commitment to sustainability [35].

- **Floating PV Installations:**

  a. **KAUST Solar Desalination Plant**: This innovative project by KAUST integrates solar energy generation with water conservation. Although not a traditional floating PV installation, it features floating solar panels that power a desalination plant, showcasing a unique approach to sustainability [36].

  b. **ACWA Power**: As a leading developer, investor, and operator of power generation and water desalination plants, ACWA Power has played a pivotal role in Saudi Arabia's renewable energy sector. The company's involvement in the Sakaka Solar Project highlights its commitment to driving sustainable energy solutions [37].

  c. **Saudi Aramco**: While primarily known for its role in the oil and gas industry, Saudi Aramco has demonstrated interest in renewable energy. The company's plans for solar power projects suggest a potential shift towards diversification and sustainability in its energy portfolio [38].

  d. **Masdar**: A prominent renewable energy company based in the UAE, Masdar has a strong track record in developing renewable energy projects globally. Its expertise and experience could make it a key player in the Saudi Arabian market. [39].

- **Pricing Strategies:**

  a. **Feed-in Tariffs (FiTs):** Saudi Arabia has implemented FiTs for renewable energy projects, including solar. These tariffs provide a fixed payment for each kilowatt-hour (kWh) of electricity generated, ensuring a predictable revenue stream for project developers, and encouraging investment in the sector [40].

  b. **Competitiveness with Traditional Sources**: The decreasing cost per kWh of electricity generated from solar energy in Saudi Arabia has made it increasingly competitive with traditional sources such as oil and gas. This trend is expected to drive further adoption of solar energy in the country [41]. The table below shows the comparison between them:

Aspect	Solar Energy	Traditional Sources (Oil and Gas)
Cost per kWh (SR)	Decreasing due to technological advances and economies of scale.	Varies, but generally higher due to costs associated with extraction, refining, and transportation.
Environmental Impact	Low carbon footprint aligns with sustainability goals.	High carbon emissions, contributes to air pollution and climate change.
Resource Availability and Sustainability	Abundant sunlight, sustainable and renewable resources.	Finite and non-renewable, subject to price volatility.
Government Support and Incentives	Strong government support, including subsidies and favorable policies.	Government policies may vary, with potential subsidies for fossil fuel industries.

- **Regulatory Environment:**

  a. **REPDO Oversight**: The Renewable Energy Project Development Office (REPDO) oversees the procurement of renewable energy projects in Saudi

Arabia. Its role is crucial in driving the development of the renewable energy sector and ensuring compliance with regulatory standards [42].

b. **Incentives and Subsidies**: Saudi Arabia offers various incentives and subsidies for renewable energy projects, including exemptions from import duties and taxes on equipment and materials used in these projects. These incentives aim to attract investment and promote the growth of the renewable energy sector [43].

c. **Alignment with Vision 2030**: The regulatory framework in Saudi Arabia is closely aligned with the goals of Vision 2030, which include promoting renewable energy and reducing dependence on oil for electricity generation. This alignment provides a strong foundation for the growth of the renewable energy sector in the country [44].

6.2.2. Revenue Streams

To estimate the potential electricity generation and revenue for a floating PV system in Al-Aqoul Lake, Madinah, and to explore relevant government and international incentives, we'll break down the analysis into two main parts:

6.2.2.1. Sale of Electricity

- **Revised Electricity Generation and Revenue Analysis:**

  System Specifications:

  - Total Utilized Area: 360,985 m^2 (about 10% of the total lake area of 3,609,849.04 m^2)
  - Number of Solar Panels: 139,744
  - Nominal System Capacity: 76,160 kWp (76.16 MWp)

- System Production: 149524 MWh/year
- Performance Ratio: 80.3%
- Normalized Production: 5.46 kWh/kWp/day
- Array Losses: 1.13 kWh/kWp/day
- System Losses: 0.21 kWh/kWp/day
- The price per kWh is approximately 0.18 SAR

Annual Revised Calculation for Revenue (in SAR):

Revenue = System Production x Price per kWh x Conversion factor (MWh to kWh)

Revenue = 149,524,000 MWh/year x 1,000 kWh/MWh x 0.18 SAR/kWh

Annual Revenue = 149,524,000 kWh x 0.18 SAR/kWh = 26,914,320 SAR

Thus, the annual revenue from selling the electricity generated by this solar power system would be approximately 26.914 million SAR

6.2.2.2. Government Subsidies and Incentives in Saudi Arabia

Saudi Arabia has implemented a variety of subsidies and incentives to promote renewable energy investment and development:

- **Feed-in Tariffs (FiTs):** Saudi Arabia may offer feed-in tariffs that guarantee a set price for solar-generated electricity for several years, ensuring stability and predictability in revenue [45].
- **Tax Incentives:** Reductions or exemptions in taxes for renewable energy projects. This can include exemptions from import duties on solar panels and other renewable energy equipment [46].

- **Direct Grants and Funding**: The Saudi government, through various initiatives and organizations such as the Saudi Industrial Development Fund (SIDF), offers grants and low-interest loans for renewable energy projects [47].
- **Research and Development Support:** Funding for research and development in renewable energy technologies is available through institutions like King Abdullah City for Atomic and Renewable Energy (KACARE) [48].
- **Renewable Energy Project Development Office (REPDO) Contracts:** These are part of the National Renewable Energy Program, aiming to achieve the Vision 2030 renewable energy targets. They often come with attractive incentives for developers [49].

With these incentives, our project can achieve higher financial feasibility and contribute significantly to the renewable energy landscape in Saudi Arabia.

6.2.3. Cost Structure

To effectively outline the cost structure for your floating PV power plant project in Alaqoul Lake, Madinah, we'll break down the costs into three main categories: Initial Capital Investment, Operational Costs, and Depreciation.

6.2.3.1. Initial Capital Investment

This includes the costs of purchasing and installing the floating PV panels, anchoring systems, electrical infrastructure, monitoring, and control systems. System Specifications:

- **PV Panels (JAM72-S30-545-MR):**

- Cost per Watt: SAR 2.50
- Total Capacity: 74,992 kWp
- Total Cost: 74,992,000 W x SAR 2.50/W = SAR 187,480,000

- **Anchoring Systems:**

- Cost per kWp: SAR 900
- Total Cost: 74,992 kWp x SAR 900/kWp = SAR 67,492,800

- **Electrical Infrastructure:**

- Cost per kWp: SAR 500
- Total Cost: 74,992 kWp x SAR 500/kWp = SAR 37,496,000

- **Monitoring and Control Systems:**

- Cost per kWp: SAR 250
- Total Cost: 74,992 kWp x SAR 250/kWp = SAR 18,748,000

- **Inverters (Fronius Tauro Eco 99-3-P):**

- Unit Power: 100 kW
- Cost per Unit: SAR 10,000
- Total Number: 762 units
- Total Cost: 762 x SAR 10,000 = SAR 7,620,000

Total Initial Capital Investment:

SAR 187,480,000 + SAR 67,492,800 + SAR 37,496,000 + SAR 18,748,000 + SAR 7,620,000
= SAR 318,836,800

6.2.3.2. Operational Costs

Operational costs for a Floating PV power plant include all expenses necessary for the continuous operation and maintenance of the plant after it has been commissioned. These costs are typically recurring and can be categorized as follows:

- **Maintenance and Repairs:**
  - Routine Maintenance: Includes cleaning of solar panels, checking and maintaining electrical connections, and ensuring the structural integrity of floating platforms and anchoring systems.
  - Repairs: Involves fixing or replacing damaged or faulty components such as inverters, panels, or parts of the floating structure.
  - Cost Estimate: Generally, maintenance and repairs cost about 1% of the initial capital investment annually, given the robustness and relatively low maintenance requirements of solar power systems.

Annual Maintenance and Repairs:

Given the total initial capital investment of SAR 318,836,800, the annual maintenance and repairs cost would be:

1% x SAR 318,836,800 = SAR 3,188,368

- **Labor Costs:**
  - Operational Staff: Technicians, engineers, and operational managers who oversee daily operations.
  - Administrative Staff: Includes office staff for administrative tasks, financial management, and regulatory compliance.
  - Cost Range: Estimated between SAR 1,800,000 to SAR 2,400,000 annually, depending on the size of the staff and the specific roles required.

Annual Labor Costs:

The estimated annual labor costs are between SAR 1,800,000 and SAR 2,400,000

6.2.3.3. Depreciation

Depreciation represents the allocation of the cost of physical assets over their useful life. It is crucial for accounting purposes and tax calculations, reflecting the wear and tear and obsolescence of the assets.

- **Depreciation Method:** For this analysis, we use the straight-line depreciation method, which is the simplest and most commonly used method. It involves evenly spreading the cost of the asset over its expected useful life.
- **Useful Life**: The typical useful life of solar panels and related equipment is about 20 to 25 years. For this calculation, we'll use 20 years as the baseline.

Annual Depreciation:

Using the straight-line depreciation method over a useful life of 20 years:

Annual Depreciation = SAR 318,836,800 / 20 years = SAR 15,941,840 per year

6.2.4. Financial Projections

To create comprehensive financial projections for the floating PV power plant, we'll compile the data from above to forecast the income statement, perform a cash flow analysis, and anticipate the balance sheet over the next 5 years.

6.2.4.1. Income Statement Forecast

The income statement forecast will include projections of revenue, expenses, and net profit over the next 5 years.

Assumptions:

- Revenue: Based on the system production of 149,524 MWh/yr and an assumed sale price of 0.18 SAR/kWh.
- Operational Expenses: Include maintenance, labor, insurance, and other running costs.
- Depreciation: As previously calculated.

Revenue Calculation:

Annual Revenue = 149,524 MWh/year x 1,000 kWh/MWh x 0.18 SAR/kWh

= 26,914,320 SAR/year

Expenses:

- Operational Expenses (maintenance + labor + insurance):

3,236,840 SAR + 2,400,000 SAR (higher labor cost estimate) + estimated 500,000 SAR for insurance = 6,136,840 SAR/year

- Depreciation:

SAR 15,941,840 per year

Net Profit Each Year:

$$\text{Net Profit} = \text{Revenue} - \text{Operational Expenses} - \text{Depreciation}$$

$$\text{Net Profit} = \text{SAR } 26{,}914{,}320 - \text{SAR } 6{,}136{,}840 - \text{SAR } 15{,}941{,}840$$

$$\text{Net Profit} = \text{SAR } 4{,}835{,}640 \text{ per year}$$

6.2.4.2. Cash Flow Analysis

- **Initial Investment:**

SAR -318,836,800 (one-time outflow in the first year)

- **Annual Cash Flows (before depreciation, as it's a non-cash expense):**

$$\text{Annual Cash Flow} = \text{Revenue} - \text{Operational Expenses}$$

$$\text{Annual Cash Flow} = \text{SAR } 26{,}914{,}320 - \text{SAR } 6{,}136{,}840$$

$$\text{Annual Cash Flow} = \text{SAR } 20{,}777{,}480$$

6.2.5. Break-even Analysis

To perform the break-even analysis for the floating PV power plant, we will calculate the amount of electricity generation necessary to cover all operational costs, including depreciation, to reach a point where the project begins generating profit.

Key Components for Break-even Analysis:

1. Total Fixed Costs: Includes the annual depreciation.
2. Total Variable Costs: Primarily operational expenses such as maintenance, labor, and insurance.
3. Revenue Per Unit: The revenue generated per kWh of electricity sold.

Assumptions:

- Annual Depreciation: SAR 15,941,840
- Annual Operational Expenses: SAR 6,136,840 (maintenance, labor, insurance)
- Price per kWh: SAR 0.18

Calculation:

The break-even point in terms of electricity generation can be calculated using the formula:

Break-even Point (kWh) = (Total Fixed Costs + Total Variable Costs) / Revenue Per Unit

Break-even Point (kWh) = (SAR 15,941,840 + SAR 6,136,840) / SAR 0.18

Break-even Point (kWh) = SAR 22,078,680 / SAR 0.18

Break-even Point (kWh) = 122,659,333 kWh

This means that the plant needs to generate approximately 122 million kWh per year to cover all costs and start generating a profit. Given the plant's expected annual production of 149,524 MWh (or 149,524,000 kWh), it appears that the plant is well above the break-even point and should be profitable under the given assumptions.

6.2.6. Investment Requirements

To ensure the successful launch and operation of the floating PV power plant in Alaqoul Lake, Madinah, we need to clearly outline the investment requirements, including total funding needs and potential sources of funding.

6.2.6.1. Funding Needs

The total capital required encompasses all costs from inception through to the point where the project becomes self-sustaining and profitable.

Key Components:

- **Initial Capital Investment**: Covers all costs associated with setting up the plant, including PV panels, inverters, anchoring systems, electrical infrastructure, and monitoring systems. The total initial capital investment is estimated at SAR 318,836,800.
- **Operational Costs**: These are the recurring expenses necessary to maintain the plant's operations until it begins generating a profit. Including the first year's operational costs add an essential buffer to ensure smooth operations.
- **Contingency Fund**: Typically, 5-10% of the total project cost to cover unforeseen expenses and mitigate risks associated with project delays or price fluctuations.

6.2.6.2. Funding Sources

Securing adequate funding is crucial for the project's success. Here are potential sources of funding:

- **Equity Investment:**
  - Private Investors: Attract investment from private entities or individuals interested in renewable energy projects. This could include venture capitalists or angel investors.

- Corporate Investment: Large corporations, especially those with a focus on sustainability, might be interested in investing as part of their CSR initiatives or renewable energy goals.

- **Debt Financing:**
  - Bank Loans: Loans from banks or financial institutions that provide financing for renewable energy projects.
  - Green Bonds: Issuing green bonds can be an effective way to raise funds for environmentally friendly projects. These bonds often attract investors looking to support green initiatives.
- **Government Grants and Subsidies:**
  - Saudi Renewable Energy Project Development Office (REPDO): Offers support and funding for renewable energy projects as part of Saudi Arabia's Vision 2030.
  - International Grants: Organizations like the World Bank and the International Renewable Energy Agency (IRENA) provide grants and financial assistance for renewable energy projects in developing countries.
- **Public-Private Partnerships (PPPs):**
- Engaging in PPPs can leverage governmental support and private sector efficiencies and investment, particularly useful in large infrastructure projects like solar power plants.
- **Crowdfunding:**
- For smaller funding portions, platforms dedicated to green energy projects can engage wider communities interested in supporting renewable energies.

Example Funding Strategy:

- 70% Debt: SAR 226,578,800 (from banks and green bonds)
- 20% Equity: SAR 64,736,800 (from private and corporate investors)
- 10% Government Grants: SAR 32,368,400 (from REPDO and other governmental support)

This diversified funding approach reduces risk and balances the financial burden across various stakeholders, enhancing the project's feasibility and attractiveness. By utilizing a mix of equity, debt, and grants, the project can secure the needed capital while maintaining a healthy financial structure to achieve long-term profitability.

6.2.7. Sensitivity and Risk Analysis

Sensitivity and Risk analysis is crucial for understanding the potential financial impact of changes in key variables on the floating PV power plant project. By assessing different scenarios, we can prepare for various outcomes and adapt strategies accordingly. Let’s explore how variations in costs, electricity prices, and interest rates could affect the project's financial viability.

6.2.7.1. Scenario Planning

Variables to Consider:

- **Cost Variations**: Changes in the cost of materials or labor can significantly affect the initial capital investment and ongoing operational expenses.
- **Electricity Price Fluctuations**: The revenue model of the project depends heavily on the price at which electricity is sold.

- **Interest Rate Changes**: For any debt financing involved, fluctuations in interest rates can impact loan repayments and overall financial costs.

6.2.7.2. Sensitivity Analysis Scenarios

1) **Scenario: Increase in Costs**
   - Assumption: Costs increase by 10% due to market volatility or supply chain issues.
   - Impact: This would increase the initial capital cost and operational expenses, requiring higher electricity generation to break even and maintain profitability.
2) **Scenario: Decrease in Electricity Prices**
   - Assumption: A 10% decrease in electricity prices, possibly due to increased competition or changes in policy.
   - Impact: Lower revenue per kWh would increase the time required to reach the break-even point and could necessitate reevaluation of the project’s long-term viability.
3) **Scenario: Rise in Interest Rates**
   - Assumption: Interest rates increase by 2%, affecting the cost of debt.
   - Impact: Higher interest expenses would increase the project's overall financial costs, potentially reducing net profits and affecting cash flow.

6.2.7.3. Detailed Analysis

Base Case:

- **Initial Investment**: SAR 318,836,800
- **Annual Revenue**: SAR 26,914,320 (from electricity sales)

- **Operational Expenses**: SAR 6,136,840 per year
- **Interest Rate**: Assumed 5% on borrowed capital

Scenario Calculations:

- **Cost Increase:**
  - New Initial Investment = SAR 318,836,800 x 1.1 = SAR 350,720,480
  - New Operational Expenses = SAR 6,136,840 x 1.1 = SAR 6,750,524
  - Effect: Increased break-even time and reduced annual net profit.
- **Electricity Price Decrease:**
  - New Annual Revenue = SAR 26,914,320 x 0.9 = SAR 24,222,888
  - Effect: Extended break-even time, requiring more efficient operations or cost-cutting measures.
- **Interest Rate Increase:**
  - If 70% financed by debt: SAR 226,578,800 at 7% interest instead of 5%
  - New Annual Interest Expense = SAR 226,578,800 x 0.07 = SAR 15,860,516 (compared to original at 5% = SAR 11,328,940)
  - Effect: Higher financial costs, lowering available cash flows for other uses.

This sensitivity and risk analysis shows that the financial viability of the floating PV power plant could be sensitive to fluctuations in key economic indicators. By preparing for these scenarios, the project team can develop strategies to mitigate adverse effects, such as securing fixed-price contracts for materials, locking in electricity prices with long-term agreements, or choosing financing options with fixed interest rates. This proactive approach in financial planning can significantly enhance the project's resilience against market volatility.

6.3. Discussion

In this section, we will discuss insights into the skills and knowledge we acquired and applied. Also, we will evaluate our results.

- Skills and Knowledge Required for the Project:

  Building the FPV Power Plant project required a diverse set of skills and knowledge, encompassing both technical and conceptual aspects. Key areas of expertise included proficiency in PVsyst for solar energy simulation, 3D design capabilities for prototype development, mechanical engineering principles, and up-to-date knowledge in solar energy technologies. Each of these competencies was crucial for the various stages of our project, from initial planning to the development of the prototype.

- Learning Processes and Techniques:

  Our learning journey was multifaceted, combining formal education with self-directed learning methods. We gained foundational knowledge through our coursework in the Electrical Engineering program at the University of Prince Mugrin. To complement this, we actively engaged in reading relevant literature and scientific papers, which provided us with a deeper understanding of current trends and advancements in solar energy.

  Additionally, we utilized online resources extensively, particularly YouTube tutorials, to further our practical skills in areas like PVsyst and 3D design software. These tutorials offered step-by-step guidance, enabling us to quickly apply these tools effectively in our project. This blend of theoretical learning and practical application formed a robust learning ecosystem, continuously enriching our skillset and knowledge base.

- Application of Knowledge and Skills:

  The application of our newly acquired knowledge and skills was evident throughout the project. In the simulation and analysis phase, our understanding of PVsyst was instrumental in creating accurate models of the FPV power plant, allowing us to predict its performance and optimize its design. The 3D design skills we developed were crucial in the prototype-building phase for the next semester, where we will translate our theoretical designs into tangible models.

  Our understanding of mechanical principles and solar technology was constantly applied, ensuring that each component of the project was designed and executed with precision and efficiency. This not only enhanced the quality of our work but also provided us with hands-on experience tackling real-world engineering challenges.

- Final Observations and Statistics:

At the end of our project, when presenting our work, we have found some crucial statistics that make our project more attractive and impressive:

1- According to [53-55], the floating systems have efficiency increase from 3%-15%, and for a solar park similar to our one, it can be from 10%-15%.

2- Studies suggest that the cooling effect of water in floating solar systems might lead to a 2-5% increase in panel longevity compared to land-based installations [53].

3- Floating solar parks reduce water evaporation by 50%-70% [56-57].

4- Our system of 137,600 Panels, and 149524 MWh/yr can power 15,000 homes [58].

- Results evaluation:

By comparing PVsyst results with real-world projects [50-52], which have been carefully selected based on their similarity to our project parameters, we can confidently assert the reasonableness and realism of our results. This comparison serves as a validation of the accuracy and reliability of our simulation outcomes. Additionally, our results demonstrate promising performance metrics, including energy generation potential, efficiency, and economic viability. This alignment with real-world data reaffirms the feasibility and potential success of our floating PV power plant project in the Madinah Region. Furthermore, our discussions on the skills and knowledge acquired throughout the project highlight the robust understanding of solar energy technologies, simulation methodologies, and financial analysis techniques employed by our team. These competencies, coupled with the thorough evaluation of our results, position our project as a significant contribution to the field of renewable energy and sustainable engineering practices.

CHAPTER 7

CONCLUSION

In conclusion, the design and implementation of a floating photovoltaic (FPV) power plant on Al-Aqoul Lake represent a significant stride towards meeting Saudi Arabia's Vision 2030 goals for sustainable energy production and environmental stewardship. Throughout the project, we successfully conducted in-depth studies, simulations, and design analyses for a large-scale FPV system, and built a functioning prototype that validated our theoretical models. In addition, we have performed a detailed financial analysis for the project.

This project demonstrates not only the technical feasibility but also the economic advantages of FPV systems over traditional land-based solar power installations. With a total area of approximately 360,985 m² utilized for 137,600 PV modules, the system's capacity to generate 149524 MWh per year at a performance ratio of 80.3% underscores its potential to efficiently meet substantial energy demands. Specifically, the project has proven capable of powering around 15,000 residential units, highlighting its significant impact on the region's energy infrastructure and its residents' daily lives.

Financial analyses confirm the cost-effectiveness of this renewable energy solution, with production costs estimated at approximately 0.18 SAR per kWh, making it an economically viable option for large-scale energy production. In addition, the payback period for the project is 5 years, which is considered small for such Mega projects, also the break-even point is 124 million kWh per year, and we have achieved at least 149 million kWh per year, which is a huge success for such project.

The project also contributes to the conservation of water resources by minimizing evaporation, further enhancing its environmental benefits.

As we look to the future, we recommend the integration of adaptive, AI-driven technologies to optimize the plant's operational efficiency and resilience to environmental changes. The FPV system not only exemplifies advanced engineering and innovative design but also sets a benchmark for future renewable energy projects within Saudi Arabia and beyond. With its scalable model and demonstrated benefits, the FPV power plant at Al-Aqoul Lake is poised to become a cornerstone of the region's sustainable energy landscape.

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APPENDIX 1

Depth Warning System – Arduino Code

```
#define BUTTON_PIN 7   // Define the pin number for the button
#define BUZZER_PIN 2   // Define the pin number for the buzzer

void setup() {
  pinMode(BUTTON_PIN, INPUT_PULLUP);  // Set the button pin as input with
internal pull-up resistor
  pinMode(BUZZER_PIN, OUTPUT);        // Set the buzzer pin as output
}

void loop() {
  // Read the state of the button
  bool buttonState = digitalRead(BUTTON_PIN);

  // Check if the button is pressed
  if (buttonState == LOW) {
    // If button is pressed, generate a tone of 4500Hz
    tone(BUZZER_PIN, 4500);
    delay(200); // Debounce delay to prevent multiple tones on a single press
  } else {
    // If button is not pressed, turn off the buzzer
    noTone(BUZZER_PIN);
  }

}
```

Solar Tracking Suggested Electronic Scheme – Arduino Code

```
//Multiple DC Motor

//
//
void setup()
{
  pinMode(13, OUTPUT);
  pinMode(12, OUTPUT);
  pinMode(11, OUTPUT);
  pinMode(19, OUTPUT);
  pinMode(8, OUTPUT);
  pinMode(10, OUTPUT);
  digitalWrite(13,HIGH);
  digitalWrite(12,HIGH);
}

void loop()
{
  digitalWrite(11, HIGH);
  digitalWrite(9, LOW);
  delay(500);
  digitalWrite(11,LOW);
  digitalWrite(9, HIGH);
  delay(500);
  digitalWrite(10, HIGH);
  digitalWrite(8, LOW);
  delay(500);
  digitalWrite(10, LOW);
  digitalWrite(8, HIGH);
  delay(2000);
}
```

APPENDIX 2

PVsyst REPORT

Version 7.4.4

PVsyst - Simulation report

Grid-Connected System

Capstone Project

Al-Aqoul Floating Solar Park

System power: 74.99 MWp
Al ‘Uqūl Lake - Saudi Arabia

UPM - EE | Marwan Bitar + Hamza Alashi

Project summary

Geographical Site	Situation		Project settings	
Al 'Uqūl Lake	Latitude	24.52 °N	Albedo	0.20
Saudi Arabia	Longitude	39.74 °E		
	Altitude	629 m		
	Time zone	UTC+3		

Meteo data
Al 'Uqūl Lake
Meteonorm 8.1 (1998-2002), Sat=100% - Synthetic

System summary

Grid-Connected System

PV Field Orientation
Fixed plane
Tilt/Azimuth 26 / 0 °

Near Shadings
No Shadings

User's needs
Unlimited load (grid)

System information

PV Array		Inverters	
Nb. of modules	137600 units	Nb. of units	586 units
Pnom total	74.99 MWp	Pnom total	58.60 MWac
		Pnom ratio	1.280

Results summary

Produced Energy	149524476 kWh/year	Specific production	1994 kWh/kWp/year	Perf. Ratio PR	80.34 %

Table of contents

General parameters

Grid-Connected System

PV Field Orientation
Orientation
Fixed plane
Tilt/Azimuth 26 / 0 °

Sheds configuration
No 3D scene defined

Horizon
Free Horizon

Models used
Transposition Perez
Diffuse Perez, Meteonorm
Circumsolar separate

Near Shadings
No Shadings

User's needs
Unlimited load (grid)

PV Array Characteristics

PV module

Manufacturer	JA Solar
Model	JAM72-S30-545-MR
(Original PVsyst database)	
Unit Nom. Power	545 Wp
Number of PV modules	137600 units
Nominal (STC)	74.99 MWp
Modules	8600 string x 16 In series
At operating cond. (50°C)	
Pmpp	68.84 MWp
U mpp	606 V
I mpp	113576 A

Inverter

Manufacturer	Fronius International
Model	Tauro Eco 99-3-P
(Original PVsyst database)	
Unit Nom. Power	100 kWac
Number of inverters	586 units
Total power	58600 kWac
Operating voltage	580-930 V
Pnom ratio (DC:AC)	1.28

Total PV power

Nominal (STC)	74992 kWp
Total	137600 modules
Module area	355455 m²

Total inverter power

Total power	58600 kWac
Number of inverters	586 units
Pnom ratio	1.28

Array losses

Array Soiling Losses
Loss Fraction 2.0 %

Thermal Loss factor
Module temperature according to irradiance
Uc (const) 29.0 W/m²K
Uv (wind) 0.0 W/m²K/m/s

DC wiring losses
Global array res. 0.088 mΩ
Loss Fraction 1.5 % at STC

Serie Diode Loss
Voltage drop 0.7 V
Loss Fraction 0.1 % at STC

Module Quality Loss
Loss Fraction -0.8 %

Module mismatch losses
Loss Fraction 2.0 % at MPP

Strings Mismatch loss
Loss Fraction 0.2 %

IAM loss factor
Incidence effect (IAM): User defined profile

0°	30°	50°	65°	70°	75°	80°	85°	90°
1.000	1.000	0.999	0.953	0.910	0.853	0.725	0.448	0.000

PVsyst V7.4.4
VC0, Simulation date:
05/12/24 22:32
with v7.4.4

Array losses

Spectral correction
FirstSolar model
Precipitable water estimated from relative humidity

Coefficient Set	C0	C1	C2	C3	C4	C5
Monocrystalline Si	0.85914	-0.02088	-0.0058853	0.12029	0.026814	-0.001781

System losses

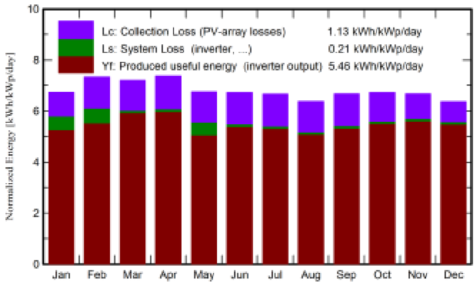
Unavailability of the system
Time fraction 2.0 %
7.3 days,
3 periods

Main results

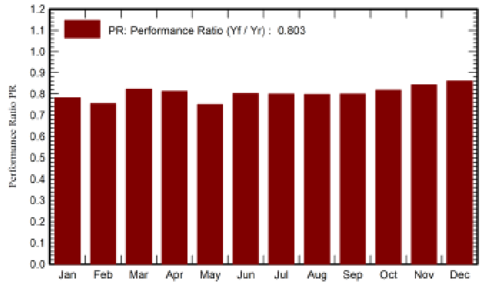
System Production

Produced Energy	149524476 kWh/year	Specific production	1994 kWh/kWp/year
		Perf. Ratio PR	80.34 %

Normalized productions (per installed kWp)



Performance Ratio PR

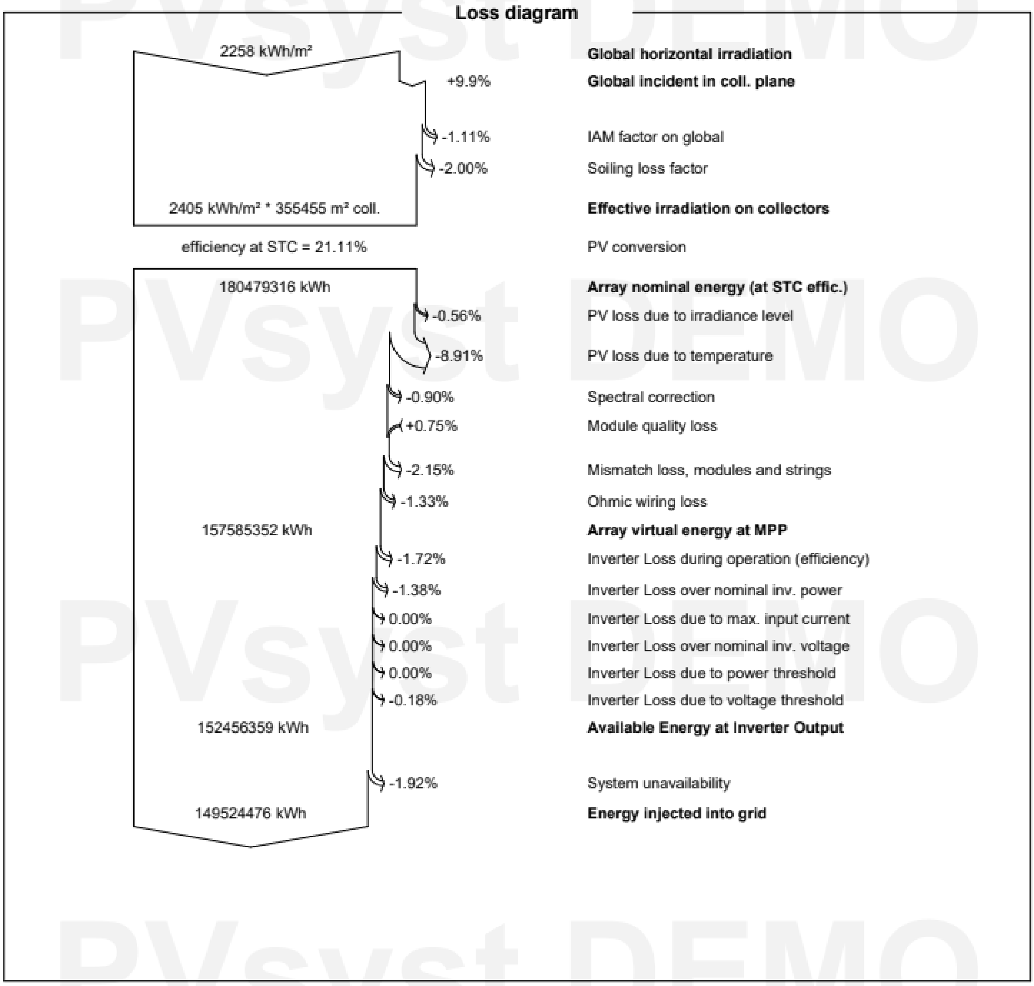


Balances and main results

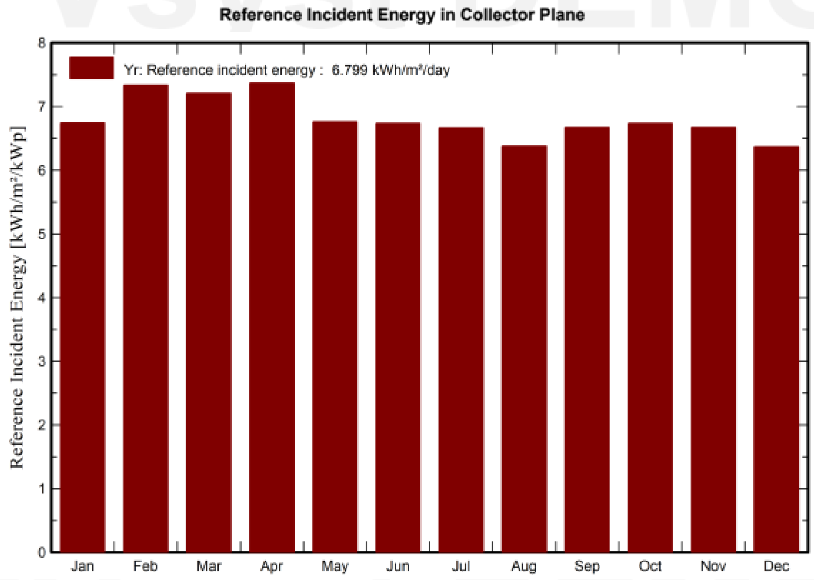
	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	E_Grid kWh	PR ratio
January	150.1	25.18	18.10	209.1	203.8	13496808	12270002	0.782
February	161.2	29.76	21.02	205.4	199.5	12860550	11617428	0.754
March	197.9	50.16	25.05	223.5	216.6	14036447	13790289	0.823
April	218.9	55.98	28.91	221.1	214.0	13722503	13478437	0.813
May	226.2	78.36	33.94	209.5	202.1	12939704	11780512	0.750
June	228.2	72.87	36.59	202.1	194.8	12355556	12144080	0.801
July	228.9	78.02	37.67	206.5	199.3	12589896	12374909	0.799
August	203.1	85.23	38.21	197.8	191.3	12034077	11827525	0.797
September	186.4	61.70	35.80	200.2	193.8	12219928	12008571	0.800
October	173.3	48.99	31.24	208.8	202.9	13052859	12824583	0.819
November	146.9	29.48	24.09	200.1	194.5	12873190	12648374	0.843
December	136.9	25.37	19.85	197.5	192.2	12988715	12759767	0.862
Year	2258.0	641.11	29.25	2481.7	2404.9	155170232	149524476	0.803

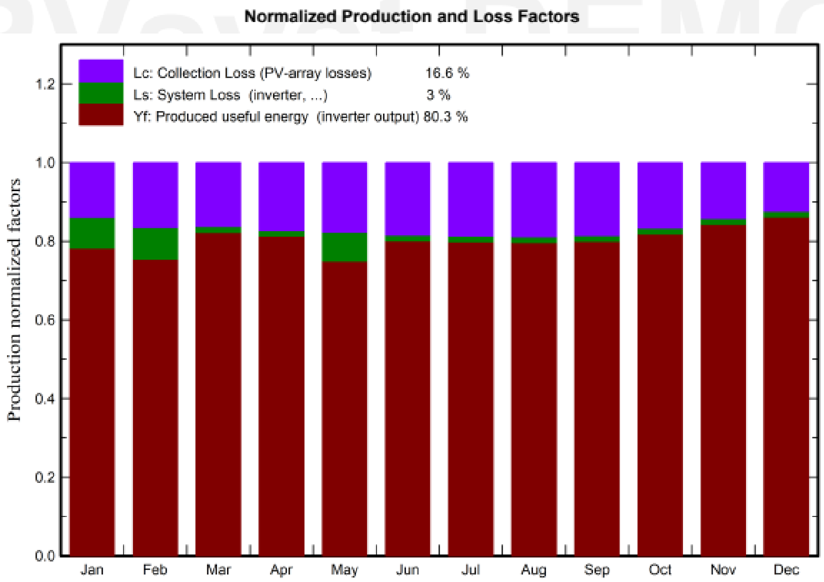
Legends

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		


Loss diagram
2258 kWh/m²
Global horizontal irradiation
+9.9%
Global incident in coll. plane
-1.11%
IAM factor on global
-2.00%
Soiling loss factor
2405 kWh/m² * 355455 m² coll.
Effective irradiation on collectors
efficiency at STC = 21.11%
PV conversion
180479316 kWh
Array nominal energy (at STC effic.)
-0.56%
PV loss due to irradiance level
-8.91%
PV loss due to temperature
-0.90%
Spectral correction
+0.75%
Module quality loss
-2.15%
Mismatch loss, modules and strings
-1.33%
Ohmic wiring loss
157585352 kWh
Array virtual energy at MPP
-1.72%
Inverter Loss during operation (efficiency)
-1.38%
Inverter Loss over nominal inv. power
0.00%
Inverter Loss due to max. input current
0.00%
Inverter Loss over nominal inv. voltage
0.00%
Inverter Loss due to power threshold
-0.18%
Inverter Loss due to voltage threshold
152456359 kWh
Available Energy at Inverter Output
-1.92%
System unavailability
149524476 kWh
Energy injected into grid

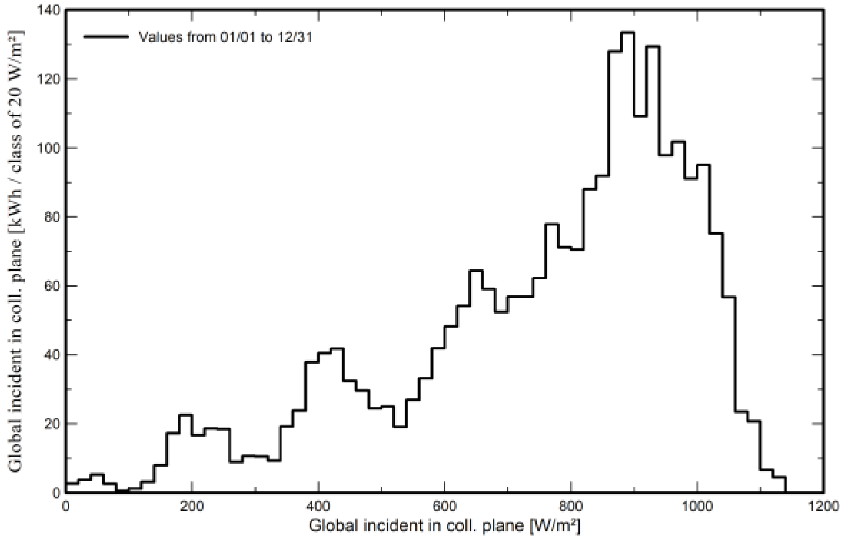
Predef. graphs



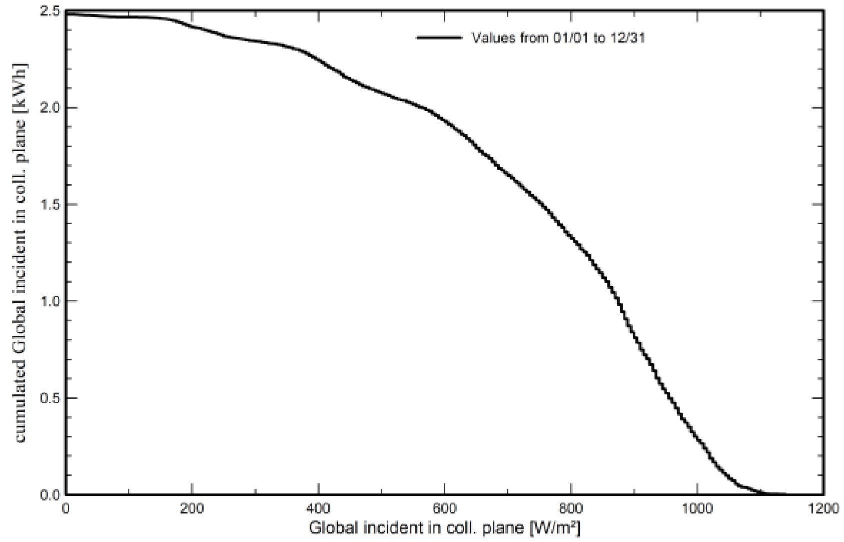


Predef. graphs

Incident Irradiation Distribution

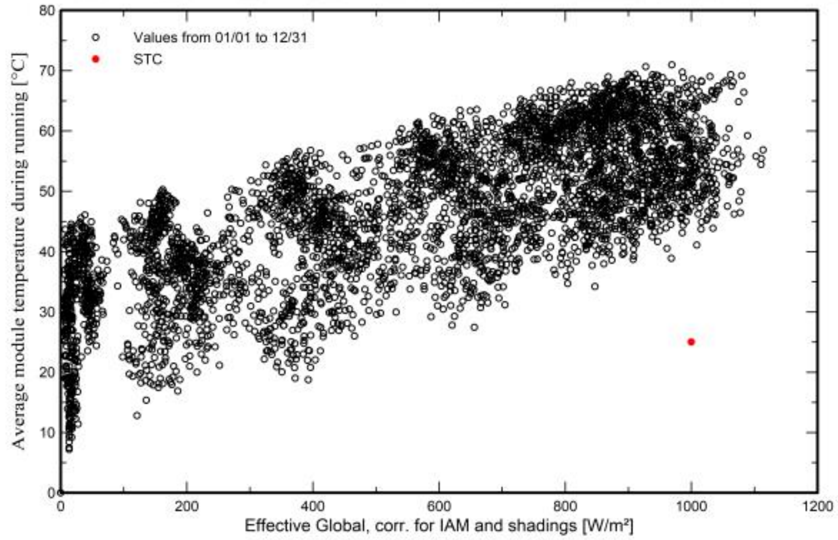


Incident Irradiation cumulative distribution

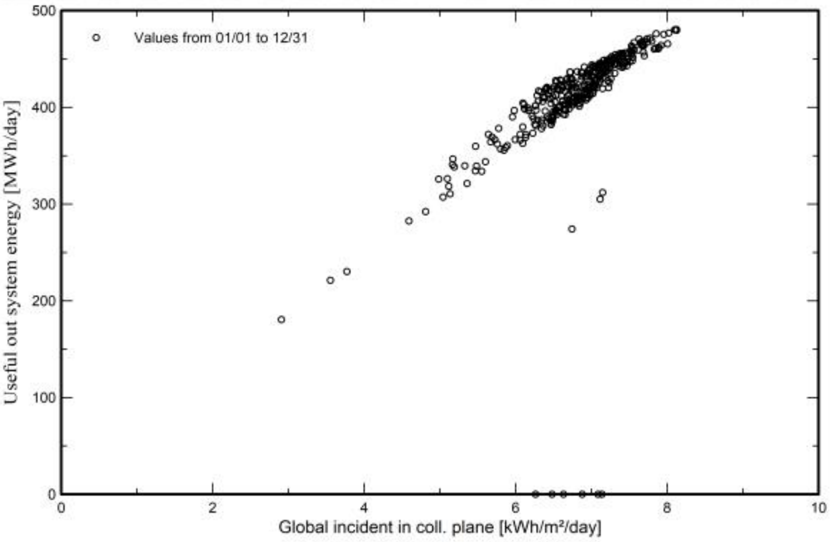


Predef. graphs

Array Temperature vs. Effective Irradiance

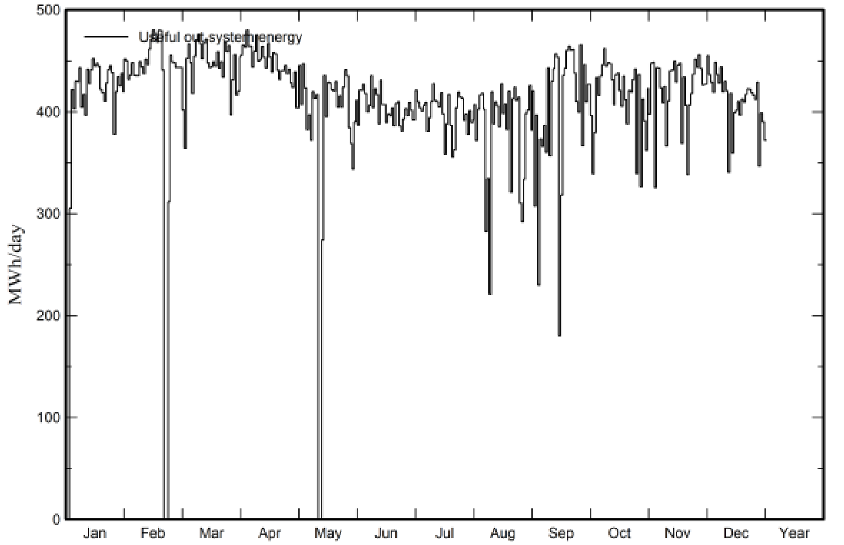


Daily Input/Output diagram

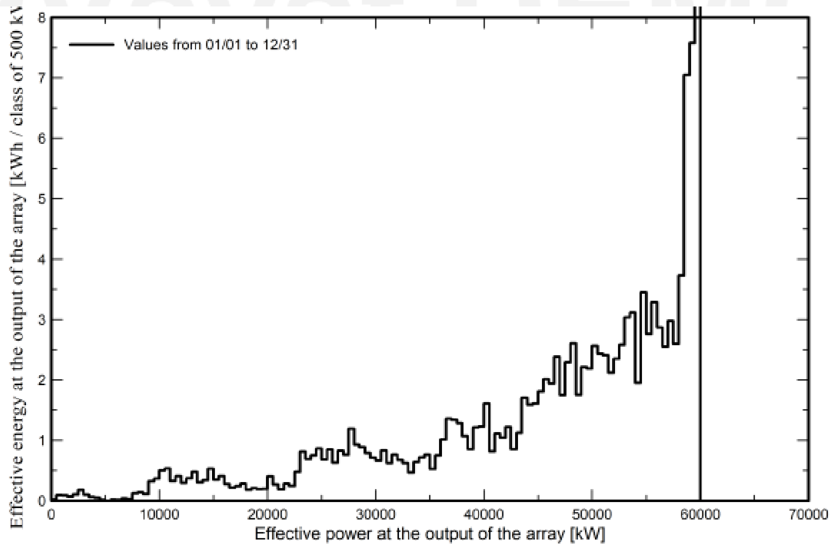


Predef. graphs

Daily System Output Energy

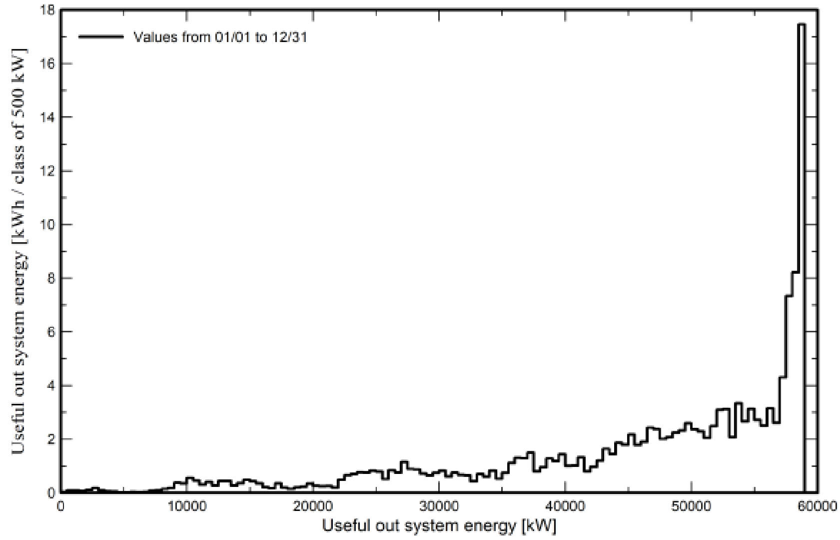


Array Power Distribution

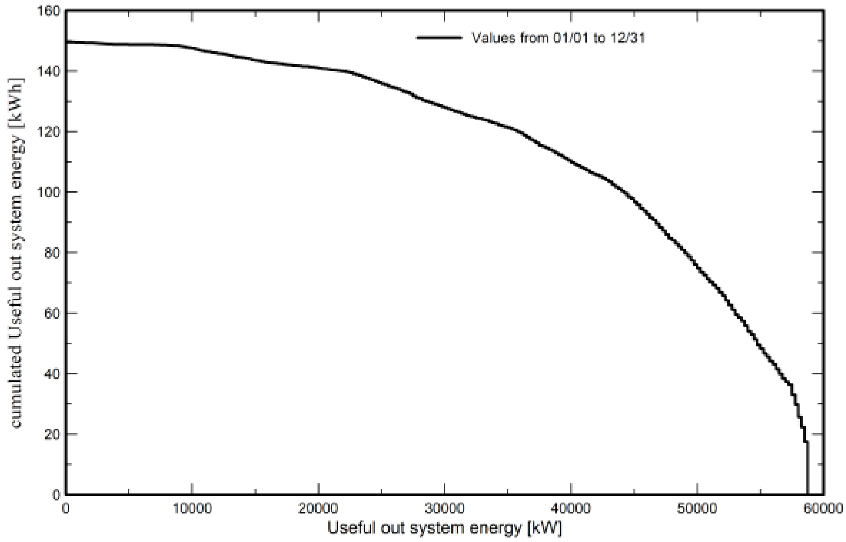


Predef. graphs

System Output Power Distribution

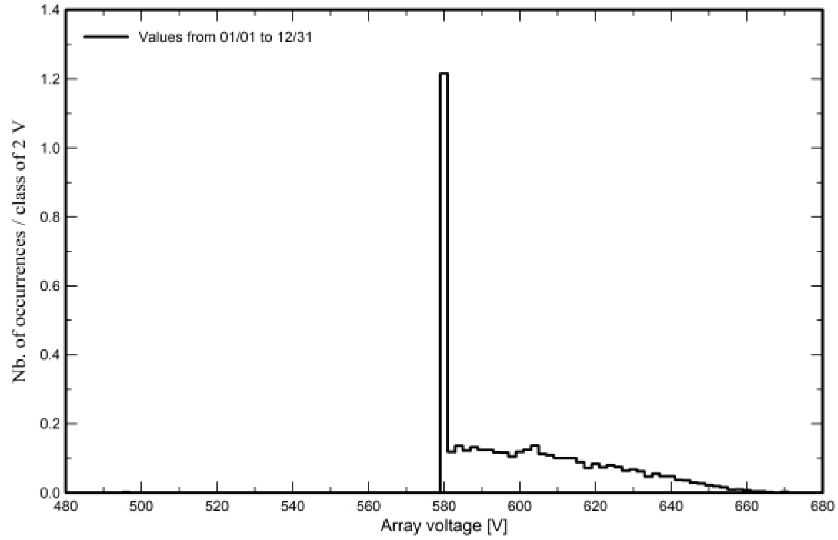


System Output Power cumulative distribution

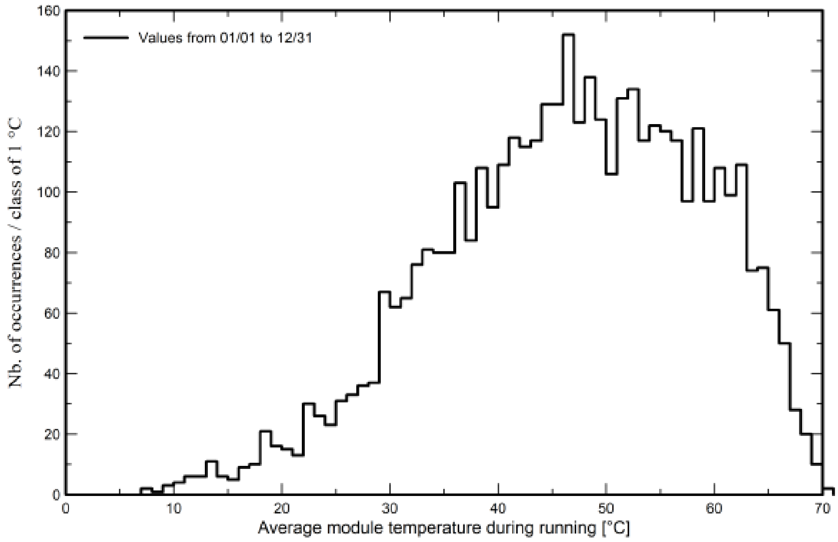


Predef. graphs

Array Voltage Distribution

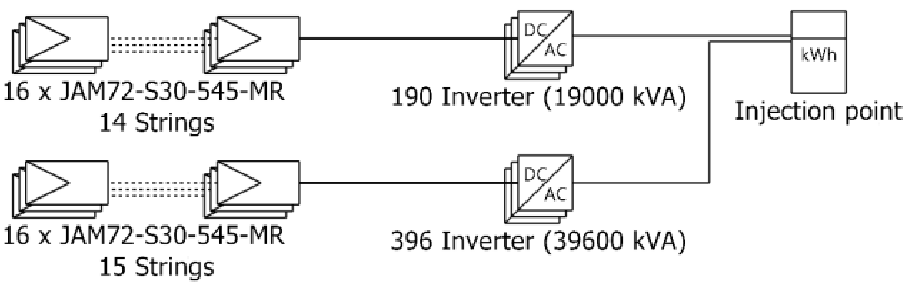


Array Temperature Distribution during running



Single-line diagram

PVsyst V7.4.4
VC0, Simulation date:
05/12/24 22:32
with v7.4.4



PV module	JAM72-S30-545-MR
Inverter	Tauro Eco 99-3-P
String	16 x JAM72-S30-545-MR

Capstone 1 Project	
VC0 : Preliminary Design	05/12/24

CO_2 Emission Balance

Total: 2203485.0 tCO_2

Generated emissions

Total: 688357.62 tCO_2

Source: Detailed calculation from table below

Replaced Emissions

Total: 3332900.6 tCO_2

System production: 149524.48 MWh/yr

Grid Lifecycle Emissions: 743 gCO_2/kWh

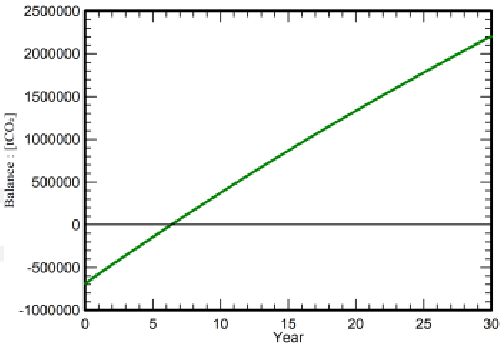
Source: IEA List

Country: Saudi Arabia

Lifetime: 30 years

Annual degradation: 1.0 %

Saved CO_2 Emission vs. Time



System Lifecycle Emissions Details

Item	LCE	Quantity	Subtotal
			[$kgCO_2$]
Modules	1713 kgCO2/kWp	380794 kWp	652192952
Supports	4.96 kgCO2/kg	6987040 kg	34626443
Inverters	491 kgCO2/	3133	1538223