UNIVERSIDAD DE VALLADOLID

ESCUELA DE INGENIERIAS INDUSTRIALES

Grado en Ingeniería de Organización Industrial

Assessing Energy Performance and Management Processes in Solar Photovoltaic Plants

Autor:

Játiva Torres, Alfonso

Rey Martínez, Francisco Javier

University of Malta

Valladolid, julio 2022.

TFG REALIZADO EN PROGRAMA DE INTERCAMBIO

TÍTULO:	Assessing Energy Performance and Management Processes in Solar Photovoltaic Farms
ALUMNO:	Alfonso Játiva Torres
FECHA:	31.05.2022
CENTRO:	Institute of Sustainable Energy
UNIVERSIDAD:	University of Malta
TUTOR:	Charles Yousif

RESUMEN:

La finalidad de la tesis es analizar cualitativamente los procesos de mantenimiento y gestión de las diferentes plantas fotovoltaicas, así como cuantitativamente los resultados de producción de energía solar y determinar las principales causas del funcionamiento actual. Los objetivos son realizar un análisis detallado de todas las características de cada instalación e identificar sus procedimientos de gestión y mantenimiento, recoger los datos de generación de energía y compararlos con un software y comparar los diferentes sistemas fotovoltaicos y aportar recomendaciones de mejora. Se utiliza una metodología para todas las instalaciones fotovoltaicas que incluye un análisis DAFO y una evaluación del rendimiento energético. Los resultados muestran varios puntos en común respecto a los principales problemas de las plantas fotovoltaicas, siguen el mismo patrón respecto a los ratios de generación de energía. Por último, se mencionan las posibles medidas de mejora a tener en cuenta para cada instalación.

PALABRAS CLAVE: energy performance assessment, solar energy, photovoltaic plants, management processes, performance ratio.

ABSTRACT:

The purpose of the dissertation is to analyse qualitatively the maintenance and management processes of the different photovoltaic plants, as well as quantitatively the results of solar energy production and determine the main causes for the current operation. The objectives are to perform a detailed analysis of all the characteristics of every installation and identify their management and maintenance procedures, to collect data from energy generation and compare it with a software and compare different PV systems and provide recommendations of improvement. There is a methodology used for all PV sites including a SWOT analysis and a energy performance evaluation. The results show various commonalities regarding the main problems of the photovoltaic plants, they follow the same pattern regarding energy generation ratios. Finally, the possible improvement measures to take into consideration for each installation are mentioned.

KEY WORDS: energy performance assessment, solar energy, photovoltaic plants, management processes, performance ratio.

ASSESSING ENERGY PERFORMANCE AND MANAGEMENT PROCESSES IN SOLAR PHOTOVOLTAIC FARMS

Alfonso Játiva Torres

Institute for Sustainable Energy

University of Malta

May 2022

ASSESSING ENERGY PERFORMANCE AND MANAGEMENT PROCESSES IN SOLAR PHOTOVOLTAIC FARMS

A dissertation presented at the

Institute for Sustainable Energy of the University of Malta, Malta

in partial fulfilment of the requirements of the award of

Bachelor's in Management Industrial Engineering

at the

Universidad de Valladolid, Spain

under the Erasmus Plus Student Exchange Programme 2021/2022.

Declaration

No portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

Signature of Student

Name of Student

Alfonso Játiva Torres

May 2022

Copyright notice

Abstract

Solar Photovoltaics have become one of the mainstream renewable energy systems around the world. According to the European Union at least 32% of the energy consumption must come from renewable energy sources by 2030. Photovoltaic farms are currently also becoming quite popular because they benefit from economy of scale and make the technology more affordable and easier to operate and maintain.

In Malta, such solar farms are still at their infancy and this dissertation aimed at studying their operation and management in order to further support their optimum output and long-term reliability. Five large solar farms installed on the ground and on rooftops were studied using two pathways, namely through an energy management analysis process and through a technical and operational performance approach.

For this purpose, the methodology implemented included a SWOT analysis for the management of such farms as well as a quantitative analysis on the performance of the PV systems. This performance was also compared to modelled data using the PVFChart software.

The performance ratio analyses showed significant differences between different solar farms. It was found that several parameters have contributed to such variance, including different inclination and orientation, cross-shading, dirt accumulation and proximity of the PV modules to the sea which helps in natural cooling. The highest annual performance ratio was found to be 86.3%. Nevertheless, the system still suffered from winter cross-shading along the PV rows, which amounted to an equivalent loss of revenue of € 28814.3 per year. Other PV farms showed more significant losses amounting up to a 6% loss of revenue per year.

Recommendations on what measures should be put into effect for each case were identified and presented. Solutions included a change in inclination of steeply inclined PV modules to avoid cross-shading in winter, more preventive maintenance measures such as grass cutting and general maintenance for wiring and inverters.

Acknowledgments

I would like to express my gratitude to Dr. Ing. Charles Yousif, supervisor of my dissertation. His knowledge, perseverance, commitment, and dedication have helped and taught me so much both in quantitative knowledge and hard-working values.

In addition, I would like to thank my home institution, the University of Valladolid, and the University of Malta, for giving me the opportunity to take part in the Erasmus programme and being able to study abroad.

I would like to thank all the owners of the PV farms for allowing me access to their facilities and providing me with all data and information needed for this dissertation.

Last but not least, I would like to give thanks to my family, my mother, my father and my sister for supporting me and always giving me the best and being by my side in all circumstances. Also, to Cristina for accompanying me in this experience and supporting each other.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
CCTV	Closed-Circuit Television
CMS	Condition Monitoring Systems
CUF	Capacity Utilization Factor
DC	Direct Current
DNI	Direct Normal Irradiance
EPDM	Ethylene Propylene Diene Monomer
EUV	Extreme Ultraviolet
FiT	Feed-in Tariff
GHI	Global Horizontal Irradiance
HV	High Voltage
LV	Low Voltage
NECP	National Energy and Climate Plan
OEM	Original Equipment Manufacturer
O&M	Operation and Maintenance
PR	Performance Ratio
PV	Photovoltaic
RES	Renewable Energy Sources
RPAs	Remoted Piloted Aircrafts
STC	Standard Test Conditions
TPO	Thermoplastic Polyolefin
TSI	Total Solar Irradiance
UAV	Unnamed Aerial Vehicles
UV	Ultraviolet

1. Introduction

1.1 Solar Energy at the Moment and Future

Over the ages, the ways of obtaining energy have evolved. From the first energy sources, the most prolific during the 20th century were non-renewable sources such as coal, oil, and gas. Now that the 21st century has arrived, the horizon includes new renewable energy sources for moving towards a sustainable and clean. This includes solar energy.

The European Renewable Energy Directive (2018/2001/EU) [1] aims at achieving 32% renewable energy share by 2030 and Malta will need to contribute towards that target like all other Member States. Given that Malta has achieved its mandatory target of 10% in 2020, it now has to make extra effort to increase this share over the years, especially through solar photovoltaics. It is to be noted that solar photovoltaic share in the EU had reached 14% overall in 2020. [2]

Malta's need to reach the desired target for renewable energy is more challenging than in other countries due to the small area that it covers and its limitation on starting projects such as hydroelectric power plants since there are no hydrological resources in the island. Nonetheless, Malta's geographical situation has an advantage in producing solar energy thanks to the days in a year that have sunshine, and its 3000 annual hours of daylight.

Photovoltaic systems and plants can be installed in the island, but there are impossibilities of carrying out projects on extensive photovoltaic plants. More and more buildings and private-owned rooftops have taken the opportunity raised by the Government of Malta and have started implementing solar photovoltaic systems with the incentives provided through subventions. Thanks to this decision, the installation of these systems has risen exponentially, helping house owners, and making it easier for them to pay their electricity and water bill whilst the country advances into a cleaner and zero-emission energy consumption.

1.2 Solar Photovoltaic Plant Performance Assessment

While the cost of photovoltaic (PV) electricity is decreasing, increasing energy production over the life of a plant is still a major aspect in determining a PV plant's economic case. If not recognized and remedied in a timely manner, various variables such as shadowing, soiling, module aging, and component defects can result in a large loss of energy production. As a result, performance evaluation has the ability to improve PV plant economics by identifying the need for timely corrective steps and so minimizing or lowering economic loss [3].

When the system is physically intact, there is no soiling, and no unexplained interruptions interfere with energy output, it is said to be in normal functioning.

The method used for evaluating performance is based on comparing measured and modelled energy generation though a software with the purpose of detecting abnormalities.

The correct estimation of the electricity production that can be reached, therefore the potential energy production, in conditions of normal operation is extremely important for the systems installed in the photovoltaic plants.

However, a wide variety of unpredictably affecting PV performance circumstances represent a severe barrier in constructing a trustworthy model for estimating PV output, necessitating additional study which is made in this dissertation.

1.3 Aim and Objectives

Firstly, the aim of this study is to analyse qualitatively the maintenance and management processes of the different photovoltaic plants, as well as quantitatively the results of solar energy production. And to determine which are the main causes for the current operation. The principal objectives are:

- Perform a detailed analysis of all the characteristics of every installation and identify their management and maintenance procedures.
- Collect data from energy generation and compare with a software its performance ratio along with its final yield.
- Compare the different photovoltaic systems as well as establishing conclusions for which are the main faults, weaknesses or failures of each PV system.

1.4 Dissertation Structure

In this dissertation, five chapters are presented. The 1st chapter is the introduction of the subject, with the explanation of the great importance and relevance nowadays. The aim and objectives of the research.

The 2nd chapter presents all relevant information from the background of PV plants in order to understand the aspects of this study. It contains explanations and operation of all system elements in a photovoltaic plant, as well as management and maintenance characteristics.

The 3rd chapter includes the methodology utilised for the development of the study, it is divided in two sections since there is a qualitative and a quantitative analysis.

The 4th chapter presents the results and the discussion of the same from each of the photovoltaic plants separately from both qualitative and quantitative point of view, along with a comparison in between them and their own specific characteristics.

The final chapter recapitulates the conclusions of this research based on the results that were obtained, it identifies the main problems of each installation and the impact they have on the final energy production.

2. Background and Literature Review

2.1 Solar Photovoltaic Modules

A solar photovoltaic (PV) cell is a small flat component that is usually made up of doped crystalline silicon and is therefore able to convert sunlight into electricity thanks to the Photoelectric Effect [4]. Doping implies the addition of small amounts of other elements, such as phosphorus and boron, which together assist in forming a potential difference across the silicon cell, with the negative band on top and the positive region on the bottom, thus enabling the creation of a potential difference across the PV cell. During the day, the electron deficiency created across the positive-negative junction drives the electrons that have exited their orbit through solar energy absorption to an external circuit, thus generating free electricity [5].

A solar (PV) module is nothing more than a large plate on which many solar PV cells are placed together and connected mostly in series. If a solar cell converts the sun's energy into electricity, a solar module integrates the production of those many cells to produce higher voltage and therefore higher power at the generated electric current according to the available solar energy. The larger the solar module, the more solar cells and surface area it has, and the more energy it will receive from the sun to convert to electricity [4].

The functioning of a solar PV module lays in its materials. Photoelectric semiconductors are those that, when light strikes them, electrons are released from their atoms. It is the photons of light that release the electrons from the semiconductor by giving up their energy [5]. Silicon is an example of a photoelectric semiconductor. In short, when the photons of sunlight reach silicon, they give up their energy to the electrons of the last layer of the silicon atoms and break the bond with its atom, leaving it free to move through the material. These free electrons will be the ones that can be transferred outside the cell’s material to produce a current in an external circuit [4].

Silicon is the most widely used semiconductor material in electronics and photovoltaic cells because it is the most abundant material and its production and manufacturing processes have matured well along the years, making its price reasonable and accessible to many nations.

2.2 Solar Inverters

In a solar energy system, an inverter is one of the most crucial components. This is a power electronic device that transforms direct current (DC) electricity generated by the solar PV modules into alternating current (AC) electricity used by the electrical grid. The inverter has also other functions such as monitoring the grid to ensure appropriate synchronisation of the generated photovoltaic power with the grid, as well as to serve as an anti-islanding safeguard, to disconnect the PV system from the grid in case of disturbances or power failure. Finally, the inverter also ensures that the PV array is operating at its maximum power point for all levels of solar radiation and operational PV cell temperatures. Nowadays, most inverters come with inbuilt monitoring systems that can be accessed via the internet or other communication modes [6].

2.2.1 Types of Inverters

The main three types of inverters in descending order in terms of size are the string inverters, power inverters and micro inverters. The most popular inverters used worldwide are the string inverters [7].

- **String inverter:** String inverters link a string of modules to a single inverter. The power generated by the entire string is converted to AC by this converter. This design, while being cost-effective, results in lower power production on the string if any individual module has problems, such as shading. Recent modifications from string inverter manufacturers are made in order to design the inverters to work in a wider range of situations. The modules are grouped together and connected in series to form strings. Many PV strings can be connected to a single inverter, which converts the direct current electricity generated by the modules into appliance-friendly power [8].
- **Power inverter:** They are a sort of module-level power electronics that provide similar benefits to micro-inverters while being less expensive. In this case, each module has its set of inverters. On the contrary, rather than converting DC to AC at the module location, the optimizers condition the DC and send it to a string inverter. In some circumstances where the roof is shadowed, their results on optimization are of a higher system efficiency than string inverters. Therefore, every solar module in a large-

scale utility plant or a mid-scale community solar project might be connected to a single central inverter [8].

- **Micro-inverter:** Micro-inverters can be installed in each and every PV module of the solar installation. They convert the DC power generated by the solar cells into AC electricity on the roof, eliminating the need of a separate central inverter. Usually, they are mounted on the back of the PV modules. Micro-inverters allow us to track the performance from each solar module [8].

2.3 Photovoltaic Installations

PV installations can be differentiated into three types depending on their connection to the grid. First of all, the most common type are the grid-connected PV installations, then there are grid-connected systems with batteries and off-grid installations.

2.3.1 Grid-connected Systems

Solar PV energy needs a connection to the grid to transfer energy from the solar modules and inverters to the main electricity network [9].

The performance of the entire solar photovoltaic installation depends on the effectiveness and reliability of the inverter [6]. In large scale PV farms, the interconnection between the PV modules and the inverter requires careful design to ensure optimum operation at the right voltage and to ensure minimum energy losses across the cables. Moreover, the interconnection between the inverter and the grid will involve complex electrical design, which includes the use of low voltage (LV) and high voltage (HV) busbars and a transformer [10].

In Figure 1, it can be observed a typical layout of a solar PV installation, including its components: photovoltaic modules, cabling, inverters, transformer, and the grid connection.

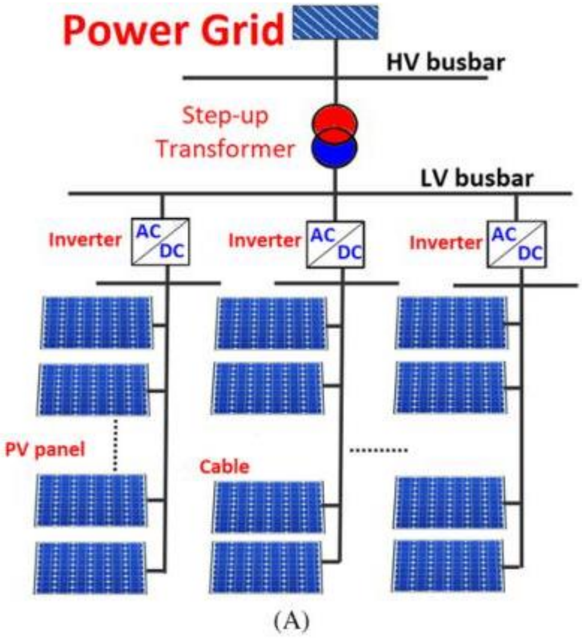


Figure 1. Topological configuration of a PV solar station [11].

The other types of PV systems include the integration of a battery storage with a hybrid inverter or better known as “Island” inverter. In such a configuration, the PV system can either charge the batteries or feed power to the grid. It is also possible for the system to continue operating as an “island” power supply, even when the grid power is cut.

The off-grid PV system does not require to be connected to the grid, but it needs a large battery bank to act as storage and the inverter would have to be tailor-made to use the battery voltage as a reference instead of the grid to operate the PV system as a whole. Such systems are popular in remote areas or inaccessible terrain such as on mountain tops.

2.3.2 Solar Mounting Structures

With regards to the total production, efficiency, and lifetime of solar PV modules, the precise and correct selection of mounting structures for the system is critical. Choosing the mounting system has to be regarded as a major consideration in the project due to the high cost it implies. Solar modules must be fixed, installed, and clamped on a truly stable and durable structure, which will protect the PV array from rain, hail, snow, wind and moderate earthquakes. Solar modules can be installed on rooftops, on the ground or on poles [12].

- **Rooftop mounted racks:** These are normally for roofs that have an inclination. They reduce wire run distances between the solar array and the inverter, but they penetrate the roof and endanger it; therefore the roof must be tightly sealed. Another downside is that if the roof orientation and angle are not appropriate, the system will waste a lot of potential solar energy. It must be guaranteed that there is no shading coming from trees or buildings in the optimum free airflow path of the solar modules [12]. For flat roofs such as in the case of Malta, the solar modules can be inclined towards the optimum direction due South and inclined at an inclination of 30° to the horizontal [13]. However, one has also to take into consideration the roof's load limitations. Also, some PV modules on roofs cannot be set either to this inclination angle, due to excessive wind loading.
- **Ground mounted racks:** These are normally adjustable so that they can be tilted up or down for maximum sunlight absorption at different times of the day.
- **Pole Mounts** are used to secure solar modules to poles. "Top-of-pole" and "side-of-pole" are the two main types of pole mounts. The first one permits the solar module to be mounted on top of a pole, a certain height above ground level. The second one secures solar modules to poles' sides [12].
- **Ballasted Mounts**: shown in Figure 2 use weights to keep the solar modules on the roof in place. This design saves labour time and money, but it also adds the problem of moving the weights onto the roof, which can be fairly difficult with larger systems. Ballasted mounts eliminate the need for roof penetrations, are quicker and less expensive to install, and allow for a module tilt of up to 20 degrees for best sun exposure. This mount, on the other hand, adds to the weight on the roof, has a lower power density, and is less ideal for high-wind environments. They have limitations, such as roof slope and building height [12].

Figure 2. PV rooftop installation with ballasted mounts [14].

- **TREE system:** This is a system developed by an Italian company [15] shown in Figure 3 which consists in three oblique inserts that are connected by an anchoring base and determine the penetration tilt in the soil mass. As a result, a volume of ground is affected due to the length of the anchoring inserts. They block the gadget that remains on the surface after being driven into the earth in different directions. The advantages are that it allows easy removal at the end of the PV plant's lifecycle, as well as avoiding excavation and cast concrete during installation. It does not need specific equipment or labour and is ideal for PV plants that have very steep slopes, and for lands that do not allow deep digging, such as quarries or landfill. This is considered to be an environmentally-benign anchoring system and is noted to have been used in several large-scale PV farms in Malta.

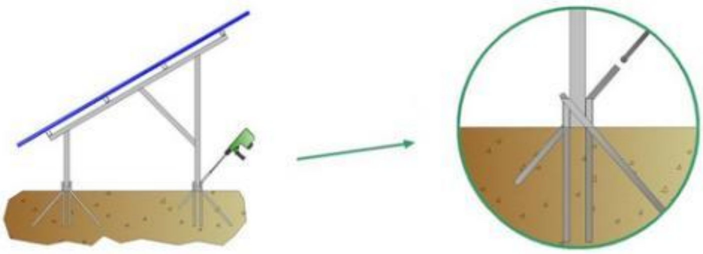


Figure 3. Tree system anchoring for ground mounted PV systems [15].

2.4 Solar Energy in Malta

2.4.1 Current Situation

The energy generated in Malta comes from different energy sources, although they are not very diverse. Most of the energy comes from non-renewable energy sources, in this case mainly from natural gas for electricity generation, LPG for cooking, fuel oil for heating in some hotels and petrol and diesel for transport, which together account for 89.96% of the total final energy consumption energy [16].

On the other hand, the remaining percentage of energy produced in the country comes from renewable energy sources (RES), mainly from solar photovoltaic systems accounting for 9.66% of the total energy consumption of the country. The remaining energy sources account for only 0.38% of the total, including wind energy [17].

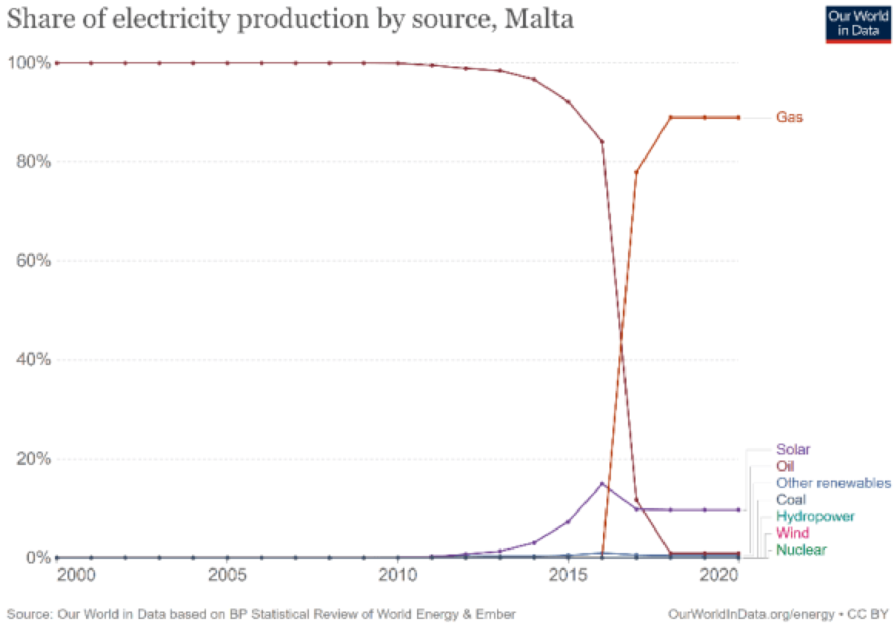


Figure 4. Share of electricity production by source in Malta [17].

Currently, as seen in Figure 4, renewable energy in Malta depends mostly on solar PV energy. This is popular due to the specific characteristics of the island, namely the strategic location in the Mediterranean Sea with over 3000 yearly hours of sunlight, the political will to promote renewable energy and public acceptance from the citizens, and also because PV has been proven to be the most resilient and effective type of RES technology.

Figure 5 below shows that in the year 2020, the electricity generation through solar PV was 233.0 GWh [17]. In the past years production of energy has increased significantly, highlighting that there has been an increase of 9.9% year-on-year compared to 2019.

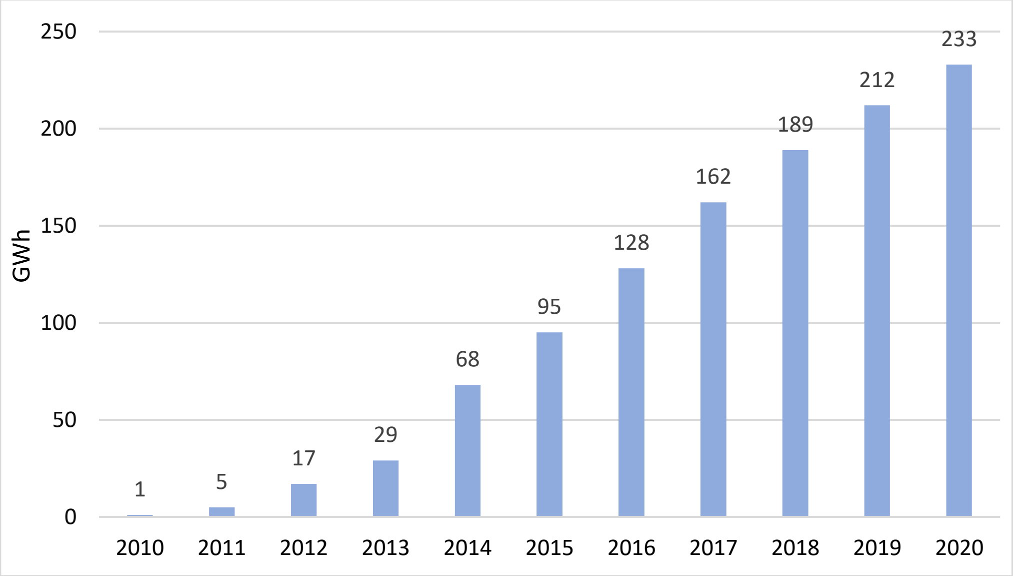


Figure 5. Solar PV electricity generation in Malta from 2010-2020 [18].

2.4.2 Objectives

Malta´s plan for 2030 regarding use of solar photovoltaic energy as a renewable energy source is set in the National Energy and Climate Plan (NECP) and has a target to reach up to 11.5% of the total final energy consumption in the country by the year 2030 [19]. Malta's RES percentage is expected to reach up to 10.3% in the year 2022, 11.0% in the year 2025 and 11.6% by the year 2027. This seems to be low, but one has to consider that the total energy consumed is continuously rising, especially due to the introduction of electric vehicles. Another issue is that Malta is small and there is limited space available to install solar photovoltaics, unless new ways become economically viable such as floating solar. The Institute for Sustainable Energy is already working on this front [20].

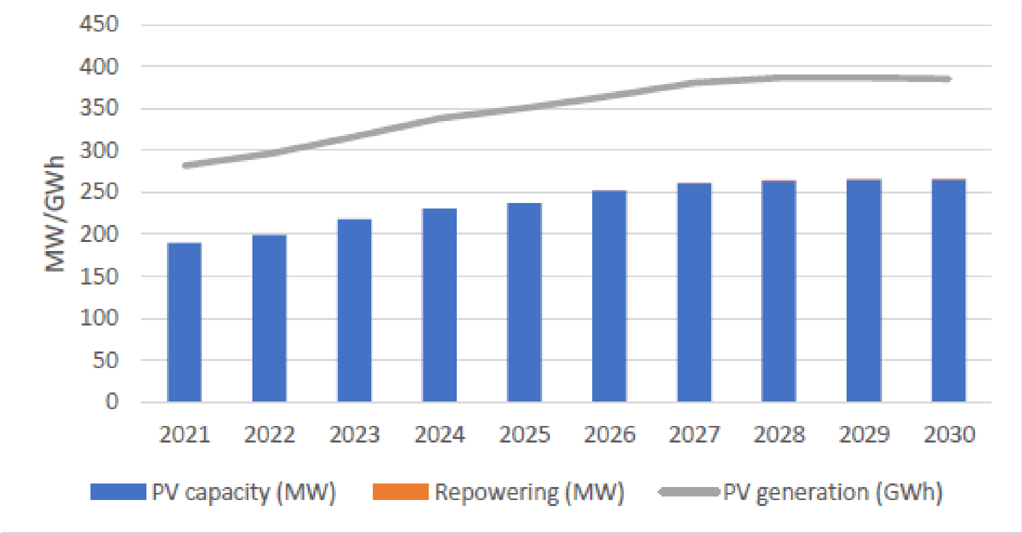


Figure 6. Forecasted solar PV capacity and generation in Malta [19].

As Figure 6 shows, PV generation is projected to reach 375 GWh by the year 2030, thanks to the recent introduction of large PV farms, which together accelerate the achievement of the expected target. There appears to be a capping of around 250MW for Malta, to be reached in 2027 as seen on Figure 6, which is caused by the small area of the island and therefore a limitation in the number of PV systems that can be implemented in the country. Many buildings have installed these systems but others suffer from overshading of nearby buildings due to uneven building height in the different localities.

2.5 Grid Connection

2.5.1 The feed-in Tariff and Long-term Contracts

Feed-in tariffs are a policy tool designed to promote investment in renewable energy sources. This generally means that producers of small-scale renewable energy systems, such as solar or wind power, are paid for their renewable energy production at a price that is higher than the market price for grid electricity. Feed-in tariffs (FITs) are considered essential for the promotion of small-scale renewable energy sources in the early stages of their development when production is often not economically viable. Feed-in tariffs generally involve long-term agreements and prices are usually linked to the cost of energy production [21].

Anyone who produces renewable energy is eligible for a feed-in tariff, but those who benefit are often not commercial energy producers. They may include homeowners, entrepreneurs, farmers, and private investors. FITs typically have three provisions [21].

- They guarantee access to the grid, which means that energy producers will have priority access to the grid.
- They offer long-term contracts, usually in the range of 15 to 25 years.
- They offer guaranteed, cost-based purchase prices, meaning that power producers are paid in proportion to the resources and capital spent to produce the energy.

On the other hand, large-scale PV farms are not usually given a feed-in tariff, but different potential PV power producers compete to offer the best bid for grid-connection. The winners are offered long-term contracts and guaranteed prices if the producers can guarantee a minimum annual energy output from the PV farm. Usually, the bid cost is lower than the average fossil-fuelled electricity tariffs, given that solar photovoltaic system costs have significantly dropped over the years, making them at par with fossil-fuelled electricity [21].

2.5.2 Situation in Malta

In Malta, electricity that is produced from the installation of photovoltaic systems is supported through several mechanisms, namely capital grants and feed-in tariffs for small-scale applications and bids for large scale PV farms. In the latter, the minimum size of a PV farm is that of 1 MWp [22].

There are two options: a monetary subsidy to assist with the cost of the initial investment and a short-term FIT or a long-term FIT for 20 years [23].

The investment is viable in both situations, and it will have a good rate of return before the FIT guaranteed term expires. After this time has passed, the user will continue to earn money by selling electricity to the grid or save money on their own electricity bill by consuming the generated electricity on site [23].

Every now and then, the government of Malta offers calls for tenders to fulfil a certain target of additional installed PV capacity. Bidders offer their projects, and the Government chooses the cheapest offers until the set target of capacity is reached.

2.6 Problems Regarding Operation of PV Systems

2.6.1 Outdoor Exposure

Degradation is one of the most considerable issues PV cells usually tend to have. It occurs due to the exposition of the modules to the environmental conditions including effects coming from the sun (UV radiation), wind, rain, temperature, etc. Delamination and corrosion are the most significant faults that take place in PV cells because of the moisture that is in the air, along with humidity that enter the modules [24].

The effects due to corrosion are harsher on organic PV cells than on polycrystalline, monocrystalline, and thin film PV modules. Concerning delamination, it mainly occurs when there is no contact in between the photo sensible part of the PV module and the encapsulant of the same. When any of these occur, there will be a performance reduction on the modules, and therefore its degradation. It is normally found in metal parts of the cell, bus bars or gridlines [25].

2.6.2 Cracks

When fissures appear inside the structure or on the surface of the PV module, it is called a crack. Performance losses on the modules due to cracks are extremely hard to measure and predict. There is not an exact and precise reason why cracks tend to occur. However, many studies have shown that they normally take place during the transport of the PV module to the desired place and under certain circumstances in mechanical tests caused by vibrations [24].

Other micro cracks could occur in the cell due to exposure to extreme weather conditions. For example, the cells would overheat in the morning due to the sun and then could cool to very low temperatures at night during winter. This thermal fatigue can induce micro cracks in the cells over time. In Figure 7 we can observe micro cracks in a PV module in several cells.

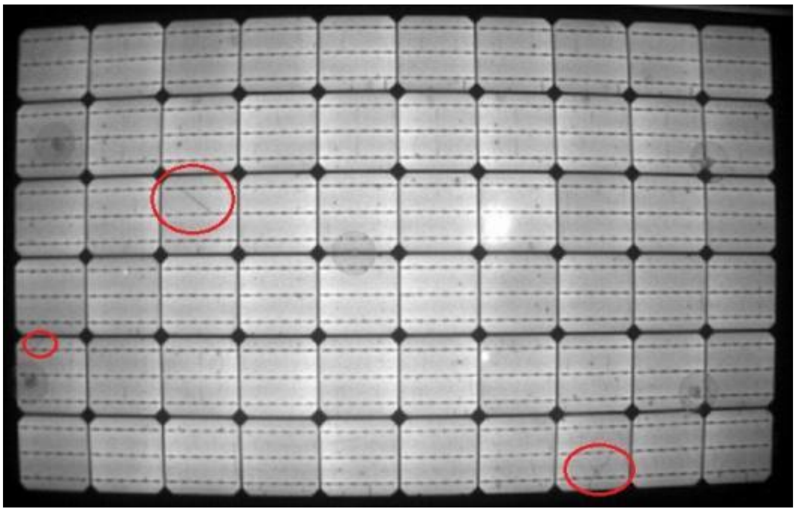


Figure 7. Micro cracks detected in PV module through Electro Luminescence Crack detection [26].

2.6.3 Hot Spots

Hot spots are another type of fault in PV modules and are described as the overheating of a cell part or one complete solar cell in comparison with the rest of the cells from the same PV module, thus causing higher resistance. Partial shading, dirt on the modules, coming from bird droppings, cell mismatches and inadequate connections in between cells result in energy dissipation through heat [24].

A study made by Moretón et al. [27] showed different methods on how to find hot spots in PV modules. Visually, bubbles and cracks in PV cells could be found but experimentally with a thermograph device, hot spots were easily identified and located in the PV module.

Simon and Meyer [28] did several experiments in which they described hot spots composed as 3 different regions: the centre of the hotspot, the surroundings, and the non-hot spot.

In short, hot spots are faults that produce higher temperature on the cell and power losses of the same. Thermography is the procedure commonly used to identify them with precision, as shown in Figure 8.

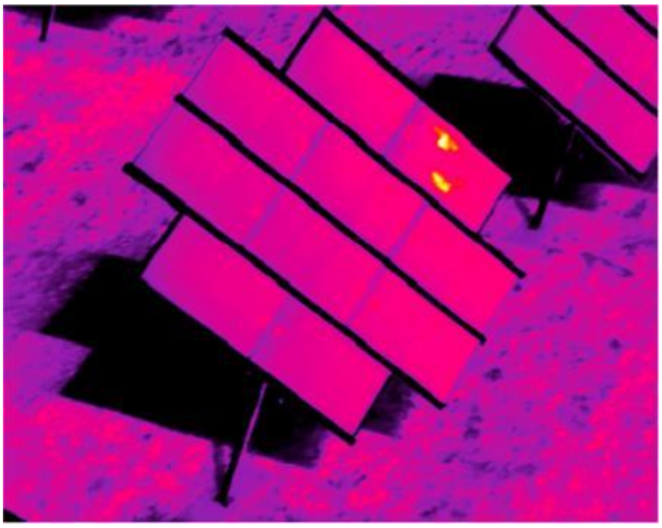


Figure 8. Hot spots in PV module through thermal inspection [24].

2.6.4 Soiling

Soiling is defined as the accumulation or deposition of dust, ice, pollen, dirt, bird droppings, leaves or any other type of element on the surface of the PV modules. It is, in fact, the most significant fault to consider since it is the most problematic aspect concerning solar energy. Numerous studies have been carried out on dust deposition in more detail than depositions of other types of elements [24].

Focusing on dust deposition, it is a temporary and non-permanent fault as its impact is reversible. There are three differentiated types of causes why dust soiling occurs. The first one is due to environmental effects, such as pollution, wind. The second cause has to do with dust itself including elements that deposit on the surface of the PV modules such as clay, sand, or bacteria. Installation characteristics build up the third group, in which the manufacturing of the PV modules, the location and orientation of the same alter dust deposition [24].

Soiling is a fault that has no harmful impact on the voltage of the installation but on the power of the same. It is more likely to appear on solar PV installations in desert areas or in areas that have high dust emissions such as near stone quarries.

Figure 9. Soiling coming from dust deposition [29].

In Figure 9 above, it can be observed that on the left part of the image there is dust deposition, and therefore soiling, while on the right part of the image, the PV modules have been cleaned and soiling does not occur.

2.7 Failure Detection

Failure detection is a key process for the correct operation of PV modules. Maintenance of these installations is based on condition monitoring systems (CMS). In a study developed by Triki-Lahiani et al. [30], they explained numerous types of faults including their effects and causes, and describing the principal parameters used to detect the failures, which are temperature, voltage, current, irradiance, power, etc.

There are several methods for failure detection. For example, Watson et al. [31] developed a pair of techniques for monitoring continuously. The first one is a spectrophotometric analysis to record the absorption of light in the cell and the progress of corrosion on the cell during a complete day (24 hours). The second technique was a digital image acquisition for one hundred hours. The conclusion reflected that depending on the material of the coating the results were different, including coating of iron, aluminium, zinc, and stainless steel. The results also showed how these two methods implemented were accurate for measuring corrosion and that different metals have diverse reactions to corrosion.

Another method employed is a system which includes a radiation sensor, two ambient temperature sensors per module, an acquisition board, a data logger, and a server for the dataset. The mentioned system examines both the predicted and measured power of the PV modules in two different conditions: before and after cleaning the surface of the PV cells. Also, with LabVIEW [32] several PV monitoring systems have been designed in order to perceive the results before and after cleaning the modules.

Several techniques such as infrared testing and thermography are commonly used to avoid PV module's faults. Image processing is used to identify types of faults on PV cells like cracks, shadowing or shading, degradation of the surface or defective connections. In a study by Dhimish et al. [33], they performed an algorithm, the six-layer detection algorithm consists of detecting faults just by focusing on the output of the power from the PV module. Another algorithm labelled the parallel algorithm is able to detect faults examining the output of grid-connected modules in a research from Holmes et al [34].

Unnamed Aerial Vehicles (UAV) or drones inspect large surfaces of PV modules in a short period of time and are commonly used for the detection of cracks, hot spots or even snail trails on the surface of the cell. UAV's can be combined with other technology such as thermographic cameras or sensors.

One of the most famous procedures is the intensity-voltage curve (I-V) and the power-voltage curve (P-V). These curves show effects when failures such as soiling, partial shading, shunts or hot spots exist [24]. The technique is based on the analysis of the anomalies appearing in the I-V characteristics curve of a PV string. The adopted technique is commonly referred to as Compare, Identify and Eliminate (CIE). The proposed fault diagnosis technique is applied on a PV string, at the optimal location of the measuring point. In order to simulate the I-V characteristics of a faulted PV string, a model based in MATLAB/Simulink is developed. Normally there is a comparison of the I-V characteristics of the PV string under different fault scenarios with that corresponding to normal operation yields the identification of four anomalies.

Symptoms are determined from comparison between the simulated I-V characteristics of a PV system in normal operation and that in real time operation. Due to the measurements of the I-V curves, the different types of faults are identified.

When faults on PV installations are detected, there needs to be a quick response in order to repair or amend the harm on them.

2.8 Orientation of PV Modules

Both the orientation and the inclination of the photovoltaic modules are decisive for optimizing and achieving the best possible yield and energy efficiency.

For Malta the optimum tilt is 30° facing south, as Yousif et al. concluded in their study [35]. Other scholars such as Marissa Hummon et al. [36] described that for the northern hemisphere the most favourable orientation for a fixed array facing due south at a tilt angle equal to latitude 5 to 15º.

There have been more scientists and experts that differ from the angle mentioned above. Some like Chwieduk et al. [37] decided that in Polish insolation conditions, horizontal and small angle tilted surfaces are not recommended. Roofs with slopes of about 30º are convenient for installation of solar systems operating during the whole year, even when the roof is oriented to the West and East. For seasonal operation in summer, horizontal surfaces are good enough for installing solar collectors, but preferably surfaces with slope of about 10–20º should be used.

However, it is clear that certain local conditions can also influence the best tilt, for example depending on the reflectivity from the ground and the surrounding objects. In a study lead by Christensen et al [38], they described and elaborated a rule of thumb for the best tilt angle for PV modules depending on the latitude of the location of the PV installation and on a specific climate factor that represented the effects of cloud cover.

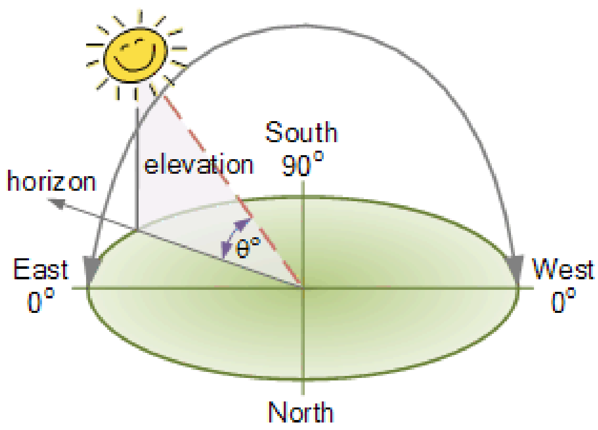


Figure 10. Scheme of the tilt angle and orientation [39].

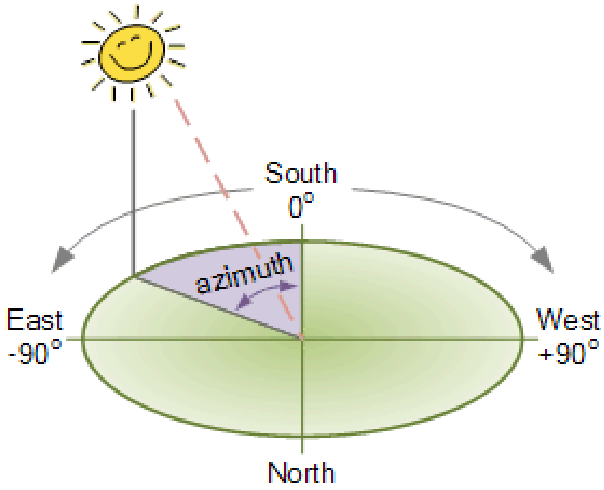


Figure 11. Scheme of the azimuth angle and orientation [39].

2.9 Solar Irradiance

Solar energy reaches the Earth from the Sun by radiation. This radiant energy is usually called and referred to as solar irradiance and is measured in W/m². Solar spectral irradiance is a measure of the brightness coming from the Sun at a certain light wavelength. There are variations of the spectral radiance that have different wavelengths of light, from the visible, passing through UV radiation, X-ray, and Extreme Ultraviolet radiation (EUV) [40].

Total Solar Irradiance (TSI) is the term used when the entirety of the radiation is measured. It is composed of two different types of irradiations. Direct solar irradiance (GD) is exactly the one that hits the surface of the Earth without losing its effect and therefore without dispersing or being absorbed by the atmosphere, while diffuse solar irradiance is the irregular and disperse radiation that reaches the surface of the Earth. The total of these two radiation components results in what is known as Global radiation, which flat plate solar PV modules see. However, it is important to note that only UV and visible light radiation has sufficient power to excite electrons and generate electricity from crystalline silicon PV cells.

The highest hourly solar radiation is reached during the summer, which in the north hemisphere refers to the middle of the year. On the contrary, the lowest hourly solar radiation is during the winter months, which are at the beginning and at the end of the year.

The Figure 12 below shows the solar radiation measured in W/m^2 in a common weather pattern for places in the northern hemisphere [40].

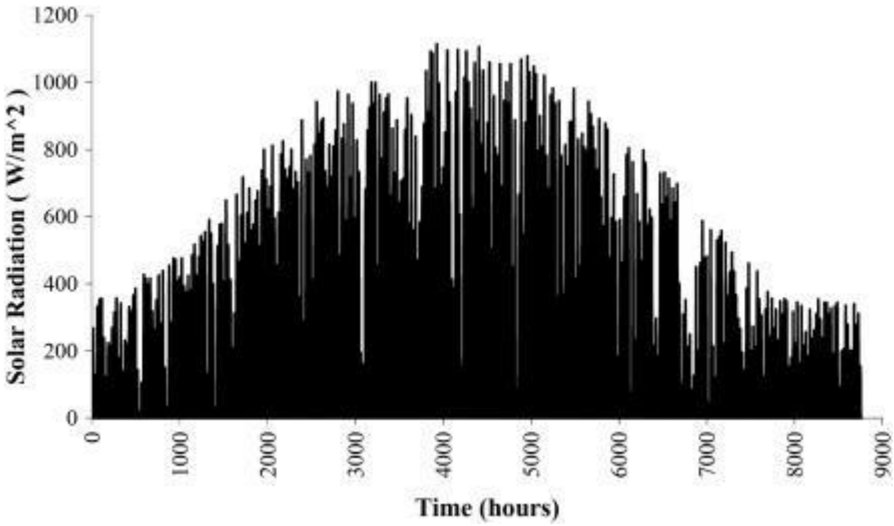


Figure 12. Solar radiation in the Northern Hemisphere [47].

Figure 13 shows two different types of irradiations, Direct Normal Irradiation (DNI) and Global Horizontal Irradiation (GHI) in Malta. The map is differentiated in different regions with more irradiations being depicted as darker colours, but it is only a decimal difference. This difference is caused by the position of the sun in each different area, where there might be a different altitude of the land. Therefore, the yearly total average DNI in Malta is 1862 kWh/m^2 and the GHI is 1826 kWh/m^2.

Figure 13. Direct Normal Irradiation and Global Horizontal Irradiation in Malta [41].

2.10 Terms of Capacity

2.10.1 Capacity

Capacity is normally described as the maximum output (generation) of a power plant. Capacity is measured in different units such as kilowatt (kW), megawatt (MW), or gigawatt (GW). Rated capacity may also be referred to as peak capacity. It has to be differentiated from net capacity of a plant as the latter is found after subtracting any power load such as tracking motors from the total peak power or gross capacity [42].

2.10.2 Capacity from PVs

Capacity of PV systems is typically measured by their AC or DC capacity. PV modules produce direct current (DC) voltage, which is later converted into alternating current (AC) through the inverter. In consequence, PV power plants have a DC rating which corresponds to the maximum output of the modules, and an AC rating. AC rating is usually lower than DC due to the system losses when converting the current from DC to AC [42].

2.10.3 Capacity Factor

Capacity factor is a measure of how much energy is produced by a plant compared to its maximum output. The calculation of this factor is obtained by dividing the total energy produced during a period of time by the maximum amount of energy that the plant could have produced theoretically if there were no losses in the same period of time. It is usually expressed as a ratio. This is also known as the Performance Ratio (PR) [42].

2.10.4 Capacity Value

Capacity value refers to the contribution of a power plant to reliably meet demand. The capacity value can be measured by the percentage of the peak capacity or by the total physical capacity either in kW, MW or GW. For example, in a PV plant with a peak capacity of 100 MW, its capacity value could be represented as 50MW or 50%. Solar plants are designed and operated in order to increase their capacity value or energy output [43].

2.11 Power Plant Operation

For all of this section, the information is obtained from the Best Practices Guidelines in operation of PV systems from Solar Power Europe group [43].

2.11.1 Plant Performance Monitoring and Supervision

In general, there is a clear line differentiating owners of PV farms from the actual technical operators. Quite often, there is an Operation and Maintenance (O&M) contractor that together with his technical team are in control of monitoring and supervising the PV plant and its conditions continuously in order to achieve a correct performance. These contractors may also be responsible for more than one plant that are owned by different businesses. Monitoring is usually done remotely with the help of a software that controls the system and plant operation centres. This contractor has access to the data coming from the PV installation so as to carry out a wide data analysis and give information to the maintenance team. The contractor is also responsible for being the link in between the grid operator and the plant owner. Another task from the operations team is to coordinate with the maintenance team. They have access to all data coming from the site including weather information, visual supervision and surveillance.

Fault Management, also defined as Incident Management is usually the type used in most PV sites. It is described with roles and levels:

- In an Operations Centre faults are detected and monitored. When this happens, they collect information and diagnostics for characterizing and categorising the problem in order to solve it on the spot. This is part of the 1st Level Support. It follows the incidents until they are resolved.
- If the problem is not categorised easily, the operations team reaches a technician who is normally a maintenance member and tries to solve the problem on site (1st Level Support). He can call the Supplier's Hotline if help is needed for the diagnosis of the fault.
- Once 1st Level Support cannot solve properly the issue, it escalates up to 2nd Level Support which consists of PV Engineers or Project Managers that have higher access permissions, technical information to analyse the incident thoroughly.

- When the faults' resolution needs special experts the engineers from the 2nd Level may contact the Supplier's own expert, which is defined as 3rd Level Support. Project Managers operate either at 2nd or 3rd Levels.
- Finally, after the fault is resolved, the initial ticket of an incident is closed.

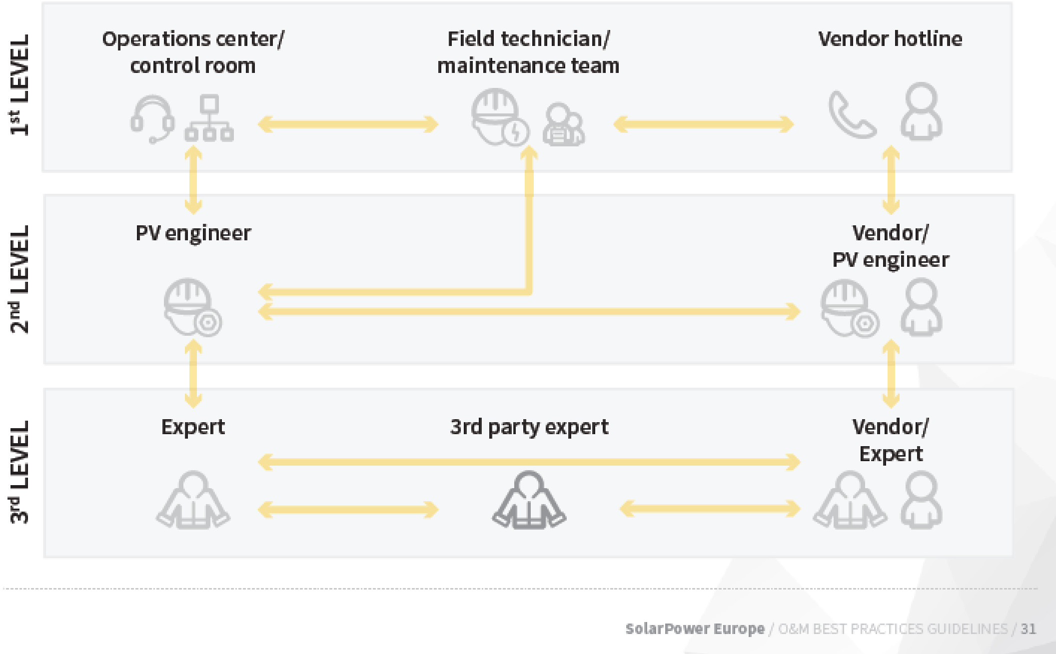


Figure 14. Support levels in fault management [43].

Figure 14 shows a scheme of support levels in fault management described above.

2.11.2 Performance Analysis and Improvement

The O&M contractor ensures that performance monitoring is appropriately carried out. Information and data must be analysed in many levels.

- Portfolio level, which means the whole PV plant under the contractor's control
- Plant level
- Inverter level
- String level

The analysis has to display the required information on every level and during several periods of time from the recording interval to monthly, quarterly, and annual levels. In addition, it has to include alarms that are customised based on client's thresholds [44].

2.11.3 Optimisation of O&M

It is crucial for the Operations team to do an analysis of all the data coming from O&M, and how it correlates to the different events and causes. Another essential analysis is a cost analysis differentiated between materials and labour. Therefore, all this information helps optimise the process and enables reducing production losses in the system and the cost of O&M.

2.11.4 Power Plant Controls

The operations team is the one in charge of contacting the grid operator when plant controls are needed. They will remotely do the plant control or delegate to the maintenance team the controls of the installation.

The contractor does the remote plant controls and emergency closing of the plant. In each country, and even regions this control varies. The control system used often is a power plant controller that directs all the parameters from the PV plant:

- Power Factor Control
- Ramp Control
- Voltage Control
- Reactive Power Control
- Active Power Control

If any command is executed, it must be notified immediately to the Operations team.

2.11.5 Forecast of Energy Generation

The Contractor has to supply the owner with information on generated energy forecasts when needed, which is usually necessary for large scale plants. Services used to forecast PV energy generation can be offered either by the operator of the monitoring service at the PV installation or by external services. There are many requisites for providing these forecasts and they vary depending on the country and the contract agreement that the owner and the service provider have for electricity transmission.

The requirements are characterized by time resolution, the horizon of the forecast, and the frequency in which it is updated. The forecast horizon tends to be under 48 hours along with time resolution from 15 minutes to one hour, all depending on the time unit from the programme coming from the market or the power system. Typically, they are classified in day-ahead forecast, which are delivered during the morning for the following day from 0 to 24 hours with two updates on that day. Another type are intraday forecasts. They are delivered and updated many times a day as they must be automatically provided by the forecast provider. Other types of horizons are weekly or even long-term for maintenance decisions. Such forecasts are usually requested by the grid operator to help in the management of the whole electricity grid that is usually comprised mostly of fossil-fuelled power stations, which sometimes need time to ramp up to their rated power output and hence, forecasts from PV farms becomes crucial for this purpose.

In fact, these forecasts used for PV power generation depend on weather predictions that have numerical data, data from satellites, and statistical methods. The best option is to have day-ahead forecast from numerical weather predictions and intraday forecasts from both weather predictions and satellite data. The provider that forecasts this information must be informed about any outages happening on site.

2.11.6 Grid Code Compliance

In this case, the O&M Contractor along with the Operations team are responsible to manage and function the PV plant in line with the grid code of each country. The grid operator is the one that provides various requirements for voltage regulation, the management of active/reactive power and the quality of the power. Particular grid codes have been published in many countries specified for generators of renewable energy such as for PV farms.

In Europe, the majority of the large-scale PV plants that are connected to the grid need to meet the requisites that their operator demands. The O&M Contractor has to be aware of both the grid code and the requirements from the operator. The grid operator is usually the one who runs the PV plant controller by remote signals, but in some cases the Operations group can take the responsibility delegated by the operator.

2.11.7 Security of the PV Plant

The PV plant must be protected so that non-authorised access is not permitted. This protection has a dual objective: keeping the materials of the solar PV plant and the public safe. The access to the site can be done accidentally without knowing the danger or purpose such as for vandalism or robbery. The provider of the security service, O&M Contractor and the owner will elaborate a protocol in case of trespassing [44].

In Europe there are special legal requirements for security service companies. For this reason, PV plants should be secured by a sub-contracted specialised security company. The security service company is in charge of the proper functioning of the security system which includes surveillance at the site, the security protocol to follow and alarms. The security provider should also carry out site patrol, ensure liability and coordinate with the O&M Contractor.

The security system is usually formed of fences or barriers around the premises of the site, alarm detection, alerting systems and cameras of surveillance with a closed-circuit television. In sites that have CCTV there should be a protocol designed to enter when works have to be carried out. Authorised access is to be maintained and done by security pad codes or a password in a phone, recommended to be changed periodically.

In areas of high risk of vandalism and intrusion it is recommended to have a backup communication line alongside with an infrastructure that monitors communication and connectivity with the security system. It is favourable to have a process related with emergency services such as the police in case that significant harmful incidents occur.

At the sites, locations that contain high voltage, the substation and other parts need to have special restricted access. Warning signs and attention notices play an important role in security as they prevent accidents to happen. In addition, more attention has to be made during periods of maintenance, since it would not be a normal day security protocol. The owner of the PV plant will have insurance policies which depend on maintaining a certain level of security. If these are not met, it will have enormous consequences in the event of a crime, theft, or accident.

2.12 Maintenance

Maintenance of the solar PV plants is usually carried out by subcontractors or technicians specialized on the matter that coordinate with the Operations group. Maintenance can be classified into different types: preventive, corrective, predictive and extraordinary maintenance. For all this section, the main reference is from the Best Practices Guidelines from Solar Power Europe [43].

2.12.1 Preventive Maintenance

Preventive maintenance is the principal element of all the maintenance services. It includes visual and physical inspections done regularly and verification activities conducted with certain frequency for all crucial factors necessary to be in accordance with the guidance from the Original Equipment Manufacturer (OEMs). A crucial part is maintaining the warranties of all the equipment on site and therefore reducing the probability of failures, faults, and degradation.

This type of maintenance is performed at determined intervals of time following the guidelines from the manuals issued by OEM and O&M. These intervals are included in the maintenance plan and there are scheduled times for each requirement. In fact, the O&M Contractor prepares the task plan including the frequencies contracted. This should be communicated to the owner or manager of the site with a report.

Thermographic inspection aims to detect faults in PV modules, as well as handheld cameras or even RPAs (Remoted Piloted Aircrafts) that have thermal and optical sensors. More and more, RPAs are being used for the preventive detection of faults in PVs as it can help the maintenance processes by saving time and cost.

When applying preventive maintenance, the best option is to execute it during the night as there are no production losses.

2.12.2 Corrective Maintenance

This type of maintenance covers all the activities needed to perform so that the system of a PV plant restores its normal operation and functionality. It happens when a failure on the system has been detected either by a normal inspection or remote supervision monitoring.

Fault diagnosis is the first step as in this process the fault is identified and located on site. Subsequent to that, there needs to be a temporary repair, so the required function is restored until a final repair. The final repair entails a permanent solution.

Besides preventive maintenance, if PV strings or the whole plant has to be offline, its execution must ideally be during the night or at low irradiation hours so that there is no effect in the total energy generation.

Concerning intervention, corrective maintenance is divided into three levels:

- 1st level: The intervention comes from restoring the functionality of any device implicated in the fault without the need to replace any component of the same. It is performed by a technician either from the company or a subcontracted company. This has to be included in the O&M agreement or issued on rates per hour apart from the O&M Contract, always depending on the nature of the agreement between the parties.
- 2nd level: The intervention in this case comes with the substitution of the component needed to restore the proper functionality of a device. This implicates not only labour action often performed by a specialised technician, but also physical intervention as the device needs the substitution of any part.
- 3rd level: The intervention takes place in order to restore the proper functionality of any device with the need to intervene in the device’s software. This type of corrective maintenance involves labour action from a specialised technician and external help either from the device manufacturer’s maintenance group or a third party, usually another company licensed to do such activity. This has to be included in the O&M agreement or issued on rates per hour apart from the O&M Contract, always depending on the nature of the agreement between the parties.

Generally, corrective maintenance has to meet the agreed minimum response times. Any interventions done for updating, renewing, or reconditioning, except for the cases included in the contract, must be classified as extraordinary maintenance.

2.12.3 Predictive Maintenance

Predictive maintenance is a service that the O&M contractors provide. They must follow principles with outstanding practices. This is a maintenance based on the condition of the system which is done by analysing and evaluating degradation parameters and elaborating a forecast from these.

Achieving and performing a good predictive maintenance exercise requires devices to be able to furnish information about their state so that the contractor evaluates and forecasts the possible events or signs of the device's deterioration. A correct procedure from the supplier is to be provided showing the characteristics and list of the possible errors and meaning along with the codes which appear on the device and the impact that it can cause on the same. The company that oversees the predictive maintenance should select precise equipment with sensors, and a proper software system for monitoring the PV plant.

Predictive maintenance is done through continuous monitoring, supervising, forecasting and performance data analysis of the PV plant, including the transformer, inverter, combiner box, DC array. This helps avoid failures or underperformances of any device as it identifies trend indicators not seen either by electrical, visual, or thermal inspection. There should be an implementation of procedures to examine historical data and identify system behaviour changes that can endanger its performance. Normally, changes of behaviour denote beginnings of a degradation process. Because of this, it is crucial to monitor all relevant parameters with sensors, algorithms implemented in the system and any other technique. They should try as well to prevent any failure that causes energy production loss or safety problems.

Some advantages of using predictive maintenance are:

- Anticipating maintenance activities
- Postponing, deleting, and optimising some maintenance activities.
- Reducing time of repairs
- Optimising the safety management of the system
- Reducing spare parts management and replacement costs
- Increasing energy production of the PV plant and performance of the system
- Meliorating predictability
- Lessening emergency work

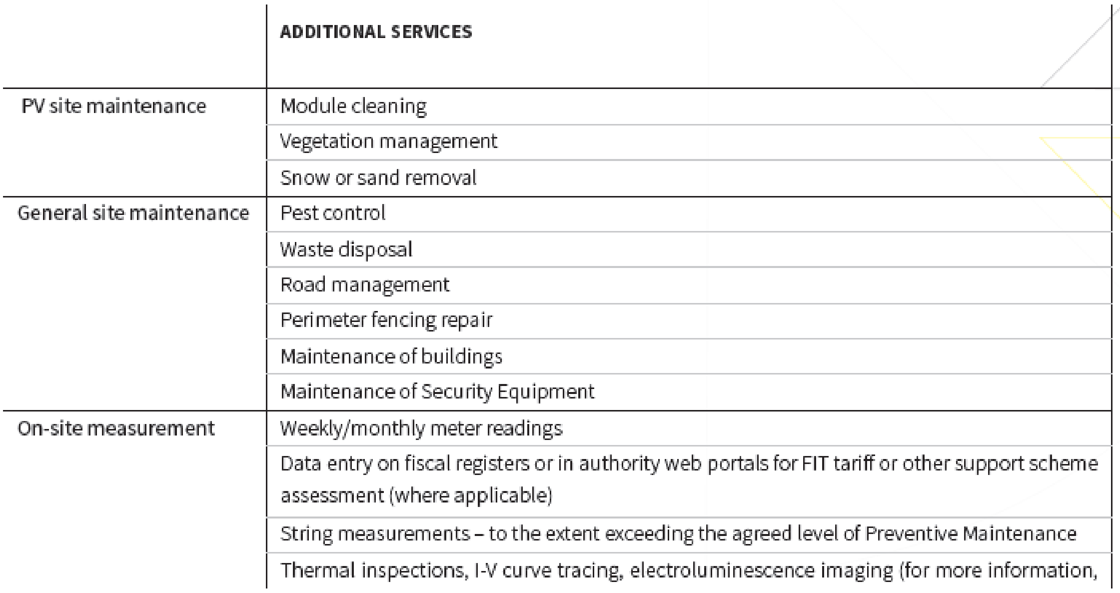
2.12.4 Extraordinary Maintenance

This is the last type of maintenance, and extraordinary actions are required when major unpredictable events happen on site. These actions are needed to restore general conditions of the PV plant and any maintenance action that is not covered in the O&M contract. These actions do not appear on the general part of the O&M contract and are managed separately.

Extraordinary maintenance is for extraordinary circumstances such as:

- Damages in the system or the PV plant due to a force majeure
- Damages due to a fire or theft
- Necessary modifications or updates coming from regulatory changes
- Serious defects on the devices, equipment from the system occurring either all of a sudden or after years of use.
- Problems with the system and its normal activity that are not covered in the O&M contract, usually caused in the design phase of the plant.

Some additional services outside of the O&M contract are also crucial for PV site maintenance. However, in come contracts these might be included. Some examples are shown in Figure 15.



	ADDITIONAL SERVICES
PV site maintenance	Module cleaning
	Vegetation management
	Snow or sand removal
General site maintenance	Pest control
	Waste disposal
	Road management
	Perimeter fencing repair
	Maintenance of buildings
	Maintenance of Security Equipment
On-site measurement	Weekly/monthly meter readings
	Data entry on fiscal registers or in authority web portals for FIT tariff or other support scheme assessment (where applicable)
	String measurements – to the extent exceeding the agreed level of Preventive Maintenance
	Thermal inspections, I-V curve tracing, electroluminescence imaging (for more information,

Figure 15. Additional services regarding PV plant maintenance [45].

2.12.5 Rooftop Installations

A roof PV system, as shown in Figure 16 may include a water-proof membrane, a cover-board, insulation, and a roof deck. Roofs that are under a warranty are to be checked and need to have a preventive maintenance for the roof itself to maintain the warranty. If a maintenance policy is not held at the site, it may result in failures on the roof, therefore needing the removal of the PV system to repair or replace the roof. The cost and reach of the maintenance for rooftop PV systems is affected by different factors [45].

First, it is more complex to repair a roof with a complicated layout and more than one orientation of the PV modules. In Malta, this may be the case if the PV array is installed on factory roofs that are usually inclined. The slope or inclination of the modules is also a factor to keep in mind because having to repair a steep roof indicates a higher cost, a much safer equipment and the process is more difficult than repairing a low-slope or horizontal roof. Ballasts to support PV arrays is only used when the roof is flat or has a low inclination. In Malta, most PV systems are installed on flat roofs, even for large PV farms exceeding 1 MW.

A study carried out by the NREL [45] identifies roof maintenance to have a significant impact on the cost of maintenance. This means that if it is damaged, the cost will increase. One of the factors to examine is water leaking into the roof deck, often noticed when revisions are periodically made. Naturally, wooden roofs may incur more maintenance requirements than concrete roofs.

Figure 16. Rooftop PV installation with a tilted angle [47].

The scale of the roof has an impact on the scope and cost of maintenance as well, since the bigger the area that is under the PV system, the higher the cost.

In addition, the type of roof is important when deciding what materials to use. Typically, membrane flat roofs are built with thermoplastic polyolefin (TPO), ethylene propylene diene monomer (EPDM), or PVC. As the study from the NREL [45] states that the cost of repairing or replacing a membrane roof reaches 70$/$m^2$ which includes the material, supplies, equipment, and labour. Asphalt roofs that are built-up reach up to 100$/$m^2$. On the other hand, asphalt shingles are the least expensive, in order to repair and maintain since the price is around 60$/$m^2$. There are other types of materials such as wood shingles that their replacement costs 200$/$m^2$, composite shingles tend to cost 70$/$m^2$. Metal roofs have an advantage since they are more convenient for PV systems, and it is rare that they need a repair or replacement. On the contrary, their cost of changing is around 430$/$m^2$. Concrete roofs are the most expensive since their cost reaches 650$/$m^2$.

Concerning the warranty of the roof, an overburden waiver is required to maintain the warranty and thereby needs an agreement for the maintenance company to be able to work on the roof. This includes removing the PV system and therefore entails a high cost and energy lost production. A warranty for the roof is used to ensure a long-term performance of the roof itself. The companies that are in charge of the warranty service have several obligations such as specifying the procedures the owner of the installation has to follow and information about the forms to fill out if there is any problem with a PV system. They must inspect the condition of the roof before repairing and determine what are the required conditioning as well as doing an inspection at final condition.

The removal of debris is quite important since the waste collected such as leaves has to be cleaned and removed from the roof in order to permit water drain and avoid vegetation from growing and nesting on the surface of the roof. The cost of removing debris is normally included in the cleaning of the roof, although it is not included in the cleaning of the PV cells [45].

2.12.6 Ground Mount Installations

Ground mount installations are considerably different from the roof installations as they avoid the maintenance issues previously stated yet they introduce new ones characterized for ground maintenance.

During the stage of design, several considerations should be made in order to reduce Operation and Maintenance (O&M) costs, such as ensuring that PV modules are placed with appropriate and uniform distance to the ground, racking is sufficiently wide to allow access to clean underneath the PV modules. On a survey done by the NREL [45], the respondents who were owners of PV installations answered that in most cases there are problems due to the little space in between the module and the ground, increasing the cost of its maintenance. When selecting the site, it is important to consider vegetation that grows in the surrounding lands and evaluate how tall it will be in one winter season to prevent shading of the PV modules. At this phase, there should be considerations that entail a correct rainwater drainage so as to avoid flooding or even rainwater collection for irrigation, and to control soil erosion on the site.

In relation to the ground cover, Hernandez et al [46] stated that investment in developing unique solutions in relation to the climate and soil condition for ground covering on each site ensures a long-term viability and lower risks of shading, erosion, and excessive vegetation abatement costs during the operations phase.

Materials such as gravel utilised for ground cover are expensive and present problems seeing that they create uneven surfaces, do not provide a long-term vegetation abatement solution, and modify runoff coefficients. It also requires either herbicides or mechanical vegetation control, which can damage the PV modules.

In a survey carried out by the NREL [45] the respondents see low vegetative covering for the ground as ideal, although they cited challenges in re-introducing vegetation after construction. Replanting low-growth species chosen by an expert in the field such as bent grass, white clover, buffalo grass, or preserving the existing vegetation is part of the solution.

Figure 17. Ground mount PV installation with tilted angle [47].

In Figure 17 it can be observed a ground mount PV installation in a field in the countryside, to show how they are installed in the ground.

Regarding vegetation management, chemical abatement for vegetation is highly efficient and has a lower cost but present problems with soil stabilization, apart from issues due to local regulations of herbicides and handling of chemicals. In arid areas such as Malta, mowing is rarely necessary with the correct soil stabilization.

On the topic of erosion control, evaluating and grading before the construction of the installation prevents issues as it exposes soil that is prone to erosion and runoff when rain reaches the site. The phenomena starts when a small amount of water runs through the ground, then more water groups together and turns into a gully. The main consequence of the erosion caused by the gully is that it can damage and risk the stability of the PV rack foundations, as well as expose cabling buried under ground and harm inverter pads. The best solution is to build and design pathways for water coming from rainfall along with check-dams that finish in channels and then in splash pads for water management. Stabilizing the aggregates at the surface with soil conditioners highly reduce runoff and erosion. The type of conditioners used are different types of polymers and its molecular characteristics make them suitable stabilizing the soil as they act as a cementing material. The application of any type or amount of polymer depends on the soil conditions at the location. Once a long-term solution results in the stabilization of the ground, no more polymers should be used [45].

2.13 Performance Analysis

With the growth of the industry, there has been an obvious demand for more use of performance standards for PV systems. These performance metrics allow for the diagnosis of operational issues; the comparison of systems that may differ in technology, design, or geographic location; and the validation of models for estimating system performance during the design process. Investors will have more trust in their capacity to acquire and maintain high-quality systems if the industry uses standard performance standards and system ratings to evaluate alternative bids and technologies [48].

Standard methods of evaluation and rating will also assist knowledgeable clients set reasonable performance expectations, resulting in enhanced credibility for the PV industry. There are many parameters and indicators that can indicate the correct functioning and operation of a solar PV installation.

2.13.1 Array Yield

The array yield (Ya) is the ratio of the PV modules' energy output during a specific period of time divided by the PV rated power. It is given by the following formula:

$$Ya = \frac{E_{DC}}{P_{PV},rated} \qquad \text{(Equation 1)}$$

$$Ya = \frac{E_A}{P_O} \qquad \text{(Equation 2)}$$

Where E_A is the same as E_{DC} and it is the DC energy delivered by the PV modules. It is measured in kWh, and it can be calculated by:

$$E_A = I_{dc} * V_{dc} * t \qquad \text{(Equation 3)}$$

P_O is the nominal peak power at STC; I_{dc} the DC current measured in A. and V_{dc} the DC voltage measured in V.

2.13.2 Reference Yield

The reference yield has to do with irradiation. It is the ratio between the total in-plane irradiance H_t and the PV's reference irradiance G_o. Therefore, the solar irradiance resource for the PV system is defined by this ratio. It is determined by the PV array's location, orientation, as well as month-to-month and year-to-year variations [53]. It is calculated as:

$$Y_R = \frac{H_t}{G_o} = \frac{\mathrm{kW/m^2}}{1\mathrm{kW/m^2}} \qquad \text{(Equation 4)}$$

G_o is the global irradiance at STC measured in $\mathrm{kW/m^2}$ and H_t is the total horizontal irradiance on array plane measured in $\mathrm{kW/m^2}$.

2.13.3 Final Yield

The final yield is the ratio in between the net AC energy output of the system during a specific period of time, either daily, monthly or annual, and the peak power of the installed PV array at STC. These conditions are a solar irradiance of 1000 $\mathrm{W/m^2}$ and a cell temperature of 25 ºC [48].

It is measured in kW $h\ /\ kW$ and calculated by:

$$Y_F = \frac{E_{AC}}{P_{maxG,STC}} \qquad \text{(Equation 5)}$$

2.13.4 Performance Ratio

The performance ratio (PR) of a PV installation is calculated dividing the Final yield by the reference yield. [49] It is defined as the actual output of the plant divided by the ideal output that could have been achieved [48]. Performance ratio depends on the losses that take place in the system such as conversions from the inverters, cables or the PV modules. In addition, losses can also be due to irradiation, weather conditions, ambient temperature, module temperature or other impacting factors [49].

Its calculation is the following:

$$PR = \frac{Y_F}{Y_R} \qquad \text{(Equation 6)}$$

2.13.5 Capacity Utilization Factor

The capacity utilization (CUF) factor is defined as the real output of the plant compared to the theoretical output of the installation. Therefore, it is the AC energy divided by the AC energy that could have been produced if the installation worked with the nominal power [51]. It is calculated as:

$$CUF = \frac{Energy\ measured}{365*24*installed\ capacity\ of\ the\ plant} = \frac{E_{AC}}{8760*P_{PV,rated}} \qquad \text{(Equation 7)}$$

2.13.6 Inverter Efficiency

The ratio of AC power generated by the inverter to DC power generated by the PV array system is the inverter efficiency, also known as conversion efficiency [48]. Its calculation is given by the formula:

$$\eta_{inv} = \frac{P_{AC}}{P_{DC}} \qquad \text{(Equation 8)}$$

2.13.7 PV Module Efficiency

The PV module efficiency is calculated by the following formula [48]:

$$\eta_{PV} = \frac{E_{DC}}{H_t*S} \qquad \text{(Equation 9)}$$

H_t being the total horizontal irradiance on array plane measured in kW/m^2. S is the module area measured in m^2.

2.13.8 System Efficiency

The system efficiency is given by multiplying the inverter efficiency by the PV module efficiency.

$$\eta_{sys} = \eta_{inv} * \eta_{PV} \qquad \text{(Equation 10)}$$

2.13.9 Previous Analysis

Many studies on assessing the performance of solar PV installations have been carried out before. In most of them, the main parameters are calculated and normally compared with the results that some programmes such as PVsyst give. In a study, evaluating the performance of a 10 MW grid-connected PV installation in India by B. Shiva et al [50], it turned out that the performance ratio was better during the month of December with a PR of 97.5%, and the month with the lowest PR was April with 73.88% They concluded that the lower PR was due to the malfunction of the system and incorrect operation. However, it is not convincing to have very high PR of above 85%, because of the inherent losses of the PV system, such as capture losses from the sun and also due to soiling, as well as system losses due to voltage drops across cables and the efficiency of the inverter. Moreover, the fact that the PV array would be operating at elevated temperature during sunshine hours will have a significant impact on the PR and therefore it is very hard to have high PR of 0.85, unless it is in a very cold country.

K. Attari et al [51] performed the same type of analysis of a PV plant but in a different location, Morocco. In this study, their results on PR were that in December it was a 58% and it went up to 98% in January. The CUF was high in July meaning a 21.42% while in the month of December it was 6.55%. They calculated that the average yearly CUF was 14.84% meaning that during 55 days in the year, the system could produce full power energy. In a rooftop PV installation in Norway [52] the average CUF was 10.58%, while in Serbia [53] it was 12.88%.

The temperature losses in the study [54] were 7.23% and the soiling losses are mainly due to soil-laden rainfall, the geographical characteristics, and the location of the installation. They observed that the soiling losses in the months of winter were lower than those during the months of summer, setting average annual soiling losses at 8.75%.

In a study carried out by the University of Valladolid, analysing the performance of a system in Castilla y León by A. De Miguel et al [55], the PR was the lowest during the month of August, due to the high temperatures with 60% and the highest in November and December with 75%.

Vidal et al [56] did a study on performance assessment of a PV system in the Patagonia, Chile and obtained many conclusions such as the following. The daily final yield of the installation appeared to be 2.27kWh/kWp, and the PR of 85.5%. The purpose of this study was to simulate between the measured data and the expected on the simulation, more energy was obtained in the real data than in the simulated data. It was concluded that a high PR was mostly due to the lower working temperature of the solar cells which was caused by the northwest local winds.

2.14 Summary

This chapter has covered literature review on solar PV modules, inverters used for PV installations as well as other components needed for the correct operation of the site. There is basic information about the FIT and situation of RES in Malta, where the study takes place. There are explanations on the different types of installations considering that all of the systems to be studied in this project are grid-connected. The advantages on the various types of anchoring to the ground or rooftop ballasted systems have also been visited and analysed.

Regarding the performance analysis, all of the studies considered show similar results. In most of the studies the PR was higher during the winter months, and lower during summer due to higher operating temperatures. The CUF measured in most of the research had an outcome of nearly 14%, translating as the portion of time during one period of time that the installation is able to produce full power energy. Correct engineering management practices for the operation and maintenance of the PV sites are described so that they are put into effect. Maintenance has to be differentiated in between three types, preventive, corrective and predictive maintenance. All installations would require a minimum level of operational control, fault management and monitoring at all times.

In addition, the chapter provided an overview of different failure modes and the means for detecting them. Malta's geographic position and climate would call for extra care with regards to maintenance due to lack of rain for at least 6 consecutive months and this creates soiling on the PV modules and should be properly managed.

3. Methodology

This chapter discusses the methodology followed in order to do a study and analysis in energy performance and in management procedures of the different PV farms to be analysed in the island of Malta, in accordance with the aim and the specific objectives of the project.

3.1 Preliminary Information

First of all, in this section it has to be stated that the work done is related to the country of Malta. Therefore, many considerations regarding the location of the country must be made. Malta is an island located in the Mediterranean Sea, and it lies only 80 km South of Italy, 284 km East of Tunisia and 333km North of Libya [57].

Figure 18. Location of Malta in the Mediterranean Sea [58].

Due to its location Malta has a special climate. According to the Köppen climate classification (Csa), it is Mediterranean climate since it has really hot summers and mild winters [16].

The important factor about the climate of Malta in this dissertation is regarding the hours of daylight during each month of the year, as shown in Figure 19. Photovoltaic solar energy needs the sun in order to produce energy, making this parameter the most decisive one.

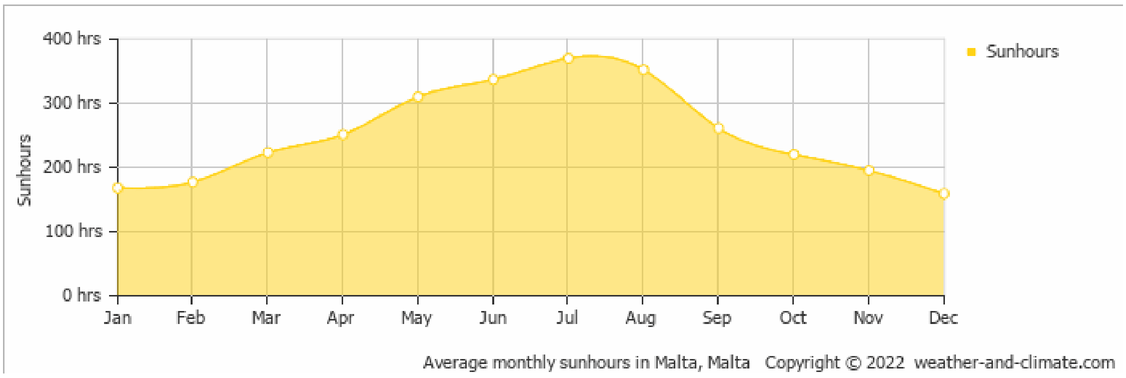


Figure 19. Average monthly hours of sunshine in Malta [59].

In Table 1, it can be observed how the months of December, January, and February are the ones with the least amount of sunlight, and therefore the least solar energy production. In the months of July and August, higher solar PV output is expected but the overall system efficiency and consequently the performance ratio would be lowest, due to high temperature of operation of the PV modules.

Table 1. Mean hours of sunlight in Malta [16].

Month	Mean Hours of Sunlight
January	169.3
February	178.1
March	227.2
April	253.8
May	309.7
June	336.9
July	376.7
August	352.2
September	270.0
October	223.8
November	195.0
December	161.2

3.2 Visits to the PV Installations

Following a preliminary invitation for owners of PV farms to participate in this project, it was possible to ultimately confirm 4 different entities who operate different PV farms on the ground and on rooftops.

Preparation for the site visits entailed the setting up of appointments and preparing a questionnaire and a list of items to be checked and verified during the visits, as explained in the different sections of this chapter. [60].

During the site visits of the installation, visual inspection is carried out, taking notes and pictures about many details, such as: the type of photovoltaic module used, along with its characteristics, the type of installation, the size of the installation and the capacity of the same, the type of inverters used, the orientation and inclination of the PV modules.

In addition, more information was obtained concerning the faults in the modules that could be identified by visual inspection, such as cracks, soiling, partial shading of the cells, degradation. Also together with the technical staff, conversation is held to understand any operational problems that the site might have encountered.

A thermal infrared camera was used at the sites for spotting any hot spots in the surface of the PV modules. An infrared camera detects and measures the infrared energy of things. The infrared data is converted into an electronic image that represents the object's surface temperature of the object by the camera. [60].

3.3 Data Collection

The project is concerned with two parallel analysis of PV operation in Malta. The first part is on energy management procedures including planning, installation, maintenance and trouble-shooting. The second part is the evaluation of the energy performance of the PV farms and comparing them to modelling results to identify any anomalies.

The energy management investigation was supported mainly by developing a questionnaire to understand the operation of the installation along with other characteristics. The mentioned questionnaire includes questions regarding different topics such as the technical aspect and characteristics of the installation, questions concerning the management and how it is carried out, and finally the features about the maintenance of the installation. The complete questionnaire is displayed in Appendix B of this dissertation, in which all the questions that are to be answered by several companies are written.

Table 10 summarizes the main technical questions, while Table 11 is concerned with the management aspects. Finally, Table 12 summarizes the questions dealing with maintenance.

Table 2. Technical aspects of PV installations.

Technical
Characteristics
Capacity of the plant
Voltage of each string
Inclination and orientation
Operation beginning and lifetime
Type of PV module and characteristics
Type of inverter and characteristics
Energy production
Solar irradiation

Table 3. Management aspects of PV installations.

Management
Feed-in Tariffs
Payback time
Impacts of the installation
Problems during installation
Financial aspects and insurance
Business model
Performance monitoring
Wind speed and ambient temperature

Table 4. Maintenance aspects of PV installations.

Maintenance
Process
Visits and inspections
Preventive, corrective and predictive
Additional services
Type of faults
Fault detection
Type of faults
Maintenance contract

3.4 SWOT Analysis

A SWOT analysis is a method of assessing these four aspects of a process, business, or procedure. SWOT are acronyms for Strengths, Weaknesses, Opportunities, and Threats. SWOT Analysis is a tool that can help the project analyse what the various installations are good at right now and design a successful future strategy. SWOT analysis can also highlight features of a company that are preventing it from growing. It examines both internal and exterior concerns, or what is going on inside and outside the installation. In either case, the appropriate course of action will become evident once as many variables as possible have been found, documented, and analysed [62].

SWOT analysis may appear straightforward, but when applied thoughtfully and cooperatively, it may disclose a lot. For instance, while being well aware of some of the installation's strengths, it may not be easy to realize how unreliable those strengths are unless they are recorded alongside vulnerabilities and dangers. Similarly, there are legitimate concerns about some of the installation's flaws, but by going through the research step by step, they may uncover an opportunity that could more than compensate.

Figure 20. SWOT Analysis scheme [63].

A SWOT analysis will be carried out for each installation regarding the maintenance and management aspects of the same as they represent the aspects that are qualitatively assessed. Furthermore, some of the technical characteristics from the installations will also be considered.

3.5 Data Analysis

3.5.1 Performance Ratio

For the technical point of view, the methodology will focus on calculating the monthly performance ratio for each system for one year. The limitations of the data set stem from two reasons. First, the PV farm are new and there is not enough data to analyse. Second, only monthly data was provided for this work, and it is therefore not possible to analyse the micro performance of the PV farms such as for cloudy days in comparison to sunny days or for hot days compared to colder ones.

A comparison between the different results will be made in different aspects:

- A month-to-month comparison between the PR in the same installation using equation 6 from Chapter 2. The performance ratio for each month will be compared and reasons for different results will be investigated.
- A month-to-month comparison across all four installations concerning their PR during the analysed years, determining which installation has a better performance ratio and in which months. This will help achieve a solid conclusion on how different inclinations and different setups (roof versus ground-mounted) would impact the performance of PV farms.
- An annual comparison using the average performance ratio calculated by the mean of all the months for the year to provide an overall picture of the four setups. Also, the final yield for each system will be provided.
- Other parameters such as system efficiency and overall capacity factor will also be determined, where possible.

3.5.2 Solar Irradiation

Where available, the solar radiation collected on the same plane as the solar PV modules in the PV farms will be used both for the calculation of the performance ratio, as well as for the system modelling by means of the software PVFChart [64].

For the case of non-availability of solar radiation, the Global Horizontal Irradiation will be provided by the Institute for Sustainable Energy of the University of Malta. In order to have the solar irradiation corresponding to the different angles of the solar PV modules in each installation, calculations have to be done.

These calculations are made with the help of the PVF-Chart programme. In this way the horizontal irradiation (GHI) is provided, and afterwards the total in-plane irradiation (DNI) will be achieved by converting it with the software used using the well-known isotropic sky diffuse model [65], after which the performance ratio can be obtained.

Moreover, an in-depth analysis of solar radiation at different inclinations will be carried out in relation to the reference horizontal irradiation, to valorise the availability of solar irradiation in the different PV farms under study.

3.6 Modelling using PV F-Chart Programme

Modelling of the solar farm using the PVF-Chart will be carried out to compare between the actual output from each project and the expected output from modelling and to evaluate the discrepancies in view of the outcomes of the site visits. The final aim is to recommend any improvements that can be made to the PV farms to improve their performance.

The PV F-Chart is a program for analysing and designing solar systems. For each hour of the day, the program produces monthly average performance estimates. The calculations are based on methods established at the University of Wisconsin that account for statistical fluctuation in radiation and load using solar radiation utilisability [64].

This software determines the ideal production of energy based on different characteristics of the PV installation such as the location, the weather conditions, the type of installation (grid-connected, battery storage, or stand-alone) and the type of PV system (flat-plate, concentrated, single-axis or double axis tracking)

Figure 21 shows the setting of the PVF-Chart to model grid-connected flat-plate PV module systems.

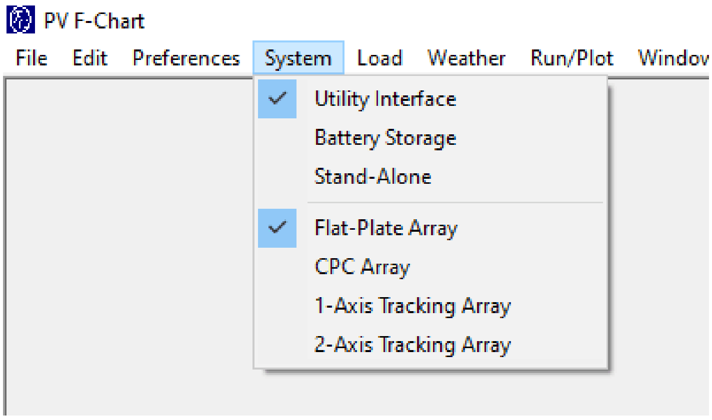


Figure 21. System parameters in PV F-Chart [66].

One of the important settings to be made in the PVF-Chart is to ensure that the default loads on the model are set to zero. Only then, the full generated PV electricity will be reported as being sold to the grid. Figure 22 shows the setup tab for setting the loads to zero.

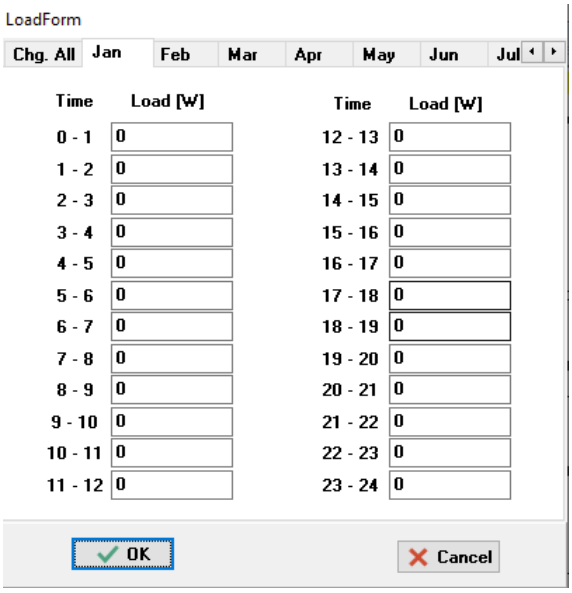


Figure 22. Load parameters in all time intervals for correct setup [66].

Another step that needs to be made is to set the appropriate weather file, which includes solar irradiation on the horizontal ambient air temperature, humidity, and reflectivity. Figure 23 shows the tab used to choose the pre-defined weather file for Malta. Data within this file can also be changed to match the actual weather values recorded in the PV farm, thus enhancing the credibility of the outputs from the modelling exercise.

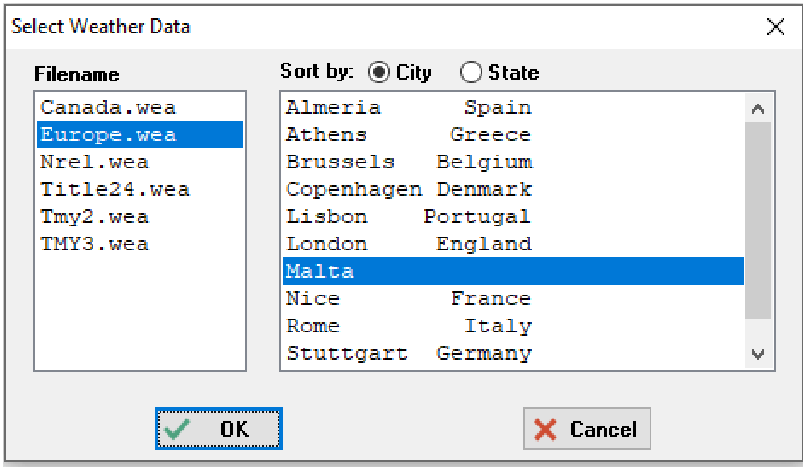


Figure 23. Weather data setup in PV F-Chart [66].

Finally, the characteristics of the installed PV modules are inputted into the software such as cell temperature at NOCT conditions (usually ranging between 44 and 49°) and the module's reference efficiency at STC. If the module efficiency is not found in the specifications sheet, it can be calculated using the following equation:

$$Efficiency = \frac{output\ (in\ kWp)}{input} \qquad \text{(Equation 11)}$$

$$Efficiency = \frac{kWp}{\frac{kW}{m^2} of\ solar\ radiation * Area\ of\ panels(m^2)} \qquad \text{(Equation 12)}$$

The array reference temperature is also set as a standard parameter established at 25 ºC.

Concerning the array power loss coefficient, this is obtained from the PV module's data sheet. It is defined as the rate at which the efficiency from the PV module drops, it decreases linearly with temperature. For silicon cells typical values range between 0.0043 and 0.0035 /ºC above 25°C. When entering it on the software it must be multiplied by 1000 and the negative sign should not be considered.

Power tracking efficiency is the efficiency of the electronic equipment and also the control logic that is used to control the array for correct operation at its maximum power point. It is usually taken as 95%, while on the programme it is 0.95.

Power conditioning efficiency is the efficiency of the electronic equipment that takes the electrical energy produced by the array and transforms it into any other form: either load, utility or battery. This is usually high at around 98%. However, it can be varied to take into consideration other physical power loss parameters such as soiling on the PV modules. By trial and error, the PVF-Chart can be calibrated to give results that are typical of PV systems in Malta, which would produce around 1600 kWh/kWp at 30° inclination and facing south. The appropriate value to input was found to be 0.95 rather than 0.98.

The standard deviation of load is considered to be zero because the load was set to zero and all the energy will be exported to the grid.

The array area is the total surface area that the PV modules occupy, in other terms, all the photovoltaic cell area in an installation.

The array slope or inclination depends on how the PV modules are constructed and set at the location. It is, indeed, the angle between the array and the horizontal, A vertical array will have a 90-degree slope and the typical degrees of inclination in the range of 5-30º.

The array azimuth determines the deviation of the PV modules from the geographical South. Considering the South to be at 0 degrees.

The overall input parameters of the programme are shown in Figure 24 below.

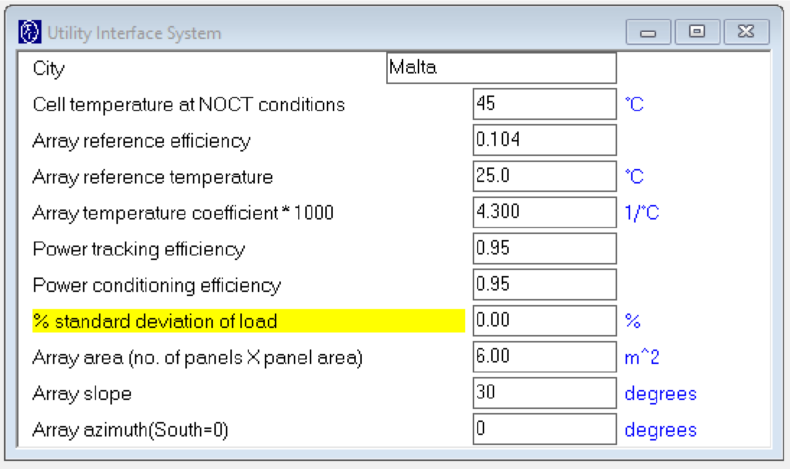


Figure 24. Parameters on programme PV F-Chart [66].

System Performance Results

Summary | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec

	Solar [kW-hrs]	Efficiency [%]	Load [kW-hrs]	f [%]	Sell [kW-hrs]	Buy [kW-hrs]
Jan	3756879.3	14.98	0.0	100.0	534749.0	0.0
Feb	5055628.7	14.90	0.0	100.0	715523.2	0.0
Mar	5754286.1	14.69	0.0	100.0	802860.1	0.0
Apr	5335641.2	14.54	0.0	100.0	737238.3	0.0
May	6071946.4	14.27	0.0	100.0	823211.0	0.0
Jun	5909646.9	14.02	0.0	100.0	787022.8	0.0
Jul	5705387.3	13.87	0.0	100.0	751600.3	0.0
Aug	6606297.7	13.81	0.0	100.0	866419.7	0.0
Sep	5329236.3	14.02	0.0	100.0	709727.4	0.0
Oct	4251620.9	14.34	0.0	100.0	579187.7	0.0
Nov	3308948.5	14.72	0.0	100.0	462774.7	0.0
Dec	3669423.8	14.88	0.0	100.0	518758.2	0.0
Yr	60754943.1	14.36	0.0	100.0	8289072.3	0.0

Figure 25. System performance results example in PV F-Chart [66].

In Figure 25 the system performance results of an example for one installation analysed in this dissertation are shown. On it, it includes many parameters explained hereafter.

Solar is either the yearly total or monthly solar radiation that incides on the array measured in kWh.

Efficiency refers to the percentage of solar radiation impacting on the collector that is converted to electrical energy. This efficiency includes the impacts of power-tracking equipment on efficiency, as well as the angular dependence of the array transmittance and absorptance of solar radiation on the collector. The product of *Solar* and *Efficiency* yields the array output in kWh.

Load is the total electrical demand on the system in kWh on a monthly or yearly basis.

F is the percentage of the load that the array supplies directly.

Sell It is the total amount of electrical energy that can be sold back to the utility in kWh on a monthly or annual basis. It is the result of the array's extra energy and the efficiency of the power-conditioning equipment.

Buy It is the entire amount of electrical energy that must be acquired from the utility on a monthly or annual basis to meet the load in kWh.

3.7 Summary of Methodology

This methodology includes various procedures indicated above. It involves the analysis from the management and maintenance point of view to the PV installation. Regarding this topic, there will be a SWOT analysis made, in which the most important aspects will be considered. On it, the strengths, weaknesses, opportunities, and threats of each installation are noted. On top of that a questionnaire showed on Appendix A contains the totality of the questions asked to the companies concerning how the management is set up, the organization of the activities taken place at the site that include the maintenance and conservation of the same.

On the other hand, the second part of the methodology involves the analytical and experimental data from the installations. That is to say, the actual calculations regarding the performance ratio, the shading of the modules, etc. On it, the technical characteristics of all of the components that are placed in each installation together with the own parameters from the same are considered. Additionally, on this section there is a software which is going to be used, PV F-Chart. There will be modelling made with this programme. In this, the ideal output of each installation, including the different solar radiations from each PV site will be calculated. Thereafter compared between the actual output of the different facilities and in between all of them. As well as a comparison between the same months of the same year.

All of these procedures are meant to understand the whole operation and management of each, and every photovoltaic plant involved in this case study. Therefore, this methodology is developed to provide final feedback in terms of recommendations for better performance of the PV farms.

The flowchart observed in Figure 27 explains a summary on how the methodology is carried out. On it, there are two parallel sides, the first one is regarding the management and maintenance side of the photovoltaic installations in which the study takes place. The first question asked is if the installation is a rooftop or ground installation since the maintenance procedures differ significantly. A management analysis is made with the following help of the questionnaire regarding all these aspects. At the end a SWOT is fulfilled to evaluate the beneficial and prejudicial aspects and define the results.

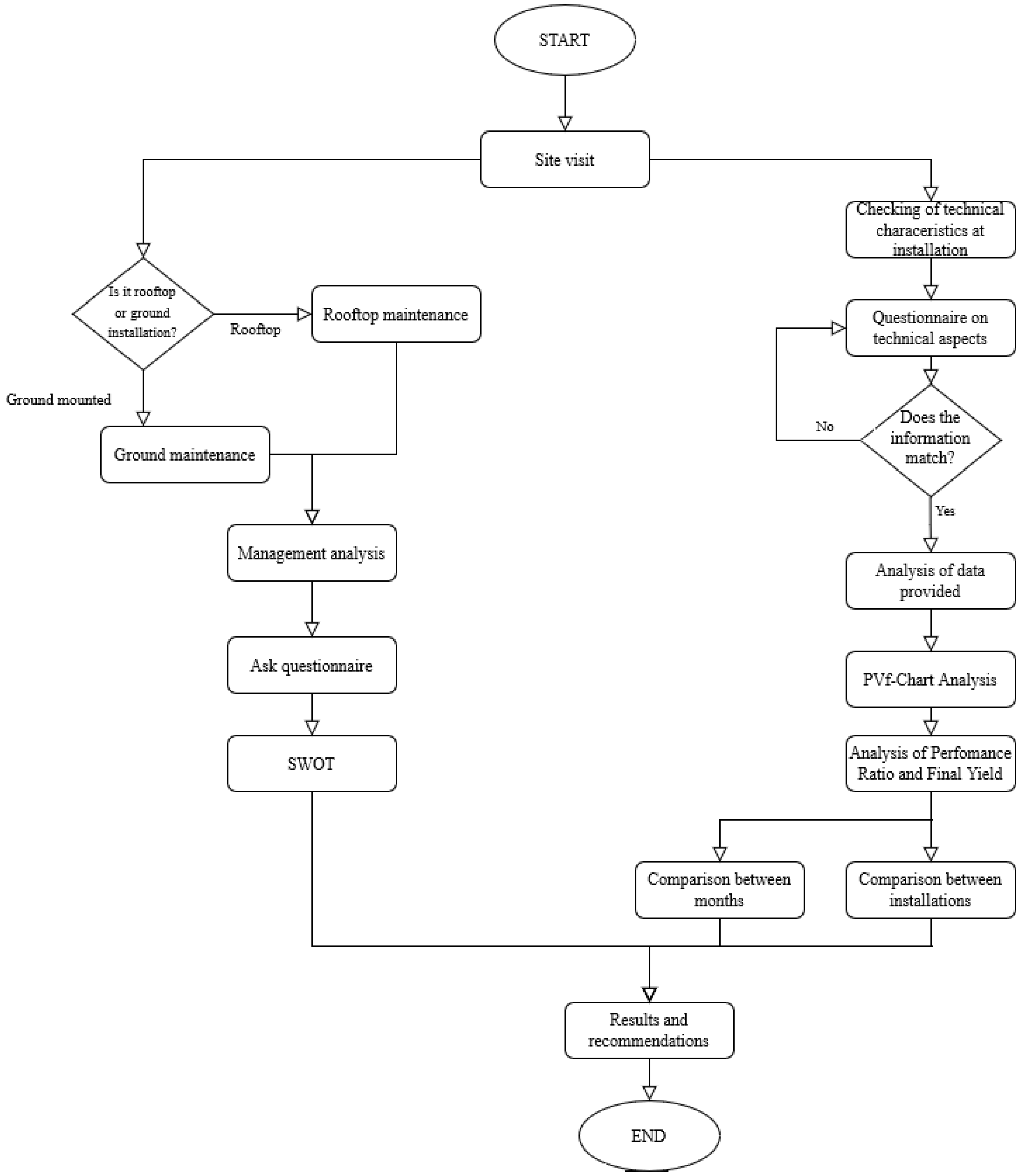


Figure 26. Flowchart of methodology process.

On the contrary, the other part of the flowchart includes and involves the technical analysis of the study. Firstly, during the visits to the PV farms, the checking of all characteristics is made and afterwards the questionnaire is asked receiving the answers regarding this topic. If the information matches the actual characteristics seen on site, the next step is to analyse all the data in depth. The data includes the solar radiation collected at each PV site as well as the total output from the PV modules.

Successive, the software PV F-Chart is used to analyse the ideal output on the PV plants and following to that, three types of comparisons are made.

Finally, the results are both quantitative and qualitative so that recommendations are advised in this case of study.

4. Results and Discussion

This chapter presents the results for the four photovoltaic installations studied. All of the installations were studied following the same methodology, but they were analysed individually. Later on, a comparison between them is carried out.

4.1 Visits to the Installations

The first step was visiting one by one all of the four installations checking all of the data needed to analyse them and show the final results in this chapter. In this section of the chapter, the technical characteristics from the photovoltaic plants will be displayed.

4.1.1 First Visit

The first visit took place on the 7th of December of 2021. During this visit all of the technical characteristics were taken into consideration. The characteristics are needed to explain and analyse the whole range of performance analysis of the PV farm concerned.

4.1.1.1 PV Installation Characteristics

This first installation visited for the study covers an area of 65,000 square meters. The total capacity of the installation is 5.2 MWp. It is a PV farm located in the South of the island of Malta and is ground-mounted in an ex-quarry that as undergone extensive rehabilitation to house the PV farm. The operation of this systems started August 2020.

Figure 27. Landscape view of the 1st PV installation.

Figure 28. Layout of the modules at PV Farm 1.

4.1.1.2 Solar Modules

The type of solar modules used in the installation is CS6U-330P, from the brand Canadian Solar. Their electrical characteristics under standard test conditions (STC) are shown in Appendix A Table 1. Standard Test Conditions are irradiance of 1000 W/m^2, solar spectrum AM 1.5 and cell temperature of 25ºC.

Figure 29. Solar PV module type CS6U-330P.

The electrical characteristics of the PV module are shown in Appendix A Table 2 under Nominal Operating Cell Temperature (NOCT), an irradiance of 800 W/m^2, spectrum AM 1.5, ambient temperature of 20ºC, and wind speed of 1 m/s.

Other data pertaining to the mechanical characteristics of the PV modules are shown in Appendix A Table 3.

In order to appropriately analyse and model the system, temperature characteristics are needed, and this is known as the power loss coefficient, shown in the first row in Table 4 of Appendix A, below.

4.1.1.3 Inclination and Orientation

At this installation the angle of inclination of the photovoltaic modules with respect to the ground is 30°, and the orientation of the PV modules is primarily facing the geographical South, i.e., an azimuth of 0 degrees. However, it was also noted that for this particular installation, the PV array is not always straight horizontal but follows the undulation of the land (Figure 28), which finally translates to experiencing different amounts of solar radiation on the PV array, effectively causing the same impact as shading.

Figure 30. Inclination and orientation of the PV modules at PV Farm 1.

4.1.1.4 Anchoring to the Ground

In this installation, the photovoltaic modules are anchored to the ground with a system called Three System, as amply explained in the Literature review section 2.3.2. This consists of putting 4- or 5-metre-long metal tubes into the ground at an inclination of 30 degrees to anchor the structure (Figure 32). In order to move by any means this anchored structure, a force equivalent to one tonne is required, which means that this system is very well suited for sustaining wind loads. Moreover, the installation could be carried out with less labour, cost, and time, while leaving minimum impact on the environment (no use of concrete ballasts). Specifically, at this installation the ground was covered with inert waste material and topped up with a soil layer, to bring about the required levelling of the land and promote growth of grass in the area.

Figure 31. Back part of the PV modules and anchoring to the ground in PV Farm 1.

4.1.1.5 Solar Inverter

In this installation there are 26 inverters which convert the energy from DC into AC and afterwards transfer the electricity to the grid via a dedicated substation. The inverters used at the installation are the model PVS-175-TL, from the company ABB (Figure 33). The inverters are mostly placed behind the PV arrays and therefore they are well protected from direct sunshine.

Figure 32. String solar Inverter PVS-175-TL at PV Farm 1.

In Table 5 of Appendix A, the technical characteristics of the input, this means the DC voltage along with the nominal power, and DC current, as well as the output of the inverter are shown.

4.1.1.6 Lifetime Expectancy and Feed-in Tariff

The lifetime expectancy is the average lifespan of any device, project, installation, etc. In this case, the lifetime for the solar photovoltaic modules is of 25 years, while the lifespan of the inverters is 10 years. This means that the installation will need the replacing of the inverters at least one time if not any other problem occurs. The project license for the PV farm in Malta is for 20 years. After that amount of time is reached, another license will have to be renewed possibly subject to new terms and conditions.

The current FiT that this installation has is 12.3 cents/kWh.

4.1.2 Second Visit

The second visit was on the 17th of December of 2021. Similarly, all technical characteristics were observed and taken into consideration since they are needed to explain and analyse the whole range of characteristics the installation is equipped with.

4.1.2.1 PV Installation Characteristics

The second installation visited for the study occupies an area of 29,326 square metres. The total capacity of the installation is 2400 kWp. It is a PV farm located also in the South of the island of Malta, really close to the sea and is ground-mounted. The PV farm started operating in April 2020.

Figure 33. Layout of the modules at PV Farm 2.

4.1.2.2 Solar Modules

The type of solar PV modules in this installation was the same as the first PV farm, CS6U-330P (Figure 35), from Canadian Solar. The specifications on electrical information, mechanical and temperature data are therefore the same as the shown in Tables 1, 2, 3 and 4 of Appendix A.

Figure 34. Solar module of PV Farm 2.

4.1.2.3 Inclination and Orientation

At this installation the angle of inclination of the photovoltaic modules with respect to the ground is 7 degrees and the orientation of the PV modules is 0° South, as shown in Figure 35.

Figure 35. Inclination and orientation of PV modules in PV Farm 2.

4.1.2.4 Anchoring to the Ground

In this installation, the same Three System anchoring was used, similar to the first PV farm.

Figure 36. Anchoring of PV modules to the ground in PV Farm 2.

As Figure 36 shows, the metal tubes are inserted into the ground. This ex-quarry was used for many years to store fly ash from the power station. This was sealed completely with special rubber covers and covered with a soil layer before placing the PV modules. The Three System anchoring was the perfect solution because it does not need to penetrate deep in the ground and therefore the risk of perforating the protective plastic layer is eliminated. Moreover, this system allows for fast dismantling and reinstating the place to its original undisturbed environment at the end of the lifetime of the PV farm.

4.1.2.5 Solar Inverter

The solar inverters used in this installation were all from the same type. They are string inverter, with one inverter per string: Sunny Highpower PEAK3 SHP 150-20.

Figure 37. String solar inverter Sunny Highpower 150-20 in PV Farm 2.

In Table 6 of Appendix A, it can be observed the technical data for the input and output characteristics of the specific inverter at this PV farm.

4.1.2.6 Life Expectancy and Feed-in Tariff

The lifetime of the PV array, inverter and project overall follow the same figures as PV Farm 1, i.e. 25 years for PV modules, 10 years for inverter and 20 years for feed-in tariff. The FiT for this installation is 13.5cents/kWh for 20 years. This is higher than that of PV Farm 1. This is expected because each project is evaluated separately by the government and as explained earlier in Section 2.5.1 long term contracts with large PV farm owners offer their bids and are accepted based on the cheapest offer first until the required ceiling target of PV power capacity is reached.

4.1.3 Third Visit

The third visit was carried out on January 10th of 2022, during which all information was gathered as detailed below.

4.1.3.1 PV Installation Characteristics

This total project area covers 11,000 square metres hosting two separate roofs in a central part of Malta. The first area had 634 kWp and the second one had 300 kWp, and in total this sums up to 934 kWp.

The first PV roof started operating in 2015, while the second one commenced in 2018, as an extension to the former one.

4.1.3.2 Solar Modules

The type of solar PV module in this installation is CS6P-225P, from the brand Canadian Solar, as shown in Figure 38.

Figure 38. Solar PV module used in PV Farm 3.

Their electrical characteristics under standard test conditions (STC) are shown in Table 7 of Appendix A.

The electrical characteristics of the PV module are shown in Table 8 of Appendix A under Nominal Operating Cell Temperature (NOCT).

Other mechanical characteristics of the PV modules are shown in Table 9 of Appendix A.

Table 10 of Appendix A shows the power loss coefficient for the PV module, which will be needed for the modelling of the solar system.

4.1.3.3 Inclination and Orientation

This installation has a mix of different inclinations at which the PV solar modules are placed. In the first roof, the inclination of the modules is at 15 degrees facing perfectly geographical South, as shown in Figure 39, on it there is also another type of setup shown in Figure 40. The second roof has a different configuration as shown in Figure 41. The inclination is that of 5° but the orientation of half of the modules is towards N75°W and S75°E.

Figure 39. Inclination of first type of PV modules in first roof of PV Farm 3.

Figure 40. Inclination second type of PV modules in first roof of PV Farm 3.

Figure 41. Inclination of PV modules in second roof of PV Farm 3.

4.1.3.4 Anchoring to the Roof

Rooftop installations require different fixtures than ground-based PV arrays. Moreover, appropriate consideration is to be given to the extra loading on the roof and wind forces.

In this project, a structure mechanism was set up for the flat roof from the company Schletter, known as A-frames [67], as shown in Figure 42. The frame is permanently fixed to the roof preventing the PVs from moving under any circumstance. Moreover, the configuration itself serves as a wind breaker due to the see-saw shape.

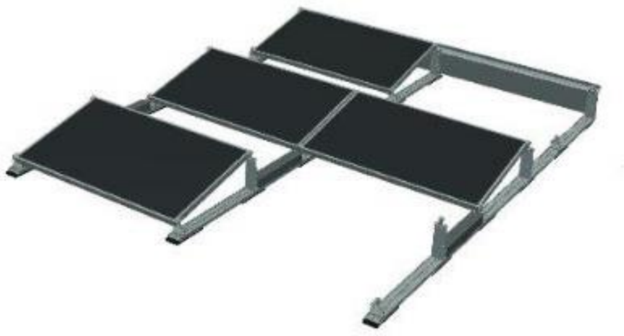


Figure 42. A-frames Fixgrid with orientation South [67].

Figure 43. Anchoring A-frames to the roof in first roof of PV Farm 3.

The second type of fixture for the inclined roof is known as ClampFit and is sourced from the same supplier Schletter (Figure 44). It consists of various clamps, one in the middle and one end clamp to fit module frames along their length and are best for mounting on trapezoidal sheet metal roofs.

Figure 44. Anchoring with Clampfit in first roof of PV Farm 3.

Finally, the last type of roof is flat, and the structure installed on it is the Fixgrid (W-E) from Schletter. Figures 45 and 46 below show how the configuration of the PV modules is on the roof. The orientation is interspersed on this type of system. The advantage of using this setup is to save on cross-shading spacing and thus increase the capacity of the roof.

The outcome is that the PV system is maximised in terms of output per m² of roof area available rather than output per kWp of installed system. Given that one of the scarscest resource of Malta is land area, maximising the system in terms of energy per unit of area is a beneficial decision.

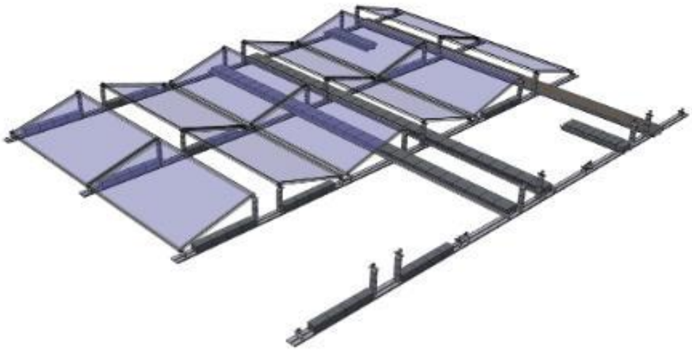


Figure 45. Fixgrid system with orientations West-East [67].

Figure 46. Anchoring with Fixgrid W-E in second roof of PV Farm 3.

4.1.3.5 Solar Inverter

This PV farm uses two different types of string inverters depending on the roof in which they are placed in. The first roof uses inverter from the brand Huawei, model SUN2000-23KTL (Table 11 of Appendix A). On the other hand, the second roof uses Huawei, model SUN2000-36TL (Table 12 of Appendix A).

4.1.3.6 Life Expectancy

The expected lifetime for this project is the same as the previous ones.

Moreover, the FiT is higher than the rest of the PV farms at 15.5 cents/kWh for 20 years.

4.1.4 Fourth Visit

The fourth visit was carried out on the 17th of January of 2022 for a rooftop PV installation in an industrial zone.

4.1.4.1 PV Installation Characteristics

The PV system covers a rooftop area of 8216 square metres with a total capacity of 943 kWp. Operation started in January 2020.

4.1.4.2 Solar Modules

The type of solar PV modules in this installation were from the brand Hanwha, model Q.PEAK-G4. The specifications on electrical information, mechanical and temperature data are shown in Tables 13, 14, 15 and 16 of Appendix A.

4.1.4.3 Inclination and Orientation

The PV modules were inclined at 10° to the horizontal and facing South 24° East.

Figure 47. Inclination and orientation of PV modules in PV Farm 4.

4.1.4.4 Anchoring to the Roof

Anchoring was carried out using precast light concrete blocks type Sunballast Connected System, which connects all the PV system into a solid piece. The network of ballasts and modules is resistant to wind and have very limited loads on the roof (max 20-25 kg/m^2 including the weight of the modules) and these are distributed evenly on the roof.

Figure 48. Anchoring to the roof in PV Farm 4.

In Figure 48 it can be observed the Sunballast connected system and how the blocks are connected in between forming a solid structure. The top part of the PV module lays in one block at a certain height and the lower part of the module lays in the next block forming an angle of 10º.

4.1.4.5 Solar Inverter

There are 15 string solar inverters in this installation from the brand Huawei, model SUN2000-60KTL-M0 and one solar string inverter also from Huawei, model SUN2000-36KTL. The specifications of this first inverter are shown below in Table 17 of Appendix A.

Figure 49. String solar inverter SUN2000-60KTL.

While the technical specifications for the inverter SUN2000-36KTL are already detailed in Table 16.

4.1.4.6 Life Expectancy

The life expectancy for the PV modules and inverters as well as the feed-in tariff contracts are the same as the previous three projects.

The FiT contracted with the Regulator for Energy and Water Services or with the Automated is of 14.5cents/kWh for 20 years renewable every 20 years.

4.2 SWOT Analysis

In this section, all the SWOT analysis corresponding to the installations will be shown. For each installation the different aspects to be considered are analysed. The strengths and opportunities make up the positive aspects. On the other hand, weaknesses and threats explain the negative points.

From an internal point of view, the strengths and weakness are analysed, while the opportunities and threats represent the external points of view.

4.2.1 PV Farm 1

Table 5 shows the internal analysis for strengths and weaknesses of PV Farm 1, while Table 6 shows the external analysis for opportunities and threats.

Table 5. SWOT Internal Analysis for PV Farm 1.

Internal Analysis	
Strengths	**Weaknesses**
• THREE System anchoring, having minimum impact on the soil. • Smart layout in an old quarry, allowing useful re-use of land. • Best type of solar modules with respect to the Bloomberg list. • Uses fault maintenance monitoring protocols. • Monitors in plane solar radiation to be able to calculate key parameter of performance ratio. • Outsourced management for upkeep of site, thus requiring no additional equipment or personnel for owner. • No trees or other obstacles on site, and therefore no shading. • Far from the city, no potential vandalism. • Cleaning and grass cutting done by hand and subcontracted, so no noise or pollution. • Best inclination 30° to maximise solar output per kWp installed.	• Partial cross-shading during the months of winter, due to insufficient distance between PV rows. • Vegetation under management with overgrowth in one site creating some overshading on lower part of PV arrays. • Problems with soiling due to prior quarry, especially during the month of May being the windiest month in Malta. • Uneven ground levels, making the PV modules follow the undulation of the land, effectively creating uneven solar energy falling on the PV modules, creating unbalance in output which effectively produce the same impact as shading.

Table 6. SWOT External Analysis for PV Farm 1.

External Analysis	
Opportunities	**Threats**
• Possible extension of the PV farm. • Upgrade system with larger and more efficient PV modules after a period of time (e.g. after 10 years). • Fix cross-shading by slightly lowering the inclination of the PV modules. • Increase distance in between PV module rows downhill on the northern sides to avoid cross-shading. • Cutting grass more often. Recommended 4 times/year or make use of sheep to eat the grass.	• Farm or building construction nearby causing shading on the modules. • Not being able to prolong the FiT after 20 years, thus the contribution of RE would drop nationally. • Tall grass growth in the area potentially shading part of the PV modules. Lack of security guards and overly dependence on security cameras, could risk higher vandalism. • When problems with inverters occur, manufacturers might take a long time to fix the issue. • As prices soar due to recent world turmoil, the sub-contractor responsible for maintenance might ask for higher payment and this would reduce the revenue to the PV farm owner.

4.2.2 PV Farm 2

Table 7 shows the internal analysis for strengths and weaknesses of PV Farm 2, while Table 8 shows the external analysis for opportunities and threats.

Table 7. SWOT Internal Analysis for PV Farm 2.

Internal Analysis	
Strengths	**Weaknesses**
• THREE System anchoring, having minimum impact on the ground and the environment. • Installation located close to the sea, allowing for excellent cooling by sea-breeze effect. • Fault maintenance and preventive maintenance protocols being used. • Cleaning often. 4 times/year. • No obstacles on site. • Solar irradiance data monitored on site, providing valuable data to calculate key parameter of performance ratio. • All risk insurance, including energy loss from the grid.	• Partial shading at the back occurring in the months of winter due to unevenness of ground level (hilltop shape). Inert waste used to cover the fly ash filled quarry, does not allow rainwater to seep through, leading to deep runoff channels in the inert material that ends up in the sea. Also, the inert waste does not allow vegetation to grow in the PV farm, which accelerates erosion. • No possible extension of the PV farm.

Table 8. SWOT External Analysis for PV Farm 2.

External Analysis	
Opportunities	**Threats**
• Investments in new devices after life of contract is reached. • Determination of I-V and P-V curves every 5 years and comparison to original graphs would predict potential faults and ensure appropriate operation of the PV farm. • Since no grass can grow on top of inert waste, the cost of cutting grass is lower.	• Possible future problems due to soiling. • Lack of maintenance: Many cable ties are already deteriorated by UV radiation leaving connecting cables dangling with the wind, which is not sound maintenance practice. • No security personnel with overdependence on security cameras risking vandalism. • When problems with inverters occur, manufacturers might take a long time to fix the issue. • As prices soar due to recent world turmoil, the sub-contractor responsible for maintenance might ask for higher payment and this would reduce the revenue to the PV farm owner.

4.2.3 PV Farm 3

Table 9 shows the internal analysis for strengths and weaknesses of PV Farm 3, while Table 10 shows the external analysis for opportunities and threats.

Table 9. SWOT Internal Analysis for PV Farm 3.

Internal Analysis	
Strengths	**Weaknesses**
• Rooftop system and therefore no need for grass cutting. • PV installation prevents the over-heating of the roof, thus supporting lower demand for cooling. • Relatively cheaper installation than land-based systems resulting in shorter payback periods. • Quick installation process due to plug-and-play construction materials and processes. • PV module cleaning is subcontracted thus reducing the need to employ personnel. • Client has the facility of either net metering or FiT. • Fault maintenance procedures adopted.	• No possible extension for the system. • A-frames anchoring to the roof are old and present added load to the structure. • Issues with nearby factories due to pollution stuck on PV module surfaces. • Partial shading caused by a nearby wall for a number of hours throughout the year. • Different heights of the building do not help get the best performance ratio possible due to shading caused by them.

Table 10. SWOT External Analysis for PV Farm 3.

External Analysis	
Opportunities	**Threats**
• Possibility of increasing inspections. • Visual inspections to be made more often (at least 4 times a year), to improve monitoring. • Reduce self-consumption energy used so more energy produced is sold to the grid. • When inverters present issues, contact the manufacturer beforehand so no energy production is lost.	• Nearby new buildings or obstacles may be built and produce shading. • No possibility to enlarge the system. • As prices soar due to recent world turmoil, the sub-contractor responsible for maintenance might ask for higher payment and this would reduce the revenue to the PV farm owner. • Need for decommissioning or disposal after the contract time is reached. • When problems with inverters occur, manufacturers might take a long time to fix the issue.

4.2.4 PV Farm 4

Table 11 shows the internal analysis for strengths and weaknesses of PV Farm 4, while Table 12 shows the external analysis for opportunities and threats.

Table 11. SWOT Internal Analysis for PV Farm 4.

Internal Analysis	
Strengths	**Weaknesses**
• Higher FiT than other installations. • Sunballast anchoring system used, allowing fast installation and providing security against wind loading. • Daily monitoring check protocols. • Less soiling issues due to roof installation away from major pollutants (e.g. traffic). • Provides green electricity to the factory making it environmentally friendly. • Subcontracted maintenance, thus no need for extra personnel or equipment. • Thermographic photos taken once a year to find fault on PV modules. • Fault maintenance protocols applied. • Safe from any potential vandalism.	• No space for expansion. • Daily shadows evident from obstacles such as perimeter wall of the roof. • Prone to PV glass module damage due to proximity to a field from where fireworks are let off during the village feast. • Insufficient cleaning frequency of the PV modules(twice/year). • Inverter errors take time and require manufacturer of person in charge to come for fixing or updating. • Has no “all risk” insurance cover.

Table 12. SWOT External Analysis for PV Farm 4.

External Analysis	
Opportunities	**Threats**
• Change PV module and inverters after the license time is reached. • Recycle materials and sell them. • Cleaning more often during the summer would prevent prolonged faults on PVs from being discovered, especially after some special events (fireworks) occurring nearby.	• Possible dirt accumulation or chemical deterioration from nearby chimneys of factories. • Higher possibility of lightning strikes due to height of building. • When problems with inverters occur, manufacturers might take a long time to fix the issue. • As prices soar due to recent world turmoil, the sub-contractor responsible for maintenance might ask for higher payment and this would reduce the revenue to the PV farm owner.

4.2.5 Common SWOT Analyses

For the location of Malta, the main commonalities regarding strengths, weaknesses, opportunities and threats are identified in Table 13.

Table 13. SWOT Commonalities

Strengths	Subcontracted maintenance, thus no need for extra personnel or equipment. Fault maintenance protocols applied.
Weaknesses	Partial cross-shading during the months of winter. No possible extension of the PV farm. Inverter errors take time and require manufacturer of person in charge to come for fixing or updating
Opportunities	Cleaning more often during the summer
Threats	As prices soar due to recent world turmoil, the sub-contractor responsible for maintenance might ask for higher payment and this would reduce the revenue to the PV farm owner.

4.3 Performance Analysis

The quantitative performance analysis for the four PV farms is presented in this sub-section. This is followed by a comparison between the actual performance and the predicted modelled performance using the PVFChart software. Finally, several comparisons are made between the different PV farms in terms of operational parameters and overall performance. Due to data protection requirements and conditions set by the PV Farm operators, specific values for energy generation will not be divulged in this dissertation.

4.3.1 PV Farm 1

The performance data for one year was provided in the form of a report that was prepared by a sub-contractor to the mother company. The energy produced by the installation during the period of one year together with the expected output using the PVFChart software have been prepared and compared. The comparison ratio between the actual energy output and the ideal energy output is shown in Figure 50 for the different months of the year.

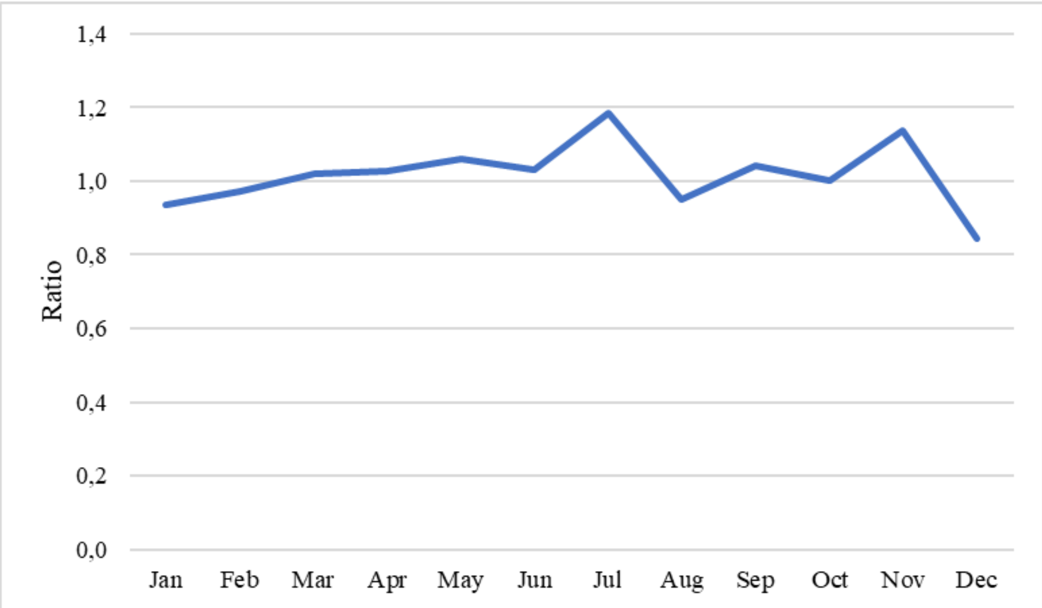


Figure 50. Comparison of actual to modelled monthly energy output for PV Farm 1.

Clearly, the ratio of actual to modelled monthly energy generation during the winter months (December-February), was lower than 1, which implies that the actual energy production was lower than that expected or modelled by the PVFChart software.

This can be explained by the fact that there is cross-shading between the PV module rows during this time of the year, as confirmed during the site visit.

As a result, the PV farm suffers losses during these winter months which amounted to 234262.8 kWh. Given that the FiT of this plant is 0.123 €/kWh, then it follows that the estimated losses due to cross shading amounts to 28814.3 Euro per year.

Another interesting feature is that the ratio for all remaining months (except for June) are only higher than the expected output by a few percentage points, which shows good correlation. Naturally, the PV modules are still new and usually manufacturers oversize their peak power by 2-5%, when compared to the nameplate, in anticipation of the fact that during the first few years of operation, the PV modules will undergo "light soaking" and permanently lose some efficiency as a direct effect of UV solar radiation.

For the month of June there is an over-performance of 18%, but there is no clear reason for such discrepancy.

The data provided in the report has also shown the performance ratio (PR) of the PV farm, as depicted in Figure 51. It is to be noted that the performance ratio is distinctly different from the overall system efficiency because it compares the output of the PV farm to the maximum theoretical output of the system (i.e. assuming that all solar energy was converted to electricity). The numerical PR for all months is above 80%, which indicates an overall efficient performance for the first year of operation.

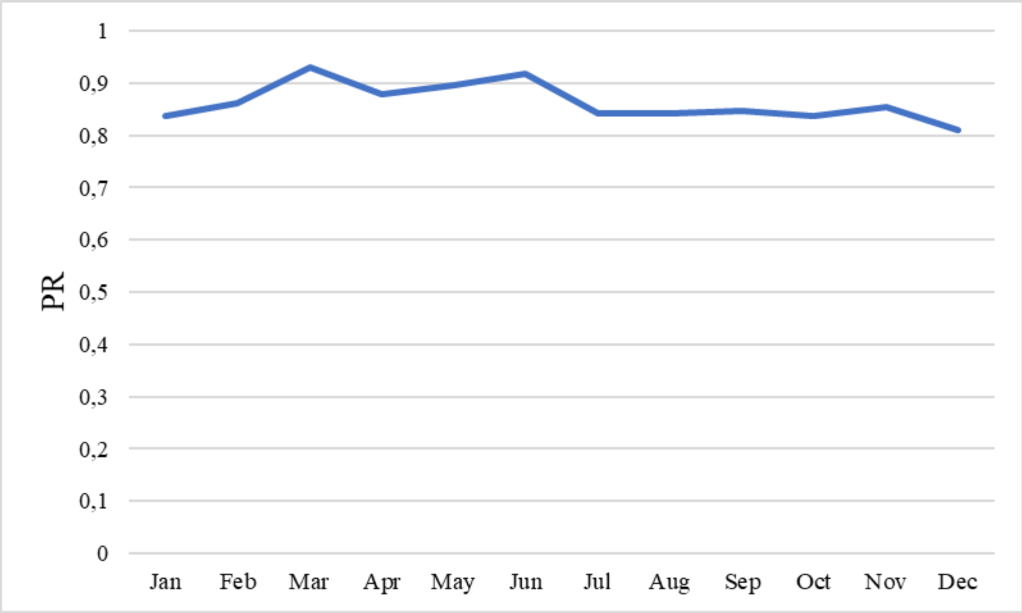


Figure 51. Monthly Performance Ratio for PV Farm 1.

Once again, the demonstrated cross-shading during winter has yielded lower PRs. In July and August, the ratio falls slightly due to the higher operational temperature of the PV modules during the hot season, while in winter it is lower because of cross-shading between the rows of PV modules.

In Spring, the best PRs are to be expected because the solar path of the sun at noon time in Malta (around 60°) would be approximately perpendicular to these PV modules (inclined at 30°), thus providing better access to solar energy (Figure 52). Moreover, the weather in Malta is characterised by windy days in spring [4] which helps to cool down the solar modules, thus enhancing performance.

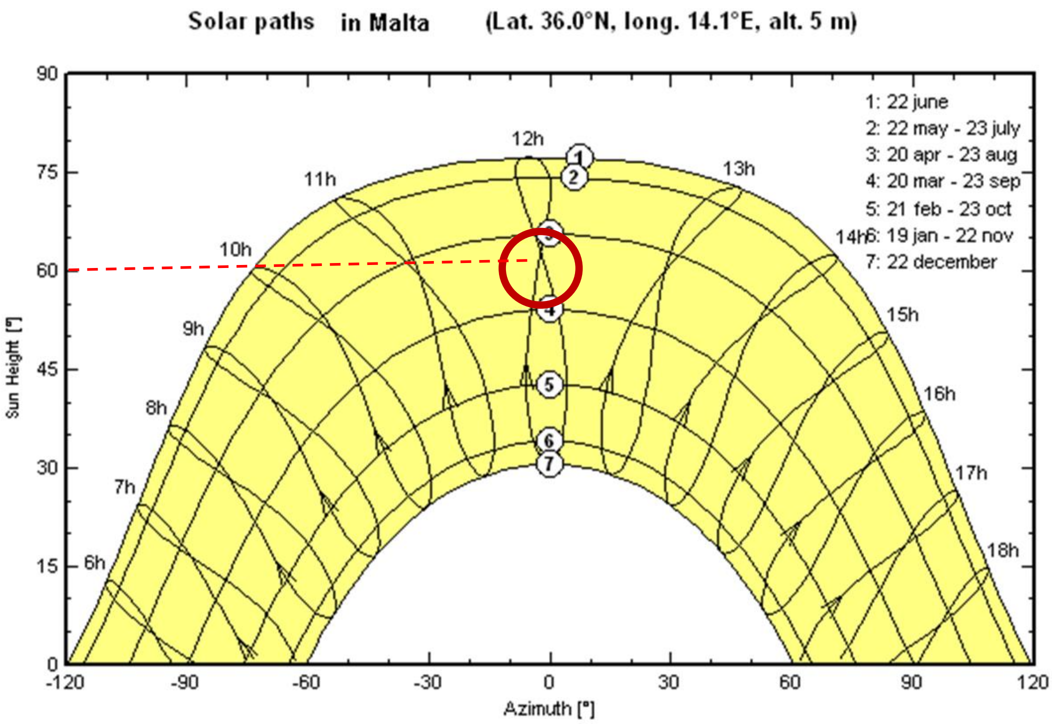


Figure 52. Sun path diagram in Malta Latitude 36ºN [68].

4.3.2 PV Farm 2

Monthly energy production data for the year 2021 was provided by the owners, together with the in-plane solar irradiation as measured on site. In this case, the provided solar radiation was used as input to the PVFChart software in order to provide a more realistic estimate of the output for this particular PV farm. Similarly, the ratio between the actual energy generated and the modelled data was plotted as shown in Figure 53.

Clearly, the system has performed much better than expected for several reasons:

1. The PV modules are still new and are generally oversized in their capacity by about 5%.

2. The site is very close to the sea and therefore benefits significantly from the sea breeze to cool the PV modules throughout the day.

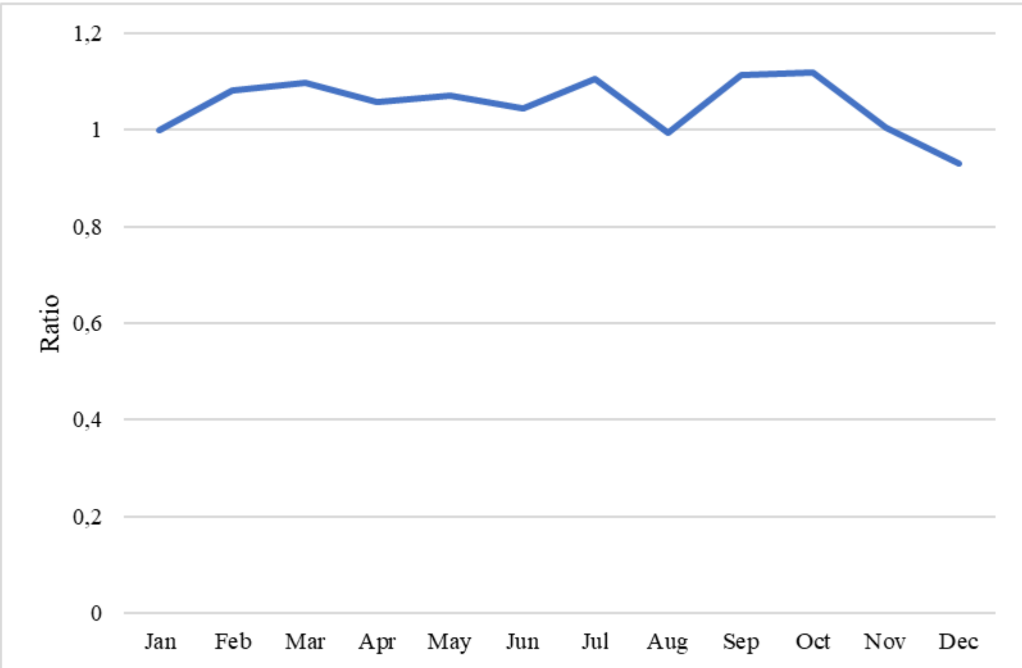


Figure 53. Comparison of actual and modelled energy output for PV Farm 2.

One can also observe that during the month of August the ratio had a lower value, because this is the month with least wind and also because one inverter had failed during this month, causing a drop in overall energy output.

This system also had cross-shading in winter on part of the system lying downhill, leading to lower PR in winter. In general, one would expect higher PR in the cooler months, but the impact of shading has offset this positive behaviour and has further degraded the PR below that of summer.

As a result, the PV farm suffers losses during these winter months which amounted to 86829.35 kWh. Given that the FiT of this plant is 0.135 €/kWh, then it follows that the estimated losses due to cross shading amounts to 11721.96 Euro per year.

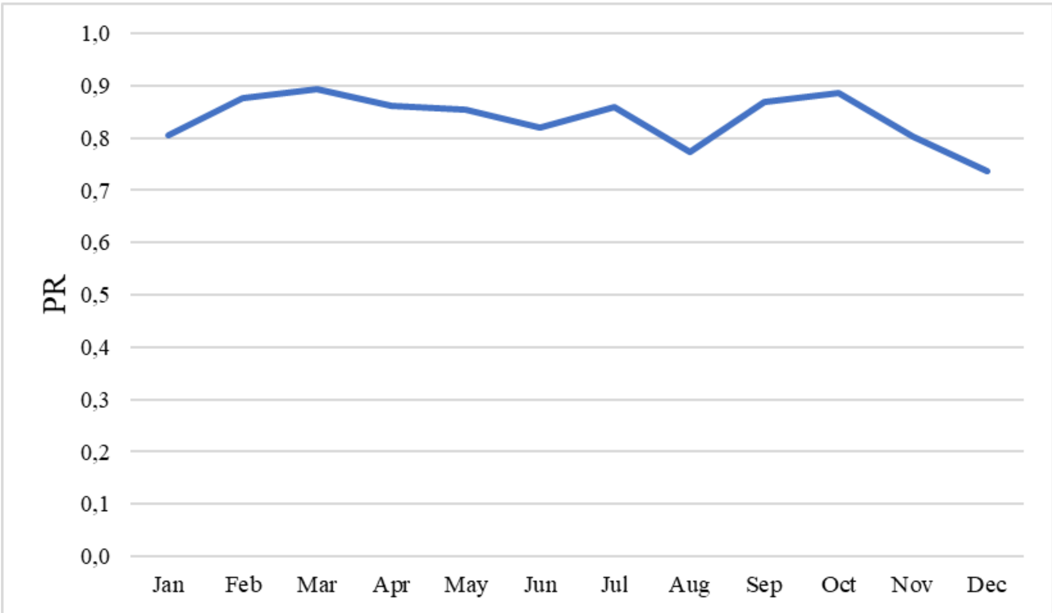


Figure 54. Monthly performance ratio for PV Farm 2.

As already mentioned above as it can be seen in Figure 54, the August low PR was due to an inverter failure which took time to be replaced. However, the PR is above 0.8 for many months which reflects good performance overall.

4.3.3 PV Farm 3

This energy generated for this rooftop system was provided for the year 2021. However, no solar radiation data was available on site. One needs to recall that this installation is divided in two different roofs, and therefore the data will be presented separately. for those two different roofs.

4.3.3.1 First Roof

For the first roof, the inclination of the PV modules is 15 degrees while the azimuth is 0 degrees, facing completely South. From the site visit, it was noted that the modules are close to a stonework factory and the amount of dust that deposits on the PV array is relatively large.

Figure 55 shows the ratio of actual to modelled energy output, while Figure 56 displays the monthly performance ratio. For this case, the solar radiation data used was the long-term average as inputted in the PVFChart. Although this may not be accurate, one needs to recall that solar radiation only varies by ±3% per annum as stated in Section 2.9 above.

The ratio plot does not take error coming from the energy meter or inverter into consideration. It's expected that this error to be small but when real data is compared to data from a simulation or calculation, such errors should be considered.

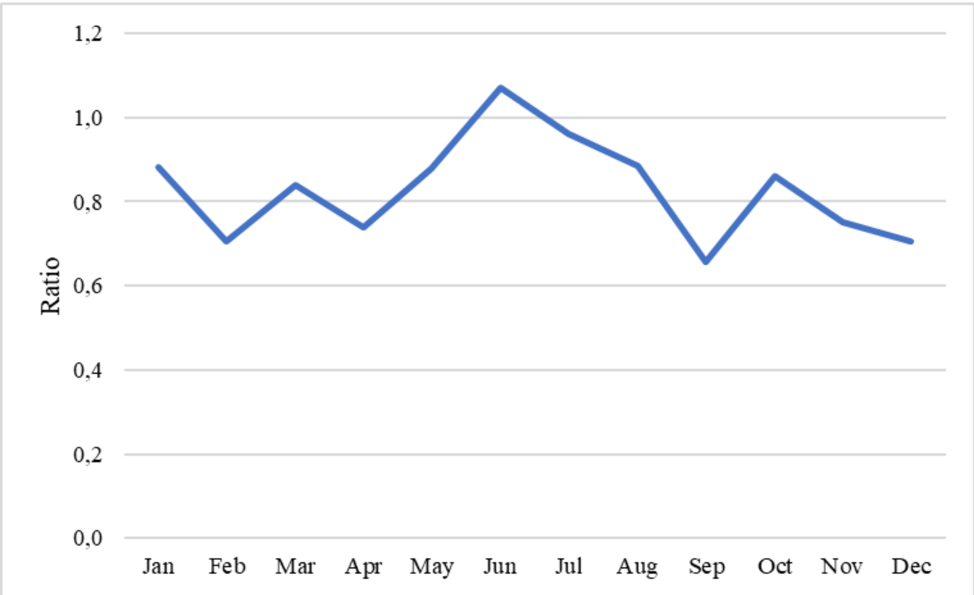


Figure 55. Comparison of monthly actual to modelled energy output ratio for the first roof of PV Farm 3.

Due to the lower-than-expected performance of this system compared to the modelled data, the PV farm suffers losses during the whole year amounting to 41995.4 kWh. Given that the FiT of this plant is 0.155 €/kWh, then it follows that the estimated losses due to cross shading amounts to 6509.3 Euro per year.

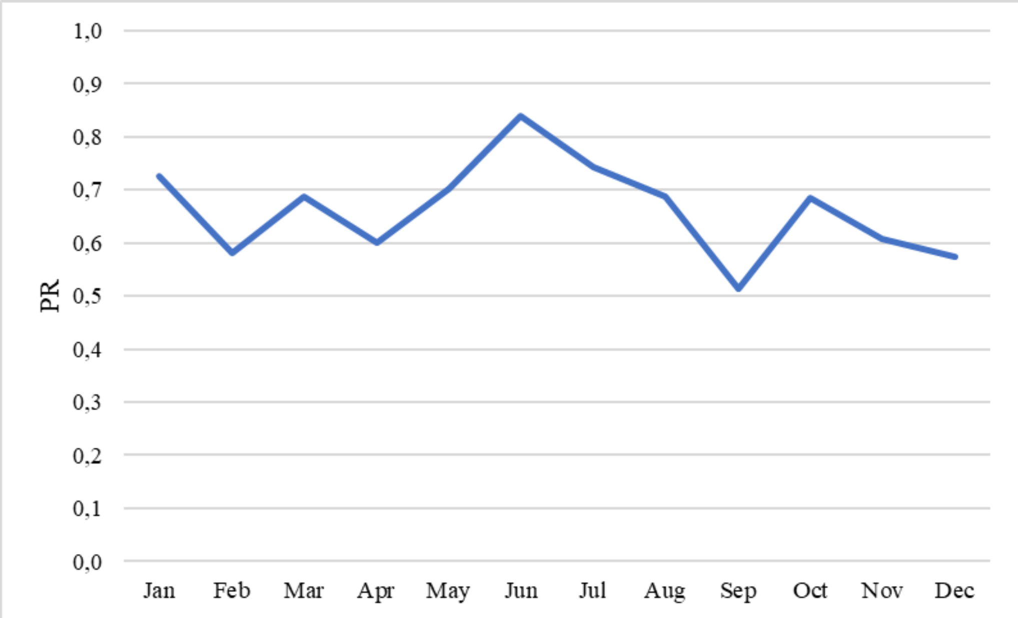


Figure 56. Monthly performance ratio for the first roof for PV Farm 3.

In Figure 55, the ratio between actual and modelled data surpasses 1 only once in June. Several reasons contribute to this lower performance as already depicted in Figure 56 on PR.

A technical fault in an inverter has reduced the performance in September quite drastically.

For example, in the month of September there was a problem with an inverter, adding to shading due to the roof's perimeter wall as well as a nearby 1.5 m high wall, all contributing to lower PR throughout the year. In addition, the modules tended to get dirty fast because of the nearby stonework factory.

From the site visit, it was noted that the PV array was cleaned in January, March, June, and October and this leads to better performance during those months and gave the see-saw shape of the graph.

Finally, this system is roof mounted and therefore it generally operates at higher temperatures than ground-mounted systems because of the energy absorbed by the concrete roof and remitted during the day. Besides, these modules have been in operation since 2015 and therefore they could have degraded to some extent, thus leading to overall lower performance than expected.

4.3.3.2 Second Roof

Concerning the second roof, the inclination is only 5 degrees, while there are two orientations for the same system, N75ºW, S75ºE.

Figure 58 shows the ratio when comparing the monthly actual to the modelled energy output.

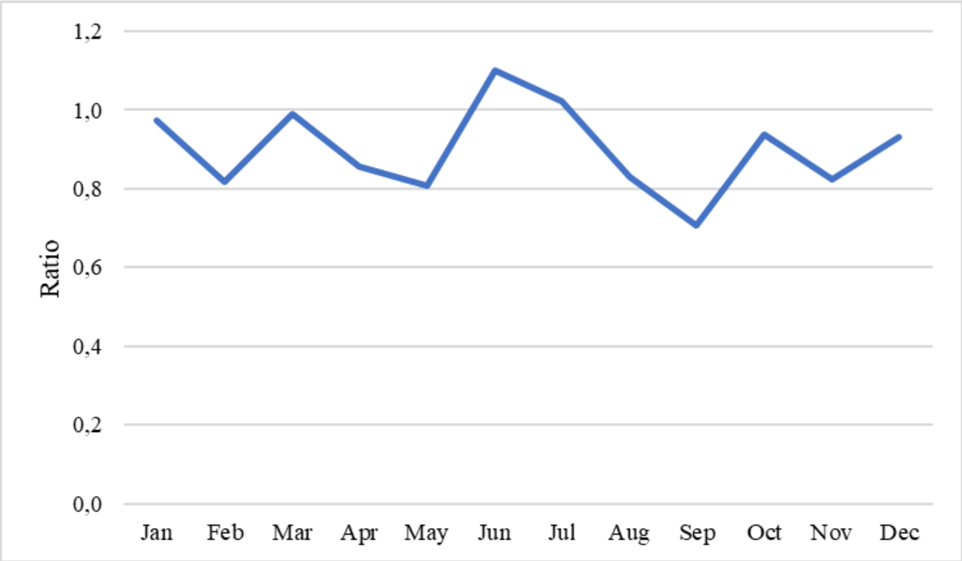


Figure 57. Comparison of monthly actual to modelled energy output ratio for the second roof of PV Farm 3.

The ratio displayed on Figure 57 shows better results for the second roof than the one that was previous analysed. The best months are still June and July, which have better outcome than the expected.

Due to the lower-than-expected performance of this system compared to the modelled data; the PV farm suffers losses during the whole year amounting to 19639.4 kWh. Given that the FiT of this plant is 0.155 €/kWh, then it follows that the estimated losses due to cross shading amounts to 3044.1 Euro per year.

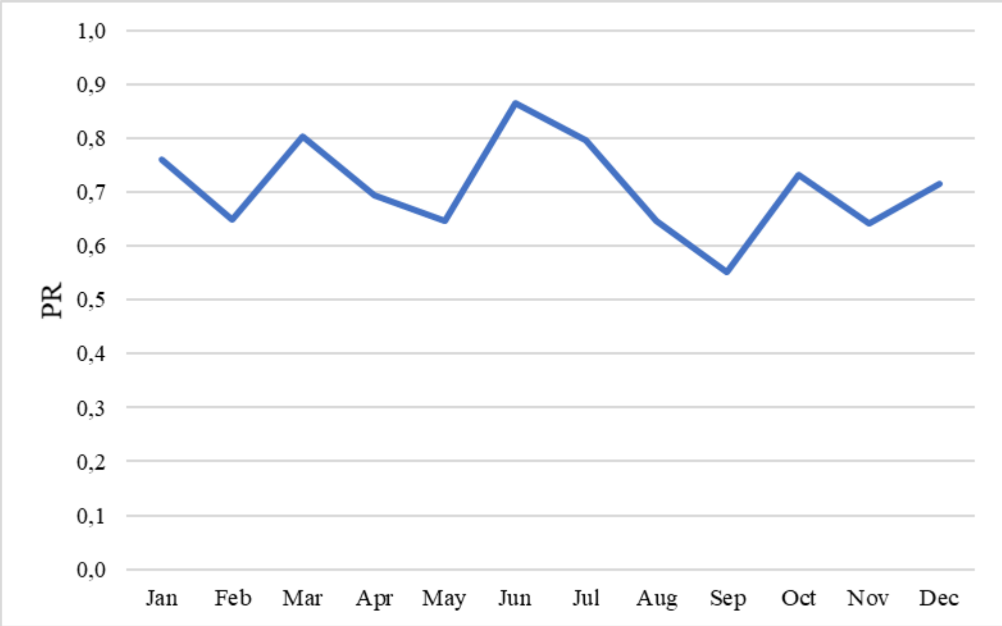


Figure 58. Monthly performance ratio for the second roof for PV Farm 3.

In Figure 58, it can be seen the PR throughout the year of 2021. March, June, and July are the months which have a PR of 80% or higher. The month of September is the worst in terms of PR due to a problem with an inverter on site, causing losses on energy production.

As stated before, there is a marble company located near the installation causing dust deposition on the modules and therefore the PVs cannot reach their highest efficiency production. The modules are cleaned four times a year, as the graph shows, meaning that when the ratio increases it is due to the cleaning by hand of the modules. This takes place in the months of January, March, June, and October. Raining in the month of October could have also helped since it is an extra way of cleaning the modules.

On the other hand, the modules of this roof were installed later than the rest, being it done in 2018. The PVs are not the same type of brand that those located on the first roof, having these more efficiency.

Since the inclination is only 5 degrees and the setup of E-W orientation means that the system of the modules is with one single structure, the cooling process is hampered. This angle is very low, and the hot air remains down, below the modules so air cannot escape. A combination of difficulties with cooling, the modules being almost horizontal and dust deposition are the main issues.

4.3.4 PV Farm 4

For this installation, the data is also provided by the company that oversees the PV farm. The period of simulation and data analysis is the whole year of 2021. From the month of January until December.

The radiation data from this site is not available because it does not include any solar radiation devices, therefore the radiation data used for the analysis on PVFChart for this site is the same one as given from the provider of PV Farm 2.

During the analysis, the radiation data provided from another installation is more accurate to use than the one provided by the software PVF-Chart because it analyses the Global Horizontal Irradiation (GHI) recorded during the period of the simulation, in this case one complete year. On the contrary, the radiation data that is used by default on the programme is a mean of the last 10 years regarding solar radiation in the location of Malta.

Due to the geographical situation of Malta and its reduced area, it can be assumed that for the entire island, there is the same GHI which fall upon all the territory.

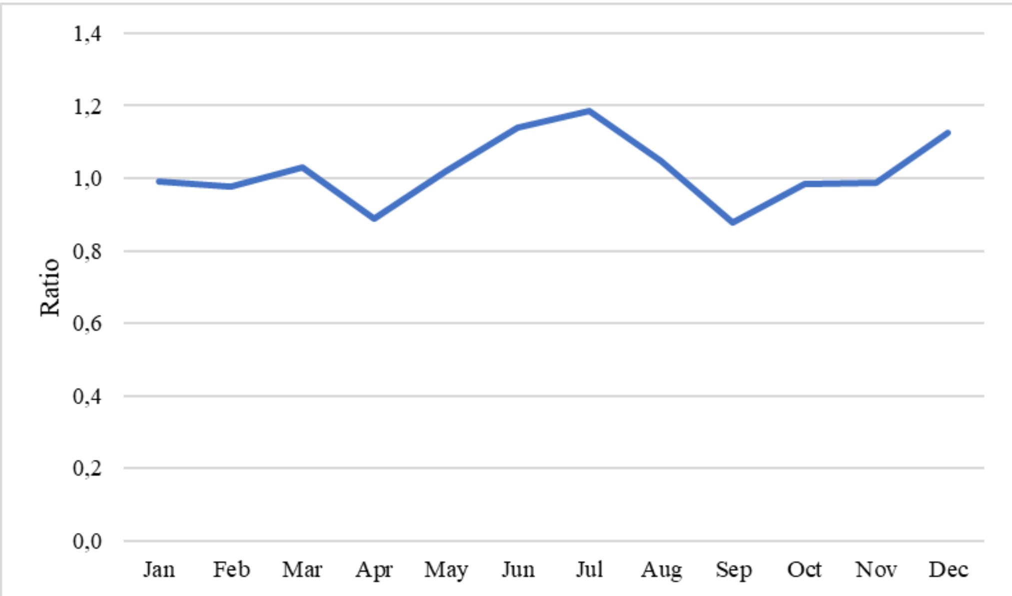


Figure 59. Comparison of monthly actual to modelled energy output ratio for the PV Farm 4.

Due to the lower-than-expected performance of this system compared to the modelled data for the months during which possible soiling is accumulated, the PV farm suffers losses amounting to 86107.37 kWh/year. Given that the FiT of this plant is 0.145 €/kWh, then it follows that the estimated losses due to cross shading amounts to 12485.56 Euro per year.

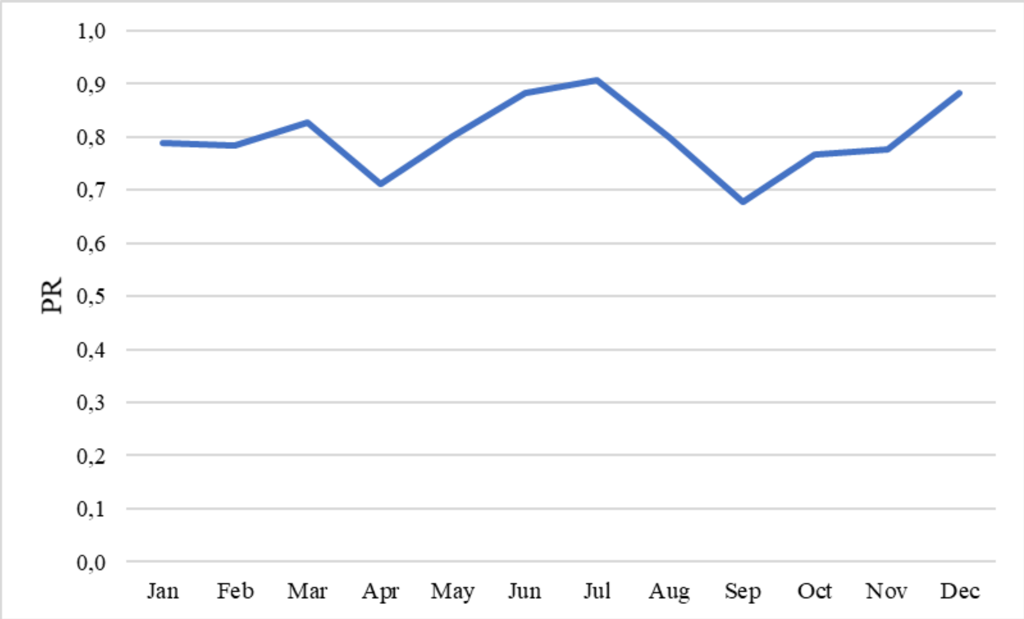


Figure 60. Monthly performance ratio for PV Farm 4.

The performance ratio of this installation is overall a good result, as seen on Figure 60. The lowest PR is in the month of September with 67.7%. In June, July, and December it reaches the highest. This installation has low shading due to the inclination of the modules and the distance in between them of 35cm in between each row. Although it does still occur and causes losses in the months of winter.

Another fact to have in mind is that every 11 modules there is a gap so that the heat is expulsed correctly. One of the advantages of this system is that it cools the building underneath because the solar rays fall directly on the PV modules instead of the roof itself and the heat hits the building less

In the month of August there was an issue originated by the festivities that took place in the municipality surrounding the building. During these festivities, fireworks took place and their ashes fell on the installation causing damage to many PV modules and its degradation.

4.4 Comparison

In the following section, a comparison in between all systems is made in terms of technical and managerial aspects.

4.4.1 Performance Ratio

The PR is different for each month but also for each PV farm. It is stated as the parameter that describes the actual and theoretical energy output, therefore outlies the proportion of energy that is available in order to export it and send it to the grid. The highest value is 100 % and means the more efficient a PV farm is.

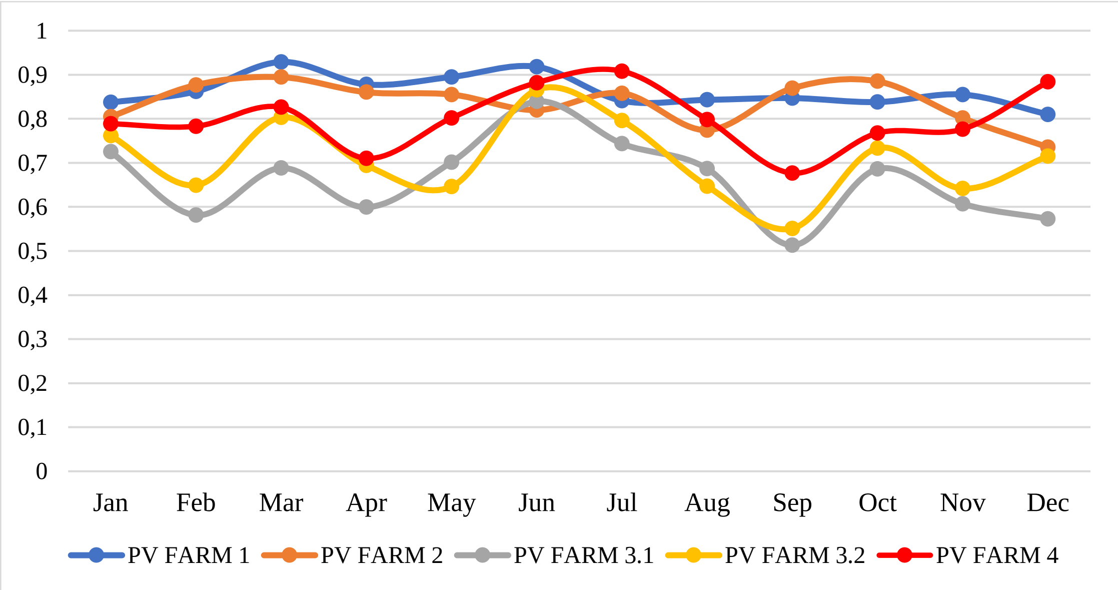


Figure 61. Performance Ratio comparison for all PV Farms.

Table 14. Average annual PR for all PV Farms.

	PV Farm 1	PV Farm 2	PV Farm 3.1	PV Farm 3.2	PV Farm 4
Average PR	0.863	0.836	0.662	0.709	0.8

As it is obvious, in Figure 61 the overall best PR is for the first installation, with an average PR of 86.3%. The worst installation in terms of performance ratio is the located on the first roof of the third PV Farm.

In summer, the best month is June as the combined ratio for all installations is the highest. Although August is a bad month due to the elevated temperatures that the modules reach, there was a problem in many caused by other factors, such as faults on inverters or PV modules.

The month of March is when most of the maintenance team cleans the modules, and the performance is higher.

During the year of 2021 in October there was consistent rainfall in Malta and heat temperatures began to lessen, increasing the PR for all systems during that period.

PV Farm 1, 2 and 4 have losses in the months of less sunlight hours due to partial shading of the modules. These months are in winter when the sun rises and sets early, meaning less hours to produce energy and a more difficult angle for sun to fall upon the cells in order to convert energy.

PV Farm 3 has two roofs and the data shown from both correlates, but it can be easily and certainly concluded that the second roof operates more favourable to the production of solar energy.

In all of the PV Farms there are conduction losses, when transmitting energy from the PV modules to the inverter, through cables, and from the inverter to the energy export meter of the grid operator. Through all of these materials, there are losses of energy.

The most productive PV system is the first one, followed by PV farm 2. Both exceed the 80% performance, followed by PV Farm 4 and on the last position, PV Farm 3.

4.4.2 Final Yield

The final yield of all of the installations was analysed according to the data provided, in particular, the total energy produced by each producer of solar energy. Each site has therefore a different peak power due to its characteristics.

The final yield is explained and mentioned thoroughly in section 2.13.3. It is therefore the ratio in between the AC energy produced and the capacity of the system from the installation.

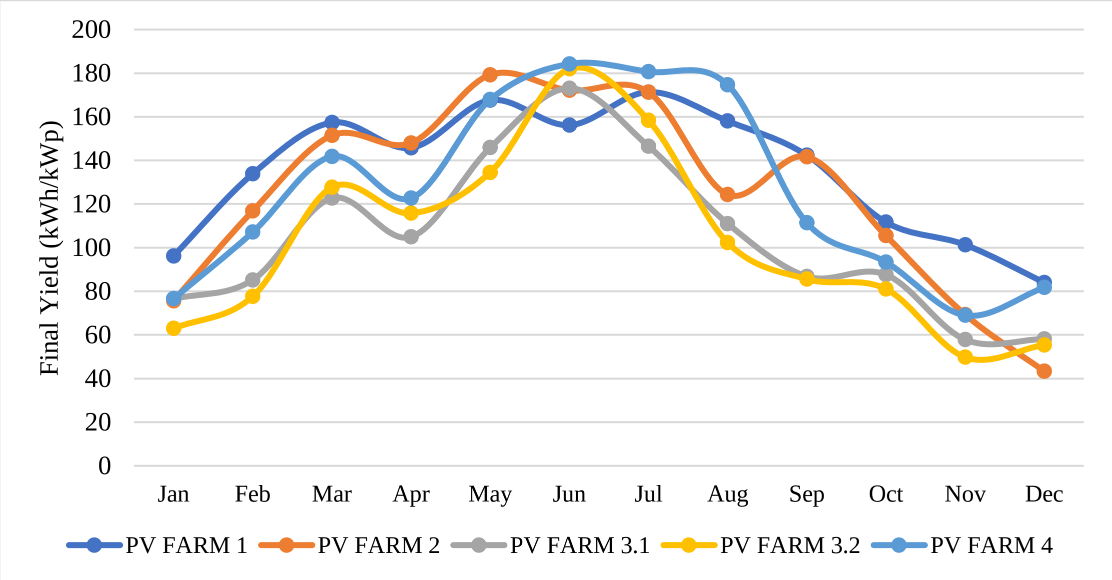


Figure 62. Monthly final yield for all PV Farms.

As one can see in Figure 62, there are discrepancies for each installation depending on the month at which we look at. The trend on the final yield increasing on the months of more solar hours is also visible. All systems show an increase in March, due to the increase in solar radiation. In contrast, in April it decreases, mostly because more rainfall happened in this period. June is in most sites the best month for the final yield, except for PV Farm 1, whose best yield takes place in July. August is the month in which many of the systems' final yield is lower since there were internal problems in each installation. October and November were the rainiest months of Malta during years, having grey skies and therefore the consequent reduction of the yield.

Table 15. Average Final Yield for all PV Farms.

	PV Farm 1	PV Farm 2	PV Farm 3.1	PV Farm 3.2	PV Farm 4
Average Final Yield kWh/kWp	135.5	124.9	104.7	102.7	125.9

As shown above, the most optimal average final yield considering all months is PV Farm 1, followed by PV Farm 4 and 2, which have a similar final yield average. The third installation presents the lowest final yield, creating a wide gap in between the rest.

4.4.3 Technical Characteristics

Within the comparison of all installations. It should be noted that certain parameters also take place in the correct operation of the PV system.

It is clear that the biggest PV Farm is also the one that has the best PR, with an inclination of 30 degrees but all of the major losses of this system are due to partial shading. The inclination and the distance in between the rows of PV modules are the key factors for the possible improvement of the PR.

The two best PV farms in terms of PR have also the same type of PV module, with a really high efficiency. A similarity in between these two is that they are ground mounted. Although PV Farm 3 roof 2 and farm 4 have the same type of module and it has a higher efficiency, the PR overall is lower in both cases than some of the other installations with lower efficiency. Something to note, is that both have an orientation completely towards the geographical South, which is beneficial.

Concerning the inclination and orientation of the PV modules, both installations from PV farm 3 have the worst PR, one of the reasons of the lower ratio is because the oldest installation is the one with the lowest PR, meaning that the modules degrade gradually. The estimation of degradation reaches 20% for 20 years.

The second roof has another orientation which is not completely South, therefore the amount of solar radiation that fall upon the PV modules is less than if the orientation was the stated before.

The second roof has anchoring to the roof with the technology Fixgrid E-W, which does not let the air escape correctly, the inclination of the modules is almost horizontal, and two modules are together, one facing West and the other one East, creating overheating in the modules and therefore loss of efficiency.

The particularity of the third installation is created by the structure and design of the roof in which it is installed. The roof is uneven, has different heights, it is flat in some parts and in other parts there is an inclination, making it more difficult to have the same characteristics in order to analyse. Most likely, there are losses based on the setup of the installation. Due to the variety of heights on site, there is shading coming from the walls that eclipse the sun from being able to reach the cells in order to produce energy.

The FiTs that each installation has reached in agreement with Enemalta is diverse. On the opposite, PV farm 3 has the highest being paid 15.5 cents/kWh.

All of the comparison results stated above can be seen in Table 15.

Table 16. Technical parameters for all PV Farms

	PV FARM 1	**PV FARM 2**	**PV FARM 3.1**	**PV FARM 3.2**	**PV FARM 4**
Type	Ground	Ground	Rooftop		Rooftop
Area (m^2)	65000	29326	11000		8216
Peak power (kWp)	5200	2400	634	300	943
Inclination (º)	30°	7°	15°	5°	10°
Orientation (º)	0º S	0º S	0ºS	N75ºW, S75ºE	S24ºE
Efficiency of PV	0.17	0.17	0.159	0.179	0.179
Year installed	2020	2020	2015	2018	2020
Average PR	0.863	0.836	0.662	0.709	0.8
Feed-in Tariff (cents/kWh)	12.3	13.5	15.5		14.5
Estimated energy lost per year (kWh)	234262.8	86829.4	41995.4	19639.4	86107.4
Estimated revenue loss per year (€)	28814.3	11721.9	6509.3	3044.1	12485.5
Estimated % of revenue loss/year	2.7	2.4	5.28	5.3	6.04

Certain parameters were also calculated such as the following:

Table 17. Analysis for extra parameters for all PV Farms.

	PV FARM 1	PV FARM 2	PV FARM 3	PV FARM 4
Capacity (kWp)	5200	2400	934	943
Area (m^2)	65000	29326	11000	8216
Wp/ m^2	80	82	85	115
PR	0.863	0.836	0.686	0.800
kWh/kWp	1626	1499	1244	1511
kWh	8,455,200	3,597,120	1,162,270	1,424,684
kWh/ m^2	130	123	106	173

It can be seen that the installed PV power per m^2 of flat PV farm area is highest for PV Farm 4, thus making best use of the limited land or roof area available in the small island of Malta, and this should also be considered by enterprises when designing such PV farms.

5. Conclusions

This dissertation has analysed the performance and energy management procedures for various large photovoltaic farms in Malta. In particular, four different installations were visited in person where one could see all of the systems in depth for the subsequent study. The photovoltaic farms had different characteristics such as ground-based and rooftop, with different layouts, orientations, and inclinations.

The key parameters and characteristics of each installation were determined. This included the performance ratio and the final yield. Moreover, a SWOT analysis was carried out to evaluate the characteristics of the energy management procedures in place.

As far as energy production is concerned, PV Farm 1 had the highest final yield out of all the considered systems, with the best figures generally achieved during summer. The best performance ratio was also experienced by PV Farm 1. The main reason for this performance is that the PV modules are inclined at the optimum angle of 30° and facing true geographic south. Nevertheless, the PV farm does suffer from partial cross-shading during the winter months, due to insufficient spacing between the PV rows. When comparing the real output to the ideal output as calculated by the software PVFChart, it was concluded that this PV Farm losses amounted to 28814.3€ per year, which is equivalent to 2.7% of the total revenue.

It should be noted that over time there may be a degradation of the PV module performance and consequently of their efficiency. The modules of the first two installations are of the same type and brand, have the same power and were installed during the same year. Normally the solar modules are oversized by up to 5% more efficiency, so during the first years better results are achieved. This explains why the results of more recently installed systems have generally achieved higher output than modelled performance as calculated by the PVFChart.

The distinction between a ground mounted and a rooftop installation also suggests dissimilar results. An important role is played by the orography of the terrain and its unevenness. In this study, those placed directly on the ground perform better than those on the roof of industrial buildings, possibly due to better natural ventilation around the modules.

Another problem that had an impact on performance was cross shading. This problem usually takes place in the months of winter due to the position of the sun as Figure 53 shows. Certainly, the distance in between rows along with the inclination and orientation of PVs make it more or less likely for this effect to happen. In the analysis of the losses caused by cross shading in PV plants 1 and 2, a large part is due to the non-uniform terrain of the site. The complication of the roof structure and shape also has an influence on the efficiency. The more complex the layout of the modules, the more losses occur.

As previously mentioned, the inclination of the modules is decisive for the generation of the highest amount of energy. Each installation uses a different inclination, but the type of anchoring that can be used and the desired inclination must also be taken into account. For example, for rooftop installations, PV Farms 3 and 4, the inclination has to be low because otherwise the wind impact on the roof is too large for the type of anchoring used. On the other hand, the reason why PV farm 2 (ground-based) had lower inclination (7°) is based on the need to limit the spacing between the rows of modules and the location near the sea, which already helps in natural cooling even at such a low inclination.

The orientation of the modules is important as it directly affects the performance ratio of each installation. In all photovoltaic plants, solar modules that have a zero-degree orientation, also known as a true geographic South orientation, present in both final yield and PR better results than those with different angles in the placement of the PVs. For instance, modules with orientation looking towards E-W had less solar radiation exposure.

In summary, the PR is altered by many factors, in this case, those mentioned above, as well as operational problems of the installed system, loss of energy potentially caused by the failure of some inverters of the system.

The performance ratios for PV Farm 1 and 2 are mainly lower in winter than expected due to cross-shading, The only way to correct this issue at this stage is by lowering the PV inclination slightly to avoid this cross-shading in winter, especially for PV Farm 1. In PV Farm 2, the cross-shading is primarily caused by the stepped down terrain of part of the PV farm and there is essentially no practical solution to it and the losses amounted to €11721.9, which is equivalent to 2.4% of the total revenue.

On the other hand, for PV plant 3, problems come from the modules which are already 7 years old, along with insufficient maintenance for cleaning and visual inspections where faults can be identified, and its limitations based on the complexity of the roof. Most significantly, the impossibility of correctly cooling down solar modules presents a notable issue, as high temperatures are reached and the anchoring structure to the roof does not permit hot air escaping the lower part of the modules. This, and the complexity of the inclinations and orientations of the site are the main reasons why lower results are achieved here than for the rest of the PV plants. Its losses amounted to 9553.3€, which is 5.3% of the total revenue.

PV farm 4 has had its difficulties because of the faults due to external factors that degraded the modules from August onwards, the installation has limitations on the inclination that it can set due to the weight that lays on the roof. Its losses amount to 12485.5€, which is 6% of the total revenue.

In conclusion, in all installations more visual inspections and revisions should be made and some of the faults related with inverters, PV modules, etc could have been identified earlier and a higher production of energy could have been achieved along with the improvement of the PR. Maintenance procedures that are not highly costly can be done more frequently together with a smoother and faster relationship with the inverter's manufacturer and could mitigate losses due to inverter failure. For example, it was noted that the cable ties in PV Farm 2 will need to be completely changed as they are degraded by ultraviolet radiation and they are cutting lose, leaving the wires of the PV modules dangling in the air.

Regarding the SWOT analysis that had previously been made, their objective is to be able to compare the different management and maintenance procedures that each installation or operator follows.

All plants at the time of installation were equipped with the best types of solar modules according to the Bloomberg list. All 4 PV Farms have outsourced management so that an external company takes care of the work. In all of them the type of maintenance used is fault maintenance, which is defined by acting once the problem has occurred. Shading on modules is a common issue encountered in all of them. Cleaning the modules is essential to obtain a good performance ratio and should be carried out at least 4 times a year for each PV plant. Grass cutting should also be kept under control.

To summarize, certain recommendations must be made for each installation. As for the PV Farm 1, lowering the inclination of 30 degrees to around 20° would solve the cross-shading in winter, as well as cutting the grass more often in winter could improve its performance.

Increasing the distance in between rows of modules for PV Farm 2 can increase the final yield and total revenue since the most common issue is cross-shading. However, the investment to carry out such an adjustment would be prohibitive. Also, in this farm it is important to devise methods to reduce soil loss during torrential rains. This can be done by planting low lying creepers in the area to hold the soil in place or by placing a layer of pebbles on top of the soil.

For PV Farm 3, it is recommended that the anchoring system is updated or modified so that the cooling of the modules is facilitated. While doing this, the orientation of the modules could also be adjusted to face the true geographic South.

Lastly, for PV Farm 4, shadows from the perimeter wall could be easily reduced by decreasing the height of the wall of the building that blocks the sunlight to the modules. Given the dangling cables, in all inspections, they should be put back into the available metal trays that follows a specific route. All risk insurance should be taken into consideration, since external factors, such as fireworks could damage the solar cells, as was the case in one of the PV farms.

Suggestions for future work

A more detailed performance of the PV farms could be carried out taking into consideration their seasonal as well as hourly performance. The interaction of the PV farms with the grid is also another area of study that can yield valuable data for optimising the interface between the PV farm and the grid. Another study that can be considered is the possible future integration of battery storage in the PV farm to support the grid in terms of balance in energy feeding and to support the local area network. One more study can focus on the performance of the PV modules and their annual degradation due to exposure to ultraviolet solar radiation. From a management point of view, a useful exercise can be carried out to determine when best to change the PV modules as they age with more modern ones to maximize profits.

6. References

[1] European Parliament, “Directive 2018/2001 of the European Parliament and of the Council of of 11 December 2018,” Off. J. Eur. Union, vol. 328, no. 82, 2018.

[2] Eurostat, “Renewable energy on the rise: 37% of EU’s electricity,” Eurostat, 26-Jan-2022. [Online]. Available: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20220126-1. [Accessed: 13-Apr-2022].

[3] J.-Y. Wang, Z. Qian, H. Zareipour, and D. Wood, “Performance assessment of photovoltaic modules based on daily energy generation estimation,” Energy (Oxf.), vol. 165, pp. 1160–1172, 2018.

[4] “Paneles Solares.”, Área Tecnología, [Online]. Available: https://www.areatecnologia.com/electricidad/paneles-solares.html/. [Accessed 20-Oct-2021].

[5] J. Svarc, “Solar panel construction”, Clean Energy Reviews, Cleanenergyreviews.info, 20-Mar-2020. [Online]. Available: https://www.cleanenergyreviews.info/blog/solar-panel-components-construction. [Accessed: 28-Oct-2021].

[6] “Solar integration: Inverters and grid services basics,” Energy.gov. [Online]. Available: https://www.energy.gov/eere/solar/solar-integration-inverters-and-grid-services-basics. [Accessed: 14-Jan-2022].

[7] CHINT, “What is solar inverter and how does it work?,” CHINT Blog, 10-Mar-2021. [Online]. Available: https://chintglobal.com/blog/what-is-solar-inverter-how-does-solar-inverter-work/. [Accessed: 14-Jan-2022].

[8] Dave, “How does Solar Inverter works and its applications,” WatElectrical.com, 23-Jul-2019. [Online]. Available: https://www.watelectrical.com/how-solar-inverter-works-applications/. [Accessed: 17-Jan-2022].

[9] K. N. Nwaigwe, P. Mutabilwa, and E. Dintwa, “An overview of solar power (PV systems) integration into electricity grids,” Mater. Sci. Energy Technol., vol. 2, no. 3, pp. 629–633, 2019.

[10] M. Bajaj and A. K. Singh, “Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques,” Int. J. Energy Res., vol. 44, no. 1, pp. 26–69, 2020.

[11] Researchgate.net. [Online]. Available: https://www.researchgate.net/figure/A-Topological-configuration-of-PV-power-station-B-The-complete-schematic-of-grid_fig5_335724191. [Accessed: 20-Dec-2021].

[12] Saurenergy, “Solar panel Mounting Structures: Racking Matters,” Saur Energy International, 07-Jul-2017. [Online]. Available: https://www.saurenergy.com/solar-energy-articles/solar-mounting-structures-racking-matters. [Accessed: 18-Jan-2022].

[13] C. Yousif, M. Grech, and L. Mule-Stagno. “Increasing PV Panels Output with Flat Reflectors. Proceedings of the 28th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2013), Paris, France.” 30 Sep - 4 Oct 2013.

[14] K. Pickerel, “What’s up with solar ballast?,” Solar Power World, 07-Apr-2016. [Online]. Available: https://www.solarpowerworldonline.com/2016/04/whats-solar-ballast/. [Accessed: 18-Jan-2022].

[15] “Tree System for ground mounting solar systems,” Treesystem.it. [Online]. Available: http://www.treesystem.it/treesystem-for-ground-mounted-pv-plants. [Accessed: 19-Jan-2022].

[16] Wikipedia contributors, “Climate of Malta,” Wikipedia, The Free Encyclopedia, 16-Sep-2021. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Climate_of_Malta&oldid=1044699489. [Accessed: 05-Nov-2021].

[17] H. Ritchie and M. Roser, “Energy,” Our World in Data, 2020. [Online]. Available: https://ourworldindata.org/energy/country/malta. [Accessed 6-Nov-2021].

[18] “Malta,” IEA. [Online]. Available: https://www.iea.org/countries/malta. [Accessed: 20-Dec-2021].

[19] Government of Malta, Malta's 2030 National Energy and Climate Plan. 2019. [Online]. Available: https://www.climate-laws.org/geographies/malta/policies/malta-s-2030-national-energy-and-climate-plan. [Accessed 15-Nov-2021]

[20] Timesofmalta.com. [Online]. Available: https://timesofmalta.com/articles/view/Solaqua-floating-solar-panels-project-nears-completion.618395. [Accessed: 02-Mar-2022].

[21] M. Tawalbeh, A. Al-Othman, F. Kafiah, E. Abdelsalam, F. Almomani, and M. Alkasrawi, "Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook," Sci. Total Environ., vol. 759, no. 143528, p. 143528, 2021.

[22] Narasimhan, "Area required for solar PV power plants - suncyclopedia," Suncyclopedia.com. [Online]. Available: http://www.suncyclopedia.com/en/area-required-for-solar-pv-power-plants/. [Accessed: 11-Jan-2022].

[23] "Feed-in tariffs," Energy Water Agency, 07-Oct-2019. [Online]. Available: https://www.energywateragency.gov.mt/feedintariffs/. [Accessed: 18-Jan-2022].

[24] A. Peinado Gonzalo, A. Pliego Marugán, and F. P. García Márquez, "Survey of maintenance management for photovoltaic power systems," Renew. Sustain. Energy Rev., vol. 134, no. 110347, p. 110347, 2020.

[25] M. Tawalbeh, A. Al-Othman, F. Kafiah, E. Abdelsalam, F. Almomani, and M. Alkasrawi, "Environmental impacts of solar photovoltaic systems: A critical review of recent progress and future outlook," Sci. Total Environ., vol. 759, no. 143528, p. 143528, 2021.

[26] Niclas, "Micro Cracks: causes and impacts on solar panels," Sinovoltaics.com, 12-Feb-2014. [Online]. Available: https://sinovoltaics.com/learning-center/quality/micro-cracks-causes-and-impacts-on-solar-panels/. [Accessed: 07-Jan-2022].

[27] R. Moretón, E. Lorenzo, and L. Narvarte, “Experimental observations on hot-spots and derived acceptance/rejection criteria,” Sol. Energy, vol. 118, pp. 28–40, 2015.

[28] M. Simon and E. L. Meyer, “Detection and analysis of hot-spot formation in solar cells,” Sol. Energy Mater. Sol. Cells, vol. 94, no. 2, pp. 106–113, 2010.

[29] Sandia National Laboratories: Energy and C. Renewables, “2014 PV Reliability, Operations & Maintenance Workshop: SunPower Oasi…,” Slideshare.net. [Online]. Available: https://pt.slideshare.net/sandiaecis/13-sun-powerautomatedcleaning/2. [Accessed: 07-Jan-2022].

[30] A. Triki-Lahiani, A. Bennani-Ben Abdelghani, and I. Slama-Belkhodja, “Fault detection and monitoring systems for photovoltaic installations: A review,” Renew. Sustain. Energy Rev., vol. 82, pp. 2680–2692, 2018.

[31] T. Watson, G. Reynolds, D. Wragg, G. Williams, and D. Worsley, “Corrosion monitoring of flexible metallic substrates for dye-sensitized solar cells,” Int. j. photoenergy, vol. 2013, pp. 1–8, 2013.

[32] “What is LabVIEW?,” Www.ni.com, 19-May-2017. [Online]. Available: https://www.ni.com/en-us/shop/labview.html. [Accessed: 11-Jan-2022].

[33] M. Dhimish, V. Holmes, B. Mehrdadi, and M. Dales, “Diagnostic method for photovoltaic systems based on six layer detection algorithm,” Electric Power Syst. Res., vol. 151, pp. 26–39, 2017.

[34] M. Dhimish, V. Holmes, and M. Dales, “Parallel fault detection algorithm for grid-connected photovoltaic plants,” Renew. Energy, vol. 113, pp. 94–111, 2017.

[35] Gomez Rebe, M., Mule Stagno, L., & Yousif, C, Optimising photovoltaic power generation and useable area by varying the solar module tilt. 28th European Photovoltaic Solar Energy Conference and Exhibition, Villepinte], 2013.

[36] M. Hummon, P. Denholm, and R. Margolis, “Impact of photovoltaic orientation on its relative economic value in wholesale energy markets: Impact of PV orientation,” Prog. Photovolt., vol. 21, no. 7, pp. 1531–1540, 2013.

[37] D. Chwieduk and B. Bogdanska, “Some recommendations for inclinations and orientations of building elements under solar radiation in Polish conditions,” Renew. Energy, vol. 29, no. 9, pp. 1569–1581, 2004.

[38] C. B. Christensen and G. M. Barker, “Effects of tilt and azimuth on annual incident solar radiation for United States locations,” in Solar Engineering 2001: (FORUM 2001: Solar Energy — The Power to Choose), 2001.

[39] Alternative Energy Tutorials, “Solar Panel Orientation,” Alternative Energy Tutorials. [Online]. Available: https://www.alternative-energy-tutorials.com/solar-power/solar-panel-orientation.html. [Accessed: 07-Jan-2022].

[40] R. Garner, “Solar Irradiance,”, NASA, 2015. [Online]. Available: https://www.nasa.gov/mission_pages/sdo/science/solar-irradiance.html. [Accessed 18-Nov-2021].

[41] “Solar resource maps of Malta,” Solargis.com. [Online]. Available: https://solargis.com/maps-and-gis-data/download/malta. [Accessed: 21-Dec-2021].

[42] National Renewable Energy Laboratory, Solar Energy and Capacity Value. 2013.

[43] “Operation & Maintenance: Best Practice Guidelines / Version 3.0,” Solar Power Europe, 2018.

[44] “SUPORTS by gonvarri - structural solutions for photovoltaic projects,” Suports.es. [Online]. Available: https://www.suports.es/en/. [Accessed: 07-Jan-2022].

[45] National Renewable Energy Laboratory, Sandia National Laboratory, SunSpec Alliance, SunShot National Laboratory, “Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems,” 2018.

[46] R. R. Hernandez et al., “Environmental impacts of utility-scale solar energy,” Renew. Sustain. Energy Rev., vol. 29, pp. 766–779, 2014.

[47] R. Karki, “Reliability of renewable power systems,” in Encyclopedia of Sustainable Technologies, Elsevier, 2017, pp. 217–230.

[48] B. Marion et al., “Performance parameters for grid-connected PV systems,” in Conference Record of the Thirty-first IEEE Photovoltaic Specialists Conference, 2005, 2005.

[49] SMA Solar Technology AG, “Performance ratio. Quality factor for the PV plant,” 2018. [Online]. Available: https://files.sma.de/downloads/Perfratio-TI-en-11.pdf. [Accessed: 31-Mar-2022].

[50] B. Shiva Kumar and K. Sudhakar, “Performance evaluation of 10 MW grid connected solar photovoltaic power plant in India,” Energy rep., vol. 1, pp. 184–192, 2015.

[51] K. Attari, A. Elyaakoubi, and A. Asselman, “Performance analysis and investigation of a grid-connected photovoltaic installation in Morocco,” Energy rep., vol. 2, pp. 261–266, 2016.

[52] M. S. Adaramola and E. E. T. Vågnes, “Preliminary assessment of a small-scale rooftop PV-grid tied in Norwegian climatic conditions,” Energy Convers. Manag., vol. 90, pp. 458–465, 2015.

[53] D. D. Milosav ljević, T. M. Pavlović, and D. S. Piršl, “Performance analysis of A grid-connected solar PV plant in Niš, republic of Serbia,” Renew. Sustain. Energy Rev., vol. 44, pp. 423–435, 2015.

[54] S. Chabachi, A. Necaibia, O. Abdelkhalek, and A. Bouraiou, “Assessment performance parameters correlation of a grid-connected PV system,” Algerian

Journal of Renewable Energy and Sustainable Development, vol. 2, no. 02, pp. 157–164, 2020.

[55] De Miguel, Argimiro & Bilbao, Julia & Cazorro, JRS & Martín, C. (2002). Performance analysis of a grid-connected PV system in a rural site in the Northwest of Spain.

[56] H. Vidal, M. Rivera, P. Wheeler, and N. Vicencio, “The analysis performance of a grid-connected 8.2 kWp photovoltaic system in the Patagonia region,” Sustainability, vol. 12, no. 21, p. 9227, 2020.

[57] Wikipedia contributors, “Malta,” Wikipedia, The Free Encyclopedia, 08-Jan-2022. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Malta&oldid=1064441843.

[58] Researchgate.net [Online]. Available: https://researchgate.net/publication/301779388_Geology_and_early_human_history_of

_the_islands_of_Malta_Mediterranean_Sea. [Accessed: 08-Jan-2022].

[59] “Average monthly hours of sunshine in Malta,” World Weather & Climate Information. [Online]. Available: https://weather-and-climate.com/average-monthly-hours-Sunshine,Malta,Malta. [Accessed: 08-Jan-2022].

[60] Fluke, “How infrared cameras work,” Fluke.com, 31-Oct-2016. [Online]. Available: https://www.fluke.com/en/learn/blog/thermal-imaging/how-infrared-cameras-work. [Accessed: 09-Jan-2022].

[61] “FLIR E40 thermal infrared camera,” Abatement.com. [Online]. Available: https://products.abatement.com/ca/irc-fre40.html. [Accessed: 09-Jan-2022].

[62] “SWOT Analysis,” Mindtools.com. [Online]. Available: https://www.mindtools.com/pages/article/newTMC_05.htm. [Accessed: 28-Jan-2022].

[63] Thunderbird, “SWOT Analysis - definition, framework, and examples,” Un-Teeth, 22-Jun-2021. [Online]. Available: https://unteething.com/swot-analysis-what-is-it-and-how-to-do-it/. [Accessed: 28-Jan-2022].

[64] e-Media Resources, “PV F-CHART: Photovoltaic systems analysis,” Fchartsoftware.com. [Online]. Available: https://fchartsoftware.com/pvfchart/index.php. [Accessed: 09-Jan-2022].

[65] P. G. Reference Loutzenhiser, “Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation,” Solar Energy, vol. 81, pp. 254–267, 2007.

[66] S. A. Klein and W. A. Beckman, “PV F-Chart User’s Manual,” 2001. [Online] Available: https://fchartsoftware.com/pvfchart/. [Accessed: 31-Jan-2022]

[67] “Schletter solar GmbH - Solar Mounting Systems,” Schletter Solar GmbH, 30-Nov-2020. [Online]. Available: https://schletter-group.com/?lang=en. [Accessed: 14-Mar-2022].

[68] “Photovoltaic panels in Malta (part II),” Interreg Europe. [Online]. Available: https://projects2014-2020.interregeurope.eu/resindustry/news/news-article/9802/photovoltaic-panels-in-malta-part-ii/. [Accessed: 08-Apr-2022].

[69] “Canadian solar CS6U-330P 330W MAXPOWER solar panel,” Solarelectricsupply.com. [Online]. Available: https://www.solarelectricsupply.com/canadian-solar-cs6u-330p-330w-wholesale-maxpower-solar-panel. [Accessed: 09-Jan-2022].

[70] “Abb pvs-175-Tl,” Europe-solarstore.com. [Online]. Available: https://www.europe-solarstore.com/abb-pvs-175-tl-sx2.html. [Accessed: 21-Apr-2022].

[71] “SMA Sunny Highpower Peak3,” Europe-solarstore.com. [Online]. Available: https://www.europe-solarstore.com/sma-sunny-highpower-peak3-shp-150-20.html. [Accessed: 21-Apr-2022].

[72] "Canadian solar CS6P-255P solar panel," Solarelectricsupply.com. [Online]. Available: https://www.solarelectricsupply.com/canadian-solar-cs6p-255p-solar-panels. [Accessed: 22-Feb-2022].

[73] "Inverter," Secondsol der Photovoltaik Marktplatz. [Online]. Available: https://www.secondsol.com/en/anzeige/8449//huawei/sun2000-23ktl-23000. [Accessed: 21-Apr-2022].

[74] "Huawei sun2000-36 ktl-m3," Europe-solarstore.com. [Online]. Available: https://www.europe-solarstore.com/huawei-sun2000-36-ktl-m3.html. [Accessed: 21-Apr-2022].

[75] "Q cells," Q-cells.us. [Online]. Available: https://www.q-cells.us/en/main/products/solar_panels/residential/residential03.html. [Accessed: 21-Apr-2022].

[76] "Huawei sun2000-60ktl-m0," Europe-solarstore.com. [Online]. Available: https://www.europe-solarstore.com/huawei-sun2000-60ktl-m0.html. [Accessed: 21-Apr-2022].

7. Appendices

Appendix A

Table 1. Electrical data under STC conditions for PV module type CS6U-330P, Canadian Solar [69].

Nominal Max. Power (Pmax)	330 W
Opt. Operating Voltage (Vmp)	37.2 V
Opt. Operating Current (Imp)	8.88 A
Open Circuit Voltage (Voc)	45.6 V
Open Circuit Current (Isc)	9.45 A
Module Efficiency	16.97%
Operating Temperature	-40°C ~ 85°C
Max. System Voltage	1000 V
Module Fire Performance	CLASS C (IEC 61730)
Max. Series Fuse Rating	15 A

Table 2. Electrical data under NOCT conditions for PV module type CS6U-330P, Canadian Solar [69].

Nominal Max Power (Pmax)	239 W
Opt. Operating Voltage (Vmp)	33.9 V
Opt. Operating Current (Imp)	7.05 A
Open Circuit Voltage (Voc)	41.9 V
Short Circuit Current (Isc)	7.66 A

Table 3. Mechanical characteristics for PV module type CS6U-330P, Canadian Solar [69].

Specification	Data
Cell Type	Poly-crystalline, 15.24 cm
Cell Arrangement	72 cells (6x12)
Dimensions	1960x992x40 mm
Weight	22.4 kg
Front Cover	3.2 mm tempered glass
Frame Material	Anodized aluminium alloy
J-Box	IP67, 3 diodes
Cable	4 mm^2 (IEC)
Connector	T4 series or PV2 series

Table 4. Temperature characteristics for PV module type CS6U-330P, Canadian Solar [69].

Specification	Data
Temperature Coefficient (Pmax)	-0.41 % / ºC
Nominal Operating Cell Temperature	45±2 ºC

Table 5. Technical data for the input and output of inverter PVS-175-TL [70].

Max. PV array power	188 kWp
Max. input voltage	1500 V
MPP voltage range/rated input voltage	600 V to 1500 V/ 1100 V
Max. Input current/max. short-circuit current	264 A / 360 A
Number of independent MPP trackers	12
Number of inputs	2
Rated power output at nominal voltage	175 kW
Max. apparent power output	185 kVA
Nominal AC voltage / AC voltage range	800 V / 552 V to 960 V
AC grid frequency range	45 Hz to 55 Hz / 55 Hz to 65 Hz
Rated grid frequency	50 Hz / 60 Hz
Max. output current	134 A

Table 6. Technical data of the input (DC) and output (AC) characteristics of inverter Sunny Highpower 150-20 [71].

Max. PV array power	225000 Wp
Max. input voltage	1500 V
MPP voltage range/rated input voltage	880 V to 1450 V/ 880 V
Max. Input current/max. short-circuit current	180 A / 325 A
Number of independent MPP trackers	1
Number of inputs	1 or 2 for external PV junction boxes
Rated power at nominal voltage	150000 W
Max. apparent power	150000 VA
Nominal AC voltage / AC voltage range	600 V / 480 V to 690 V
AC grid frequency / range	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 66 Hz
Rated grid frequency	50 Hz
Max. output current	151 A

Table 7. Electrical data under STC conditions for PV module type CS6P-255P, Canadian Solar [72].

Nominal Max. Power (Pmax)	255 W
Opt. Operating Voltage (Vmp)	30.2 V
Opt. Operating Current (Imp)	8.43 A
Open Circuit Voltage (Voc)	37.4 V
Open Circuit Current (Isc)	9.00 A
Module Efficiency	15.85%
Operating Temperature	-40°C ~ 85°C
Max. System Voltage	1000 V
Module Fire Performance	CLASS C (IEC 61730)
Max. Series Fuse Rating	15 A

Table 8. Electrical data under NOCT conditions for PV module type CS6P-255P, Canadian Solar [72].

Nominal Max Power (Pmax)	185 W
Opt. Operating Voltage (Vmp)	27.5 V
Opt. Operating Current (Imp)	6.71 A
Open Circuit Voltage (Voc)	34.4 V
Short Circuit Current (Isc)	7.29 A

Table 9. Mechanical characteristics for PV module type CS6P-255P, Canadian Solar [72].

Specification	**Data**
Cell Type	Poly-crystalline, 15.24 cm
Cell Arrangement	60 cells (6x10)
Dimensions	1638x982x40 mm
Weight	18.5 kg
Front Cover	3.2 mm tempered glass
Frame Material	Anodized aluminium alloy
J-Box	IP67, 3 diodes
Cable	4 mm^2 (IEC)
Connector	MC4

Table 10. Temperature characteristics for PV module type CS6P-255P, Canadian Solar [72].

Specification	Data
Temperature Coefficient (Pmax)	-0.43 % / ºC
Nominal Operating Cell Temperature	45±2 ºC

Table 11. Technical data of the input (DC) and output (AC) inverter SUN2000-23KTL [73].

Max. DC usable power	23600 W
Max. input voltage	1000 V
MPP voltage range/rated input voltage	200V to 950 V/ 620 V
Max. Input current/max. short-circuit current	18 A / 25 A
Number of independent MPP trackers	3
Number of inputs	6
Rated power at nominal voltage	23000 W
Max. apparent power	23000 VA
Nominal AC voltage	220 V / 380 V
AC voltage range	230 V to 400 V
Rated grid frequency	50 Hz / 60 Hz
Max. output current	34.9 A

Table 12. Technical data of the input (DC) and output (AC) of inverter SUN2000-36KTL [74].

Max. input voltage	1100 V
MPP voltage range/rated input voltage	200V to 1000 V/ 620 V
Max. Input current/max. short-circuit current	22 A / 30 A
Number of independent MPP trackers	4
Number of inputs	2
Rated power at nominal voltage	36000 W
Max. apparent power	40000 VA
Nominal AC voltage	220 V / 380 V
AC voltage range	230 V to 400 V
Rated grid frequency	50 Hz / 60 Hz
Max. output current	60.8 A

Table 13. Electrical data under STC conditions for PV module Q.PEAK-G4 [75].

Nominal Max. Power (Pmax)	300 W
Opt. Operating Voltage (Vmp)	32.41 V
Opt. Operating Current (Imp)	9.26 A
Open Circuit Voltage (Voc)	39.76 V
Open Circuit Current (Isc)	9.77 A
Module Efficiency	18.0%
Operating Temperature	-40°C ~ 85°C
Max. System Voltage	1000 V
Module Fire Performance	CLASS C (IEC 61730)
Max. Series Fuse Rating	20 A

Table 14. Electrical data under NOCT conditions for PV module type Q.PEAK-G4, Hanwha [75].

Nominal Max Power (Pmax)	222 W
Opt. Operating Voltage (Vmp)	30.52 V
Opt. Operating Current (Imp)	7.27 A
Open Circuit Voltage (Voc)	37.19 V
Short Circuit Current (Isc)	7.29 A

Table 15. Mechanical characteristics for PV module type Q.PEAK-G4, Hanwha [75].

Specification	**Data**
Cell Type	Monocrystalline
Cell Arrangement	60 cells (6x10)
Dimensions	1670x1000x32 mm
Weight	18.8 kg
Front Cover	3.2 mm pre-stressed glass
Frame Material	Anodized aluminium alloy
J-Box	IP67, 3 diodes
Cable	4 mm^2 (IEC)
Connector	MC4

Table 16. Temperature characteristics for PV module type Q.PEAK-G4, Hanwha [75].

Specification	**Data**
Temperature Coefficient (Pmax)	-0.39 % / ºC
Nominal Operating Cell Temperature	45±3 ºC

Table 17. Technical data of the input (DC) and output (AC) of inverter SUN2000-60KTL [76].

Max. input voltage	1100 V
MPP voltage range/rated input voltage	200V to 1000 V/ 600 V
Max. Input current/max. short-circuit current	22 A / 30 A
Number of independent MPP trackers	6
Number of inputs	2
Rated power at nominal voltage	60000 W
Max. apparent power	66000 VA
Nominal AC voltage	220 V / 380 V
AC voltage range	230 V to 400 V
Rated grid frequency	50 Hz / 60 Hz
Max. output current	100 A

Appendix B

Characteristics of the PV installation.

1. How much land is occupied by the installation?
2. Is it a roof top installation or on the ground?
3. How many kWp is the solar farm?
4. What is the DC voltage per string? 600 V dc? 800 Vdc? 1000 V dc?
5. How many PV modules and cells are there on the installation?
6. What is the inclination of the modules? (e.g 5,10,15,20,25 or 30º)?
7. What is the orientation of the PV array? Facing south? At a different angle?
8. When did the farm start operating?
9. What is the lifetime expected for the PV modules and installation?
10. What is the composition of the PV modules? Is it Silicon mono-crystalline, Silicon poly-crystalline, or thin film (CIGS, CdTe), Perovskite or other? Detailed
11. What type of inverters are there on the installation?
12. Power rating of one inverter: kW?
13. Annual energy production, data? Do you have operational data for one year to provide us for the study please? Or representative months (January, April, July, October)
14. How are the PV modules anchored to the ground?

Management

15. How is the management of the PV farm carried out?
16. What is the energy payback time for the installation, which is defined as the time required for a system to generate as much energy as it was used to manufacture it?
17. What is the price of the energy sold, in cents€/kWh? i.e., feed-in tariff or agreed price for selling the PV electricity and for how many years? Data
18. How much time did the installation take to be completely ready to operate?
19. Is there shadowing in any of the solar modules at any time of the day? In which season?
20. Are the PV modules one axis tracking PV array, two-axis PV array or PV array with fixed tilt?
21. Are there trees or obstacles around the premises that shadow any part of the PV modules?

22. How many times is the installation checked?
23. Is there a Global Irradiance graph of the installation? Could you provide solar radiation data if available?
24. Are there issues with soiling on the modules? E.g., from nearby quarry, etc. When does it happen more?
25. Have you detected any issues with the PV modules? E.g. hot spots, cracks, degradation, delamination, etc.
26. What are the impacts on the land due to the installation? How has the PV system helped or not the surrounding area (e.g. land degradation, habitat loss, etc.)?
27. What are the impacts on the environment on the installation?
28. What problems did you face during the construction of the installation?
29. How was the installation financed? Own finances, loan, public/private partnership, bonds?
30. What is the business model of the installation assuming that the land is not owned by the company? Do you rent the land or share the profits?
31. For how many years is the license of the installation valid?
32. How is the performance monitoring done for the installation? What programmes are used? Detailed
33. Do you have a plan for upgrading the system? If yes, in what way?
34. When the lifetime of the installation is reached, what is the process of decommissioning/disposal?
35. What type of insurance does the installation have?
36. Do you have the data about the mean temperature of the modules?
37. Do you have annual data about the wind speed on the installation?

Maintenance

38. What maintenance process does the company follow? Detailed if possible.
39. Is the maintenance of the installation done by the company or with a subcontractor?
40. How often are the PV modules cleaned? How do you clean them (inhouse or by hiring some people)?
41. In the maintenance of the site, are thermography sensors or electroluminescence used in order to detect soiling, micro cracks in PV cells?
42. In the maintenance of the site, are I-V and P-V curves used for the detection of failures in the PV modules?

43. In the maintenance of the site, is there visual inspection every day? How often?
44. In the maintenance of the site, what are the procedures of the company for preventing faults on PV modules?
45. What are the procedures that the company follows to mitigate faults on PV modules?
46. Is there visual pollution where the installation is located?
47. How does the security on the site/surveillance work?
48. How many times is the grass cut in order to prevent issues?
49. What are the guidelines you follow when there is an issue on one of the modules?
50. What is the solution taken when there is an electrical fault on the installation?