SCHOOL OF SCIENCE AND ENGINEERING

Maintenance Management of Solar Installations

Capstone Design

Hajar Grar

Spring 2020

Capstone Report

Student Statement:

I, Hajar Grar, pledge that I have applied ethics to the design process and in the selection of the final proposed design. And with that, I have held the safety of the public to be paramount and have addressed this in the presented design wherever may be applicable.

Hajar Grar

Approved by

Nada Belkebir

Spring2020/Capstone

Dr. H. Darhmaoui

ACKNOWLEDGEMENTS

Before anything, I would like to address my deepest gratitude to Dr. Hassane Darhmaoui for agreeing to be my capstone supervisor and for getting me the opportunity to do an internship within the company Ecotaqa Services. This great chance allowed me to realize that I would like to pursue my master's studies in the field of renewable energies, especially the solar energy field, rather than doing a master's in mechanical engineering. So I seize this acknowledgment section to thank him for his supervision and trust. It was an honor to be your student as well as being your supervisee.

I would also like to address my gratitude and great thanks to Ms. Nada Belkebir for her daily support and supervision during my internship in Ecotaqa Services. I would like to thank you for the welcome and the time you have given me during my internship with your company. This first experience is very important for me since it really helped me consolidate my knowledge and develop new ones.

Last but not least, my deepest thanks go to my parents. Since the first day of September 1996, they have always supported, encouraged and helped me. They allowed me to have every opportunity to thrive in life. In carrying out this work, may they find the expression of my most affectionate gratitude and extreme love.

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Abstract

Throughout this capstone design project, different failures that can happen within a solar installation will be identified to open up a new part in which various test methods necessary for the detection of these failures are being studied. The aim of this capstone project is to set up different maintenance plans for the solar installations including preventive and corrective maintenance measures.

The Ecotaqa Services company is a solution engineering company specialized on the energy field, it accompanies clients from the design to the implementation of energetic solutions, putting at their disposal optimal solutions to their energy needs, making sure that it is economically profitable during and after the energy transition. This company works along with another one which is Ecowatt. This latter is specialized in industrial electricity and renewable energy, and is responsible of all installations. Thanks to the expertise of its multidisciplinary team, it offers customized solutions for the client's needs, in terms of technical studies, installation and supply of solar equipment (panels, inverters, batteries, cables and accessories, etc.).

Introduction

Energy is one of the determining elements for the improvement and survival of populations: it is important for each human activity and fundamental for the fulfillment of everyday needs (water, food, health and wellbeing, and so on.), in addition to guaranteeing a minimum of economic and social development. Fossil fuels are limited and being reduced day by day. These sources of energy will soon be drained. The solution to this problem will without a doubt come from sustainable natural energies considered everlasting and unlimited: water, wind, sun, geothermal energy and plants. Yet they don't create any harmful waste, ozone draining substances, or nuclear waste, according to Rogers and Wisland (2014) in their article Solar Power on the Rise, solar energy is able to deliver a very much rising extent of electricity that is desirable worldwide, environmentally and economically speaking: “Unlike fossil fuels, solar panels generate electricity with no air or carbon pollution, solid waste, or inputs other than sunlight.” [2, Page 5]. Sun is without any doubt the most vital origin of energy on the planet, its use is growing day by day since it could provide for the needs of all humanity. The quantity of solar radiation that is reflected every day on planet Earth is measured to be 174PWwhich is approximately 10 000 times more energy than we need on a regular basis, using all the other forms of energy sources; such as oil, coal, natural gas, nuclear and hydroelectric power combined [1].

Since the discovery of the photovoltaic effect by Alexandre Edmond Becquerel in 1839, many applications have seen the light of day, applications like household electrification, safety and traffic lights, agricultural applications, solar pumping, rural electrification in remote areas, spatial applications, street lighting and telecommunications [1]. Solar energy comes directly from the collection of solar radiation. Specific sensors are used to absorb the energy from the sun’s rays and to rebroadcast it according to two main uses. The first one is when solar energy is directly transformed into electrical energy through photovoltaic solar cells. These cells are most of the time composed of Silicon electrons that wander when in contact with the sun, therefore generating electricity. The second main use of solar energy is the generation of heat from the sun's radiation, where thermal sensors absorb the sun's energy and transmit it to a fluid that transports heat to heating systems or hot water, electricity can also be generated from that heat (example: CSP systems). Solar thermal energy is used in a solar water heater, heating and solar thermal panels [1].

There is a third use that combines the first and second ones. According to the research done by the UK Department for Business, Energy and Industrial Strategy; Evidence gathering - Hybrid solar photovoltaic thermal panels (PVT), the hybrid solar collectors perform two functions: as a photovoltaic collector, it produces electricity through solar energy and as a thermal collector, it produces heat, for the production of domestic hot water and heating. This technique improves the efficiency of traditional photovoltaic solar panels up to 20% [8].

Steeple Analysis:

In order to make an effective diagnosis to develop a project, the Steeple analysis focuses on various approaches from which we find the: societal aspect, technological aspect, economical aspect, environmental aspect, political aspect, legal aspect, and finally the ethical one [16]:

SOCIETAL IMPACT

From a demographical point of view, the number of people living on Earth is growing day by day, and with this demographical extension comes an expansion in energy resources demand, leading to the increase in demand for more energy needs and use, which will help create more job opportunities.

TECHNOLOGICAL IMPACT

The use of PV Solar panels has known a huge improvement these past years, making efficiency higher than it was before. The technological improvement in generating electricity or heat from natural resources has allowed this sector to be more innovative and competitive.

ECONOMIC IMPACT

The PV Solar panels are a way to save money by generating one's own electricity leading to a decrease in energy consumption, therefore reducing the electricity bill. Also, these panels have known a noticeable decrease in their prices these past years.

ENVIRONMENTAL IMPACT

Solar energy is considered as being clean energy, which means that it is produced through means to not pollute the atmosphere. It has a noticeable low CO2 emission as opposed to traditional energies, which is lined up with the goal of all the worldwide environmental organization as well as our Morocco.

POLITICAL IMPACT

The solar energy may help Morocco get rid of his energy dependence on European markets by producing his own energy using solar panels.

LEGAL IMPACT

Law No. 13-09 from the Moroccan constitutional amendment on renewable energy, composed of 44 articles, intervenes with laws allowing citizens to develop and adapt the renewable energy sector to future technological developments by encouraging private initiatives.

ETHICAL IMPACT

The use of solar energies helps to save the environment by decreasing energy consumption, which respects the future generations by making the world they are going to live in, a better and unpolluted one.

Literature Review:

Types of PV systems:

In the "Driving Technological Innovation for a Low-Carbon Society" report, it is stated that there are different types of solar installations: grid-connected solar installations, off-grid solar systems and hybrid PV systems:

- The off-grid solar systems are also called stand-alone PV systems, they are systems non-connected to the electrical grid: photovoltaic cells produce electricity during the day, which will be used according to the user's needs. It is especially popular for places far from the public service for which the connection to the network would be too expensive. These installations then require an adequate dimensioning to meet all the electrical needs of the house. The excess produced during the day will be stored in batteries and used at night and on less sunny days [17].
- According to the Stockholm Environment Institute's article Solar Photovoltaics, grid-connected systems are solar installations that are connected to the electrical grid, they are divided into:
  - Centralized installation: large scale photovoltaic power generation centralized in photovoltaic power stations [17].
  - Decentralized installation: alternative form of power generation, distributed in units located straightforwardly at the place of the consumer, which can be in any building, private or public [17].
- Hybrid PV installations are systems that are linked to the utility grid but additionally contain a storage option [17].

Solar Systems Components:

There are diverse types of maintenance depending on the different components of the solar panels. In fact, the photovoltaic panels are most of the time composed of photovoltaic modules deposited on mounting structures, a battery, a charge controller and an inverter.

1. Photovoltaic modules:

PV modules are electrical devices that are composed of solar cells. These modules are the main factor responsible for converting sunlight into direct current. There are different types of silicon cells compositions: monocrystalline, polycrystalline and thin-film photovoltaic modules which can be either amorphous, microcrystalline, CdTe (cadmium telluride), CIS (copper indium gallium selenide) or OPC (organic photovoltaic cells) [7].

SOLAR PANEL TYPE	ADVANTAGES	DISADVANTAGES
Monocrystalline	• High efficiency. • Aesthetics.	• High costs.
Polycrystalline	• Low costs.	• Low efficiency.
Thin-Film	• Portable and flexible. • Lightweight. • Aesthetics.	• Low efficiency.

Table 1: Advantages and disadvantages of different types of solar panels

The solar cells, connected in series are called strings, therefore generating an additive voltage. These strings are, after that, connected in parallel, generating an additive current. The parallel-connected strings are called arrays [6].

All panels to be interconnected must be equal, that is, they must be from the same manufacturer or have the same characteristics. The interconnection of panels is done, first, through the association of panels in series to obtain the desired voltage level; and later, through the parallel association of several strings to obtain the desired current level.

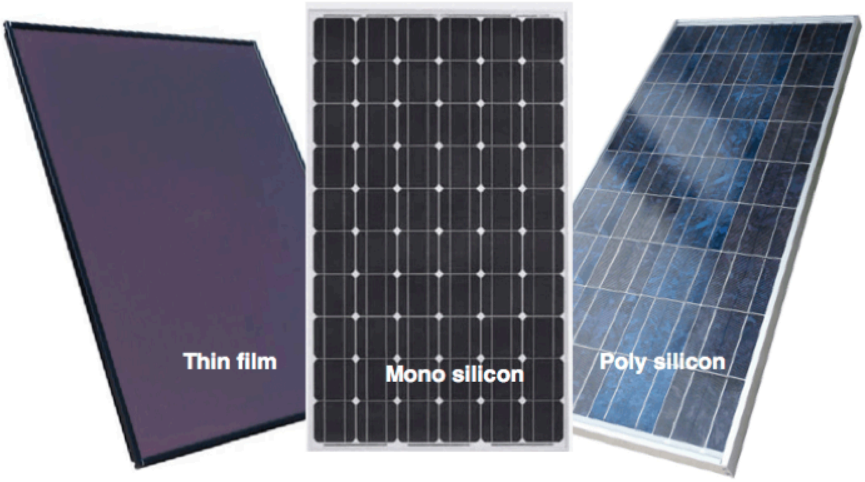

Figure 1: Photovoltaic modules

2. Array Mounting Racks:

The PV module mounting structures are generally used to fix the solar panels in a certain angle and orientation to store maximum daylight radiations. The two parameters that define the orientation of the area are the azimuth and inclination. The azimuth α measures the rotation of the surface around an axis perpendicular to the earth (horizontal plane). The inclination of an area β is the angle between the plane of the area and the horizontal.

According to the "Best Practices in Operation and maintenance of Rooftop Solar PV Systems in India" article, when mounting solar panels, certain concerns must be respected, stating them as:

- "The weight of the PV system; considering the load-bearing ability of the space where the panels are going to be fixed.
- The typical and maximum wind load for a particular location and also snow loads. Ecotaqa Services generally uses **120km/h** as wind loading.
- Seismic zone safety factors.
- Other considerations such as saline or corrosive environments." [6]

Figure 2: Array Mounting Racks

3. Inverter:

An inverter is a device whose mission is to convert direct current (DC) to alternating current (AC). It is a necessary component of solar systems as photovoltaic panels generate direct current electricity, while most appliances used in a home or in professional premises work with alternating current [17].

It exists different types of solar inverters:

1) The Grid Tie Inverters are responsible for transforming the DC power supplied by the modules into an AC power adjusted to the grid's frequency, phase and voltage of the existing power grid to be fed with that power [6].

   These kinds of inverters exploit the power delivered by the photovoltaic module by making it operate at its maximum power point. It also provides reliable monitoring of the network to protect it from breakdowns, and the interruption of the power supply in the event of problems with either the network or the installation.

2) The Stand-alone Inverters are used especially in installations not connected to the grid electrical grid. It transforms the direct current produced by the photovoltaic panels

under a voltage of 12V, 24V or 48V to an AC voltage of 220V. It is connected to the batteries from which it receives power [18].

3) Hybrid Inverters are a new generation of smart inverters dedicated to solar applications for self-consumption. They allow the choice between the renewable energy, the grid energy and the storage energy based on consumption in an optimal way [6].

Figure 3: Inverter

In the case where the solar installation does have the option to store the electrical energy, a battery backup is needed. Therefore, two other main components are necessary:

4. Battery:

The function of the battery is to store part of the energy produced by the panels (the portion of energy that is not immediately consumed) so that it is available during periods when solar radiation is low or non-existent.

The most commonly utilized batteries are the lead-acid batteries (Pb), known for their lower costs and high obtainability in the market, which replaced the more expensive and polluting ones: cadmium-nickel (Nicd). New battery generations that entered the market, especially in professional applications, are nickel-metal-hydride (Nimh) and lithium-ion (Li-ion).

Batteries are chosen depending on the power and energy requirement of the panels [6].

Figure 4: Battery

5. Charge Control System (Regulator):

The role of the solar regulator is to ensure and regulate the charge of the batteries. It optimizes the power of the panels and prevents deep discharges/overcharges, harmful to the battery life: it is responsible for the protection of the battery against extreme situations so as not to damage it. It is in charge of taking information on the charging status of the system and compare it with the maximum and minimum allowable values so that the battery does not suffer extreme overcharges or discharges [18].

There are currently 2 types of solar regulators on the market: PWM (Pulse Width Modulation) solar regulators have good efficiency and allow to optimize the battery charge [10].

The MPPT (Maximum Power Point Tracking) solar controllers make the most of the energy supplied by the panels by varying their voltage according to the solar radiance [9].

Depending on the conditions, they can be up to 35% more efficient than PWM controllers.

MPPT regulator is a power electronic tool responsible for incrementing the panel's production of energy. When exploiting it, the system works at the Maximum Power Point (MPP) and produces its maximum power output. An MPPT boosts the system's productivity, resulting in minimizing the system's cost [9].

Figure 5: Charge Controller

How do Solar PV Systems work?

Actually, sunlight enters through the surface of the photovoltaic panels, where it is converted into a direct current electrical energy (PV Modules). When the charges to be supplied are of DC, they are supplied directly. When the charges are of alternating current, the energy is sent to a current inverter where it is converted into alternating current [19].

If the installation has a storage option, this energy is collected and driven to the charge control system whose function is to send this energy totally or partially to the battery, where it is stored with care not to exceed the electrical overcharge and discharge limits. This stored energy is therefore used for refueling electrical charges at night, on days of low sunlight or when the photovoltaic system is unable to meet the demand itself [19].

Solar Water Pumps

Moroccan agriculture accounts for 13.66% of the country's final energy in the 2018 annual report of the ONE. This consumption is reduced by 8,78% from 2017 to 2018 [20].

Here intervene the renewable energies providing a solution for the energy deficit in Morocco. Solar water pump are normal water pumps but instead of using electricity or fossil fuels, sun is used to generate the electricity needed to get the water.

It is considerate a reliable and efficient solution for the irrigation that perfectly meets the needs of isolated sites, whose connection to the electricity grid may be too expensive. Indeed, solar pumping is a way that frees farmers from problems related to fuel supply, or the existence of easily accessible power lines. For both irrigation and water supply, solar pumping allows access to water even in the most remote areas, at very competitive cost compared to pumping solutions based on fossil fuels (motor pumps or generators). The water pumped may be used directly or stored in a reservoir for subsequent use, depending on one's need. It is easy to install and to use, needing minimum maintenance and having a long service life.

Solar pumping systems include, in addition to the photovoltaic panels, a subsystem consisting of an electric motor to operate the pump. Since a solar panel provides direct current, the electric motor must be DC. Conventional AC electric motors require an inverter converter to convert current from DC to AC [21].

The solar pump system is chosen depending the desired total manometric head (TMH), the desired flow rate and the required pump supply voltage [21].

Solar Water Pump Components:

Ecowatt offers to their clients two types of solar water pump: submersible pumps and surface pumps, either on-grid or off-grid, depending on the need of the customer.

- The submersible pump is as its name indicates completely submerged in water. This pump is the ideal solution for deep water, with a high water level.

- o The surface solar pump is more suitable for use at low depths and with low water level.

Their on-grid solar pumping system is composed of:

- Array Mounting Racks.
- Solar Panels.
- Hybrid Solar Inverter.
- Junction Box (DC/ AC Protection Boxes).
- Solar cable.
- Connectors.
- Power Meters.
- Circuit Breakers.

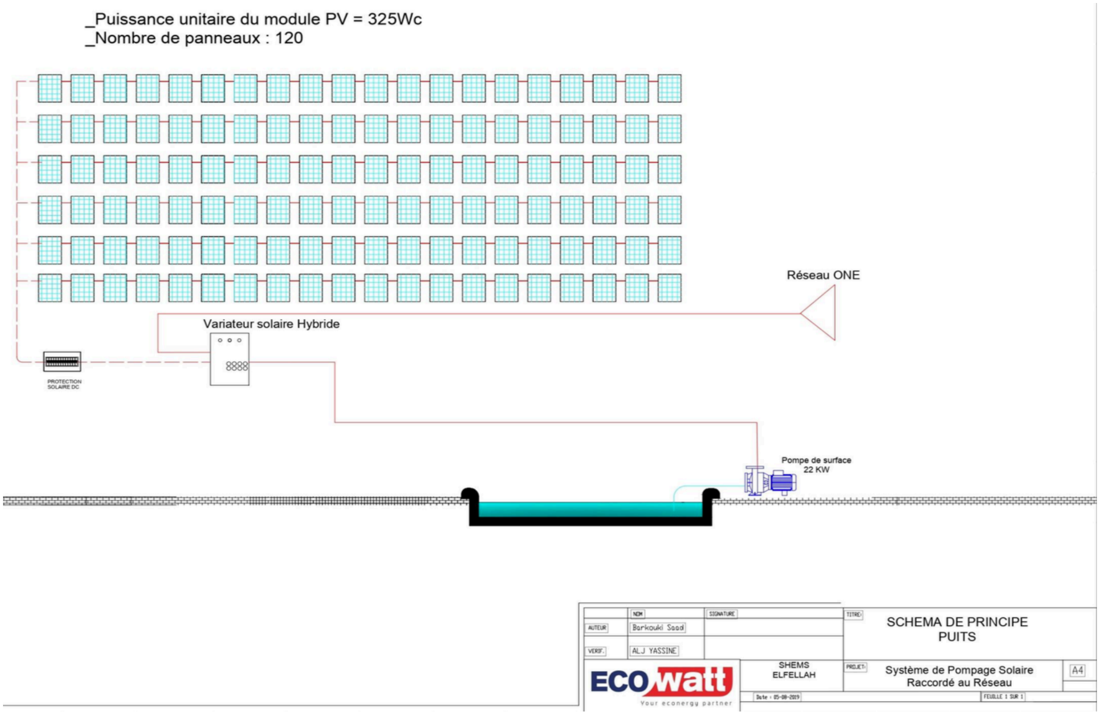

Figure 6: On-grid solar pumping system

Their off-grid solar pumping system is composed of the same elements of the on-grid system, in addition to batteries and charge controllers.

Frequent Failures of PV modules

The Review of Failures of Photovoltaic Modules defines the failures in the PV Solar panels as being any defect that:

- can cause the efficiency of the panels to be reduced, without being able to reverse it using a normal operation.
- Can be the cause of a safety problem [11].

When wanting to protect and maintain the solar systems, these components must be checked:

1. PV Panels:

Dust Accumulation:

As time goes by, dust and dirt accumulate on top of the PV modules which affects the panels negatively. It causes a noticeable reduction in the energy output of the solar cells. By diminishing the panel's performance, the dirt amassed induces a decrease in any potential savings, and a reduction in the lifetime of the solar modules [6].

Figure 7: Dust accumulation on a solar panel

Module Shadowing:

Photovoltaic solar panels produce energy depending on the quantity of the sun's irradiance, consequently, when a panel is shadowed because of leaves or branches, animal infestation, trees, poles, building, or any obstacles that can obstruct the sunlight's way to the panels, the energy efficiency decreases significantly [6].

Figure 8: Shaded solar panels

Shading, even in small surfaces, can be the cause of fluctuations in electricity production, which with time, can cause serious problems such as hotspots.

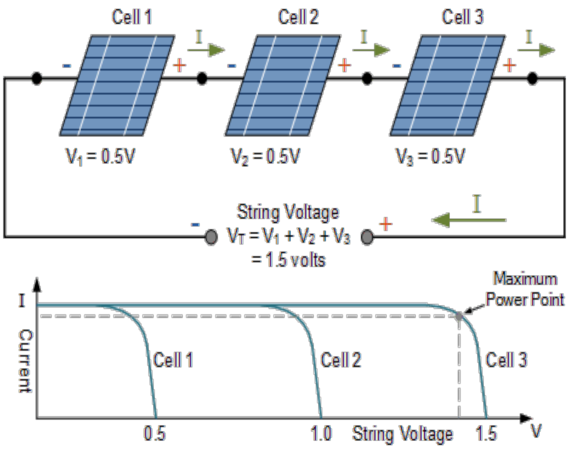

Figure 9: Solar cells connected in series

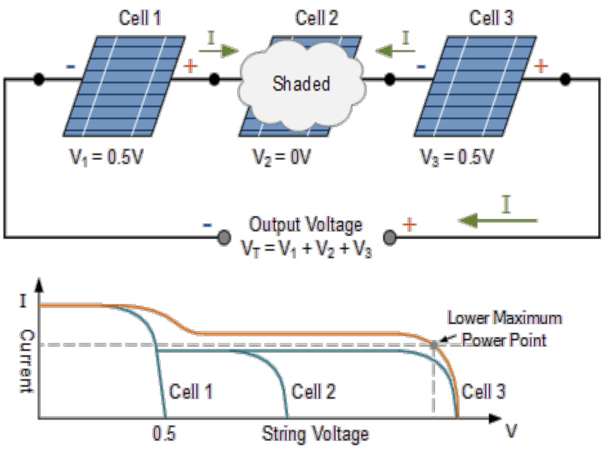

Figure 10: Shadowed solar cell

To avoid the undesirable effects of the hotspots, manufacturers have implanted a protection called by-pass diodes. It aims to improve the performance of shaded modules.

Since the cells are mounted in series in a photovoltaic module, one or more cells in the shade are overheated, which can lead to their destruction. As a result, it blocks the passage of the current to the other modules and an increase of the voltage at the terminals of this shaded cells.

The shaded cell acts in this case as a resistance therefore stopping the production of energy [18]. In order to overcome these kind of issues, bypass diode protection is applied. It consists of short-circuiting the shaded cells. In fact, the bypass diode is connected in parallel with the solar cells. In case one of the cells is being shadowed, the bypass protection insures the crossing of the current in it, preventing in power loss.

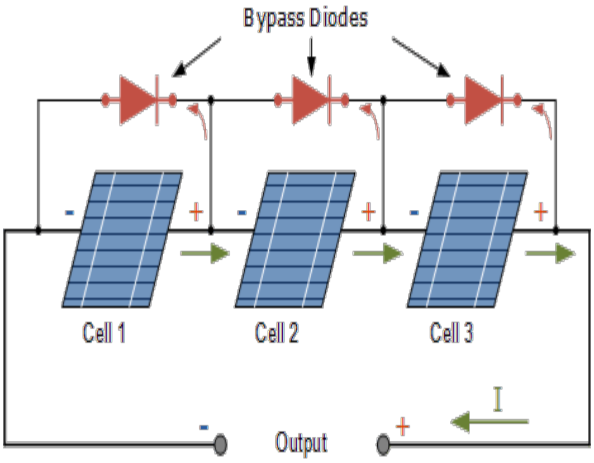

Figure 11: Bypass Diode Protection

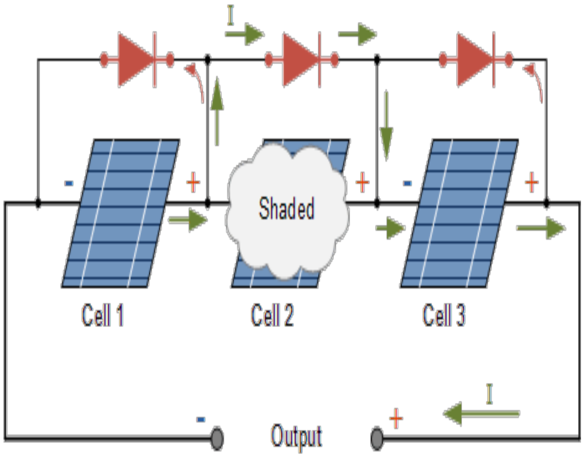

Figure 12: Shadowed solar cell with bypass diode

Module Mismatch:

According to the PVEducation website, mismatch losses can lead to lower electricity production. Because of the interconnection of panels with different properties, or experience production under different environmental conditions from one another, the energy output faces a reduction [22].

Magal and Vasita point out that these mismatches can be a direct result of:

- Manufacturing defaults.
- The difference in orientation, or dust spreading.
- The difference in ages.
- The difference in module technologies on the same pair of arrays.
- Cells from different manufacturers, thus different properties.
- Partial shadowing from one cell to another.
- The panels should be fixed, oriented and inclined correctly.

Figure 13: Different types of panels in the same installation

Physical Integrity:

Physical defaults are common. It can be in the form of corrosion, moisture condensation, discoloration, delamination or cracks.

Cells cracking can be formed because of various factors; mainly physical crashes, oscillation due to the wind or problems caused by a defect in manufacturing. Before purchasing any PV solar panels, it is mandatory to check them for any smalls and tiny cracks because they may lead to delamination or bubble formation [6].

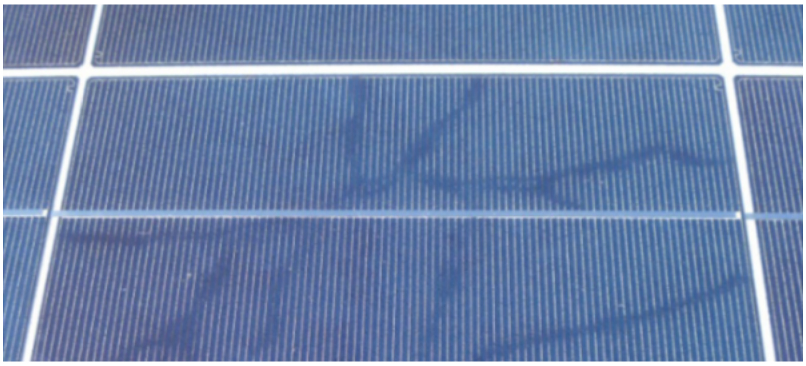

Figure 14: Delamination of a solar panel

2. Module Mounting Structures:

According to the "Review of Failures of Photovoltaic Modules" module mounting structures can break because of a heavy PV panels, strong wind loads or snow loads [11] .They also can be bent, broken or scratched because of rust and corrosion.

Another failure happens when the clamps of the array mounting racks are not tightened the right way.

3. Inverters:

The most frequently observed photovoltaic problem is unquestionably the failure of inverters. With a large variety of electronic components, the inverter can sometimes be affected by bad weather, leading to moisture and cable insulation issues. According to the “Best Practices in Operation and Maintenance of Rooftop Solar PV Systems in India” guide, most failures happen when:

- Since inverters have fans, it happens that dust gets accumulated on it, leading to ventilation problems.
- Often failures are due to the oldness of the device, overvoltage of the network or an overheating of the panels.
- AC and DC connection cables that come to and go from the inverters get loose or simply disconnected. Additionally, cables can face insulation, overheating and corrosion [6].
- Inverters can also show external casualties such as burns, dust accumulation, corrosion, and boards or a non-sealed base, or it can be simply because it was unprotected from the sun’s heat [6].
- Like many electronical devices, inverters contain IGBT (insulated gate bipolar transistors) that can get discolored.
- Input DC or output AC can get defected because of overheating.
- Inverters come with manuals, therefore the indicator lights LED must be conformed with that as given in the manual because it is considered the major indicator of a potential default.

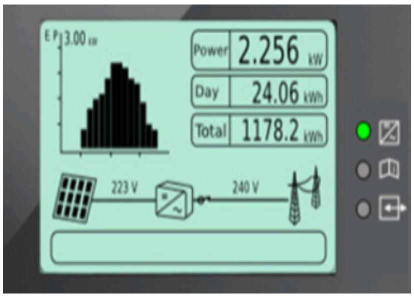

Figure 15: Inverter in good conditions

Figure 16: Inverter showing an error message

4. Cables:

The cables can face:

- cracks, breaks, corrosion, detachment, deterioration in the insulation.
- Voltage drop.
- wrong routing, or sizing.
- they can simply be loose or disconnected. Also, physical damage to these can be caused by rodents or other animals [3].
- The cables can also be short-circuited, open-circuited.

Figure 17: Damaged cable

5. Battery:

Battery breakdowns can be caused by many factors such as:

- The lack of control of the good functioning of charge controllers.
- The battery terminal can get loose, rusted, weak, faulty or simply discharged.
- It may happen that the terminals of the battery be connected in a wrong way.

- In case of lead-acid batteries, sulfating may happen if the batteries are left discharged. When they get discharged, the active lead material on the battery plates bonds with the sulfate and the electrolyte, forming lead sulfate. If it stays in the condition of not being fully charged, the lead sulfate gets more and more hard, leading to a significant decrease in the battery's capacity [18].
- A late refill of the electrolyte. The batteries can be damaged because of electrolyte leakages, corrosion or cracks [3].

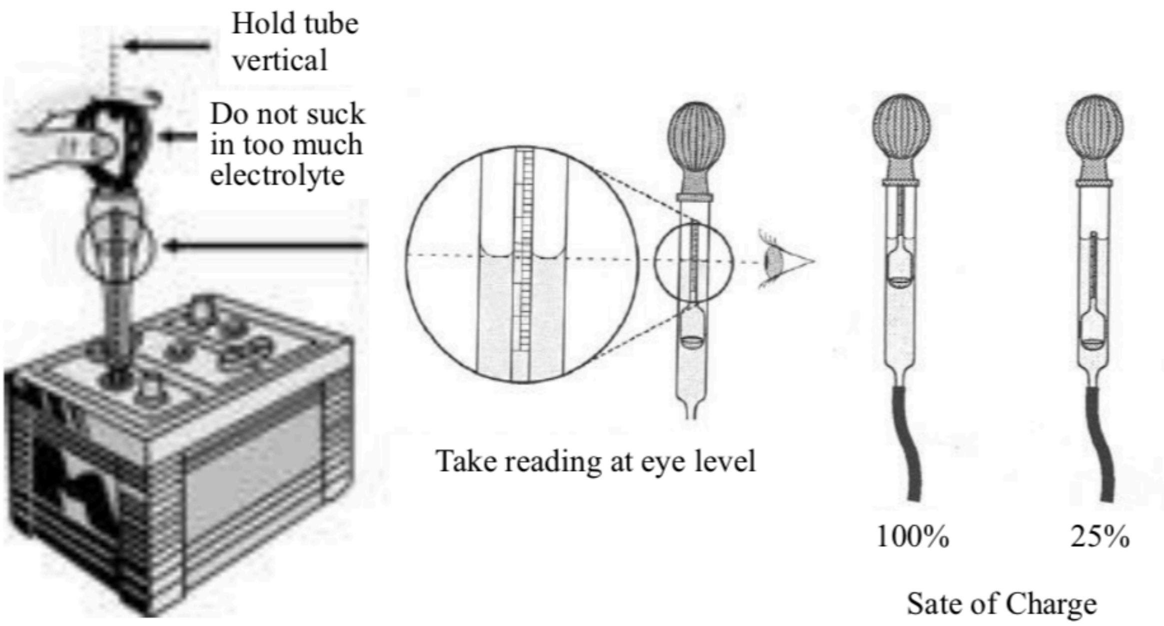

Figure 18: Observation of battery using a hydrometer

6. Charge Control System (Regulator):

Like the other electronical devices, the charge control system can be exposed to loose connections, wrecked, rusted or burnt constituents. Another defect that can cause the charge controller to fail is the collapse of the overcharge and undercharge protections [6].

Test Methods to Detect PV Modules Failures

When wanting to detect PV modules failures, different methodologies are to be taken into consideration:

1. Visual Inspection:

The easiest and fastest technique to undertake is the visual inspection method. It consists of observing the surface by global means such as the human eye or by more punctual means such as a magnifying glass or other magnifying instruments. A visual inspection enables the uncovering of any defect on the surfaces of any component of the solar installation: cracks, scratches, porosities, cold drops, lines, corrosion traces, deposits, migrant bodies, tearing, glass breakage, dust accumulation, module shading, corrosion, moisture condensation, discoloration or delamination, bent mounting structures, loose or detached cables.

2. The Use of an Infrared Camera (Thermography Camera):

The visualization of photovoltaic panels by infrared thermography makes it possible to detect possible malfunctions and thus optimize the efficiency of the installation. Several defects can influence the performance of panels such as faulty bypass diodes, shadows, water infiltrations, oxidations, hot cracked cells, soiling of panels, manufacturing defects or bad connections since they appear to have a higher temperature than good connections while current is passing through them.

According to Vasita & Magal, the thermography camera is mostly used when:

- Damage is suspected but without being sure of where. As an exploratory approach, it allows the detection of power shortages in the different constituents of the solar installation.
- Wanting to check after cleaning panels to ensure that the surface quality has not been altered, to make sure that the glass has not been scratched or coated with a shiny polishing agent that will increase the reflection of the glass.

- Wanting to keep track overtime of the thermal data and thus of the efficiency of its panels (can be used to determine if panels should not be deactivated because their performance is too poor compared to others).

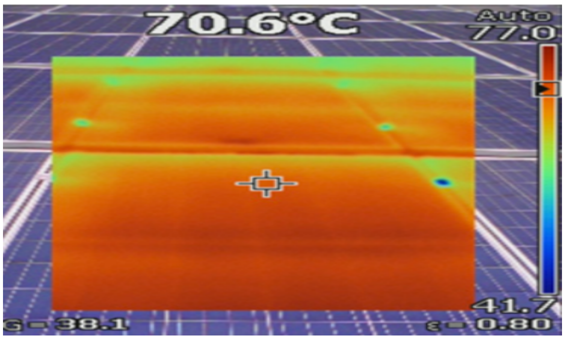

Figure 19: Thermography image of a normal panel

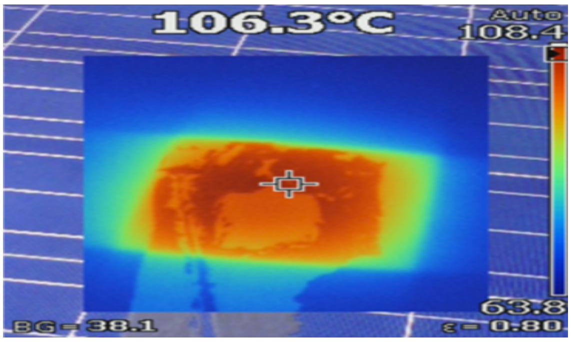

Figure 20: Thermography image of a hotspot

3. The use of a Digital Multimeter:

A multi-meter is essential to measure important electrical parameters: current measurement (amps), voltage measurement (volts), resistance (ohms), capacitance (farad) and continuity. It is particularly useful for detecting all electrical problems in any system, giving high accurateness.

Normally, any solar panel, when manufactured, has a tag that has the information of its voltage, current, weight size, etc. So when connecting the multimeter correctly, it should give the exact number on the tag, or a number that is just below it. This process identifies if there is any anomaly.

4. The use of a Clamp Meter:

The current clamp meter is a type of ampere meter to measure the current flowing through a conductive wire without having to open the circuit to place a conventional current meter. It is a testing device merging a digital multimeter and current sensor [6].

5. Measurements of module I-V curve, using an I-V tracer:

According to professor Arno Smets, the graph below shows a typical IV curve, meaning a current Vs voltage graph of a solar cell under illumination.

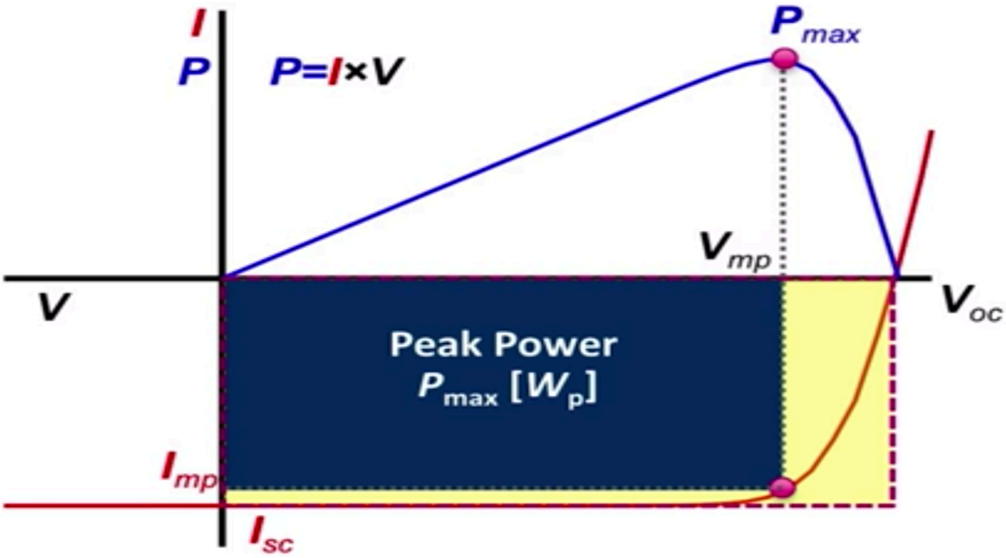

Figure 21: IV Curve graph

First if all, the **red line** represents the IV curve. When passing through the x-axis, the current is 0, therefore that point represents the voltage of a solar cell exhibits when disconnected from any external circuit. This point is called the Open Circuit Voltage $V_{oc.}$ Similarly, the point where the curve crosses the y-axis is equivalent to short-circuiting the solar cell as the voltage on either electrode of the solar cell is equal. This point is called the Short Circuit Current $I_{sc.}$

This curve allows us to value the power of a solar panel, which is calculated by multiplying the current and the voltage.

The **yellow area** represents the product of the open-circuit voltage and the short circuit current. This power is greater than the maximum power a solar cell can produce, however, it is useful to calculate the solar cell’s efficiency [23].

The **blue line** represents the power as a function of voltage. P_{max} is the maximum power generated by the solar cell, where V_{mp} is the voltage at the maximum power point and I_{mp} is its current. V_{mp} and I_{mp} are always less V_{oc} and I_{sc}.

The **blue area** represents the maximum power the solar panel can generate P_{max}.

PVEducation website presents the ratio of P_{max} which is called the fill factor (FF) as a ratio showing the quality of the solar cell [23]. It is calculated by dividing the blue area over the yellow area or using the equation below:

$$FF = \frac{I_{mp} \times V_{mp}}{I_{sc} \times V_{oc}}$$

where the higher the fill factor, the higher the maximum power generated.

The IV curve tracer calculates all the previous components and allows the immediate identification of the presence of damages in the module.

Solar PV Systems Maintenance

Importance of Maintenance:

The fact that the equipment is brand new never guarantees them eternal life, no matter what the warranty contract says. If the equipment is effective despite its age, there is no miracle, it is because they have been well maintained. The main reasons for maintaining machines are: improving the performance, preventing breakouts and ensuring proper operation of the production line. Maintaining industrial equipment is as important as caring for one's car, but on a much broader scale. In other words, maintenance and repair are part of a package designed to protect machinery from malfunctions and premature aging.

The main goal of maintenance of solar systems is guaranteeing the plant's efficiency and expanding its life expectancy. Furthermore, considering that the PV systems are electrical structures having both the AC and DC elements, safety is an important reason for keeping maintaining the PV modules [6]. When industrial equipment is not operating under optimal conditions, this can create unsafe working conditions and even emergencies where workers are injured. According to Vasita and Magal, when guaranteeing maintenance at suitable time interludes, one can limit the damages and increment energy production from the plant.

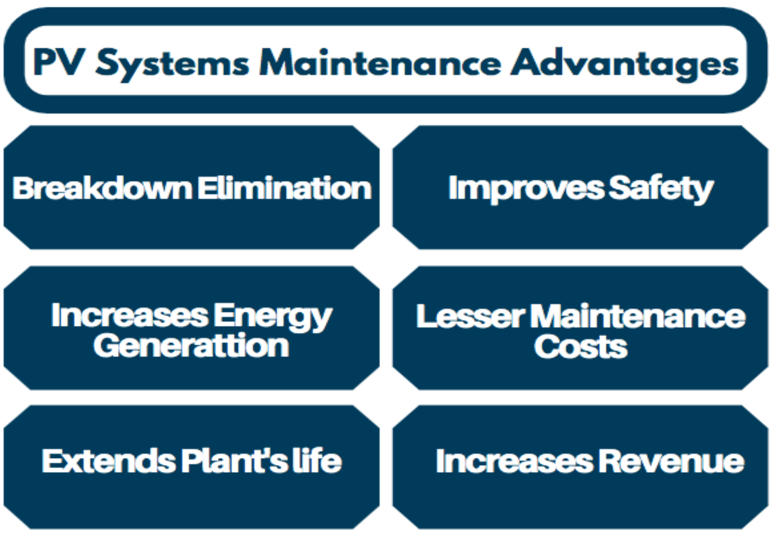

Figure 22: Benefits of maintaining PV systems

Maintenance Strategies

A photovoltaic plant is an important investment; therefore, it must operate optimally. This is the reason why the installation settings must be reviewed (orientation, sunshine, etc.). If one of the components that make up the facility is flawed or filthy, then its efficiency goes down. Solar systems require minimal maintenance but it is very much necessary. There are two main levels of maintenance:

1. Preventive Maintenance:

Preventive maintenance must be carried out regularly by the user. It allows better management of breakdown risks thanks to early visits. This maintenance is performed at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of failure or degradation of the photovoltaic panels [4]. The preventive maintenance measures for solar panels must consist of checking each item of the solar installation as shown below:

MAIN COMPONENTS	PREVENTIVE MAINTENANCE MEASURES FOR ECOwatt	FREQUENCY
Photovoltaic Modules	☐ General cleaning and vegetation control	Condition-based
	☐ Dust removal and cleaning of surfaces with water with no chemicals	Condition-based
	☐ Visual inspection of general condition: shading, hotspots, animal damage …	As needed
	☐ Control of mounting racks for corrosion, rust, bending or loosed clamps	Annual
	☐ Check the good state of connections, their cleanliness and absence of corrosion	Annual
	☐ Use infrared camera to inspect for hot spots (bypass diode failure)	Annual
	☐ Test open-circuit voltage of series strings of modules (using a digital multi-meter)	Annual
	☐ Perform a short-circuit current test (using a multi-meter or a clamp meter)	Annual
Inverters	☐ Visual inspection of the general state of the inverter	Annual
	☐ Check the state of the Led indicators and displays	Condition-based
	☐ Check the tightening of the AC and DC connection cables, conduits and insulation	Annual
	☐ Check the state of the fans	Condition-based
	☐ Check the emergency shutdown devices of the inverter	Annual
	☐ Verification of the durability and absence of corrosion of all the fasteners	Annual
	☐ Cleaning or changing of the inverter filters	Annual
	☐ Check the state of the fuses (using a digital multimeter to measure its resistances)	Annual
	☐ Inverter must be cleaned inside and out from any dust accumulation.	As needed

Wiring and Routing	☐ Inspect cabling for signs of cracks, defects, overheating, arcing, short or open circuits, and ground faults ☐ Check for loose electrical connections ☐ Examination of the track of cables	Annual Annual Annual
Electrical Protection System	☐ Check for proper insulation, no animal damage, corrosion, intrusion of water or insects ☐ Check the tightness of connections ☐ Check for blown fuses (using a digital multi-meter to measure its resistances) ☐ Check DC Protections ☐ Check Continuity of Equipotential Connections ☐ Measure DC currents and voltages (using a multi-meter or a clamp meter) ☐ Measure DC and AC isolation cables (using a digital multi-meter to measure its resistances) ☐ Test emergency stop devices ☐ Verification of protective devices ☐ Cleaning of DC and AC protection boxes	Annual Annual Annual Annual Annual Annual Annual Annual Annual Condition-based
Batteries	☐ Visual inspection of battery enclosure to check for cracks in cases or signs of corrosion ☐ Check that no dust or foreign matter has fallen into the cells ☐ Inspection for loose or corroded connections ☐ Measure the open circuit voltage (using a digital multi-meter) ☐ Verification of the level of electrolyte (if level is down, top up using distilled water or demineralized water) ☐ Cleaning the top of the batteries using distilled water (in order to remove sulfation)	Annual Quarterly Annual Condition-based As needed As needed
Charge Controller	☐ Check for loose electrical connections ☐ Check for blown fuses (using a digital multi-meter to measure its resistances) ☐ Look for evidence of high temperature or high humidity in the area where the charge controller is installed	Annual Annual Condition-based

Table 2: Preventive Maintenance Measures.

- PV Modules:

Dirty solar panels mean less electricity. To overcome this, only the cleaning process works but there are precautions to be taken to not damage the photovoltaic cells. It is necessary to note that rain does not clean the panels completely since the dirt layer will stick on the surface of the solar panel, that is why a regular intervention using suitable brushes is needed in order to remove the dirt that is stuck on the PV cells.

1. It is very much recommended to avoid using:

- ❖ Hard water (calcareous water) since it can leave white traces that causes the reduction of the module's efficiency. The better choice of water to use is the deionized water [6].
- ❖ Abrasive sponges that causes the panels to be scratched.
- ❖ Water that is too cold: on a hot panel, this could create a thermal shock that would permanently damage the solar panel.
- ❖ Water at too high a pressure: this could deteriorate the joints of the panel frame.
- ❖ Hard solvents and detergents: which can damage the surface of solar panels.

After cleaning the panels, it is necessary to dry them and to verify if the filth did not amass on the ends of the modules.

2. Before performing an open-circuit voltage test and short-circuit current test, it is necessary to have the open-circuit voltage and the short-circuit current of the panels from the specification sheet of the panels.

- Batteries:

To be safe from any short-circuit or electrical sparks, when cleaning the batteries, it is necessary to shut down the inverter and any other power supply to it.

- ❖ Before beginning any intervention, it is preferable to have gloves, a pair of safety goggles and a basin of water to wash any electrolyte splashes.
- ❖ When cleaning and drying the top of the batteries by removing any acid using a wet sponge.
- ❖ If there is any dust, it must be removed without using a metal tool.
- ❖ The terminals of each element must be greased with natural grease to avoid any corrosion [3].

- Charge Controller:

When testing the regulator, it is necessary to check that the batteries are not charged completely

2. Corrective Maintenance:

As opposed to preventive maintenance, which anticipates malfunctions, corrective maintenance occurs after the failure of an element. It involves repairing, restoring to the previous condition, replacing a part of the equipment, or correcting a bug or bad computer programming. Corrective maintenance is performed by a specialized and equipped technician. It provides a quick response to an unplanned failure to allow the most normal operation of equipment, minimize any loss in energy production and is performed when needed.

In the corrective maintenance, it is important to know that different approaches are applied to different situations, depending on the failure:

CORRECTIVE MAINTENANCE MEASURES FOR ECOwatt	
Module Shadowing	☐ Remove the obstacles creating the shadow on the panels: • If it is caused by vegetation, it is recommended to just trim the portions that are provoking the shaded parts. • if a new construction is built next to the solar installation, causing shaded panels, it is recommended to add other bypass diodes.
Physical Integrity	☐ Replace the racks in case of corrosion or physical damage in the mounting racks. ☐ Replace defective fuses. ☐ Replace wires that loose, corroded or cut. ☐ Replace defective bypass diodes. ☐ Replace the solar modules if infrared test shows: • too much hotspots • cell cracking • discoloration • delamination • signs of water (moisture condensation or bubble formation)
Cables	☐ Replace broken/crushed wiring conduit and fittings ☐ High losses or voltage drop in cables: replace with larger cables

Table 3: Corrective maintenance measures for PV modules and cables.

SYMPTOMS	CAUSES	SOLUTIONS
Excessive battery discharge	Faulty charge resumption function in the charge controller.	Repair, readjust or replace the charge controller.
Under charging batteries	Very high temperature.	PV module may have to be changed so that the IV curve may be convenient with hot conditions.
Battery capacity limited	One of the battery cells is faulty.	Check cells and replace
Reverse current flow at night discharging batteries	• Faulty blocking diode **or** • No diode, **or** • Faulty charge controller.	• Replace or add bypass diodes, **or** • Repair or replace series relay charge controller.
Battery self-discharging (Voltage loss overnight even when no loads are on).	• Old or faulty batteries, **or** • Bypass diode is faulty.	• Replace batteries, **or** • Replace diode.
Low electrolyte level **Electrolyte Leakage**	• The battery is overcharged, **or** • Battery container is broken leaking, **or** • The load is too large.	• Add distilled water, **or** • Replace battery.
Battery do not accept charge	• Power demand is too large, **or** • There is shadow, or the weather is cloudy for several days	• Readjust load, **or** • Reduce operating time, **or** • Remove shadow or wait till weather is sunny.
No power from the PC panels are going into the batteries	Faulty charge controller.	Repair or replace the charge controller.
Shortened battery life, possible damage to loads: • **Battery experiencing high water loss, or** • **Battery voltage over voltage regulation setpoint**	• Faulty charge controller, **or** • Controller always in full charge, never in float charge, **or** • Poorly configured charge controller.	Repair or replace the charge controller and possibly the batteries.
Battery voltage remains low	• Loose or corroded battery connections, **or** • There is a shadow or weather is cloudy for several days, **or** • Charge controller is too small for array.	• Repair or replace cables or battery. • Reduce operating time. • Remove shadow.

Battery voltage remains constantly high	• Charge controller is faulty, **or** • The battery capacity is too small for array, **or** • The charge controller is mis-adjusted.	• Increase battery capacity, **or** • Replace the charge controller, **or** • Increase battery capacity, **or** • Adjust charge controller.
Controller turns on and off at incorrect times	Timer is not synchronized with the actual time of day.	• Wait until automatic reset the next day, **or** • Disconnect array then reconnect it, **or** • Replace charge controller if the above actions does not work.
Electrical noise from the inverter	Rapid on and off cycling.	Connect the inverter directly to batteries, putting the filters on load.

Table 4: Corrective maintenance measures for batteries and charge controllers.

- **Corrective Maintenance for different failures in inverters:**

INVERTER DOES NOT TURN ON	
Possible causes	**Solutions**
Power switch is defective	Inverter must be taken to the service center.
Inverter has tripped	Start/stop inverter (reboot to clear the unknown error).
Battery terminals are loose	Battery terminals must be connected correctly.
Battery terminals are corroded or rusty	Battery terminals must be cleaned.
Battery is weak	Battery must be charged, and in case it's old, it must be replaced.
Battery terminals are loose	Battery terminals must be connected correctly.

Table 5: Corrective maintenance measures when inverters don’t switch on

AMOUNT OF POWER BEING GENERATED IS LESS THAN POWER IN TYPICAL CONDITIONS	
Possible causes	**Solutions**
System is not optimally designed	• The PV arrays and inverter are not well matched, **or** • High losses/ voltage drop in the cables: Replace the cables with appropriate ones.
Incorrect installation	Check for incorrect DC polarity in circuit : • Strings are not correctly wired, **or** • not plugged into connectors properly, **or** • loose connections, **or** • no voltage on terminals in PV array combiner box.
Modules not uniformly aligned (different tilts or orientation) (Mismatch losses due to non-optimal design or installation).	Correct the module mismatches (page 23 of the report).
Array shading	Remove the obstacles creating the shadow on the panels: • If it is caused by vegetation, it is recommended to just trim the portions that are provoking the shaded parts. • if a new construction is built next to the solar installation, causing shaded panels, it is recommended to add other bypass diodes.
Inverter overheating due to clogged vents or bad ventilation and is de-rating itself	• Check for any dust accumulation. • Clean inverter • Check proper wiring and insulation. • Check proper ventilation condition.
Defect or fault in modules, junction box, wiring or caused by overheating, storms or lightning.	• Check strings in PV array combiner box by measure open-circuit voltage (Voc) and short circuit-current (Isc) by using digital multi-meter, **or** • Disconnected terminals may be loose or the connectors are burned, **or** • Defective bypass diodes or blocking diodes in the modules caused by lightning, overvoltage or surge.
Blown fuse, a tripped breaker, or broken wires.	• Replace defective fuses, **or** • Replace discolored IGBT (insulated gate bipolar transistors), **or** • Replace breakers.
AC overloading of the inverter	Reduce the loads or replace the inverter with one that has a larger output.

Table 6: Corrective maintenance measures when inverters shows a power underneath the power that the system needs to produce.

NO INPUT VOLTAGE FROM THE ARRAY AND NO INJECTION ONTO THE GRID	
Possible causes	**Solutions**
No DC voltage at the inverter input	• Not enough sunlight, **or** • Check voltage at disconnect or isolator input: defective disconnect or isolator, **or** • Excess voltage suppressor has short-circuited the array to earth: Check surge protection device, **or** • Open or short circuit in the array, damaged cables or modules: Open PV array combiner box and test strings.
There is a DC voltage at the inverter input but the inverter indicators are not showing anything	Too dark, not enough light.

Inverter indicates DC input voltage during the day but nothing is being put onto the grid	• Utility grid black-out. The inverter should operate again when the grid comes back on, **or**
	• Blown fuses, activated circuit breakers and ground fault interrupters on the AC side between inverter and grid: Check the main utility fuse, **or**
	• Check any fault indicators: The inverter has detected a fault in the array and has shut down:
	  ▪ Test strings individually in the PV array combiner box: Possibly isolate the string that is causing the inverter to shut down by disconnecting one string at a time until string with fault is identified.
	• The inverter has detected a grid fault or grid operating outside design parameters for the inverter causing the inverter to shut down:
	  ▪ Check inverter indicators (Faults/ Warnings): Inverter should automatically start up again when problem clears.

Table 7: Corrective maintenance measures when inverters does not show an input voltage.

Conclusion

This Capstone Design Project consisted of setting up a maintenance plan for the solar installations of Ecowatt, after introducing different failures and defects that any solar installations can suffer from, and also after establishing a list of techniques used to detect these failures.

The preventive maintenance plan established was in the form of a table looking like a checklist including all the necessary checkups needed to be done in order to keep a solar installation working in good conditions. These checkups were indicated with the frequency necessary for each checkup in addition to the instruments needed to be used. On the other hand, the corrective maintenance plan established was in the form of a case by case maintenance. Since any failure in one component can lead to the failure of another one, it was necessary to study different defects and determine its individual solutions.

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Appendix

GRAR Hajar
EMS
Ecotaqa Services Project
Dr. Hassane Darhmaoui
Spring 2020

Energy is essential to our society to ensure our quality of life and to underpin all other elements of our economy. Renewable energy technologies offer the promise of clean, abundant energy gathered from self-renewing resources such as the sun.
For this capstone, I'm going to be working within the company Ecotaqa Services on developing one of their solutions pertaining to the implementation of solar energy. Ecotaqa Services is a company based in Agadir, it accompanies its clients from the design to the implementation of solutions. Ecotaqa Services puts at service optimal solutions to energy needs, make sure their clients are economically profitable during and after the energy transition.

With its group of scientific experts and state engineers, specialists in the field of renewable energy and energy efficiency, Ecotaqa services works to support high energy (industries, farms, tourist complexes. Supermarkets...) in different phases of their approach to energy transition.

In working on a project proposed by Ecotaqa services, I will get the chance to analyse the design of the project, then be able to proceed to its simulation, testing, and if time permits to its implementation.

Approved by the Supervisor

Spring2020/Capstone

Dr. H. Darhmaoui