JOSÉ RICARDO OLIVEIRA DA COSTA

CASE STUDY OF THE OPERATION & MAINTENANCE STANDARD PRACTICES OF A COMPANY IN THE PHOTOVOLTAIC SECTOR

Trabalho de Conclusão de Curso apresentado à Escola Politécnica da Universidade de São Paulo para obtenção do diploma de Engenharia de Petróleo.

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RESUMO

Uma das questões mais frequentemente levantadas nas discussões sobre desenvolvimento sustentável é a transição energética. Devido a este impulso, as fontes renováveis de energia foram colocadas na vanguarda, com o setor fotovoltaico em uma tendência ascendente nos últimos anos, sem perspectivas de desaceleração. Plantas geradoras de energia solar são instalações complexas e com longos ciclos de vida. O ponto focal de qualquer projeto é uma operação com o mínimo possível de variáveis que podem causar eventos imprevistos. Tais eventos resultam em custos adicionais devido a dificuldades técnicas e desvio de recursos dedicados a outras atividades, principalmente mão-de-obra contratada, e podem até, em casos extremos, impactar negativamente a imagem das partes envolvidas. Assim, o departamento de Operação & Manutenção (O&M) tem papel importante em assegurar o bom funcionamento evitando falhas e garantindo níveis ótimos de operação.

O objetivo do trabalho é compilar as melhores práticas em Operação e Manutenção (O&M) adotadas por uma empresa do setor fotovoltaico. Para isso foi realizado estudo de caso com uma importante empresa do setor: TotalEnergies Renewables International. O primeiro passo foi conduzir um levantamento minucioso da documentação da empresa, que incluiu dados de cada região do portfólio, e organizar as informações. Em seguida, especialistas de vários departamentos foram consultados para avaliar o material obtido e sugerir as melhorias necessárias. Finalmente, as melhores práticas de Operação e Manutenção (O&M) foram compiladas e classificadas em: Monitoramento e Performance, Manutenção Preventiva, Manutenção Preditiva, Gerenciamento de Limpeza e Manutenção Corretiva.

O documento final mostra o mais próximo possível da totalidade de situações e os melhores procedimentos operacionais e de manutenção adotados pela empresa e que, portanto, devem ser padronizados. Adicionalmente, novas informações podem ser adicionadas à medida que o tempo avance, acompanhando qualquer desenvolvimento ou estratégias.

Palavras-chave: Operação & Manutenção, Monitoramento, Fotovoltaica, Central Elétrica Solar, Estudo de Caso

ABSTRACT

One of the most frequently brought up issues in discussions on sustainable development is the energy transition. Due to this push, renewable energy sources have been brought to the forefront with the photovoltaic sector going on an upward trend in the last years with no prospects of slowing down. Solar power plants are complex installations with long life cycles. The focal point of any project is an operation with the minimum possible variables that may cause unforeseen events. Such events result in additional costs due to technical difficulties and diversion of resources dedicated to other activities, mainly contracted labour, and may even, in extreme cases, negatively impact the image of the parties involved. As consequence, the Operations & Maintenance (O&M) department will gain importance and become more crucial than ever in order to ensure that the power plant will be functioning at optimal levels.

The objective of this work is to offer some considerations that ought to be made while creating contracts and manuals that are relevant to O&M in the form of best practices. This was achieved by carrying out a case study at a company with a global clientele that is constantly expanding. The first step was conducting a thorough research of company documentation, which included data from every region in the portfolio and then consulting with experts from various departments to assess the material obtained and suggest the required improvements. The end result was a compilation of Operation and Maintenance (O&M) practices performed by said company covering the topics of Monitoring and Performance, Preventive (and Predictive) Maintenance, Cleaning Management and Corrective Maintenance.

The final document shows as close as possible the totality of situations and the best operating and maintenance procedures adopted by the company and which, therefore, should be standardised. Additionally, new information can be added as time progresses, following any developments or strategies.

Keywords: Operations & Maintenance, Monitoring, Photovoltaics, Solar Power Plant, Case Study

LIST OF FIGURES

LIST OF TABLES

SUMMARY

1 INTRODUCTION

In the last few years, the energy transition has been one of the most recurring topics and is at the forefront of any discussion regarding sustainable development. The year of 2022 marks the first time capital investment in renewables has surpassed the one for fossil fuels, according to a report by RYSTAD ENERGY (2022), mainly due to the price of electricity decreasing the payback time to close to a year.

Many of *today's* Big Oil companies such as Shell, TotalEnergies and British Petroleum have expanded their portfolio to enter the renewable market, designing, financing, building and operating projects all over the world, with most of them being either wind or solar farms.

Running wind and especially solar power plants is a complex endeavour, as is any major undertaking, requiring technical, managerial, social and legal knowledge to operate it at or as close as possible to peak performance. Though all are of import, none take more precedence than its maintenance, since it is an activity that will remain a constant throughout the entire lifetime of the project, which is generally advertised by solar panel manufacturers to be 25 years (SADDLER; GLOVER, 2022). This service is the one that most reflects on the performance of the power plant and translates directly to a gain or loss in revenue, so constantly surveilling the data produced by the equipment and acting upon this information so as to avoid any downtime is invaluable.

Ideally speaking failures should only occur under extraordinary situations, hence why the first step to an optimal maintenance plan is performing regular checks and inspections which reduce the probability of equipment malfunction, called preventive maintenance. If patterns can be identified through the analysis of the performance data that herald system or component faults then this falls under the umbrella of predictive maintenance.

Even after all of these precautions, failures can still occur. This is when corrective maintenance procedures are employed to remedy the problem quickly, being intrinsically tied to the management of the warranties of the equipment under use and the spare parts inventory available, both of which need to be carefully administrated, risking an even greater financial loss.

1.1 Objective

The main goal of this study was to compile a standard for Operation and Maintenance (O&M) practices of TotalEnergies *Renewables International's photovoltaic branch* that can be easily consulted and be based upon when and if needed.

As previously mentioned, there are many topics that can be touched upon to have a more global view of the O&M for photovoltaic (PV) plants but here the focus shall be on those more closely linked with the technical side, tied to the upkeep of the equipment and its monitoring.

Also, since this document was made available to the company, new information can and will be gradually added as it becomes available with the purpose of covering as many of the procedures as possible, with reasonably high reliability and applicability since the geographical context (and socio-political landscape) has a considerable impact on the running of a solar power plant and can vary drastically from site to site.

1.2 Justification

The focal point of any project, be it industrial, commercial or otherwise, is an operation with the minimum possible variables that may cause unforeseen events. Such events result in additional costs due to technical difficulties and diversion of resources dedicated to other activities, mainly contracted labour, and may even, in extreme cases, negatively impact the image of the parties involved.

Thus, the existence of robust documentation covering as close as possible to the totality of situations and procedures to standardise their respective responses is highly desirable.

TotalEnergies Renewables International is a recently created subsidiary of TotalEnergies and has been growing very fast in the sustainable energy market. As such there is a very big push for standardization of the information that is sent and received.

Inaccurate numbers require someone to figure out the reason for the disparity and do a crosscheck of all available sources. Entries in a logbook without proper form or prior verification can lead to multiple of the same event being indexed which in turn generate confusion.

Simply having the same KPIs (Key Performance Indicators) reported by all sites has a considerable impact on the amount of time spent to analyse the performance of an asset because the data can be treated easily and in a straightforward manner, opening the way even for the automatization of such process.

A standard framework such as the one proposed in this work can serve as a baseline for drawing up future contracts, setting up the minimal terms with which the O&M contractor needs to comply.

1.3 Scope

The O&M encompasses a multitude of aspects that if considered for this work, would render it far more exhausting than it can already be. With that in mind, four topics were selected for the case study that follows. These topics are:

- Monitoring and Performance: systems used for the surveillance of the solar power plant and its Key Performance Indicators (KPIs) to assess whether or not it is operating acceptably.
- Preventive Maintenance: inspections and interventions done on a regular basis to keep the plant functioning as optimally as possible.
- Corrective Maintenance: intervention done when a defect or a failure is identified, covering also the need to manage warranties and spare parts.
- Cleaning Management: actions and strategies adopted to remove dust, filth (and snow) from the PV modules. Sometimes considered a type of preventive maintenance but significant enough to stand as a topic on its own.

An important remark is that these topics are not necessarily standalone and as so have an inherent interdependence with one another, so many of the points present in one can be addressed more than once.

1.4 Work Organization

This work is divided in a manner such as that the information herein can be grasped with relative ease, containing an introduction, followed by a bibliographic review in chapter 2 that goes over some of the previous works performed in the same area and serve as a stepping stone for the main themes of this document, the methodology in chapter 3, explaining in relative the way used to structure this study and present its results, which appear on chapter 4.

2 BIBLIOGRAPHIC REVIEW

Here a brief explanation is given of how photovoltaic power plants work, going over *their main equipment’s function*s. After that, an overview of the literature on the O&M aspect of solar systems is made to better contextualize this study.

2.1 Solar Power Plant Basics

According to the National Renewable Energy Laboratory (2022) photovoltaics (PV) gets its name from the process of converting light (photons) to electricity (voltage), which is called the photovoltaic effect. This phenomenon was first exploited in 1954 by scientists at Bell Laboratories who created a working solar cell made from silicon that generated an electric current when exposed to sunlight.

As for the general layout of a solar power plant, the Office of Energy Efficiency and Renewable Energy (2022) starts by describing its smallest unit, the photovoltaic cell. It is a device comprised of semiconductor materials, often silicon, covered by a protective layer of glass and/or plastics to lessen environmental deterioration. The power output of PV cells is increased by chaining them together to create bigger units called as modules or panels. Modules can be used alone or linked together to create arrays. A full PV system then includes one or more arrays linked to the electricity grid.

PV arrays need to be installed on a solid, long-lasting framework that can hold them up and endure corrosion, wind, rain, and hail for many years. These structures tilt the PV array at a set angle that depends on the local latitude, the structure's orientation, and the necessary electrical load. Currently, rack mounting is the most used technique since it is reliable, adaptable, and simple to build and install. Methods that are more complex and less costly are always being created (OFFICE OF ENERGY EFFICIENCY AND RENEWABLE ENERGY, 2022).

Tracking devices for PV arrays mounted on the ground mechanically move panels to follow the sun as it crosses the sky, resulting in more energy and greater returns on investment. Typically, one-axis trackers are made to follow the sun from east to west. Modules can stay directed directly at the sun all day long using two-axis trackers.

Naturally, tracking implies higher initial expenses, and complex systems are more costly and require more upkeep (OFFICE OF ENERGY EFFICIENCY AND RENEWABLE ENERGY, 2022).

The direct current (DC) power produced by solar photovoltaic modules is converted into alternating current (AC), by use of inverters which is then utilized for local electricity transmission. PV systems can have one (central) inverter that converts the electricity generated by all of the modules, microinverters that are attached to each individual module*" or have one inverter connected to a set of modules* which is called a string (OFFICE OF ENERGY EFFICIENCY AND RENEWABLE ENERGY, 2022).

Finally, the voltage of the energy produced by the plant is increased for its injection on energy grid. This is done by means of transformers. Depending on the size of the power plant there can be one transformer to convert from low voltage (LV) to medium voltage, then another one from medium to high voltage (HV) if so needed.

2.2 Operations and Maintenance (O&M)

With regards to the basics of O&M as a whole, many works go over these topics and if one is not necessarily familiar with this area's terms and terminologies it is possible to check some of them. Namely, the books by Ben-Daya (2009) and Levitt (2009) are excellent examples and offer extensive knowledge in the area.

One cannot approach the O&M of solar power plants without first getting acquainted with SolarPower Europe (SPE), a member-led association which represents over 280 organizations spanning the whole solar sector of the European continent. They are responsible for many publications that give a good outlook on the solar market and its trends and also an O&M Best Practices Guide (SOLARPOWER EUROPE, 2021) which contains standards based on the knowledge of asset owners and managers, O&M service providers, legal consultants and others who have extensive experience in the solar and renewable energy sector. It is an extremely valuable document that is more often than not used as a reference for the drafting of official contracts. It makes an important classification of minimum requirements, setting a minimal quality standard, below which the O&M service is deemed inadequate or subpar; best practices, state-of-the-art techniques that balance the technical side with the financial side to provide the best outcomes; and recommendations whose execution is contingent on the responsible party's considerations, but which improve the service quality (SOLARPOWER EUROPE, 2021).

A study by Rediske et al. (2022) highlights how globally, there is an increasing number of sizable photovoltaic (PV) power plants and energy sales often occur after demand contracts with specific duties and penalties for non-supply are stipulated. The authors state that performance of PV plants is severely impacted by not producing the agreed-upon amount of electricity, but this problem may be reduced with appropriate operation and maintenance (O&M) procedures. These become more crucial as a PV plant becomes older in order to maintain or increase performance. Performance evaluation is a complicated procedure that requires gathering several characteristics, measuring indicators, and developing action plans to address any problems that are found. An indirect increase in generating capacity is produced by effective management of O&M procedures, which also ensures adherence to energy supply agreements. They then identified 33 key performance indicators (KPIs) in operation or maintenance categories, and then further in technical or economic subcategories, using a thorough literature study and the Delphi approach with experts.

Iftikhar; Sarquis and Branco (2021) stressed the importance of practical and affordable O&M methods to improve the plant's energy output, even when carried out by individual employees and backed by a comparison of real-world data with simulations. Additionally, they conducted a case study on an 18 MW solar power plant in Pakistan, comparing its actual energy output with an anticipated energy output determined through simulation using the widely used software PVSyst, and reviewing its operations and maintenance reports and comparing them to international best practices in the solar industry.

Oviedo Hernandez et al. (2022) presents how new technologies are influencing and shaping the PV O&M scenario, giving key avenues for future study and pertinent insights into developing domains, as well as analysing the concept of circular economy and its adaptation to the solar power plants in order to reduce the waste generated. The work also provides a brief market analysis on the O&M sector with predictions indicating a steady growth of O&M expenditures due to the progressively greater installed capacity. Figure 1 illustrates the decreasing cost per kW with increasing facility capacity, while Figure 2 points out how important O&M tasks are left out of the scope (which are then charged as additional services) to keep contract prices down, resulting in low contract prices that constitute a false reference in the sector.

O&M costs by project size, 2020 US dollars

Market	20kW (US$/kW)	1MW (US$/kW)	5MW (US$/kW)	20MW (US$/kW)	50MW (US$/kW)	100MW (US$/kW)	200MW (US$/kW)	500MW (US$/kW)
Australia	47.22	11.99	10.80	9.65	9.51	9.01	8.93	8.68
Brazil	28.24	4.30	3.99	3.12	3.10	3.03	3.02	2.98
Canada	36.44	8.76	8.29	6.80	6.70	6.32	6.27	6.08
Chile	26.10	6.29	4.75	3.51	3.48	3.37	3.35	3.30
China	26.25	3.41	2.85	3.04	3.01	2.91	2.89	2.84
France	43.02	8.77	9.03	9.11	9.00	8.60	8.54	8.34
Germany	48.01	11.42	9.66	9.58	9.45	8.96	8.89	8.64
India	32.40	5.17	4.84	4.72	4.68	4.53	4.51	4.44
Italy	39.48	7.50	7.34	7.89	7.83	7.57	7.53	7.41
Japan	45.21	9.71	9.58	11.10	11.00	10.63	10.57	10.38
Mexico	24.13	6.02	3.98	2.90	2.89	2.83	2.82	2.79
Netherlands	47.63	10.64	10.54	10.63	10.48	9.94	9.86	9.58
South Africa	33.70	4.72	3.80	5.11	5.09	5.06	5.05	5.03
Spain	36.95	7.58	6.57	6.73	6.67	6.41	6.38	6.25
United Kingdom	48.04	10.54	9.19	9.22	9.12	8.74	8.68	8.49
United States	53.84	12.31	11.53	9.73	9.58	9.01	8.93	8.64

Figure 1 – Full scope of O&M cost

Source: Hernandez *et al*. (2022)

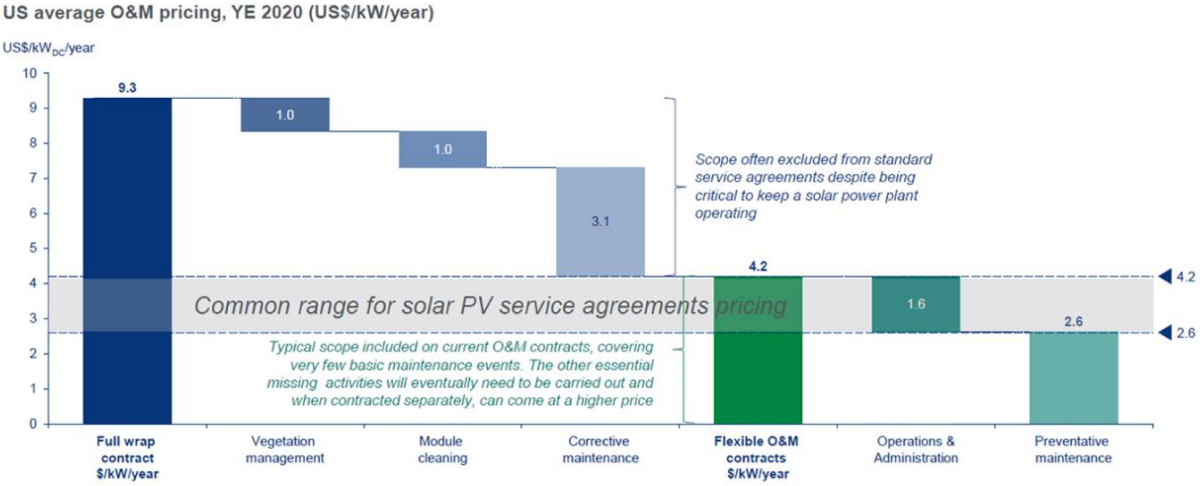


Figure 2 – O&M contractual pricing average on the US

Source: Hernandez *et al*. (2022)

Keisang; Bader; Samikannu (2021) presented a model for creating an O&M program and outlining the essential components for its success, such as a management and execution approach for improved risk-return balance and savings from the O&M expenditure. The authors address the lack of clearly defined steps taken in the development of an O&M program for PV systems and the evaluation of its performance. It further mentions how O&M depends heavily on a system's size, particular design, and geographical setting, being the reason why maintenance implementation strategies change and why various installations have distinct needs. In order to prevent system downtime and a reduction in the system's service lifespan, a maintenance management structure is required, as shown in Figure 3.

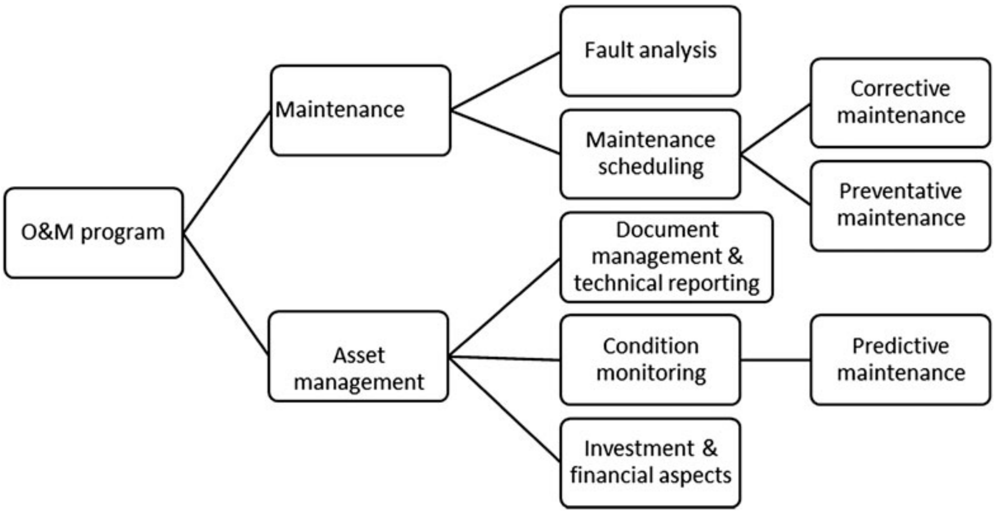


Figure 3 - Schematic for the main aspects of a maintenance program

Source: Keisang; Bader; Samikannu (2021)

Livera et al. (2022) performed O&M actions that consider component malfunctions and failures through stochastic simulations. The results exhibited a net economic gain of approximately 4,*17 €/kW/year*. This was reached by using a specially-made decision support system (DSS). The system operates entirely on raw field measurements, recommends decisions that can be taken to resolve fault and performance loss events, and incorporates technical asset and financial management features. The benchmarking process used historical measurements from a sizable PV system that was installed in Greece.

3 METHODOLOGY

The chosen method for the analysis was Case Studies. It employs qualitative information that was gathered from actual occurrences in order to explore, describe, or otherwise explain contemporary phenomena in their own context. It is distinguished by being a thorough examination of a small number of items, or perhaps just one, resulting in in-depth understanding (BRANSKI et al., 2010). The case study was carried out with the company TotalEnergies Renewables International, more specifically in its photovoltaic sector.

The steps taken during the development of the work are showcased on the flowchart on Figure 4.

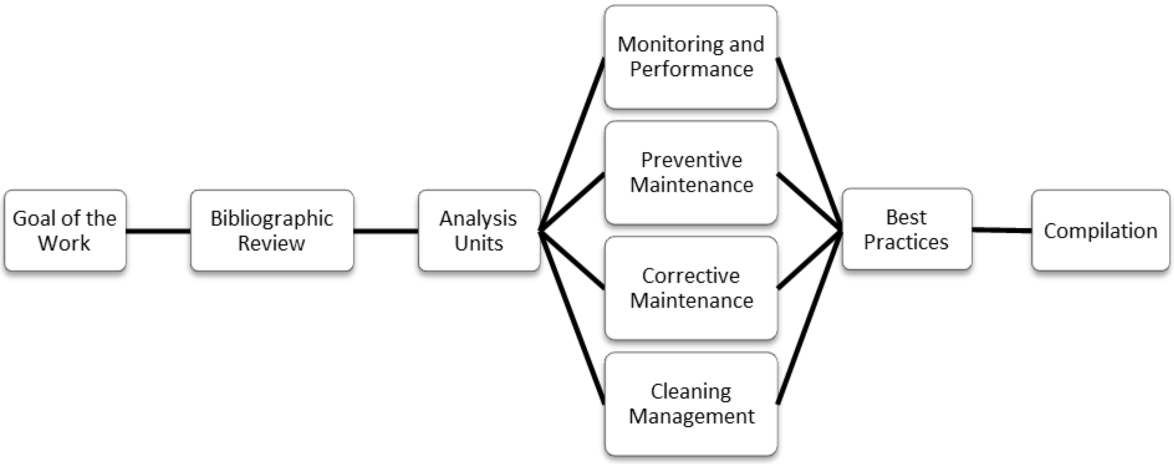


Figure 4 – Steps of the case study

Source: Author (2022)

The objective of the research was to analyse how the topics highlighted before are structured in a company and how they can be used to create a guide of best practices. A framework for analysis was created from the examination of the bibliographic review, and it served as the foundation for the formulation of the proposition and the creation of the case study.

The proposition that jump-started all was that all processes and procedures used for the Operation and Maintenance (O&M) of a solar power plant should be standardized to avoid confusion, ease the drafting of contracts and the onboarding of workers as well as increase efficiency.

The information used to take the conclusions present in this work were retrieved in two stages:

- The first was the checking of multiple site-specific contracts and manuals, either from the Engineering, Construction and Procurement (EPC) phase (before Commercial Operation Date) or the Operations and Maintenance (O&M) phase (after Commercial Operation Date), which contained data from all geographies within the portfolio of the company so to have data as widespread as possible.
- Second was, after creating a compilation from the previous documents, setting up a team of Subject Matter Experts that would review the gathered information and propose the necessary adjustments according to their know-how and experience.

Finally, all information was organized into a best practices manual that could be distributed to the company as a whole. Four categories were highlighted as the most important with regards to keeping the solar power plant operating optimally: Monitoring and Performance, Preventive Maintenance, Cleaning Management and Corrective Maintenance The results obtained in the survey will be presented on the following pages.

4 RESULTS

TotalEnergies Renewables International (TERI) is a subsidiary of the TotalEnergies Group that focuses on the development of renewable energy projects, mainly in the wind and solar domains, outside of the French territory.

Its portfolio is very diverse, with a presence in Chile, USA, Spain, Japan, South Africa, UAE and Qatar, totalling almost 1,8 GWp (maximum DC output capacity produced by the solar panels) of installed gross capacity plus the plants in India which are operated in conjunction with the Adani Group and are counted separately, with new projects on the pipeline or already under construction that will be ready for production in the coming years.

The Asset Performance department is the one responsible for supporting and ensuring that the companies working for the Special Purpose Vehicles (SPV) running the power plant or portfolio will conform to the obligation set out on the contracts. This means helping them maximise the energy production while decreasing costs, plant downtime and risks, thus increasing the revenue obtained in order that the plant is following its business plan model.

The head of Asset Performance was the one who first put forth the idea of compiling the best practices for the Operation & Maintenance which then evolved into a large-scale project and paved the way for this study.

4.1 Monitoring and Performance

One vital part of running a photovoltaic power plant is the collecting, treating and analysing the critical information of an asset to know its operational status and Key Performance Indicators (KPIs). TERI uses this information to have a meaningful Management Information System (MIS) for fact-based decision making and way forward for continual improvement.

4.1.1 Supervisory Control and Data Acquisition System (SCADA)

A SCADA can be used to manage assets and gather vital data about them. Based on its design, equipment installation, and the unique data and control requirements of the owner, plant operator and grid operator, a SCADA set-up (combination of hardware and software monitoring platform) might differ from plant to plant.

Typically, the SCADA system enables:

- Remote monitoring capability of the Project on a 24/7 basis locally at the plant level as well as at a remote location such as the corporate head office
- Receiving alerts about any anomaly (warnings, errors, stop/ start notification) in the plant resulting in a quicker response by the crew of an operator
- Remote control of key equipment provided the equipment has an appropriate capability and the feature is offered by the respective OEM.
- Handle any compliance requirement asked by the Grid operator/ Load Dispatch Centre but also environmental requirements.
- Acquire important operational data from all the critical equipment installed within the plant to assess the proper functioning and performance.
- Provide project company, any financing party and their respective advisers access to the on-site monitoring systems, including data concerning weather resources and system output.

Various types of connectivity infrastructure are used to connect different equipment to a central SCADA, such as Optical Fibre Cable (OFC), Radio Frequency (RF) and directly connected to a Network Operations Centre (NOC) typically, located at a remote location such as the head office.

It is important to store the historical data for operational analysis and hence, adequate storage and backup infrastructure set-up is mandatory at both the site level as well as the central level.

4.1.2 Monitoring and Control

Several service providers offer ready-made and adaptable solutions for the real-time monitoring of a renewable plant, both globally and locally. These monitoring solutions typically connect to the site SCADA (as previously described) and offer remote supervision and control capabilities via Human-Machine Interface (HMI) displays ().

Figure 5 – Example of monitoring platform interface used for some sites

Source: Internal company documents and knowledge (2022)

These platforms also include fundamental analytical tools that turn the unprocessed data from plant equipment into a useful graph, trend chart, or table to immediately identify the areas that require the owner's or operator's urgent attention. Such system-generated feedback promotes asset performance and safety. Some monitoring solutions also provide a detailed view of performance KPIs, management reports and dashboards. Typically, it contains the following:

- Basic plant and equipment information – size (MWp or MWac), geographical location, number of equipment
- Real-time view of basic plant performance data (instantaneous and trend) – for example, but not limited to
  - Power, Current and Voltage at different plant equipment levels
  - Weather resource and temperature (horizontal and incident irradiance, *wind speed, wind direction, ambient temperature…)*
  - Reactive power
  - Grid quality (voltage, current, frequency, curtailment)

    - Connectivity infrastructure healthiness status
    - Equipment availability
    - Performance Ratio (PR)
    - Equipment temperatures Alarms and warnings recorded on equipment
    - Heat maps – showing best performing and worst performing equipment
    - Features to remotely operate and control equipment
    - Soiling/snow loss

4.1.3 Computerized Maintenance Management System (CMMS)

These monitoring solutions frequently include a service ticketing system or CMMS. The ticketing system is used to record all anomalous events, which are often referred to as breakdown or unplanned maintenance events, in the form of a maintenance ticket or service call. The system would produce a service ticket in the case of such equipment/plant failure, which could then be transferred to a site O&M team.

The appropriate remedial action will be taken by the selected and authorised employees to eliminate the anomaly and restart the equipment/plant. A typical service ticket has the following information related to breakdown and correction action taken:

- Standard static information (plant name, capacity, number of equipment, etc)
- Date and time of the event
- Failed equipment detail
- Probable cause of the breakdown
- Upon restoration of an equipment/plant, the O&M team can further add
    - Date and time of completion of breakdown maintenance
    - Timesheet
    - Details of activities carried out for restoration
    - List of tools and spares/ consumables used if any
    - Supportive documentary/ photographic evidence of restoration

It goes without saying that the information captured by such a ticketing system is extremely valuable for several operational analyses, like Mean Time To Repair (MTTR), Mean Time Between Failure (MTBF), equipment serial failure, spares and consumable planning etc.

Additionally, the ticketing can be done not only for unscheduled events but also for the normal maintenance procedures, so that they can be automatically added to a logbook.

4.1.4 Plant Performance Analysis

One of the essential tasks to guarantee the safety of the assets and maximum production from the plant is the performance analysis through Key Performance Indicators (KPIs). The following Charter 1 shows examples of operational KPIs used by TERI for a PV power plant:

KPIs	Brief Description
Energy Generation (MWh)	Actual vs Budget
Weather Resource Analysis	Horizontal and Incident Solar Irradiance (kWh/m^2) Actual vs Budget Wind Speed (m/s) (if deemed necessary) Ambient temperature
Plant Availability (%)	Time/Energy-based availability of installed equipment
Grid Availability (%)	Time-based availability of grid infrastructure
Performance Ratio (PR) (%)	The efficiency of a PV Solar plant - the ratio of measured energy output to expected output for a given reporting period based on the system name-plate rating and the actual weather conditions (irradiance and temperature)
Waterfall analysis	Identify main contributors (and hence, key focus areas) to the variance of actual performance about the budgeted/expected performance and the known causes of losses.
Inverter PR deviation Histogram	Normal distribution of inverter performance variation
Mean Time To Repair (MTTR) (hours)	The efficiency of the O&M team – how quickly under-breakdown equipment is restored?
Mean Time Between Failure (MTBF)	Reliability of installed equipment – how frequently a piece of equipment is failing/ going out of operation?
Top 10 / 20 error analysis	To understand count (occurrence), duration of breakdown and associated energy loss
Spares consumption	To understand the pattern of consumption and are there any serial defects and for better Just In Time (JIT) inventory planning
SCADA Data Quality and Availability	Ensure the health of the SCADA infrastructure on site

Charter 1 - List of KPIs for a PV power plant

Source: Internal company documents and knowledge (2022)

The raw data accessible at the plant or at the SCADA/monitoring system may be used to gather all of the KPIs above to perform the analysis and, based on the company's needs and the importance of the information, the frequency with which it is carried out may be decided upon (ideally monthly). The quantitative KPIs are usually compared to budgeted values obtained from a P50 (measure of reliability in which it is assumed that the resource will be at least equal to a value, 50% of the time) simulation ran via a software such as PVSyst, plus a buffer that usually is added for a more financially conservative approach. The qualitative KPIs on the other hand are compared to the results of previous analyses. This process can be automated by the monitoring platforms or semi-automated by using robust spreadsheets were the data needs to be input.

There are more specialised analyses that can be taken into consideration dependent on location and event since the aforementioned indicators are general and do not cover the complete spectrum.

4.2 Preventive Maintenance

The key component of maintenance services for a PV plant is preventive maintenance operations. They include routine visual and hands-on inspections as well as verification procedures carried out at predetermined intervals on all crucial components and are required to adhere to the operating instructions and guidelines provided by the Original Equipment Manufacturers (OEMs). As well as lowering the likelihood of failure or deterioration, it must uphold any equipment and component. The actions must comply with the relevant regulatory requirements, such as national standards for the routine examination of certain electrical components, and HSE regulations. This list of services, together with the frequency of each task, should be included in the O&M contract (SOLARPOWER EUROPE, 2021).

This upkeep is done at pre-set intervals or by the recommended OEM and O&M manuals. These are outlined in a thorough yearly maintenance plan, which also offers a set timeline and a predetermined number of maintenance iterations. Failures and deviations must be fixed before being reported in the yearly report.

The following non-exhaustive examples of procedures and checks (Charter 2) highlight the intricate nature of the preventive maintenance of a PV power plant.

Equipment	**Actions**
PV modules	Integrity inspection & replacement, Thermographic inspection, Measurement inspection, Check tightening of clamps, Module cleaning, Sample internal inspection of junction boxes (if possible), Cables conditions
Inverters	Visual inspection, Input/output cables and terminals condition verification, tightening when necessary, Grounding and ventilation system verification, Inverter cleaning, Thermographic scans/analysis, Clean and replace filters, Preventive maintenance *routine as per manufacturer's requirements*
LV/MV transformer	Visual inspection and cleaning, Input/output cables and terminals condition verification, tightening when required, Functional verification of sensors, relays and protection devices and systems, Check parameters, Thermographic inspection, Oil condition sampling and laboratory analysis (if oil transformer), Grounding connection testing, Check of cooling system (fans) if applicable, Check MV surge discharger *devices (if applicable), Preventive maintenance routine as per manufacturer's* requirements
Communication network and monitoring system	Visual inspection & cleaning, Verification of cable connections and terminals, Fibre optical splices verification, Check and record operational settings of the Power Plant Controller, Ensure that there is no abnormal or irregular reading and alert trigger when abnormal results appear, Functional communications check, Preventive maintenance on SCADA, connections, and data integrity test as per manufacturer requirements
Weather station	Integrity check & cleaning, Functional test of sensors, Check correct operation, Check batteries (if applicable), Monitoring operation test, Recalibration of sensors
Irradiation sensors	Integrity check & cleaning, Calibration, Monitoring operational test
Tracking system	Integrity check & cleaning, Check correct operation, Check tightening, General maintenance, Mechanical lubrication, Batteries check, Preventive maintenance *routine as per manufacturer's requirements*

Charter 2 – List of actions performed during preventive maintenance per equipment

Source: Internal company documents and knowledge (2022)

It is important to mention that there are other equipment or systems that warrant preventive maintenance checks like DC electrical cabinets and switchboards, DC cables, MV switchgear, Energy meter, Power control unit, Emergency generator (if applicable), PV support structure, Buildings, Civil works (roads, rain drainage, fire corridor, etc) and HSE systems and equipment (fire extinguishers and detectors, lightning protection system, pest control measures, etc).

4.2.1 Predictive Maintenance

Predictive maintenance is described as condition-based maintenance done in response to a forecast originating from the investigation and assessment of the key indicators of the item's degradation. For this the devices used on-site must be able to give information on their condition, allowing for the evaluation of patterns or occurrences that signify device deterioration (SOLARPOWER EUROPE, 2021).

By continuously monitoring, supervising, forecasting, and analysing performance data (such as historical performance and anomalies) of the solar PV power plant, the O&M can do predictive maintenance. This can spot tiny patterns that would otherwise be missed until the subsequent cycle of circuit testing or thermal imaging examination and that foreshadow component or system breakdowns or underperformance.

These alterations in behaviour are frequently connected to the predictable or unpredictable process of equipment deterioration. It is crucial to identify and keep track of all critical wear-out status factors based on the installed sensors, the algorithms used in the monitoring system, and other methodologies.

Following said research, the O&M may put predictive maintenance procedures in place to guard against potential failures that can result in safety concerns or a reduction in energy production.

4.3 Cleaning Management

One of the most important maintenance tasks is cleaning PV modules since dirtier PV modules absorb less solar energy and reduces the operational plant's output of electricity. Based on various site and operating conditions, this section describes how to adapt and apply several cleaning methodologies that are best suited for a typical PV solar plant. However, it is also advised to take all the plant-specific conditions and challenges before finalizing the cleaning methodology.

4.3.1 Factors Affecting Module Cleaning Philosophy

Two major aspects of module cleaning – frequency and methodology – are driven by the following factors:

- Climatic conditions – tropical, deserted, cold
- Terrain of the PV solar plant – flat, hilly, undulated
- Type of soil – sand, red soil, black cotton soil, muddy, salty
- *Surroundings (fields with heavy machinery spreading dust, roads…)*

- Type of Module Mounting Structure (MMS) – fixed tilt, seasonal (or manual) tilt, trackers
- Ease of getting water for cleaning, consumption/demand and cost of water
- Cost of cleaning versus revenue loss due to soiling
- Cost of labour

To determine the best cleaning process and frequency, each component and/or combination of factors might have a different influence. For this reason, it is advised to carefully evaluate all of the aforementioned criteria (as well as any additional plant-specific conditions) before making a decision.

TERI uses several methodologies to clean the solar module: Fully autonomous robotic dry cleaning, Semi-automatic robotic dry/wet cleaning, Hydrant system for wet cleaning, Manual wet cleaning and Snow removal. They will be presented in the following sections.

4.3.2 Fully autonomous robotic dry cleaning

Fully autonomous robotic dry cleaning is the most advanced and desirable method of PV module cleaning. Figure 6 shows visual examples of autonomous dry-cleaning process.

Figure 6 - Visual examples of the autonomous dry-cleaning process

Source: Internal company documents and knowledge (2022)

There are bad and good arguments to use the autonomous robotic. Positive factors are: higher frequency of cleaning possible, lesser soiling loss, remotely operated through the SCADA, self-powered (no plant auxiliary consumption), no water required and less O&M intervention. Negative factors are: attracts higher initial capital, dependency on OEM for after-sales services such as spare parts, restricted operation in case of adverse climatic conditions

- Difficult to implement in already operational plants
- The technology is still evolving for seasonal tilt and tracker type
- Requires very precise coordination between the structure suppliers and the *robots' suppliers (ex: maximum angle between tables to let the robots move from one table to another…)*

It is advisable to involve a robotic cleaning OEM at the time of designing the plant to optimize the layout that is most suitable for robotic cleaning solution implementation and for equipment warranties.

4.3.3 Semi-automatic robotic dry/wet cleaning

Semi-automatic robotic dry/wet cleaning is the next most desirable method of PV module cleaning used by TERI (Figure 7).

Figure 7 - Visual examples of the semi-automatic cleaning process

Source: Internal company documents and knowledge (2022)

Pros:

- Cleaning effectiveness is better than the manual cleaning
- Larger installed base (MWp) per day can be cleaned
- Lower capital investment is required as compared to fully autonomous robots
- Lower/ no water consumption for cleaning

Cons:

- Dependency on labour to mount and unmount the robots from the table which could be very difficult in desert environment (no labour allowed to work during daytime)
- Complex to be incorporated with seasonal tilt and tracker
- Potential risk of module damage in case of improper handling

4.3.4 Cleaning using a Hydrant System or Manual cleaning

Cleaning using a hydrant system or Manual cleaning are widely used for cleaning PV modules in most of the older plants (5 years or more).

In the case of the hydrant system, a plant-wide network of pipelines is installed along with plant construction and tapping points are provided near the PV module arrays. A team of labourers attaches the flexible hose pipe to these tapping points and uses the pressurized water flow and portable mops to carry out the cleaning

In the case of manual cleaning, a combination of a tracker-mounted water tanker and labour are used to move between the PV module arrays to carry out the cleaning of PV modules as seen on Figure 8.

Figure 8 - Visual examples of the manual cleaning process

Source: Internal company documents and knowledge (2022)

While the hydrant system is a capital-*intensive installation, manual cleaning doesn’t* require any initial capital investment. Water is required in both cases and hence, the availability of an adequate amount of water with appropriate quality, at the point of cleaning is a prerequisite for adapting these methodologies. Also, there is a dependency on labourers to carry out mopping of PV modules to ensure no water remains. Considering sustainability, the average size of the single plant, and water being a precious resource, the above methodologies are being used less and less.

4.3.5 Snow removal

Finally, for regions with colder (sub-zero temperatures) climatic conditions, the removal of a layer of snow from the PV Module is also an essential maintenance activity to ensure the optimum output. Various semi-automatic and manual methodologies can be adapted to remove the snow (Figure 9).

Figure 9 - Visual examples of different snow removal processes

Source: Internal company documents and knowledge (2022)

However, snow removal is a much more complex topic than the usual module cleaning; it is more expensive, requiring more specialized equipment and because snowfall is a regular event during the winter season in some regions, removing the snow cover is a continuous effort that might not be worth the extra production gained.

Various factors contribute to this analysis, but mainly the frequency of the snowfall, thickness of cap, good weather on the days following the cleaning, technology cost and upkeep and/or workforce cost. The development of more innovative solutions like module heating or the application of chemical treatment can help cheapen this process in the future but currently, they are evaluated as far too costly.

4.4 Corrective Maintenance

Any task carried out to put a PV plant system, piece of equipment, or component back in working order is known as corrective maintenance. It can take place following a defect or a failure discovered by remote monitoring and supervision, as well as during routine inspections and particular measuring tasks (SOLARPOWER EUROPE, 2021).

Defects are categorized as any issue resulting from supplies or construction executed differently from the one foreseen and specified in the project execution approved by the client. Failure or malfunction of equipment is understood as any malfunction or issue found in the equipment of the solar PV power plant. In both cases if the equipment is still under the supplier warranty period, the reparations and costs are managed by the supplier.

Corrective Maintenance includes three activities:

- Fault diagnosis – determine a fault's origin and location
- Temporary repair or workarounds – for a brief period of time, while repairs are being made, swiftly restore the necessary functionality of a broken item
- Repair – permanently restore the necessary function

The execution of planned corrective maintenance during the night, grid planned curtailment or low irradiation hours would be regarded as optimal in circumstances when the PV plant or segments need to be taken offline since the total power generation would be either barely or completely unaffected.

The ability to trace problems back to their origin is a crucial component of corrective maintenance. This is most frequently a fault with the manufacturer or model, although it may also be related to poor installation or ambient factors like enclosure temperature. The effectiveness of solutions to issues should be monitored as part of corrective maintenance procedures.

The corrective maintenance can be classified into three levels of intervention:

- 1st level: Intervention without the need for substitution
- 2nd level: Intervention with the need for substitution
- 3rd level: Intervention with the need to intervene on the software of a device

It can also be divided according to the time that was taken to identify, arrive at the site and correct the issue, as per Figure 10:

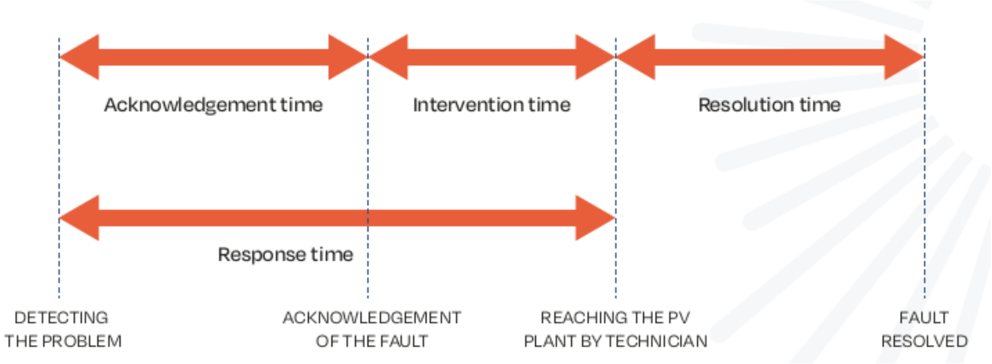


Figure 10 - Time divisions used when dealing with unplanned events

Source: SolarPower Europe (2021)

It is of utmost importance to keep all of the intervals specified above as low as possible to reduce the downtime losses and, in case it evolves into a serious event such as a fire, ensure the safety of the on-site personnel and minimize property damage.

4.4.1 Spare Parts

As previously mentioned, defects and failures can potentially have a major impact on the production of a solar power plant so any parts or components whose malfunctions or breakdown have a major impact on plant production must have a counterpart available in the spare parts inventory ready for the replacement process.

The parameters below are the ones taken into consideration by TERI when compiling a spare parts list:

- Frequency of failure
- Impact of failure
- Cost of spare parts
- Degradation over time
- Possibility of consignment stock with the manufacturer
- Equipment reliability
- Replenishment and delivery time
- Management risk
- Ownership and responsibility of the insurance
- Stocking level
- Equipment warranty starting date (at delivery or at commissioning)
- Location of storage
  - Proximity to the plant
  - Security
  - Environmental conditions

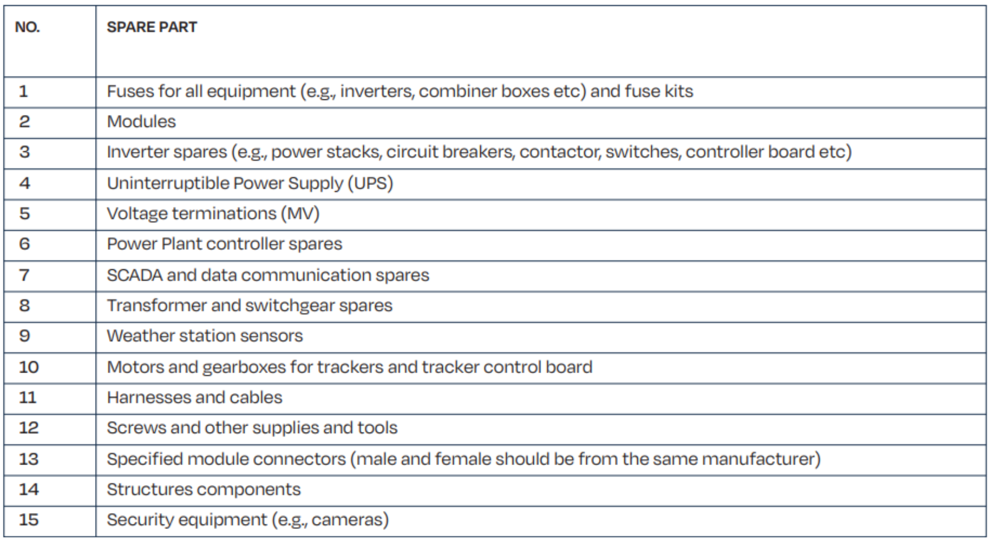
Each region has different needs and demands tied to the expected failure modes. For example, a PV power plant located in a desertic location is more subject to abrasion due to the sand movement and so keeping a larger stock of panels and inverters is advised. On the other hand, a plant in a humid environment is more susceptible to insulation failures so having extra spare cables and conduits is a good practice.

Any equipment in stock must be maintained under the appropriate conditions to avoid degradation and/or damage before usage, be easily identifiable and have the necessary security measures to avoid theft. Also, if other assets are sufficiently close, coordinating with them to have some level of redundancy or a joint stock of spare parts is a very effective solution to reduce costs and ensure a quick response time if an unplanned event occurs.

Any addition or removal of parts from the stock must be registered and reflected on eventual reports. The restocking must be with factory-new equipment and components which are under the specifications of at least equivalent quality, free from defects and with all applicable OEM warranties.

It is also important for the O&M and the asset owner to agree on a set of pieces of equipment that will be the responsibility of the O&M within the agreed-upon fee or if the asset owner must bear the costs of replenishment. Also, there should be a minimum stock that needs to be maintained below which an automatic order for new pieces is made. It is highly recommended to perform an inventory of the spare parts every six months.

The following Figure 11 presents a typical list of equipment that should be present in the spare parts inventory.



NO.	SPARE PART
1	Fuses for all equipment (e.g., inverters, combiner boxes etc) and fuse kits
2	Modules
3	Inverter spares (e.g., power stacks, circuit breakers, contactor, switches, controller board etc)
4	Uninterruptible Power Supply (UPS)
5	Voltage terminations (MV)
6	Power Plant controller spares
7	SCADA and data communication spares
8	Transformer and switchgear spares
9	Weather station sensors
10	Motors and gearboxes for trackers and tracker control board
11	Harnesses and cables
12	Screws and other supplies and tools
13	Specified module connectors (male and female should be from the same manufacturer)
14	Structures components
15	Security equipment (e.g., cameras)

Figure 11 - Example of a spare list for a PV power plant

Source: SolarPower Europe (2021)

4.4.2 Warranty Management

*Keeping a record of the manufacturer's warranties for each piece of equipment on-*site and their possible extension is equally important while operating a PV field.

- Pay attention to and activate the administrative handover by the contractor of the equipment warranty
- Follow equipment manufacturer maintenance requirements
- Store and keep track of dates and conditions of all equipment warranties
- Quickly notify the responsible party or parties of any defects detected to execute the warranty
- A few months before the warranty ends, perform some site inspections to verify the conditions of the equipment and perform the necessary warranty claims if necessary
- Analyse the possibility of warranty extensions when close to the expiration date

A warranty may be avoided by mishandling or not observing instructions or conditions therein. As such the management and supervision of repair activities, including verification of replaced equipment, is essential.

5 CONCLUSION

With the rise of more sustainable global view, focused on renewable energy sources, the photovoltaic sector will only increase in the coming years and, by extent the O&M department will grow in importance being needed more than ever to reassure asset owners and shareholders.

This study's main objective was to create a standard for the photovoltaic branch of TotalEnergies Renewables International's Operation and Maintenance (O&M) procedures. The minimum conditions that the O&M contractor must adhere to can be established by a standard framework like the one that has been proposed as the foundation for creating future contracts.

On the Monitoring and Performance front, the company diligently manages their assets and installs the necessary equipment for their remote surveillance. As for Preventive Maintenance, apart from the Predictive Maintenance which is not widely used yet due to its high cost, they carry out the inspections on all crucial components and adhere to the operating instructions and guidelines provided by the Original Equipment Manufacturers (OEMs) as set out in the annual plan. Finally, for Corrective Maintenance, TERI carefully oversees the execution of corrective procedures, the spare parts inventory and equipment warranties so that power generation is minimally affected.

It is possible to say that even being a rather recent addition to the TotalEnergies group, TERI has rapidly gathered the tools and the knowledge needed to effectively design, build and manage solar power plants in the most diverse environments. As time goes on it will become more challenging to administrate a bigger portfolio but so will the experience play a very important role for an efficient operation.

The present study provides some points that should be taken into consideration when planning the O&M related documentation such as contracts and manuals. Ultimately it falls under TERI to decide, along with eventual contractors and subcontractors, which procedures are to be implemented and which are judged to be unnecessary. At the very least it is advised to check with other sources such as the SolarPower Europe

O&M Best Practices Guide to see what the bare minimum is required for an adequate service.

5.1 Contributions of the work

As previously mentioned, the intention behind this study was to compile a list of best practices for the O&M of photovoltaic power plants that could be used by TotalEnergies in the future.

This is a field that is in constant change with technological advancements and new techniques being developed to better deal with the demands of such complex systems, hence the focus on this being a live document, one that can be updated and worked upon by the company.

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ANEXO A - ARTIGO SÍNTESE

Universidade de São Paulo

Engenharia de Petróleo – Escola Politécnica

Número USP: 10404232 **Data: 22/11/2022**

Case Study of the Operation & Maintenance Standard Practices of a Company in the Photovoltaic Sector

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Co-Orientador: Prof. Dra. Regina Meyer Branski

Artigo Sumário referente à disciplina PMI3349 – Trabalho de Conclusão de Curso II
Este artigo foi preparado como requisito para completar o curso de Engenharia de Petróleo na Escola Politécnica da USP. Template versão 2021v01.

Abstract

One of the most frequently brought up issues in discussions on sustainable development is the energy transition. Due to this push, renewable energy sources have been brought to the forefront with the photovoltaic sector going on an upward trend in the last years with no prospects of slowing down. Solar power plants are complex installations with long life cycles. The focal point of any project is an operation with the minimum possible variables that may cause unforeseen events. Such events result in additional costs due to technical difficulties and diversion of resources dedicated to other activities, mainly contracted labour, and may even, in extreme cases, negatively impact the image of the parties involved. As consequence, the Operations & Maintenance (O&M) department will gain importance and become more crucial than ever in order to ensure that the power plant will be functioning at optimal levels.

The objective of this work is to offer some considerations that ought to be made while creating contracts and manuals that are relevant to O&M in the form of best practices. This was achieved by carrying out a case study at a company with a global clientele that is constantly expanding. The first step was conducting a thorough research of company documentation, which included data from every region in the portfolio and then consulting with experts from various departments to assess the material obtained and suggest the required improvements. The end result was a compilation of Operation and Maintenance (O&M) practices performed by said company covering the topics of Monitoring and Performance, Preventive (and Predictive) Maintenance, Cleaning Management and Corrective Maintenance.

The final document shows as close as possible the totality of situations and the best operating and maintenance procedures adopted by the company and which, therefore, should be standardised. Additionally, new information can be added as time progresses, following any developments or strategies.

1. Introduction

In the last few years, the energy transition has been one of the most recurring topics and is at the forefront of any discussion regarding sustainable development. The year of 2022 marks the first time capital investment in renewables has surpassed the one for fossil fuels, according to a report by RYSTAD ENERGY (2022), mainly due to the price of electricity decreasing the payback time to close to a year.

Many of today’s Big Oil companies such as Shell, TotalEnergies and British Petroleum have expanded their portfolio to enter the renewable market, designing, financing, building and operating projects all over the world, with most of them being either wind or solar farms.

Running wind and especially solar power plants is a complex endeavour, as is any major undertaking, requiring technical, managerial, social and legal knowledge to operate it at or as close as possible to peak performance. Though all are of import, none take more precedence than its maintenance, since it is an activity that will remain a constant throughout the entire lifetime of the project, which is generally advertised by solar panel manufacturers to be 25 years. This service is the one that most reflects on the performance of the power plant and translates directly to a gain or loss in revenue, so constantly surveilling the data produced by the equipment and acting upon this information so as to avoid any downtime.

The main goal of this study was to compile a standard for Operation and Maintenance (O&M) practices of TotalEnergies Renewables International's photovoltaic branch that can be easily consulted and be based upon when and if needed. A standard framework such as the one proposed here can serve as a baseline for drawing up future contracts, setting up the minimal terms with which the O&M contractor needs to comply.

2. Bibliographic Review

Here a brief explanation is given of how photovoltaic power plants work, going over their main equipment's functions.

According to the National Renewable Energy Laboratory (2022) Solar Photovoltaic Technology Basics site, photovoltaics (PV) gets its name from the process of converting light (photons) to electricity (voltage), which is called the photovoltaic effect. This phenomenon was first exploited in 1954 by scientists at Bell Laboratories who created a working solar cell made from silicon that generated an electric current when exposed to sunlight. These cells are then grouped in modules to increase the power output.

The modules are installed in their mounting systems which can have an integrated tracking system to further increase the efficiency by accompanying the sun's trajectory. The direct current (DC) power generated by the modules, is transferred to the inverters, converting it to alternating current (AC) for proper transmission. Finally, the voltage is increased for its injection on energy grid by means of transformers.

3. Methodology

The chosen method for the analysis was Case Studies. It employs qualitative information that was gathered from actual occurrences in order to explore, describe, or otherwise explain contemporary phenomena in their own context. It is distinguished by being a thorough examination of a small number of items, or perhaps just one, resulting in in-depth understanding (BRANSKI et al., 2010). The case study will be carried out with the company TotalEnergies Renewables International, more specifically in its photovoltaic sector.

The steps taken during the development of the work are showcased on the flowchart on Figure 1.

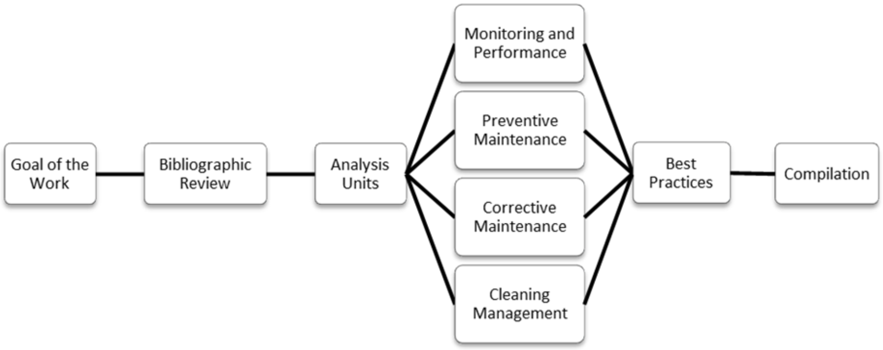

Figure 1 - Steps of the case study

Source: Author (2022)

The objective of the research was to analyse how the topics highlighted before are structured in a company and how they can be used to create a guide of best practices. A framework for analysis was created from the examination of the bibliographic review, and it served as the foundation for the formulation of the proposition and the creation of the case study.

The proposition that jump-started all was that all processes and procedures used for the Operation and Maintenance (O&M) of a solar power plant should be standardized to avoid confusion, ease the drafting of contracts and the onboarding of workers as well as increase efficiency.

The information used to take the conclusions present in this work were retrieved in two stages:

- The first was the checking of multiple site-specific contracts and manuals, either from the Engineering, Construction and Procurement (EPC) phase (before Commercial Operation Date) or the Operations and Maintenance (O&M) phase (after Commercial Operation Date), which contained data from all geographies within the portfolio of the company so as widespread as possible.
- Second was, after creating a compilation from the previous documents, setting up a team of Subject Matter Experts that would review the gathered information and propose the necessary adjustments according to their know-how and experience.

Finally, all information was organized into a best practices manual that could be distributed to the company as a whole. Four categories were highlighted as the most important with regards to keeping the solar power plant operating optimally: Monitoring and Performance, Preventive Maintenance, Cleaning Management and Corrective Maintenance The results obtained in the survey will be presented on the following pages.

4. Results

TotalEnergies Renewables International (TERI) is a subsidiary of the TotalEnergies Group that focuses on the development of renewable energy projects, mainly in the wind and solar domains, outside of the French territory.

Its portfolio is present in a wide spread of geographies including Chile, USA, Spain, Japan, South Africa, UAE and Qatar, totalling almost 1,8 GWp (maximum DC output capacity produced by the solar panels) of installed gross capacity plus the plants in India, which are operated in conjunction with the Adani Group and are counted separately, with new projects on the pipeline or already under construction that will be ready for production in the coming years.

The Asset Performance department is the one responsible for supporting and ensuring that the companies working for the Special Purpose Vehicles (SPV) running the power plant or portfolio will conform to the obligation set out on the contracts. This means helping them maximise the energy production while decreasing costs, plant downtime and risks, thus increasing the revenue obtained in order that the plant is following its business plan model.

The head of Asset Performance was the one who first put forth the idea of compiling the best practices for the Operation & Maintenance which then evolved into a large-scale project and paved the way for this study.

4.1. Monitoring and Performance

Collecting, treating and analysing the critical information of an asset to know its operational status and Key Performance Indicators (KPIs), then using them to have a meaningful Management Information System (MIS) for fact-based decision making and way forward for continual improvement is a vital part of running a photovoltaic power plant.

4.1.1. Supervisory Control and Data Acquisition System (SCADA)

A SCADA can be used to manage assets and gather vital data about them. Based on its design, equipment installation, and the unique data and control requirements of the owner, plant operator and grid operator, a SCADA set-up (combination of hardware and software monitoring platform) might differ from plant to plant.

It enables 24/7 remote monitoring both locally and in the head office, anomaly notifications, remote control of key components, compliance with grid operator requirements, acquisition of operational data to assess the performance and access to on-site monitoring systems by the project company, any financing party and their respective advisers.

It is important to store the historical data for operational analysis and hence, adequate storage and backup infrastructure set-up is mandatory at both the site level as well as the central level.

4.1.2. Monitoring and Control

Several service providers offer ready-made and adaptable solutions for the real-time monitoring of a renewable plant, both globally and locally. These monitoring solutions typically connect to the site SCADA and offer remote supervision and control capabilities via Human-Machine Interface (HMI) displays.

These platforms also include fundamental analytical tools that turn the unprocessed data from plant equipment into a useful graph, trend chart, or table to immediately identify the areas that require the owner's or operator's urgent attention. Such system-generated feedback promotes asset performance and safety. Some monitoring solutions also provide a detailed view of performance KPIs, management reports and dashboards.

4.1.3. Computerized Maintenance Management System (CMMS)

These monitoring solutions frequently include a service ticketing system or CMMS. The ticketing system is used to record all anomalous events, which are often referred to as breakdown or unplanned maintenance events, in the form of a maintenance ticket or service call. The system would produce a service ticket in the case of such equipment/plant failure, which could then be transferred to a site O&M team. The appropriate remedial action will be taken by the selected and authorised employees to eliminate the anomaly and restart the equipment/plant.

It goes without saying that the information captured by such a ticketing system is extremely valuable for several operational analyses, like Mean Time To Repair (MTTR), Mean Time Between Failure (MTBF), equipment serial failure, spares and consumable planning etc.

Additionally, the ticketing can be done not only for unscheduled events but also for the normal maintenance procedures, so that they can be automatically added to a logbook.

4.1.4. Plant Performance Analysis

One of the essential tasks to guarantee the safety of the assets and maximum production from the plant is performance analysis of the plant. The operational Key Performance Indicators (KPIs) for a plant are, for example, Energy generation, Weather resource analysis, Plant availability, Grid availability, Performance ratio (PR), Waterfall analysis, Inverter PR deviation histogram, Mean Time To Repair (MTTR), Mean Time between Failure (MTBF), Top 10 / 20 error analysis, Spare parts consumption, SCADA data quality and availability.

The raw data accessible at the plant or at the SCADA/monitoring system may be used to gather all of the KPIs above to perform the analysis and, based on company needs and the importance of the information, the frequency in which it is carried out may be decided upon, with monthly being the ideal and most widely adopted. There are more specialised analyses that can be taken into consideration dependent on location and event since the aforementioned indicators are general and will not cover the complete spectrum.

4.2. Preventive Maintenance

The key component of maintenance services for a PV plant is preventive maintenance operations. They include routine visual and hands-on inspections as well as verification procedures carried out at predetermined intervals on all crucial components and are required to adhere to the operating instructions and guidelines provided by the Original Equipment Manufacturers (OEMs). As well as lowering the likelihood of failure or deterioration, it must uphold any equipment and component. The actions must comply with the relevant regulatory requirements, such as national standards for the routine examination of certain electrical components, and HSE regulations. This list of services, together with the frequency of each task, should be included in the O&M contract (SOLARPOWER EUROPE, 2021).

This upkeep is done at pre-set intervals or by the recommended OEM and O&M manuals. These are outlined in a thorough yearly maintenance plan, which also offers a set timeline and a predetermined number of maintenance iterations.

Equipment require integrity, thermographic and measurement inspections, tightening, cleaning, verification of sensors, oil sampling, grounding tests, cabling and battery checks, calibration, not to mention the more streamline practices like replenishing fire extinguishers, tending to roads, building and fences, putting in place pest control measures.

4.2.1. Predictive Maintenance

By continuously monitoring, supervising, forecasting, and analysing performance data (such as historical performance and anomalies) of the solar PV power plant, the O&M can do predictive maintenance. This can spot tiny patterns that would otherwise be missed until the subsequent cycle of circuit testing or thermal imaging examination and that foreshadow component or system breakdowns or underperformance.

These alterations in behaviour are frequently connected to the predictable or unpredictable process of equipment deterioration. It is crucial to identify and keep track of all critical wear-out status factors based on the installed sensors, the algorithms used in the monitoring system, and other methodologies.

Following said research, the O&M may put predictive maintenance procedures in place to guard against potential failures that can result in safety concerns or a reduction in energy production.

4.3. Cleaning Management

One of the most important maintenance tasks is cleaning PV modules since dirtier PV modules absorb less solar energy, which reduces the operational plant's output of electricity. Based on various site and operating conditions, this section describes how to adapt and apply several cleaning methodologies that are best suited for a typical PV solar plant. However, it is also advised to take all the plant-specific conditions and challenges before finalizing the cleaning methodology.

Factors such as climatic conditions, terrain, type of soil, surroundings, type of module mounting system, water accessibility, demand and cost, cost of cleaning versus loss due to soiling and cost of labour influence how often and what type of methodology to use when cleaning.

Charter 1 shows the pros and cons of the current strategies used by TERI.

Charter 1 – Comparison between different cleaning methods

Source – TotalEnergies Renewables International (2022)

Cleaning strategy	Pros	Cons
Fully autonomous robotic dry cleaning	High frequency, less soiling loss, remotely operated, self-powered, no water consumption, less O&M intervention	High CAPEX, after-sales services, restricted operation in adverse climatic conditions, precise coordination between the structure and robots
Semi-automatic robotic dry/wet cleaning	Better than manual cleaning, larger installed base (MWp) can be cleaned per day, lower CAPEX and water consumption for cleaning	Dependency on labour to mount and unmount the robots, potential risk of module damage if improperly handled
Hydrant system or Manual cleaning	Manual cleaning does not require initial investment	Hydrant system is capital-intensive installation, water needs to be close to the point of cleaning, dependency on labourers and unsustainable

4.3.1. Snow removal

For geographies with colder (subzero temperatures) climatic conditions, the removal of a layer of snow from the PV Module is also an essential maintenance activity to ensure the optimum output from the PV solar plant. Various semi-automatic and manual methodologies can be adapted to remove the snow.

It is more expensive than normal cleaning processes, depends on the frequency of snowfall and the thickness of the cap, has a high cost and upkeep and the cost of labour is also high considering the weather.

There are new and innovative solutions in development but currently these are far too costly to be viable.

4.4. Corrective Maintenance

Any task carried out to put a PV plant system, piece of equipment, or component back in working order is known as corrective maintenance. It can take place following a defect or a failure discovered by remote monitoring and supervision, as well as during routine inspections and particular measuring tasks (SOLARPOWER EUROPE, 2021).

Corrective Maintenance includes three activities:

- Fault diagnosis – determine a fault's origin and location
- Temporary repair or workarounds – for a brief period of time, while repairs are being made, swiftly restore the necessary functionality of a broken item
- Repair – permanently restore the necessary function

The execution of planned corrective maintenance during the night, grid planned curtailment or low irradiation hours would be regarded as optimal in circumstances when the PV plant or segments need to be taken offline since the total power generation would be either barely or completely unaffected.

The ability to trace problems back to their origin is a crucial component of corrective maintenance. This is most frequently a fault with the manufacturer or model, although it may also be related to poor installation or ambient factors like enclosure temperature. The effectiveness of solutions to issues should be monitored as part of corrective maintenance procedures.

There are three levels of intervention:

- 1st level: intervention without the need for substitution
- 2nd level: intervention with the need for substitution
- 3rd level: intervention with the need to intervene on the software of a device

It can also be divided according to the time that was taken to identify, arrive at the site and correct the issue which all be as small as possible to reduce the downtime losses and, in case it evolves into a serious event such as a fire, ensure the safety of the on-site personnel and minimize property damage.

4.4.1. Spare Parts

As previously mentioned, defects and failures can potentially have a major impact on the production of a solar power plant so any parts or components whose malfunctions or breakdown have a major impact on plant production must have a counterpart available in the spare parts inventory ready for the replacement process.

Any equipment in stock must be maintained under the appropriate conditions to avoid degradation and/or damage before usage, be easily identifiable and have the necessary security measures to avoid theft. Also, if other assets are sufficiently close, coordinating with them to have some level of redundancy or a joint stock of spare parts is a very effective solution to reduce costs and ensure a quick response time if an unplanned event occurs.

Any addition or removal of parts from the stock must be registered and reflected on eventual reports. The restocking must be with factory-new equipment and components which are under the specifications of at least equivalent quality, free from defects and with all applicable OEM warranties.

4.4.2. Warranty Management

Keeping a record of the manufacturer’s warranties for each piece of equipment on-site and their possible extension is equally important while operating a PV field.

A warranty may be voided by mishandling or not observing instructions or conditions therein. As such the management and supervision of repair activities, including verification of replaced equipment, is essential.

5. Conclusion

With the rise of more sustainable global view, focused on renewable energy sources, the photovoltaic sector will only increase in the coming years and, by extent the O&M department will grow in importance being needed more than ever to reassure asset owners and shareholders.

This study's main objective was to create a standard for the photovoltaic branch of TotalEnergies Renewables International's Operation and Maintenance (O&M) procedures. The minimum conditions that the O&M contractor must adhere to can be established by a standard framework like the one that has been proposed as the foundation for creating future contracts.

It is possible to say even being a rather recent addition to the TotalEnergies group, TERI has rapidly gathered the tools and the knowledge needed to effectively design, build and manage solar power plants in the most diverse environments. As time goes on it will become more challenging to administrate a bigger portfolio but so will the experience play a very important role for an efficient operation.

The present study provides some points that should be taken into consideration when planning the O&M related documentation such as contracts and manuals. Ultimately it falls under TERI to decide, along with eventual contractors and subcontractors, which procedures are to be implemented and which are judged to be unnecessary. At the very least it is advised to check with other sources such as the SolarPower Europe O&M Best Practices Guide to see what the bare minimum is required for an adequate service.

6. References

Internal company documents and knowledge

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