Techno economic analysis of improving energy output of an existing solar PV power plant

Hamid Iftikhar
hamid.iftikhar@tecnico.ulisboa.pt
Instituto Superior Técnico, Universidade de Lisboa, Portugal
November 2019

Abstract

Solar photovoltaic deployment has shown an exponential growth in the last decade owing to huge decrease in production cost, receiving the largest investments and has provided maximum number of jobs in renewable energies sector. Research is being carried out to improve energy conversion efficiency and on the other hand existing power producers are finding ways to improve operations and maintenance to increase the energy output. In this regard, performance assessment of an 18 MW single axis tracking solar PV power plant in Pakistan has been conducted. In the light of best global practices, plant operations and maintenance practices have been evaluated and software simulations have been performed to verify the overall performance by comparing the simulated results with the plant annual energy output. It has been found out that the plant is underperforming by 4.13% leading to a potential monetary loss of € 175,042/year which can lead to a loss of € 2,575,811 throughout the effective lifetime of the project. This loss can be converted into additional revenue through improvement of operations and maintenance practices, measurement of key performance indices, measurement of power plant losses, data collection at strings level, portfolio level performance comparison and incorporating latest techniques such as aerial drone thermography, automated plant diagnosis etc.

Key words: Performance Assessment, Single axis tracking solar PV, PVsyst, Global best practices, Operations and Maitenance

1. Introduction

Renewable energy deployment has been on the rise since the last decade. Statistics from International Renewable Energy Agency (IRENA) Renewable Capacity Statistics report 2019 shows a 107% increase in the last decade in terms of installed power capacity from 1136 GW in 2009 to 2351 GW in 2018 [1]. Amongst the renewable energy technologies, hydro, wind and solar account for the majority share of the installed capacity which contribute up to 50%, 24% and 20% respectively [2]. In the last decade solar photovoltaics has not only shown an exceptional percentage increase of approximately 2000 percent, but has also shown the maximum installed capacity in the last year with 94 GW of new capacity installed in 2018 [1], [2], [3]. Similarly in terms of jobs creation by renewable enegry technologies, solar PV has led the way with 3,605 thousand jobs followed by liquid biofuels, hydropower and wind [4]. This rapid deployment and job creation can be accredited to a sharp decrease in the cost of technology. A report from IRENA Renewable power generation costs in 2018 shows that since 2010 prices for utility scale solar PV power plants have decreased from 66% in United States to as much as 84% in India [5]. Decrease in price of installed capacity led to decrease in price of energy production as well. Average LCOE declined from 62% in Japan to as much as 80% in Italy. [5].

After installation, operations and maintenance (O&M) is one of the most critical aspects of the power plant. It is the most jobs intensive segment employing 1/3rd of the total workforce employed in the solar PV sector and entails the longest phase during the lifecycle of a PV power plant lasting 25-35 years [6]. Effective operations and maintenance has the potential to improve LCOE and positively impact returns on investment [6]. As per a report by published by International Finance Corporation (IFC) [7], power plant operations and maintenance's objective is to maximize the energy yield and the useful life of the plant while minimizing the costs. A holistic approach is adopted to address O&M issues (natural degradation, component failures, weather conditions and other issues such as fixing SCADA faults, repairing tracker faults etc.) under the operations and maintenance annual plan, which is usually divided in preventive, corrective and conditioned-based maintenance categories [8]. The performance of the power plant is judged based on its operations and maintenance data collection, reporting, and effectiveness of response on O&M issues arising throughout the year. International standard IEC 61724 published by International Electro Technical Commission (IEC) is considered the basis for performance assessment of solar PV power plants [9]. The standard ICE 61724, lists and describes the mandatory parameters that need to be evaluated to determine the performance of the solar PV system. The parameters are array yield, final yield, reference yield, performance ratio, capacity factor, module, inverter and system efficiency and total energy generation. These indicators provide a foundation on which solar PV systems can be compared, operating under different conditions [10].

The objective of this study is to analyze operations and maintenance practices and perform performance assessment to an existing power plant. The methodology opted has been to acquire power plant operations and maintenance data, energy output results and weather data; compare the O&M with global best practices and compare the plant energy output with globally recognized software simulation results, simulated with inputs of actual ground weather data to reach precise results. A case study of an existing 18 MW single axis tracking solar PV power plant in Pakistan has been used for the study and recommendations concerning any improvements based on best global practices have been provided.

2. Best practices in Operations and Maintenance of powerplants

Solar PV power plant operations and maintenance are categorized as separate divisions of activities at the plant site. Plant operations correspond to remote and on-site monitoring, control and supervision of the plant, in which documentation management is an integral part (datasheets, input record control – alarm descriptions, etc.). Maintenance on the other hand involves inspection and restoration of the plant to its normal conditions, which can be divided down in preventive, corrective, annual and extraordinary maintenance categories. Detailed data collection and analysis of the power plant is the first step in precise performance analysis. As a minimum requirement, plant's performance should be compared at various levels, starting from *portfolio level*, going to *plant level* then to *inverters level* and down to *strings levels* as a best practice which allows accurate troubleshooting possibilities in shortest times, helping improve plant availability. Key performance indicators (KPIs) mentioned tabulated in Table 12 and explained as follows, provide a technical basis to compare and evaluate performance at various levels. *Reference yield* (Y_r) corresponds to theoretically possible yield at ideal conditions with no losses considered over a specific time period (daily, month, yearly). It is the total in-plane irradiance (H_{POA}) divided by reference irradiance (G_{STC}) of 1000 W/m^2 at Standard Test Conditions [11],[12].

$$Y_r = H_{POA}/G_{STC} \quad \text{(i)}$$

Specific yield (Y_i) is the actual, total energy generated (E_i) per installed power capacity (P_o) over a specific time period (daily, month, yearly)[6].

$$Y_i = E_i/P_o \quad \text{(ii)}$$

Performance ratio (PR) is a quality indicator that is defined by the ratio of specific yield (Y_i) per reference yield (Y_r) [13].

$$PR = (Y_i/Y_r) \times 100 \quad \text{(iii)}$$

Expected Yield ($Y_{exp\,(i)}$) is calculated by multiplying reference yield by expected PR. It is based on previous values of irradiation data.

$$Y_{exp\,(i)} = PR_{\,exp\,(i)} \times Y_r \quad \text{(iv)}$$

Energy Performance Index (EPI) is the ratio between specific yield and the expected yield.

$$EPI = Y_i/Y_{\,exp\,(i)} \quad \text{(v)}$$

Technical availability (Uptime) and *energy-based availability* are closely described terms. Technical availability corresponds to the time the plant operated divided by the possible time it was able to operate. Possible time of operation corresponds to the time, the plant received irradiations above the minimum irradiance threshold level. *Plant uptime* shows the downtimes in the plant irrespective of the cause while energy based availability contains certain exclusion factors [6]. *Acknowledgment time*, also called reaction time is the time between detection of a problem and dispatching a technician to rectify the fault. *Intervention time* is the time taken by the technician or third-party support to reach the site of fault. *Response time* is the sum of acknowledgment and intervention time. *Resolution time* corresponds to the time taken to resolve the issue from the time the technician or the third party reaches the site.

2.1. Additional Key Parameters

Apart from the key performance indicators, field inspections such as infrared thermography, IV curve tracing, electroluminescence imaging and soiling measurements are recommended. *Infrared thermography* is used to detect the heat differential between solar cells through which it is determined whether any of those cells are damaged or defective (such as hotspots, inactive substrings and inactive modules) [6],[14], [15] . It is also be used to inspect inverters, cables, switches, fuses, and batteries. *IV curve characteristic measurements* are conducted to determine open-circuit voltage, short-circuit current, power, series and shunt resistance, fill factor etc. of PV modules. *Electroluminescence imaging* helps to identify microcracks, which are not conclusively identified by infrared thermography. For *soiling*, generally ground based measurements are conducted where a reference module is soiled, another reference cell is cleaned, and a third reference cell is automatically cleaned. Digital solutions such as satellite imagery, remote sensing techniques combined with machine learning algorithms are a recent trend.

2.2. Power Plant Maintenance

According to guidelines in operations and maintenance [6], power plant maintenance should be categorized in five sectors and be conducted in coordination with the analysis of operations' team. The five sectors are; *Preventive maintenance* which includes physical inspections and compliance with operations manuals. Annual maintenance plan is a part of preventive maintenance. *Corrective maintenance* is performed to restore the faults in equipment or components to bring them back to functioning state properly. *Predictive Maintenance* is condition based maintenance carried out after keen monitoring, analysis and evaluation of main parameters of the degradation of equipment under observation. *Additional maintenance* includes activities such as modules cleaning, vegetation control, buildings control, perimeter security etc. *Extraordinary maintenance* aims to cover unpredictable events taking place on the plant such as force majeure, event of theft, fire, modifications mandated subsequently by regulatory authorities.

3. Analysis of Power Plant based on a predictive Software Simulation

Various software are used to simulate energy production in solar PV systems. A study has been conducted to determine which software to use to create a baseline against which the plant output could be compared.

A review article published in 2014 [16], mentioned approximately 50 solar PV industry related software tools categorized as tools for simulation, economic evaluation, PV industry relevance, analysis and planning, string design, system sizing, monitoring and control tools, solar radiation maps and online software. Amongst them the authors compared 12 simulation software namely PVsyst, Homer, RETScreen, TRANSYS, INSEL, PV F Chart, SAM, solar design tool, ESP-r, Solar Pro, PV Design Pro-G and PVSOL. They recommend PVsyst to be the most appropriate software to be used amongst all. A detailed study was published in 2015 [17], compared 7 different solar PV design software, Homer, PV F chart, PV Planner, PVsyst, RETScreen, SAM, Solar Pro on the basis of functions, user interface, historical weather data, module and inverter information and pricing. For user interface and functions categories Solar Pro was on top followed by PVsyst. In terms of weather data PVsyst stood at the first place while for module and inverter information PVsyst along with Solar Pro shared the top position. For pricing PVsyst and SAM received the highest points of the table. Another review article published in 2018 [18], compared main features of 10 simulation software. The software compared were HelioScope, HOMER, PVsyst, PVSOL, PV F Chart, RETScreen, SAM, Solarius PV, Solar Pro and SOLARGIS. The research focused on degradation and performance analysis of 1 MW PV power plant and compared software simulations results to actual power plant data. The results found out PVsyst, Homer, RETScreen and SAM to be the suitable software in the comparison. Considering the results of all these review articles, PVsyst seems to be the most appropriate choice to be used for the simulation of solar PV power projects. PVsyst has also been used by the 18 MW power plant during their design phase for setting a baseline; additionally, in Pakistan, the electricity regulatory authority, “National Electricity Power Regulatory Authority (NEPRA)” and global commercial banks consider the simulations performed by PVsyst to be authentic and use its simulations as an integral part for their economic assessment and financing of solar PV projects. Considering all the reasons, PVsyst has been preferred as an analysis tool for simulation of the 18 MW single axis tracking solar PV power plant.

3.1. Power Plant Losses

During powerplant operations, many factors lead to losses and degradation of the system. A study conducted in Ghana [19], calculated a decrease of 18.2 – 38.8% of generated power during the lifetime of the power plant which they mention is equivalent to degradation of 1.54% per year. A study performed in India [20], reported that the solar PV power-plant degradation ranges between 0.6% to 5% per year. In this regard, it is important to consider various factors that lead to energy losses and system degradation while performing power plant simulations. PVsyst, the software used for the simulations, allows the users to input and modify several loss factors. *Near or linear shading loss* is shading produced by near objects which create losses because of less inter row/column spaces between tables of the solar modules as some irradiance does not fall on the panels [21]. *Array incidence loss or IAM (Incidence Angle Modifier)* refers to decrease of the irradiance reaching the PV cells' surface, in comparison with the irradiance falling under normal incidence. This loss occurs due to the glass cover on the panel which increases the angle of incidence. Results show that this loss should not be more than 3% [21]. *Soiling loss* is the loss in power of the module due to dirt, snow, dust and particles that cover the surface of the PV panel. A study conducted by Kimber et. al in 2001 [22], studied 250 sites and applied a linear regression model to characterize soiling losses. They found out that soiling losses account for a range of 1.5% to 6.2% of losses depending upon the location of the plant. A report on uncertainty in long-term photovoltaic yield predictions states 2% reduction in efficiency for losses due to soiling [23]. *Loss due to irradiance level & temperature* correspond to decrease in solar PV system efficiency because of lower level of irradiance or higher level of temperature [21]. *Module quality loss or module rating* is the difference between the nameplate and actual power of the module. It is the tolerance specified by the manufacturer (e.g. +- 5%), which is generally on the negative side. PVsyst recommends a 1.5% average module quality loss in its simulations [21], [23]. Crystalline solar cells show *light-induced degradation* (LID) during an initial prolonged exposure to light. As per a publication by NREL, LID can reduce cell efficiency by 0.5% to 1.5% [24]. A research conducted in India has taken this factor to be 2.5% [20]. PVsyst’s default setting takes this value as 2%. *Module array mismatch loss* is loss which arises because of inequality of voltage and current when modules of same nameplate power capacity are connected together in series of parallel connections [22]. A study on performance comparison on mismatch losses [25] shows that mismatch losses can be minimized to less 1% using genetic algorithm technique. *Ohmic wiring loss* between PV module and the inverter should not be more than 2% at standard test conditions whereas with optimum design and selection of right cables it can be reduced up-to 1% [21]. Another study revealed that for a well-designed plant the losses usually range between 1.2% to 1.5% [26]. PVsyst, takes a default value of 1.5% for this loss. *System unavailability* refers to the downtime in production due to planned and unplanned maintenance activities. PVsyst takes an average of 2% as a default value for this loss. Other studies suggest it to be decided based on operations and maintenance contract and an average value for this should be between 0.5% to 1% [21], [26].

3.2. Latest Trends

Operations and maintenance activities are anticipated to reduce the levelized cost of electricity by 0.8% to 1.4% from 2015 to 2030 [27]. This reduction shall be materialized using latest trends and innovative techniques, two of which have been described as follows: *Aerial Drone Thermography:* Infrared thermographic can be conducted by mounting thermographic cameras on unmanned aerial vehicles instead of using handheld devices [15]. A power plant as large as 12 MW_p can be inspected in one day using this technology, saving time, labour and resources [6],[14]. *Automated Plant Diagnosis* using bottom-up approach utilizing big data mining techniques, starting from string level data acquisition and processing, combined with predictive maintenance and artificial intelligence is an approach to save time by reduction in expert data handling and provide improved analysis [6]. Research carried out on park of six solar PV power plants up to 10 MW of installed capacity with data from more than 100 different inverter modules collected over two years, indicated that fault prediction (automated plant diagnosis) of up to 7 days in advance was possible with sensitivity of 95% [28].

4. Power Plant Operations & Maintenance Review – Case Study of power plant in Pakistan

Solar PV power plant with an 18 MW installed capacity and single axis tracking system is located at latitude of 30.5815^0, longitude 72.8944^0 and an altitude of 144m in Harappa, Pakistan. As per the power plant management, the location for the plant was selected considering the amount of annual solar irradiation, availability and cost of the land and availability of national grid to transfer the energy produced. Each PV modules mounted on the plant has 320 Wp power rating, open-circuit voltage of 31 V and is made of polycrystalline silicon, produced by Phono Solar, model PS 320P-24/T. Modules are installed in rows with a 7 meters distance to avoid the impact of shading.. PV modules and inverters specifications have been listed in Table 1.

Table 1: PV Modules and Inverters Specifications

PV Modules		**Inverters**	
Manufacturer	Phono Solar	Manufacturer	Sungrow
Model	PS 320P-24/T	Model	SG500MX
Technology	Polycrystalline Silicon	Technology	Tri-phase, 50-60 Hz
Power	320 W	Power	500 kW
Short Circuit Current	8.950 A	Nominal AC Current	917 A
Current I mpp	8.640 A	Maximum AC Current	1008 A
Open Circuit Voltage	46.4 V	Minimum Voltage	460 V
Voltage V mpp	37.0 V	Maximum Voltage	850 V
Module efficiency	16.59 %	Euro Efficiency	98.7 %

In terms of operations and maintenance reporting and documentation, the power plant management creates comprehensive monthly reports. The reports for O&M have been provided for a time period of one year from January 2018 till December 2018 covering the following aspects

- Plant operations and performance
- Outages (Planned, External and Internal)
- Plant maintenance (Corrective, preventive and spare parts)
- Areas of improvements
- Safety, housekeeping and accidents
- Trainings (Internal and external)

4.1. Plant Operations and Performance

Operations and performance reports of the plant from every month have been summarized and presented in Table 2. Key figures such as plane of array (POA), performance ratio, capacity factor, plant availability and energy export are measured on regular basis.

Table 2: Plant operations and performance data

	Operations					**Maintenance**
Months	**Energy Export (MWh)**	**POA (kWh/m^2)**	**Performance Ratio (%)**	**Capacity Factor (%)**	**Plant Availability (%)**	**PV Modules Cleaning**
January	1873.12	121.82	85.43	13.99	99.63	4.5
February	2158.26	140.41	85.38	17.84	100	4
March	3048.09	210.52	80.43	22.76	99.98	4
April	3216.25	224.14	79.71	24.86	99.99	4

May	3207.55	228.89	77.84	23.95	100	4
June	2773.8	195.08	78.98	21.4	100	4
July	3206.63	219.63	81.10	23.94	100	1.5
August	3113.4	215.41	80.28	23.25	100	4.5
September	2860.82	193.06	82.31	22.07	99.99	4
October	2386.89	161.58	82.05	17.82	99.99	4
November	1704.41	118.42	79.95	13.15	100	4
December	1777.95	118.01	83.69	13.28	100	4
Total	**31327.7**	**2146.97**	81.43	19.86	99.96	3.875

4.2. Plant Outage / Unavailability

Three types of outages/plant unavailability have been reported. *Planned outages* correspond to planned, informed plant shutdown. *Internal tripping* corresponds to unforeseen events taking place on the plant site. *External outages* are unforeseen events taken place on the national grid which when trips, leads to loss of energy produced. As per the reports planned outage kept the plant unavailable for 1009 minutes during the year, external tripping resulted in loss of 874 minutes and internal tripping only took place for a total of 13 minutes. During the internal outages, most of these issues were caused by problems within inverters.

4.3. Plant Maintenance

Maintenance conducted at the power plant site has been categorized into corrective and preventive maintenance categories. Corrective maintenance has been performed and documented with pictorial evidences of maintenance activities performed on the plant site. Table 3 shows the number of corrective maintenance performed on different plant components throughout the year. As per the documented record, most of the maintenance activity has been performed on the trackers followed by transmission lines, combiner boxes and inverters.

Table 3: Corrective maintenance performed on plant components throughout the year

Equipment	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
Tracker Systems	2	2	3	3	3	42	25	61	82	116	109	112	560
Transmission lines/Grid	0	0	2	5	10	5	10	1	2	3	3	6	47
General	0	0	0	0	1	2	9	3	1	4	9	4	33
Combiner Boxes	1	2	4	3	2	3	4	0	1	0	1	0	21
Inverters	0	0	1	1	1	3	3	0	3	2	0	0	14
CCTV	0	0	0	0	2	0	1	0	7	2	1	0	13
RO Plant	0	0	0	0	0	0	1	1	0	2	0	1	5
Transformers	1	1	0	0	0	0	0	0	0	0	0	1	3
UPS	0	0	0	0	0	0	0	0	0	1	0	1	2
PV Modules	0	0	0	1	0	0	0	0	0	0	0	0	1
Cables	1	0	0	0	0	0	0	0	0	0	0	0	1
Fire Alarm	0	0	0	0	0	0	0	0	1	0	0	0	1
Total	5	5	10	13	19	55	53	66	97	130	123	125	**701**

Preventive maintenance at the power plant is performed through a detailed and documented annual plan. Reports show components (PV modules, PV arrays, Inverters, Controllers, AC wiring, DC wiring, Combiner and Junction boxes, IT, Trackers, Transformers, Sub-station and Transmission Line Equipment), executed preventive maintenance activities and the time schedule after which inspection, servicing, testing or cleaning has to be performed. Annual activities take place in September while bi-annual activities took place in March and September.

5. Results, Analysis and Recommendations

5.1. Software Simulations for 18 MW single axis tracking power plant

PVsyst has been used as software simulations tool for the 18 MW single axis tracking power plant. Simulations have been performed on three different weather data sets (Meteonorm weather data, NASA weather data and Plant site weather data) available on the software. Four potential system losses cases have been considered during the set of simulations carried i.e.

- Simulation with no losses (Theoretical maximum energy production)
- Simulation with software default losses (Industry average losses)
- Simulation with plant site conditions losses (Closest to actual plant conditions)
- Simulation with minimum losses achievable as per literature review (Aspiration to achieve)

Simulation with no losses provides an insight into the theoretical maximum energy that can be produced. It is practically impossible to have such a system output but provides a valuable information of amount of losses created by different types of losses under comparison. In simulation with *software default losses*, the software uses the industry average losses to simulate the system and generally this is considered as baseline against which the actual power plant results are compared. For simulation with *plant site losses conditions*, values of losses have been input in the software after detailed discussions with the plant manager. The results of this simulation should be considered as future baseline for the power plant against which the actual output should be compared. Finally, for simulation using *literature minimum losses*, the values have been taken from literature review of optimally operated plants across the world. The results of this simulation should be used as a reference against which the power plant managers should aspire to operate. Table 4 shows the values of losses considered in four cases whereas Table 5 presents the energy output of the power plant for each case simulated with three weather data sets.

Table 4: Power plant system losses cases

Sr. No.	Losses	Zero Losses	Software Default	Plant site conditions	Literature Minimum
	Field Thermal Loss Factor	29 W/m^{2}K	29 W/m^{2}K	29 W/m^{2}K	29 W/m^{2}K
1	Soiling Loss	0	3%	1.5%	1.5%
2	Light Induced Degradation	0	2%	2%	1.5%
3	Plant unavailability	0	2%	0.4%	0.5%
4	Ohmic Loss (Loss fraction at STC)	0	1.5%	1.5%	1%
5	Module Quality	0	1.5%	0.8%	0.5%*
6	Module Mismatch (Power Loss at MPP)	0	1%	1%	1%
7	Strings Voltage Mismatch	0	0.1%	0.1%	0.1%

*This could be any value (e.g. +-5%). For sake of simulation purpose, it has been taken 0.5.

Table 5: Simulations with different weather data sets and losses scenario

		Annual Results (MWh)				
Sr. No.	Weather Data Sets	Simulation Cases (Losses)				Actual Plant Output
		Zero losses	Literature Minimum	Plant site conditions	Software default losses	
1	Plant site weather data	35,060	**33,113**	**32,678**	31,627	**31,328**
2	Meteonorm weather data	35,061	33,123	32,770	**31,496**	
3	NASA weather data	35,060	33,115	32,811	31,551	

At zero losses scenario (theoretical maximum value), all weather data sets provided same results on annual basis i.e. 35,060 MWh. Similar results were found on the literature minimum losses scenario with all results close to 33,113 MWh. However, the results obtained using the plant site conditions and software default values have shown some considerable differences. A comparison on a monthly basis between the actual plant output and simulated results of plant plant site losses and all weather data sets is listed in Table 6. Percentage differences have also been listed to get a better idea of both the over and underperformance of the power plant.

Table 6: Plant output comparison with simulated results (weather databases with plant site losses conditions)

Months	Actual Plant Output	PVsyst Simulated Results (Weather Databases)					
		Plant site weather data		Meteonorm		NASA	
	MWh	**MWh**	**Percentage Difference**	**MWh**	**Percentage Difference**	**MWh**	**Percentage Difference**
January	1,873	1,911	1.99	1,911	1.99	1,911	1.99
February	2,159	2,226	3.01	2,225	2.97	2,226	3.01
March	3,048	2,858	-6.65	2,928	-4.10	2,950	-3.32
April	3,216	3,208	-0.25	3,195	-0.66	3,177	-1.23
May	3,208	3,271	1.93	3,315	3.23	3,310	3.08
June	2,774	3,184	12.88	3,183	12.85	3,184	12.88
July	3,207	3,129	-2.49	3,127	-2.56	3,129	-2.49
August	3,113	3,175	1.95	3,173	1.89	3,175	1.95
September	2,861	3,067	6.72	3,065	6.66	3,067	6.72
October	2,387	2,539	5.99	2,582	7.55	2,574	7.26
November	1,704	2,224	23.38	2,182	21.91	2,222	23.31
December	1,778	1,886	5.73	1,885	5.68	1,886	5.73
Annual	**31,328**	**32,678**	4.13	**32,771**	4.40	**32,811**	4.52

Major difference can be seen between plant site weather data simulation and actual plant energy output which is 1,350 MWh (4.13 %) on annual basis. This shows that the power plant has not been operating at the ideal conditions and there is a room for improvement in operations and maintenance of the plant. In month of March, April and July the plant has shown better output than the simulated results while the rest of the year the plant has lagged behind. Major underperformance is seen in the months of November, June, September, October and December with underperformance as high as 23.38%, 12.88%, 6.72%, 5.99% and 5.73% respectively.

A comparison between differences in values between the simulated results shows that differences are minor. Difference between simulations of plant site weather data and Meteonorm is 93 MWh (0.28 %) on annual basis while that between simulations of plant site weather data and NASA is 133 (0.40 %) MWh. The results are an indication of the credibility and reliability of two different weather data sets, with Meteonorm database being more reliable as its results are closer to the plant site weather data simulated results.

In feasability studies for the power plant, Meteonorm simulation with the default losses scenario (31,496 MWh) has been considered as baseline and the plant's annual output (31,328 MWh) is compared with this value. The difference is 169 MWh or meagre 0.53% on annual basis which is not significant and the plant performance in this case is considered satisfactory. But to reach a precise figure of how much actual energy the plant should be producing; the baseline should be set using the simulation with actual plant site weather data and actual losses taking place in power plant. As per that simulation, the power plant should be producing 32,678 MWh annually instead of 31,328 MWh. The difference now is quite significant at 1,350 MWh or 4.13%. Table 7 shows the monthly values of actual power plant and compares it with the *present baseline* (Meteonorm data with default losses simulation) and *recommended baseline* (plant site weather data with plant site losses conditions).

Table 7: Plant energy output comparison with simulated results for current baseline & recommended baseline

Months	**Actual Plant Energy Output**	**PVsyst Simulated Results (Baseline)**			
		Meteonorm + Default Losses Condition		Plant site weather data + Plant site losses condition	
		Present Baseline Scenario		**Recommended Baseline Scenario**	
	MWh	**MWh**	**Percentage Difference**	**MWh**	**Percentage Difference**
January	1,873	1,870	-0.16 %	1,911	1.99 %
February	2,159	2,178	0.87 %	2,226	3.01 %
March	3,048	2,890	-5.47 %	2,858	-6.65 %
April	3,216	3,146	-2.23 %	3,208	-0.25 %
May	3,208	3,049	-5.21 %	3,271	1.93 %
June	2,774	2,952	6.03 %	3,184	12.88 %
July	3,207	3,063	-4.70 %	3,129	-2.49 %
August	3,113	3,109	-0.13 %	3,175	1.95 %
September	2,861	3,003	4.73 %	3,067	6.72 %
October	2,387	2,364	-0.97 %	2,539	5.99 %
November	1,704	2,028	15.98 %	2,224	23.38 %
December	1,778	1,845	3.63 %	1,886	5.73 %
Annual	**31,328**	**31,496**	**0.53**	**32,678**	**4.13**
Difference		**168**	**0.53**	**1,350**	**4.13**

Plant management needs to look into their operations and maintenance scheme to improve their energy output to reach annual output of 32,678 MWh in first instance and then reach the literature minimum losses. Table 8 compares the output of power plant in case of present power plant site losses and literature minimum losses scenarios. In case of reaching the literature minimum losses, annual output can reach up to 33,113 MWh which can increase the revenues even further.

Table 8: Plant energy output comparison with recommended case and future aspiration

Months	**Actual Plant Output**	**PVsyst Simulated Results**	
		Plant site weather data + Plant site losses condition	Plant site weather data + literature minimum losses conditions
		Recommended case	**Future aspiration**
	MWh	**MWh**	**MWh**
Annual	31,328	32,678	33,113
Difference	MWh	1350	1786
	%	4.13	5.39

There is a major potential of increasing the annual revenues through improving the plant energy output. The tariff awarded to the power plant in Pakistan by NEPRA (National Electric Power Regulatory Authority) for first 10 years (out of 25 years of plant life) of plant operation is 14.3961 ¢ (USD)/kWh and 6.0422 ¢ (USD)/kWh for the next 15 years. Since the plant started its operation in 2017 and considering they will begin improving their energy output from 2020, Table 9 shows the amount of annual revenue increment the plant can potentially achieve over its lifetime (25 years). Unit conversion from dollar to euro has been considered as 1 $ = 0.9 € .

Table 9: Additional revenue in case of achieving energy output of recommended software simulated results

Years	**Additional energy**	**Tariff**	**Additional Revenue**	**Additional Revenue**
	kWh	**¢**	**$**	**€**
2020	1,351,000	14.3961	194,491	175,042
…	1,351,000	14.3961	194,491	175,042
2027	1,351,000	14.3961	194,491	175,042
2028	1,351,000	6.0422	81,630	73,467
…	1,351,000	6.0422	81,630	73,467
2043	1,351,000	6.0422	81,630	73,467
Total			**2,862,012**	**2,575,811**

Now, in case of achieving the literature minimum energy losses, the power plant can further increase the revenues as shown in Table 10.

Table 10: Additional revenue in case of achieving energy output of literature minimum losses simulated results

Years	Additional energy	Tariff	Additional Revenue	Additional Revenue
	kWh	¢	$	€
2020	1,786,000	14.3961	257,114	231,403
…	1,786,000	14.3961	257,114	231,403
2027	1,786,000	14.3961	257,114	231,403
2028	1,786,000	6.0422	107,914	97,122
…	1,786,000	6.0422	107,914	97,122
2043	1,786,000	6.0422	107,914	97,122
Total			**3,783,534**	**3,405,180**

5.2. Operations and Maintenance

From standpoint of operations and maintenance, it can be seen that the plant management is doing well in many areas but there is a room for improvement. Precise data collection and reporting is being performed, maintenance is being categorized as predictive and corrective maintenance and annual maintenance plan is in place. Cleaning of PV modules is done four times a month which is more than the industry average cleaning cycles on monthly basis. The reason for such a high rate of cleaning is fine particles, as dirt and dust which are generated and brought to the surface by wind, vehicular movement (created because of uncarpeted road), wheat crop harvesting and coal ash coming from nearby coal ash disposal sites. Operations and maintenance reports do not show details of problems in five months where power plant has underperformed i.e. June, September, October, November and December, but comparing results of Table 3 and Table 6 we can assess that most corrective maintenance activities have been performed on trackers in the months where there has been major underperformance. Table 11 shows the comparison. From this observation, it can be inferred that faults in *trackers* are major contributors to reduction in plant performance and predictive maintenance should be adopted to address the issue.

Table 11: Corrective maintenance vs Plant underperformance

Months	June	September	October	November	December
Plant Underperformance	6.03%	6.72%	5.99%	23.38%	5.78%
Tracker Maintenance Activities	42	82	116	109	112
Total Maintenance Activities	55	97	130	123	125

There is a need for automated plant diagnosis with a bottom up approach with data acquisition and processing starting from strings level combined with predictive maintenance in addition to preventive and corrective maintenance at the plant.

Some of the key performance indicators for performance assessment are being measured. Table 12 shows the key performance indicators, which as per guidelines of the best practices in O&M of solar PV power plants, should be measured as minimum requirement, recommendation or best practice [6]. Table 12 shows, whether it is being measured at plant site or not. Power plant management should measure the indicators which are not being measured presently and determine the actual amount of losses generated at various areas of the plant.

Table 12: Key performance indicators in operations and maintenance of the PV power plant

Type of Data	Indicator	Requirement	Measured at plant site
Raw Data Measurement	Irradiation	Minimum	Yes
	Active Energy Produced	Minimum	Yes
	Active Energy Consumed	Best practice	Yes
PV Power Plant KPIs	Reference Yield	Recommendation	Yes
	Specific Yield	Recommendation	Yes
	Performance Ratio	Minimum	Yes
	Temperature corrected PR	Best practice	No
	Energy Performance Index	Best practice	No
	Uptime	Best practice	No
	Availability	Minimum	Yes
	Energy based Availability	Recommendation	No
O&M KPIs	Acknowledgement time	Minimum	Yes
	Intervention time	Minimum	No
	Response time	Minimum	No
	Resolution time	Minimum	Yes
Equipment KPIs	Mean time between failures	Recommendation	No
	Inverter specific losses	Recommendation	No
	Inverter specific efficiency	Recommendation	No
	Module soiling losses	Recommendation	No
Incident Reporting	Warranty issues	Best practice	Yes
	EH&S issues	Best practice	Yes
	Spare parts stock levels & status	Best practice	Yes
	Preventive maintenance tasks performed	Best practice	Yes

5.3. Recommendations

Based on the results and analysis of energy output with software simulated results and comparison of plant operations and maintenance practices and globally adopted best practices of the 18 MW single axis tracking solar PV power plant in Pakistan, following set of recommendations have been provided by the author to the power plant management.

- The **baseline for comparison** should be the simulation with plant site weather data with actual plant site losses instead of Meteonorm weather data with industry average losses.
- **Actual losses** taking place at the power plant such as soiling, ohmic losses, module quality, mismatch, all must be **measured and documented.**
- Measurement of following **Key Performance Indicators** on the power plant should be conducted as a minimum requirement (intervention time and response time), recommendation (mean time between failures, inverter specific losses, inverter specific efficiency, module soiling losses, energy based availability) and best practice (temperature corrected performance ratio, energy performance index, uptime)
- Large number faults in the trackers have been documented which could be the cause of underperformance in five months. **Predictive maintenance** in addition to corrective and preventive must be adopted to counter the issues before hand.
- It has been observed that internal shutdowns have taken place mostly because of problems within inverters. Combiner boxes issues have also been reported. **Automated plant diagnosis** with a bottom up approach, with data acquisition and processing starting from strings level combined with predictive maintenance in addition to preventive and corrective maintenance is recommended.
- As per the O&M reports, whenever there has been **a cable repair** job, cables have been repaired with HT & PVC Tape. Use of cable connectors designed for such cables should be considered instead of only using HT & PVC tape to reduce the wire losses.
- **Aerial drones infrared thermography** can be used to reduce the manhours and cost of labor and used for the portfolio of the power plants under operations and maintenance of the operator.
- A recent coal ash dumping site has been created near the power plant which accumulates a lot of dust on the PV modules. Similarly, during wheat harvesting season, dust accumulation on modules demands more cleaning cycles on monthly basis. During the **site selection**, these matters should be taken into consideration as they can potentially increase the O&M costs.

6. Conclusion

Performance analysis of 18 MW single axis tracking solar PV power plant has been conducted based on the comparison of its actual energy output with an expected energy output obtained through simulation using specialized software. In addition, a review of its operations and maintenance reports have been performed, comparing them with global best practices in the solar PV industry.

Software simulations have been performed with three different weather data sets and losses taking place at the plant site. The reference performance value obtained based on Meteonorm weather data with average industry losses (present baseline for performance assessment) is significantly different than the value obtained using the site weather data and losses' coefficients reflecting the actual condition of the power plant (recommended baseline for performance assessment). Power plant management needs to change their approach towards setting the baseline because comparing the annual energy output with the software simulated results of plant weather data with actual plant losses coefficients, it has been found out that the powerplant is underperforming by 4.13% at current state which in monetary terms translates into a loss of € 175,042 per year and can lead to a loss of € 2,575,811 throughout the lifetime of the project. Improving the operations and maintenance this loss can be translated into additional revenue. Moreover, if the power plant strives to reduce the losses to lowest in the industry the software simulated results show that the annual yield can be increased by 5.39% which would provide an annual additional revenue of € 231,403 per year and over the lifetime of the project would generate € 3,405,180 of additional revenue.

Operations and maintenance reports do not show details of problems in five months where power plant has underperformed i.e. June, September, October, November and December but comparing results of underperformance with corrective maintenance activities performed, it can be assessed that major issues in tracker systems led to the underperformance. Moreover, issues in inverters and combiner boxes have also been reported leading to internal shutdowns. In this case, predictive maintenance and automated plant diagnosis with a bottom up approach with data acquisition and processing starting from strings level is recommended.

7. References

[1] IRENA Statistics, "Renewable Energy Capacity Statistics 2019," 2019.

[2] International Renewable Energy Agency (IRENA), "Renewable Capacity Highlights," 2019.

[3] M. Z. Jacobson and M. A. Delucchi, "Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials," *Energy Policy*, vol. 39, no. 3, pp. 1154–1169, 2011.

[4] International Renewable Energy Agency, "Renewable Energy and Jobs Annual Review 2019," 2019.

[5] International Renewable Energy Agency (IRENA), "Renewable Power Generation Costs in 2018," 2018.

[6] Solar Trade; Inter Solar; Solar Power Europe, "Operation & Maintenance Best Practices Guidlines, Version 3.0," 2018.

[7] Interantional Finance Corporation, "Utility-Scale Solar Photovoltaic Power Plants in partnership with a project Developer's Guide," *Int. Financ. Corp.*, pp. 1–216, 2015.

[8] Solar-DAO, "Everything You Need to Know About Operations & Maintenance (O&M) For Utility Scale PV Solar Plants," 2017. [Online]. Available: https://medium.com/@solar.dao/everything-you-need-to-know-about-operations-maintenance-o-m-for-utility-scale-pv-solar-plants-9d0048e9b9a2.

[9] IEC Technical Specs IEC TS;, "Photovoltaic System Performance - Energy Evaluation Method," 2016.

[10] S. Mccormack and M. Conlon, "Measured Performance of a 1.72 kW Rooftop Grid Connected Photovoltaic System in Ireland," *Energy Convers. Manag.*, vol. 52, no. 2, pp. 816–825, 2011.

[11] B. S. Kumar and K. Sudhakar, "Performance evaluation of 10 MW grid connected solar photovoltaic power plant in India," *Energy Reports*, vol. 1, pp. 184–192, 2015.

[12] R. Sharma and S. Goel, "Performance analysis of a 11 . 2 kWp roof top grid-connected PV system in Eastern India," *Energy Reports*, vol. 3, pp. 76–84, 2017.

[13] S. M. Achim Woyte, Mauricio Richter, David Moser, Nils Reich, Mike Green, *Analytical Monitoring of Grid-connected Photovoltaic Systems*. 2014.

[14] H. Denio, "Aerial solar Thermography and condition monitoring of photovoltaic systems," *Conf. Rec. IEEE Photovolt. Spec. Conf.*, pp. 613–618, 2012.

[15] J. A. Tsanakas, L. Ha, and C. Buerhop, "Faults and infrared thermographic diagnosis in operating c-Si photovoltaic modules: A review of research and future challenges," *Renew. Sustain. Energy Rev.*, vol. 62, pp. 695–709, 2016.

[16] V. V. and A. P. S. Dinesh Kumar Sharma, "Review and Analysis of Solar Photovoltaic Softwares," *Int. J. Curr. Eng. Technol.*, vol. 4, no. 2, pp. 725–731, 2014.

[17] I. Bhattacharya, "A detailed study of 7 unique solar PV design and simulation software," 2015. [Online]. Available: https://www.linkedin.com/pulse/comparative-analysis-7-most-popular-solar-pv-design-bhattacharya/?trk=mp-reader-card.

[18] N. Umar, B. Bora, C. Banerjee, and B. S. Panwar, "Comparison of different PV power simulation softwares : case study on performance analysis of 1 MW grid-connected PV solar power plant," *Int. J. Eng. Sci. Invent.*, vol. 7, no. 7, pp. 11–24, 2018.

[19] D. A. Quansah and M. S. Adaramola, "Ageing and degradation in solar photovoltaic modules installed in northern Ghana," *Sol. Energy*, vol. 173, pp. 834–847, 2018.

[20] N. M. Kumar, R. P. Gupta, M. Mathew, A. Jayakumar, and N. K. Singh, "Performance, energy loss, and degradation prediction of roofintegrated crystalline solar PV system installed in Northern India," *Case Stud. Therm. Eng.*, vol. 13, no. January, p. 100409, 2019.

[21] A. Upadhyay, "PVsyst Losses & Some Remedies," 2017. [Online]. Available: https://www.linkedin.com/pulse/pvsyst-losses-some-remedies-amit-upadhyay/.

[22] M. R. Maghami, H. Hizam, C. Gomes, M. A. Radzi, M. I. Rezadad, and S. Hajighorbani, "Power loss due to soiling on solar panel: A review," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1307–1316, 2016.

[23] Didier Thevenard, "Uncertainty in Long-Term Photovoltaic Yield Predictions," 2010.

[24] P. Bhushan Sopori *et al.*, "Understanding Light-Induced Degradation of c-Si Solar Cells: Preprint," 2012.

[25] A. Al Mansur, M. Ruhul Amin, and K. K. Islam, "Performance comparison of mismatch power loss minimization techniques in series-parallel PV array configurations," *Energies*, vol. 12, no. 5, 2019.

[26] GENSOL, "Generation Assessment and Loss Justification of 315 Wp panels in 1 MW power plant." [Online]. Available: https://www.slideshare.net/AnmolJaggi/analysis-of-pvsyst-loss-diagram.

[27] KIC-InnoEnergy, "Future renewable energy costs: solar photovoltaics. how technology innovation is anticipated to reduce the cost of energy from European photovoltaic installations," 2015. [Online]. Available: http://www.innoenergy.com/wpcontent/%0Auploads/2016/01/KiC-innoEnergy-Solar-%0APV-anticipated-innovations-impact.pdf.

[28] C. L. Alessandro Betti, Maria Luisa Lo Trovato, Fabio Salvatore Leonardi, Giuseppe Leotta, Fabrizio Ruffini, "Predictive Maintenance in Photovoltaic Plants with a Big Data approach," *J. Chem. Inf. Model.*, vol. 53, no. 9, pp. 1689–1699, 2013.