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

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of Universidade de Lisboa

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Abstract

Renewable energy technologies have shown an exponential increment in the last decade. Amongst these technologies, solar PV deployment has been instrumental owing to highest decrease in production cost, receiving the largest investment and has provided maximum number of jobs in renewable energies sector. Research is being carried out to improve energy conversion efficiency and on 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 and incorporating latest techniques such as aerial drones thermography etc.

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

Resumo

As tecnologias de energias renováveis têm mostrado um incremento exponencial na última década. Entre estas tecnologias, a implantação da energia solar fotovoltaica tem sido instrumental devido à maior diminuição dos custos de produção, recebendo o maior investimento e proporcionando o máximo número de postos de trabalho no sector das energias renováveis. Investigações estão a ser realizadas para melhorar a eficiência da conversão de energia e, por outro lado, os produtores de energia seguem a encontrar formas de melhorar a operação e manutenção dos sistemas existentes de forma a aumentar a produção de energia.

Neste contexto, foi realizada uma avaliação do desempenho de uma central de energia solar fotovoltaica com sistema de rastreio de eixo único de 18 MW no Paquistão. À luz das melhores práticas internacionalmente recomendadas, foram avaliadas as operações e as práticas de manutenção da central e foram realizadas simulações de software para verificar o desempenho global, comparando os resultados simulados com a produção anual de energia da central.

Descobriu-se que o desempenho da central está 4,13% aquém do esperado, conduzindo a uma perda monetária potencial de € 175,042/ano, o que pode levar a uma perda de € 2,575,811 ao longo da vida útil do projecto. Esta perda pode ser convertida em receitas adicionais através da melhoria das práticas de operações e manutenção, da medição de indicadores de desempenho, da medição de perdas, da recolha de dados ao nível das strings e da incorporação das técnicas de inspeção mais recentes, como por exemplo a termografia com auxílio de drones aéreos.

Palvaras-chave: Avaliação de desempenho, Operação e manutenção, Melhores práticas internacionais em sistemas fotovoltaicos, Sistema fotovoltaico com rastreamento de eixo único, PVsyst

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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 provides an insight into an increase in the installed renewable power generation in GW over the last ten years [1]. Table 1 shows renewable capacity increase across the globe, Europe and specific countries relevant to the study.

Table 1: Increase in renewable power generation in the last decade

Regions	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**Percentage increase**
	GW	GW	GW	GW	GW	GW	GW	GW	GW	GW	%
World	1136	1224	1329	1441	1563	1693	1848	2008	2179	2351	107
Europe	239	265	303	336	359	378	402	424	446	466	95
Poland	1.75	2.18	3.02	4.09	5.12	5.64	6.92	7.88	7.98	8.23	370
Portugal	8.96	9.61	10.55	10.9	11.14	11.57	12.15	13.21	13.54	13.79	54
Pakistan	6.93	7.01	7.02	7.34	7.56	7.91	8.09	8.62	9.30	13.05	88

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 as shown in Figure 1 [2].

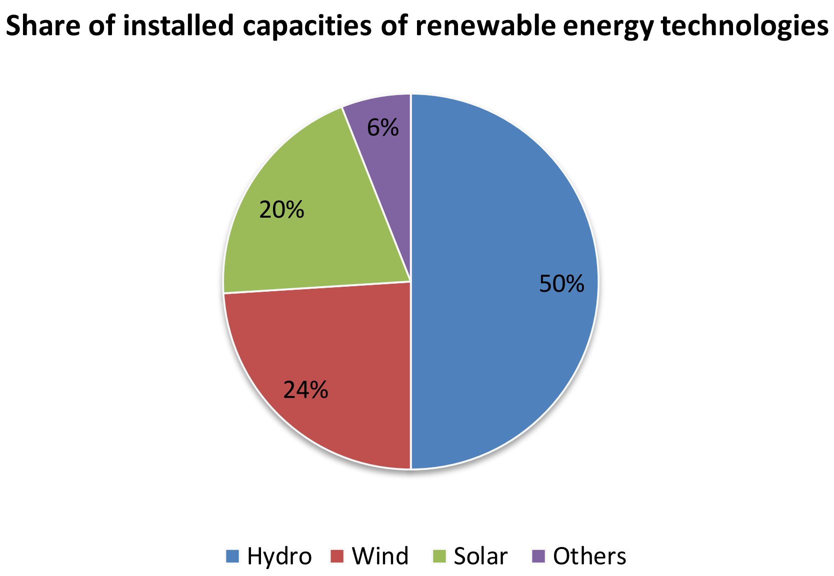

Figure 1: Share of installed capacities of renewable energy technologies [2]

Statistics of gradual increase in the last decade of these major technologies have been listed in Table 2. Solar photovoltaics has not only shown an exceptional percentage increase of approximately 2000 percent during the decade, but has also shown the maximum installed capacity in the last year with 94 GW of new capacity installed in 2018 [1]–[3]. Figure 2 shows the cumulative increment in last five years and individual technology deployment in the last year.

Table 2: Increase in power generation capacity of major RE technologies in the last decade

Technology	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	**Percentage Increase**
	GW	GW	GW	GW	GW	GW	GW	GW	GW	GW	**%**
Hydro	**992**	**1026**	**1057**	**1089**	**1136**	**1174**	**1210**	**1244**	**1271**	**1293**	**30**
Conventional	891	925	953	983	1028	1064	1097	1126	1150	1172	32
Pumped	101	101	104	107	108	110	113	118	121	121	19
Wind	**150**	**181**	**220**	**267**	**300**	**349**	**416**	**467**	**515**	**564**	**276**
Onshore	148	178	216	262	293	340	404	453	496	540	265
Offshore	2	3	4	5	7	9	12	14	19	24	994
Solar	**23**	**41**	**73**	**103**	**140**	**177**	**226**	**297**	**391**	**486**	**1979**
PV	22.6	39.6	71	100	136	173	221	292	386	480	2025
CSP	0.8	1.3	2	3	4	4.5	4.9	5	5	5.5	615

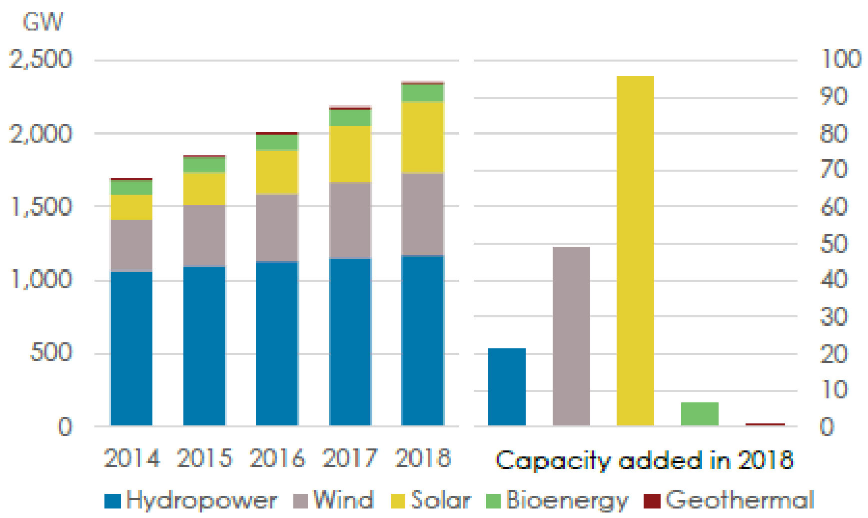

Figure 2: Comparison of major renewable power generation sources installed in last five years [2].

Another representation of comparison of increase in specific renewables is shown in REN21 (Renewables Now), Renewables 2019 Global Status Report [4]. Figure 3 shows the amount of annual addition of renewable power capacity by technology and the total from 2012 to 2018. It can be inferred that 181 GW of renewable energy technology capacity addition took place in 2018 amongst which more than 50 percent came from solar PV technology [4].

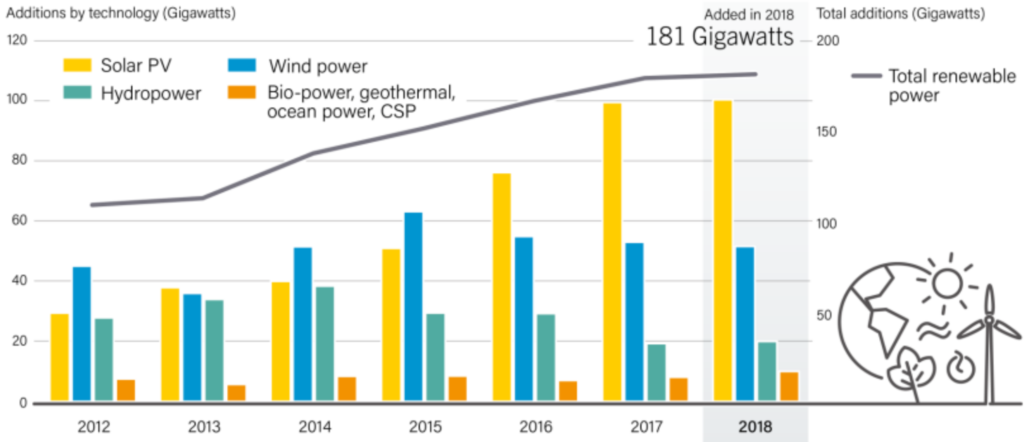

Figure 3: Annual addition of renewable power capacity by technology and total 2012-2018 [4].

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 energy [5], shown in Figure 4.

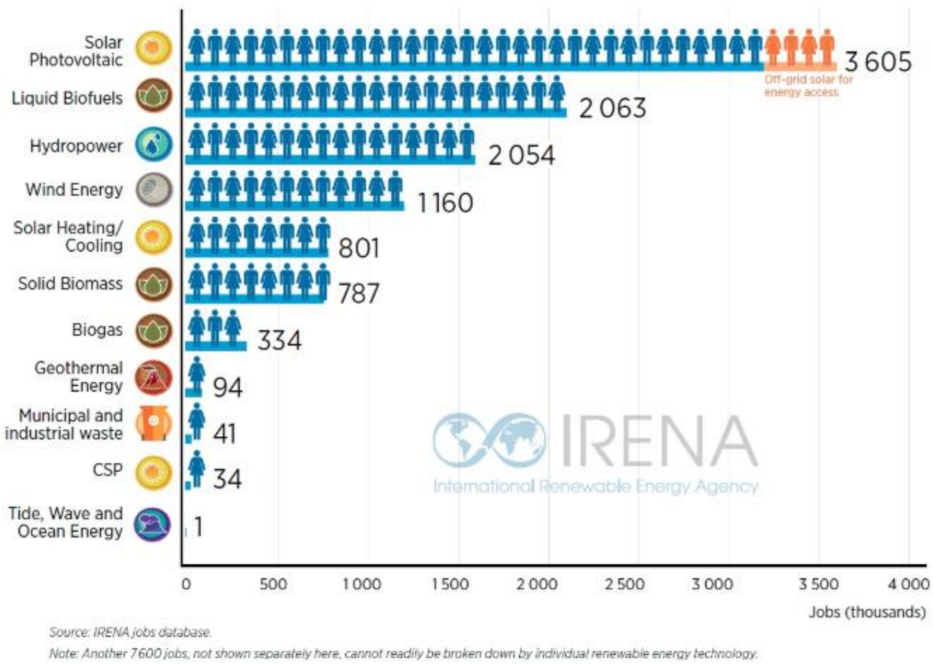

Figure 4: Jobs created by renewable energy technologies [5].

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 compares selected countries and 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 as represented in Figure 5. The lowest average value has been recorded in India at USD 793/kW [6].

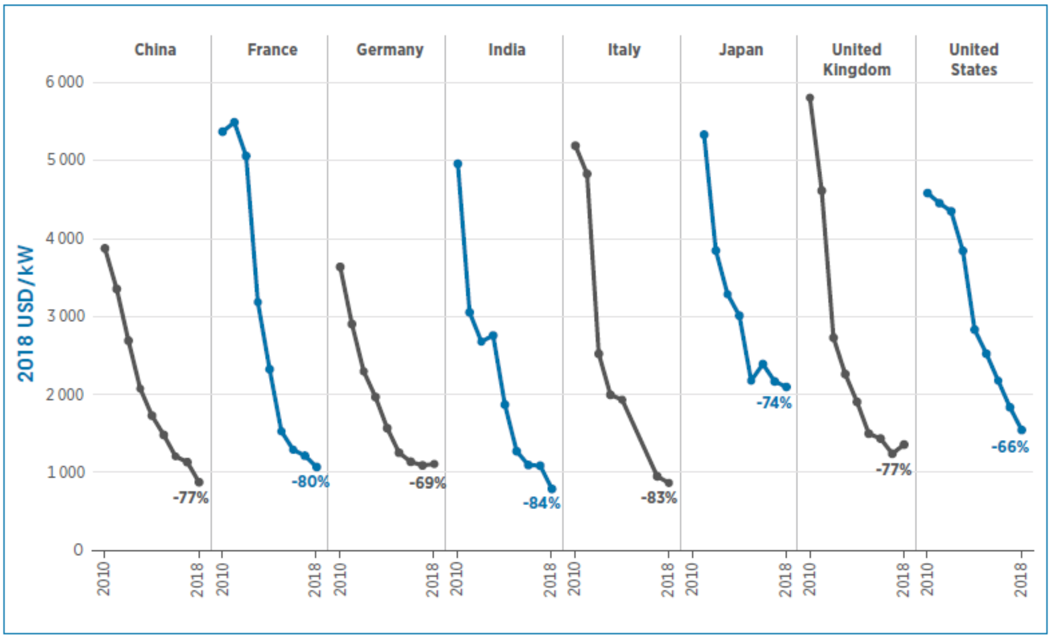

Figure 5: Decline in solar PV system cost across different countries from 2010 to 2018 [6].

Decrease in price of installed capacity led to decrease in price of energy production. Average levelized cost of energy (LCOE) declined from 62% in Japan to as much as 80% in Italy as shown in Figure 6. Once again, the lowest value has been observed in India with USD 0.06/kWh [6].

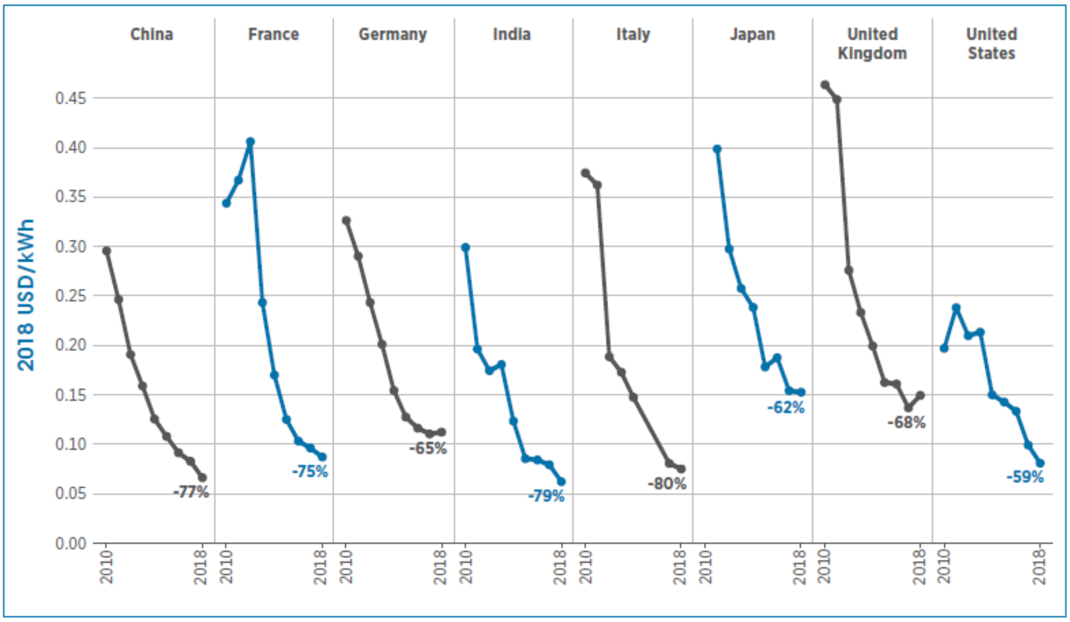

Figure 6: Decrease in levelized cost of energy production in solar PV sector from 2010 to 2018 [6].

To increase the returns on investment further, at one hand, research is being carried out to improve energy conversion efficiency of solar PV technologies using novel materials and different mechanisms of generation; and on another, existing power producers are trying to improve the output of power plants by improving their operations and maintenance (O&M) activities.

Operations and maintenance of solar PV power plants 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 [7]. Effective operations and maintenance has the potential to improve levelized cost of energy and positively impact returns on investment [7]. As per a report by published by International Finance Corporation (IFC) [8], power plant operations and maintenance's objective is to maximize the energy yield and the useful life of the plant while minimizing the costs.

During the lifecycle, the power plant faces a range of issues such as natural degradation, component failures (module cracking, hotspots, inverter failures, trackers alignment and positioning etc.), faces weather conditions (snow, soiling and wind), and other issues such as tightening loose cable connections, replacing fusses, fixing SCADA faults, repairing tracker faults etc. A holistic approach is adopted to address these issues under the operations and maintenance annual plan, which is usually divided in preventive, corrective and conditioned-based maintenance categories [9]. Recent trends opted in operations and maintenance of solar PV power plant include smart monitoring, data driven operations and maintenance followed up by predictive maintenance and application of retrofit coatings to improve energy output and decrease the costs.

The performance of the power plant is judged based on its operations and maintenance data collection, reporting, and also judged based on the effectiveness of response on operations and maintenance issues arising throughout the year. International standard IEC 61724 published by International Electro Technical Commission (IEC) in 1998 is considered the basis for performance assessment of the solar PV power plants [10]. The standard IEC 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 [11].

1.1. Objectives

The objective of this thesis is to analyze and systemize the main set of used operations and maintenance practices and assessing the power plant performance. To accomplish this, a case study of an existing 18 MW solar PV power plant in Pakistan will be studied and recommendations concerning any improvements based on best global practices will be provided. The objectives of the study are shortlisted as

- Analysis of operations and maintenance of the PV power plant in comparison with best global practices;
- Analysis and review of performance assessment conducted on the power plant, and;
- Identification of possible improvements in light of global best practices.

1.2. Methodology

In regard to the objectives set for this thesis, a technical advisory for an 18 MW single axis solar PV power plant located in Harappa region in Pakistan, has been aimed for. Power plant energy output, operations and maintenance data and weather data has been provided by the power plant management. The methodology adopted shown in Figure 7, has been to compare the plant operations and maintenance with the best global 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. In the light of technical evaluation, it has been intended to provide recommendations which could lead to increase in energy output and consequently provide economic benefits to the plant. Figure 7 summarizes the steps of methodology used in the study.

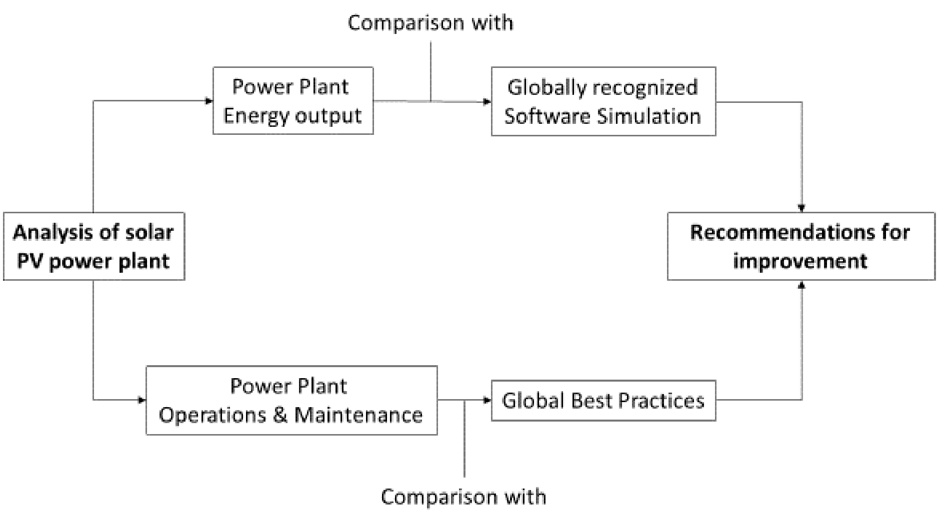

Figure 7: Power plant assessment methodology

1.3. Thesis Structure

Chapter 1 provides an overview of increase in solar PV deployment due to exponential decrease in production costs, making it a key renewable energy technology and highlights the importance of operations and maintenance in the existing solar PV power plants.

Chapter 2 provides literature review on the best global practices employed in solar PV operations and maintenance, selection of software to analyze solar power plant's energy output while incorporating various losses taking place at the site and the latest trends in the industry.

Chapter 3 briefly describes the power plant in terms of actual operations and maintenance performed at the site and chapter 4 illustrates the use of simulation software to assist the technical assessment and comparison with actual energy output.

Chapter 5 provides the results obtained by software simulation and provides an insight in how the plant operations and maintenance can be improved to achieve economic benefits.

Chapter 6 concludes the thesis by providing site specific recommendations for the power plant.

Table 3 gives a short description of each chapter.

Table 3: Thesis structure

Chapters	**Content**
Chapter 1	Importance of solar PV technology in general and operations and maintenance in particular.
Chapter 2	Best global practices in operations and maintenance, Performance assessment using software simulation, Latest Trends in operations and maintenance.
Chapter 3	Power plant description, operations & maintenance practices conducted at the site.
Chapter 4	Software simulation for energy output determination.
Chapter 5	Results, analysis and recommendations.
Chapter 6	Conclusion.

2. Literature Review

2.1. 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.

In the lifecycle of a PV powerplant O&M is generally the longest phase lasting 25-35 years. Other phases of powerplant are development and construction which last up to 1 to 3 years and few months respectively. Dismantling, which is the final stage, generally takes place within few months at the end of lifetime. A report published by Solar Power Europe, Operations and Maintenance, Best Practices Guidelines [7], has been used as main reference for comparing plant O&M with the best practices adopted within the solar PV industry.

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* where performance, operations and maintenance are compared with other PV power plants operated and maintained by the operator. Factors other than the operations and maintenance (such as installed capacity, location, weather data, difference in installed equipment such as modules, inverters, transformers, cabling etc.) create a difference in the plant output; however a comparison of key performance indicators (KPIs) mentioned in Table 4, provide a technical basis to compare and evaluate performance of different plants in the portfolio. After the portfolio level, *plant level* and then *inverter level* parameters assessment and comparison are also considered minimum requirements for optimum O&M practices. Best practice and recommended approach is to perform monitoring down to the string level, which allows accurate troubleshooting possibilities in shortest times, helping improve plant availability.

Table 4: Key performance indicators [7]

Type of Data	Indicator	Requirement
Raw Data measurement	Irradiation	Minimum
	Active Energy Produced	Minimum
	Active Energy Consumed	Best practice
PV Power Plant KPIs	Reference Yield	Recommendation
	Specific Yield	Recommendation
	Performance Ratio	Minimum
	Temperature corrected PR	Best practice
	Energy Performance Index	Best practice
	Uptime (Technical Availability)	Best practice
	Availability	Minimum
	Energy based Availability	Recommendation
O&M KPIs	Acknowledgement time	Minimum
	Intervention time	Minimum
	Response time	Minimum
	Resolution time	Minimum
Equipment KPIs	Mean time between failures	Recommendation
	Inverter specific losses	Recommendation
	Inverter specific efficiency	Recommendation
	Module soiling losses	Recommendation
Incident Reporting	Main incidents and impact on production	Minimum
	Warranty issues	Best practice
	EH&S issues	Best practice
	Spare parts stock levels & status	Best practice
	Preventive maintenance tasks performed	Best practice

2.1.1. Key Performance Indicators

Key performance indicators listed in Table 4 have been explained as follows:

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 [12],[13].

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

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)[7].

$$Y_i = E_i/P_o \quad (ii)$$

Performance ratio (PR) is a quality indicator that is defined by the ratio of specific yield (Y_i) per reference yield (Y_r) [14].

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

Temperature corrected performance ratio is calculated when PR needs to be measured for less than annual values for example for few months. In this case it is recommended to include temperature in measurements to counter PR fluctuations caused due to variations in temperature.

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

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

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

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

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 [7].

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.

2.1.2. 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) [7],[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. Failures are generally identified through shape of the IV curve which also provides a quantitative value of power losses. 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. Recently, digital solutions are coming up which use satellite imagery, remote sensing techniques and combine it with machine learning algorithms.

2.1.3. Power Plant Maintenance

According to guidelines in operations and maintenance [7], power plant maintenance should be split in five categories and be conducted in coordination with the analysis of operations' team. The five categories are:

- *Preventive maintenance* which includes physical inspections and compliance with operations manuals. Annual maintenance plan is a part of preventive maintenance and includes a schedule of inspections performed on different intervals, (daily, bi-monthly, monthly, quarter-yearly, bi-annually and annually).
- *Corrective maintenance* is performed to restore the faults in equipment or components to bring them back to functioning state properly. Main elements of corrective maintenance include fault diagnosis and repair.
- *Predictive Maintenance* is condition based maintenance carried out after keen monitoring, analysis and evaluation of main parameters of the degradation of equipment under observation. For instance, if power loss in inverter due to overheating is observed, several reasons such as filter obstructions, problems in the air flow or high seasonal temperature could be the reasons. As per predictive maintenance air flow inspection, ventilation systems inspection or cleaning/replacement of filters shall be performed to avoid damage and loss of equipment.
- *Additional maintenance* includes activities such as modules cleaning, vegetation control, road management, buildings control, perimeter security etc.

- *Extraordinary maintenance* aims to cover unpredictable events taking place on the plant. It covers events such as force majeure, event of theft, fire, modifications mandated subsequently by regulatory authorities.

2.2. 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. Since PVsyst takes top position in most of the criteria it can be considered most appropriate software for simulation.

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 to find out the most effective software simulation. 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. Moreover, since PVsyst has also been used by the 18 MW power plant under analysis during their design phase for setting a baseline, it has been recommended to use similar software to reach close to real time results. 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 these 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 solar PV power plant.

2.3. Power Plant Losses

During powerplant operations, many factors lead to losses and degradation of the system. For example, 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. Another study in India [20], forecasted a degradation rate of 0.502% on annual basis using machine learning tools. A study performed in northern India [21], close to the installed power plant under consideration, reported that the solar PV power-plant degradation ranges between 0.6% to 5% per year.

In this regard, it is very 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 described as follows.

Near or linear shading loss is shading produced by near objects which in power plant corresponds to losses because of less inter row/column spaces between tables of the solar panels in the plant. It is related to irradiance loss which occurs because of lack of space between rows/columns, as some irradiance does not fall on the panels [22].

Array incidence loss or IAM (Incidence Angle Modifier) refers to module dependent loss calculated by the software which is a 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% [22], [23].

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 [24]. A study conducted by Kimber et. al in 2001 [24], 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. Moreover, in this study it was found out that rain does not necessarily always clean the modules. Sometimes a light shower can make it worse by dampening the dust and making mud on the surface of the panels, adding to the soiling of the modules. At least 20 mm of rainfall is required to clean the surface of the modules. Another study [25] on soiling losses details that soiling losses generally range between 3% to 6% which can go as high as 30% depending on location and number of cleaning cycles observed. A study [26] reviewed effect of dust, humidity and air velocity on efficiency of photovoltaic cells and found out that efficiency reduction of 1% to 4.7% took place in United States in two months, 40% in 6 months in Saudi Arabia and 17% to 65% in 38 days in Kuwait, all depending upon tilt angle and time of cleaning. A report on uncertainty in long-term photovoltaic yield predictions states 2% reduction in efficiency for losses due to soiling [27].

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. PVsyst computes these losses based on the site meteo-data and the .PAN file of module manufacturer input in the software [22]. Generally, open-circuit voltage increases logarithmically with increase in solar radiation and short-circuit current increases linearly, which results in increase in power output and vice versa. On the other hand, an increase in temperature of the module/cell results in decrease in open-circuit voltage. Even though short-circuit current increases fractionately with increase of the cell temperature, the overall cell efficiency drops. Hence, to improve the efficiency of the module, it is advised to reduce the surface temperature, which can be achieved by either employing a cooling mechanism or reduction of heat stored within the module under operation [28].

Module quality loss or module rating is the difference in performance of the module as specified by the manufacturer and as operated in the field. It is the difference between the nameplate and actual power of the module. It corresponds to the tolerance specified by the manufacturer (e.g. +- 5%), which is generally on the negative side than ever being on the positive. PVsyst recommends a 1.5% average module quality loss in its simulations [22], [27].

Crystalline solar cells fabricated using Czochralski method show *light-induced degradation* (LID) during an initial prolonged exposure to light. It occurs when oxygen impurities in the silicon wafers react with the doped (p type) boron during initial illumination of the cell (A boron-oxygen defect in the wafer). As per a publication by NREL, LID can reduce cell efficiency by 0.5% to 1.5% [29]. Another research conducted in northern India has taken this factor to be 2.5% [21]. PVsyst's default setting takes this value as 2%.

During the modules production process, modules with same nameplate power capacity, do not necessarily have exactly the same current and voltage characteristics. When these modules are connected together in series or parallel connectivity, the inequality of voltage and current between modules results in the loss of power called *module array mismatch loss* [24]. A study on performance comparison on mismatch losses [30] shows that mismatch losses can be minimized to less 1% using genetic algorithm technique while it is higher than 1.02% for other module arrangement techniques.

Ohmic wiring loss corresponds to the losses between the PV module and the inverter. These losses 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% [22]. Another study revealed that for a well-designed plant the losses usually range between 1.2% to 1.5% [31]. In PVsyst, the software takes a default value of 1.5% for this loss [32].

System unavailability refers to the downtime in production due to planned and unplanned maintenance activities at the plant site such as annual/biannual plant shut down for maintenance, plant internal tripping and external grid tripping, etc. PVsyst takes an average of 2% as a default value for this loss [33]. 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% [22], [31].

Table 5 represents a comparison of the default values of losses taken by PVsyst and literature reviewed results.

Table 5: PVsyst default losses and literature minimum losses in PV systems

	Losses	**PVsyst Default**	**Literature Minimum Losses**
	Field Thermal Loss Factor	29 W/m^2K	29 W/m^2K
1	Soiling Loss	3%	1.5%
2	Light Induced Degradation	2%	1.5%
3	Plant unavailability	2%	0.5%
4	Ohmic Loss (Loss fraction at STC)	1.5%	1%
5	Module Quality	1.5%	0.5% *
6	Module Mismatch (Power Loss at MPP)	1%	1%
7	Strings Voltage Mismatch	0.1%	0.1%

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

2.4. 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 [34]. This reduction shall be materialized using latest trends and innovative techniques, some of which have been detailed as follows:

2.4.1. Aerial Drones Infrared Thermography

Infrared thermographic inspections are an established tool in preventive and corrective maintenance of solar PV power plants; however, the amount of time, labor and ultimately finances required for just gathering the data continues to be a challenge. This process can be conducted by mounting thermographic cameras on unmanned aerial vehicles (UAVs) instead of using handheld devices. A power plant as large as 12 MW_p can be inspected in one day using this technology, thus saving time, labor and financial resources [7],[15]. Faults within the modules such as optical faults (delamination, discoloration, glass breakage), electrical mismatches and degradation (cell cracks, poor soldering, short circuit cells, shading), hot spots and potential induced degradation can be detected through aerial drones IR thermography [35].

2.4.2. Automated Plant Diagnosis

Currently, the performance assessment of solar PV power plants is executed following a top-down approach i.e. assessment takes place starting from substations to inverters to junction boxes down to strings level. This technique is expert dependent, time consuming and does not assure to uncover all under-performing matters. 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 [7]. 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% [36].

2.4.3. Retrofit Coatings

- **Anti-soiling coating**

Solar PV modules' surfaces are exposed to dirt deposition and weathering conditions, which lead to soiling of the module and subsequently decrease in efficiency of the system. To prevent efficiency losses, anti-soiling coatings are applied to the modules. These coatings must have high transparency, abrasion and weather resistance and dust repellent properties. Generally two types, hydrophobic and hydrophilic coatings are used for anti-soiling purposes, which help to accumulate lesser dust molecules, making it easier to clean and reduce the water consumption apart from improving energy efficiency [37],[38]. An increased gain (yield) of 3% is achievable using these coatings [37].

- **Anti-reflective coating**

Losses caused by reflection are one of initial losses of solar PV systems while converting solar irradiation to energy. These losses are reduced by applying antireflective coatings to the modules already installed in the field. These coatings can increase the energy output by 3-4% [7]. A long-term field test was conducted to examine patterned and un-patterned anti-reflective films. Moth-eye pattern and micro-cone pattern were fabricated using ultraviolet-nanoimprint lithography process, which does not use high-temperature or vacuum process. In seven months of testing it was found that moth eye pattern film (patterned film) improved the transmittance by 5% and conversion of electricity by 2.85% than a flat un-patterned film [39].

2.4.4. Agro Photovoltaics

Agro-photovoltaics encourages the use of land for both agriculture and solar PV power production simultaneously. Research conducted by Fraunhofer Institute for Solar Energy Systems (ISE) with a 194-kW plant in Heggelbach, Germany, found out that the land use efficiency rose to 186% by planting potato farm underneath the solar photovoltaic farm. Another research conducted by Fraunhofer ISE with a pilot plant in India, concluded that shading effect and lesser evaporation led to 40% increase in tomato and cotton crops [40]. During research on the lines of food-energy-water nexus, researchers from university of Arizona found out that through agro-PV system, chiltepin fruit yielded 3 times greater produce, tomatoes showed twice the yield as per usual production and jalapenos production shown 65% less transpiration losses. Agro-PV comes as a potential solution for effective use of land against land scarcity [41].

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

In this chapter, power plant description and actual practices adopted in terms of operations and maintenance have been documented.

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. Google image for the location has been presented in Figure 8.

Figure 8: Google image of 18 MW Harappa Solar PV power plant

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. These rows can be seen in Figure 8 and in an on-ground image in Figure 9.

Figure 9: Rows of solar PV modules with 7 meters distance to avoid near shading

Inverters with 500 kW rating, voltage range of 460-850 V and frequency of 50-60 Hz produced by Sungrow, model SG 500 MX have been installed. PV modules and inverters specifications have been listed in Table 6.

Table 6: PV Modules and Inverters Specifications

Modules		**Inverters**	
Manufacturer	PhonoSolar	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).

3.1. Plant Operations and Performance

Operations and performance reports of the plant from every month have been summarized and presented in Table 7. Key figures such as plane of array (POA), performance ratio, capacity factor, plant availability and energy export are measured on regular basis.

Table 7: 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	21.40	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
Annual	**31327.7**	**2146.97**	81.43	19.86	99.96	3.875

Figure 10 shows the annual energy export, plane of array (POA) and performace ratio at the power plant. It can be witnessed in the graph that the POA has a direct impact on the energy export of the plant.

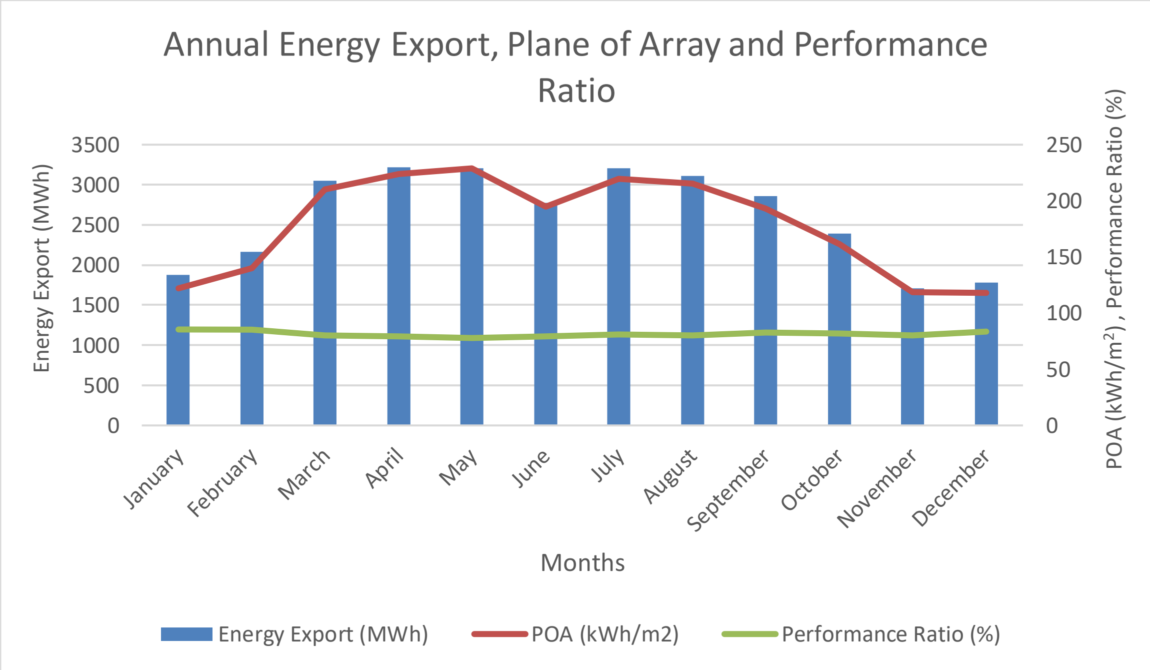

Figure 10: Annual Energy Export, Plane of Array and Performance Ratio of the power plant

In terms of number of times of the cleaning, the month of July has the lowest value with 1.5 times, meanwhile in all other months it is greater or equal to 4 times. The reason for lesser cleaning in one month is extensive rains, which makes the cleaning a less intensive task.

3.2. 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, which is then not utilized. The plant operators have no control over external outages. Both internal and external tripping have been classified under forced outages as per the reports. Table 8 represents the plant unavailability throughout the year.

Table 8: Plant Unavailability

Months	Planned Outage	External Tripping	Internal Tripping	Total	Total	Total
	(Minutes)	(Minutes)	(Minutes)	(Minutes)	(Hours)	(Days)
January	70	7	0.42	77	1.29	0.054
February	0	4	0.035	4	0.07	0.003
March	534	2	4	540	9.00	0.375
April	0	121	3.74	125	2.08	0.087
May	0.21	408	0	408	6.80	0.283
June	0	87	0	87	1.45	0.060
July	0	66	0	66	1.10	0.046
August	0	4	0	4	0.07	0.003
September	0	8	3.17	11	0.19	0.008
October	0	106	1.25	107	1.79	0.074
November	405	22	0.774	428	7.13	0.297
December	0	39	0	39	0.65	0.027
Total	**1009**	**874**	**13**	**1897**	**31.6**	**1.317**

As per Table 8, it is only 13 minutes in the whole year that the plant had to be shutdown based on the internal problems. From the reports studied, most of the internal plant shutdowns were caused by problems within inverters.

- January - Cable in trip circuit grounded,
- February - High temperature of bus bar,
- March - Inverters internal fault,
- April - Inverter not synchronizing with grid,
- May - Inverter with anti PID fault,
- September - Inverters had island fault, Inverters had DSP communication fault,
- October - Inverter fault,
- November - DC breaker of combiner box tripped,

Reporting of outages in the report on monthly basis has been resumed in Table 9.

Table 9: Annual plant outage reporting

Months	Reasons
January	Internal Tripping: During troubleshooting one of the cables in trip circuit found grounded, transformer taken back in service at 15:47 hours (just in 5 minutes). Planned outage: All feeders opened to perform a rectification job at K-02 feeder lines on WAPDA (national grid).
February	Internal Tripping: Block #02 SCB # S3SCB1 observed high temperature of bus bar. During troubleshooting bus bar was changed and tighten all connections according to the given standards.
March	Internal Tripping: All the inverters of whole plant were tripped due to the internal fault (PDP). All inverters turned back on and whole plant restored back to normal. Planned outage: Plant shutdown for annual maintenance of grid station
April	Internal Tripping: One of the inverters of block #3 was not synchronizing with the grid.
May	Internal Tripping: One of the inverters # S5NB2 of block #3 had Anti-PID fault. After examination & performing appropriate actions, problem was rectified and working fine.
September	Internal Tripping: Four of the inverters (S10IN1, S10IN2, S6IN1, and S5IN2) and one inverter# S9IN2 had ISLAND Fault. After thorough inspection, all the faults were rectified. Two of inverter of Block # 5 (S10IN1, S10IN2) had DSP-communication fault. After thorough inspection, fault was rectified.
October	Internal Tripping: One of the inverters #S7NB2 had fault. After thorough inspection, fault was rectified.
November	Internal Tripping: Main DC breaker of Combiner Box (S7SCB12) tripped. It was reset after thorough inspection of associated PV cables.

3.3. Plant Maintenance

Maintenance conducted at the power plant site has been categorized into corrective and preventive maintenance categories.

3.3.1. Corrective Maintenance

Corrective maintenance has been performed and documented with pictorial evidences of maintenance activities performed on the plant site. Table 10 shows the number of corrective maintenances 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 10: 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**

Key points from corrective maintenance report of month of July have been presented as a reference because in this month, maintenance activities were performed on the maximum number of components.

1. Main cable trench slipped down near slope area of Block – 5, which was rectified by pumping out water and then it was filled with soil before compaction as shown in Figure 11 and 12.

Figure 11: Cable trench slip due to rain

Figure 12: Cable trench slip rectified after pumping out water

2. Inverter S9NB1 faced RISO fault that was rectified after thorough inspection (Figure 13).
3. Inverter S8NB2 faced anti PID fault that was rectified after thorough inspection (Figure 13).

Figure 13: Inverter faults as seen on SCADA screen

4. Four Strings of SCB - S8SCB8 showed zero current and it were rectified after cable repair.
5. String A5 of Combiner Box S5SCB12 showed zero current. Cable was repaired with HT & PVC Tape (Figure 14).

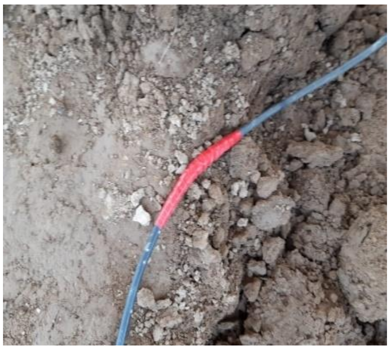

Figure 14: Cable repair with HT & PVC tape

6. Three string cables of SCB S9SCB2 (A13, A14 & A16) showed zero current. When examined, cables were not showing continuity. Weak insulation was found over the whole strings. All damaged cables were repaired.
7. Boundary wall supportive soil of DB structure area was displaced, which was rectified by pumping out water and then it was filled with soil before compaction (Figure 15 and 16).

Figure 15: Boundary wall support soil displaced due to rain

Figure 16: Boundary wall support soil rectified

8. Due to heavy rains in the month of July, many of trenches in the PV area were displaced. All the displaced trenches were refilled and compacted.

9. Fire Alarm of Reverse Osmosis (RO) plant was found faulty during daily checklist of maintenance team. After complete inspection, weak insulation in the Circuit Breaker was found which was repaired (Figure 17).

Figure 17: Fire alarm fault detected and repaired at circuit breaker level

10. One of the PV module in Block – 2 was damaged. After complete inspection damaged PV module was replaced (Figure 18 and 19).

Figure 18: Damaged solar PV module

Figure 19: Damaged module replaced with a new module

11. Tracker Box 1-83 had charging issues. On examination, it was found that battery of the tracker box was faulty, and it was replaced with old charged battery.
12. One of the classic pile head of Tracker 6 in Block – 6 was bent down. After following all the PPEs, new head was inserted (Figure 20).

Figure 20: New pile head installed at a tracker

13. In Block – 2, one of the inverters S3NB1 was detected with the "fault stop" fault. After complete inspection, fault was rectified.
14. Guy wire of internet tower broke due to the heavy rain and wind. After complete inspection, guy wire was repaired and tightened.
15. One of the tracker boxes # 5-9 had communication issues. When examined, it was not communicating with the OT SERVER. New tracker box was installed and configured with the OT server (Figure 21).

Figure 21: Tracker box communication issues rectified

16. One of the LED of SCADA system had fault. After complete examination, LED connection was reset, and issue was rectified (Figure 22 and 23).

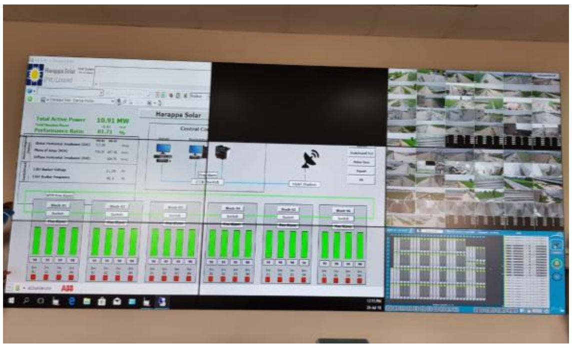

Figure 22: Fault on LED screen of SCADA system

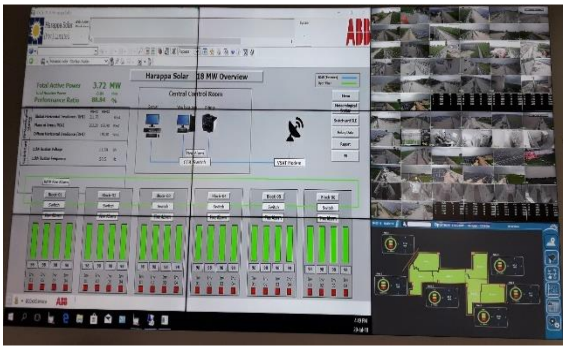

Figure 23: Fault rectified on LED screen of SCADA system

17. Twenty-two tracker boxes had communication and battery charging problems. After examination, software was updated, battery was charged, and error was rectified.

3.3.2. Preventive Maintenance

Preventive maintenance at the power plant is performed through a detailed and documented plan. Table 11 shows the components, executed preventive maintenance activities and the time schedule after which inspection, servicing, testing or cleaning has to be performed. The timespan has been abbreviated as A (annually), B (bi-annually), D (daily), M (monthly) and W (weekly). Annual activities took place in September while bi-annual activities took place in March and September. Table 11 represents the activities performed in March 2018.

Table 11: Preventive Maintenance Schedule

Sr. #	Components	Activities	Inspection	Cleaning	Service	Testing
1	PV Module	Clean PV modules with plain water or mild dishwashing detergent.	D	M		
		Dust: Agricultural /Industrial/Pollen Cleaning	D	B		
		Use infrared camera to inspect for hot spots; bypass diode failure				
		PV module torque check & visual inspection				
		Galvanization inspection	B			
		Test output of modules that exhibit cracked glass, bubble formation oxidation of busbars, discoloration of busbars, or PV module hot spots (bypass diode failure)				
		Test modules showing corrosion of ribbons to junction box				
2	PV Array	Test open circuit voltage of series strings of modules				
		Check all hardware for signs of corrosion and remove rust and re- paint if necessary.	M		M	
		Walk through each row of the PV array and check the PV modules for any damage. Report any damage to rack and damaged modules for warranty replacement. Note location and serial number of questionable modules.	M			
		Inspect ballasted, non-penetrating mounting system for abnormal movement	B			
		Determine if any new objects, such as vegetation growth, are causing shading of the array and move them if possible. Remove any debris from behind collectors and from gutters.	M			
		Remove bird nests from array and rack area.	M			
		Nesting vermin removal, nesting vermin prevention	M			
3	Inverter	Observe instantaneous operational indicators on the	D			

		faceplate of the inverter to ensure that the amount of power being generated is typical of the conditions. Compare current readings with diagnostic benchmark. Inspect Inverter housing or shelter for physical maintenance required if present				
		Replace transient voltage surge suppression devices				
		Install any recent software upgrades to inverter programming or data acquisition and monitoring systems				
		Clean (vacuum) dust from heat rejection fins				
		Replace any air filters on air-cooled equipment such as inverter.				
		Test overvoltage surge suppressors in inverter				
4	**Controller**	Check electrical connection and enclosure for tracking motor/controller	**M**			
5	**AC Wiring**	Inspect electrical boxes for corrosion or intrusion of water or insects. Seal boxes if required.			**B**	
		Check position of disconnect switches and breakers.			**M**	
		Exercise operation of all protection devices.			**M**	
		AC disconnect box inspection			**M**	
		Re-torque all electrical connections on AC side of system.				
6	**DC Wiring**	Test system grounding with "megger"			**B**	
		Scan combiner boxes with Infrared camera to identify loose or broken connections				
		Inspect cabling for signs of cracks, defects, pulling out of connections; overheating, arcing, short or open circuits, and ground faults.	**M**			
		Check proper position of DC disconnect switches.			**B**	
		Check grounding braids for wear	**B**			
		Re-torque all electrical connections in combiner box				
7	**Combiner and Junction Boxes, DC Wiring**	Open each combiner box and check that no fuses have blown and that all electrical connections are tight. Check for water incursion and corrosion damage. Use an infrared camera for identifying loose connections because they are warmer than good connections when passing current.	**M**			

8	**IT**	Check central SCADA/network manager, include software IT and IT hardware updates as required				
9	**Monitoring**	Spot-check monitoring instruments (pyranometer, etc.) with hand-held instruments to ensure that they are operational and within specifications.	**M**			
10	**Tracker**	Anemometer Inspection	**W**			
		Driveshaft torque check & visual inspection	**W**			
		Inclinometer inspection	**W**			
		Limit switch inspection	**W**			
		Module table inspection	**W**			
		Screw jack inspection	**W**		**B**	
		Slew gear torque check & wear inspection	**W**		**B**	
		Torque inspection	**W**			
		Tracking controller inspection	**W**			
		Universal joint inspection, gears, gear boxes, bearings as required or documented by manufacturer	**W**			
		Lubricate tracker mounting bearings/gimbals as required by manufacturer	**W**			
		Lubricate gearbox as required by manufacturer	**W**		**B**	
		Screw jack greasing as required by manufacturer	**W**		**B**	
		Slew gear lubrication as required by manufacturer	**W**		**B**	
		Universal joint greasing (zerk fitting) as required by manufacturer	**W**		**B**	
11	**Transformer**	Inspect transformer meter, oil and temperature gauges, include housing container, or concrete housing if presentment	**M**			
		Transformer/switchgear inspection	**M**			
12	**Motor**	Check electrical connections	**M**			
13	**Substation & Transmission Line Equipment (Transformer, Circuit Breaker,**	Visual inspection (A walk around visual inspection from ground level and keeping in view the safe limits of approach to live and moving parts to check apparent condition, abnormal noise, rust on body of the equipment and component parts, etc.)	**D/W**			
		Oil level	**D/W**			

	Isolator, Measuring Transformer, Busbar, Earthing System etc.)	De-railing locking devices	**D/W**			
		Cooling System	**D/W**			
		Oil Temperature Gauges	**D/W**			
		Oil Temperature Indicators	**D/W**			
		Winding Temperature Gauges	**D/W**			
		Winding Temperature Indicators	**D/W**			
		Ground Connections of Neutral Terminal	**D/W**			
		Ground Connections of Body	**D/W**			
		Oil Leakages all around the equipment	**D/W**			
		Bushing Condition (HV, LV, Neutral, Tertiary, etc.)	**D/W**			
		Bushing Terminal Connections (HV, LV, Neutral, Tertiary, etc.)	**D/W**			
		Doors, Door locks, Door packing, Door stops, Light, Cleaning, Ground connections, Proper glands at wiring cable entrance, Wiring cable numbering, Vermin proofing, etc.	**D/W**			
		Control Switches and Accessories	**D/W**			
		Space heaters & Thermostat setting	**M**			
		Wiring and Terminal Blocks	**M**			
		Steel Structure Ground Connections	**D/W**			
		Inter Phases Mechanical Linkages	**D/W**			
		Lubrication of moving/sliding/rolling parts	**D/W**			
		Manual Operation: Close/Open				
		Wiring and Terminal Blocks				
		Ground Potential Gradient Control Mat Condition and Grounding				
		Test Operation: ON/OFF Local/Remote				
		Interlocking of system				
		Insulation Resistance test (Megger test)				
		Capacitance and Dissipation Factor test				
		Leakage Current Monitoring Test				
		Operation Counter Function Test				

4. Power Plant Software Simulation

This chapter provides the use of selected design software (PVsyst) to simulate the 18 MW single axis tracking solar PV power plant to compare the simulated results with the actual energy produced by the plant. Several simulations have been performed and a comparative analysis conducted under different scenarios. The software allows the users to select either a preliminary or a detailed project design, after which the options of system selection from grid connected, standalone, pumping system or DC grid system are provided. Amongst this selection, the project design section followed by grid connected system has been opted for a detailed simulation. Once grid connected system is selected, the next step is to provide description to the project. Sections such as simulation file name and project name are filled in, as illustrated in Figure 24.

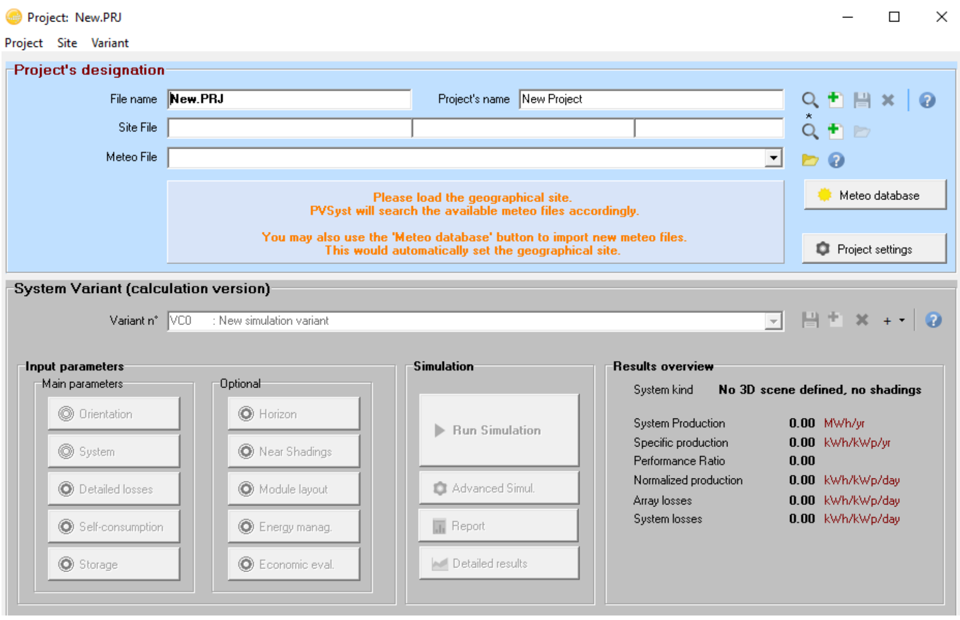

Figure 24: Project Description

The geographical coordinates of the power plant such as latitude, longitude, altitude and time zone are input, as shown in Table 12 and Figure 25.

Table 12: Geographical coordinates of the power plant

Sr. No	Coordinates	Values
1	Latitude	30.5815^{0}
2	Longitude	72.8944^{0}
3	Altitude	144 m
4	Time Zone	+5 hours

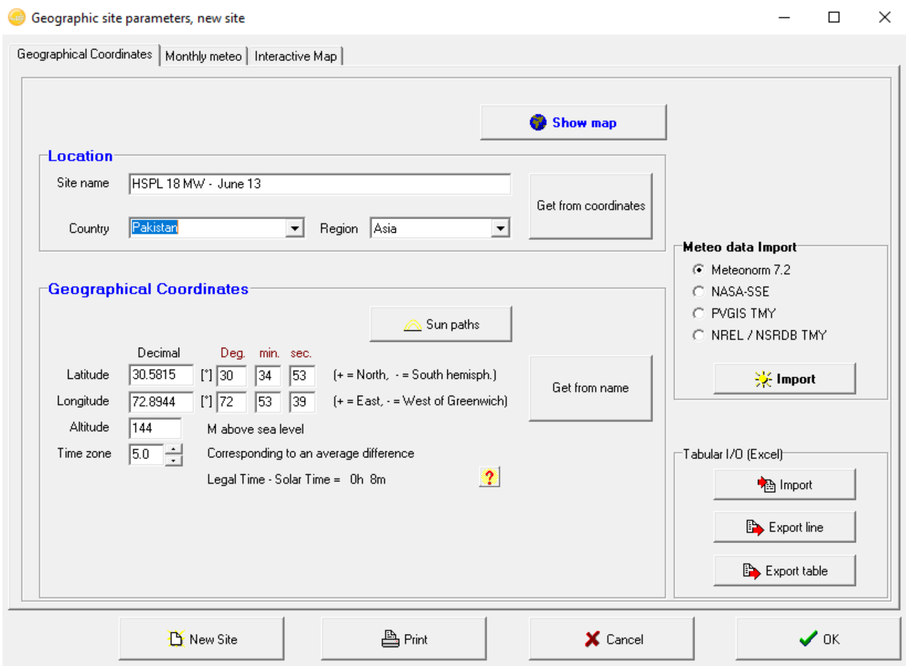

Figure 25: Geographical site parameters: Geographical Coordinates

The software provides an option to import the meteo data from four sources i.e. Meteonorm 7.2, NASA-SSE, PVGIS TMY, NREL /NSRDB TMY or input the ground data if available. Simulations on Meteonorm, NASA-SSE and plant site ground data have been performed and compared with actual plant output for analysis of most appropriate data set. Data for PVGIS and NREL for the location of the power plant are not available in the software. As an example, Figure 26 shows how data from Meteonorm appears listed by the software.

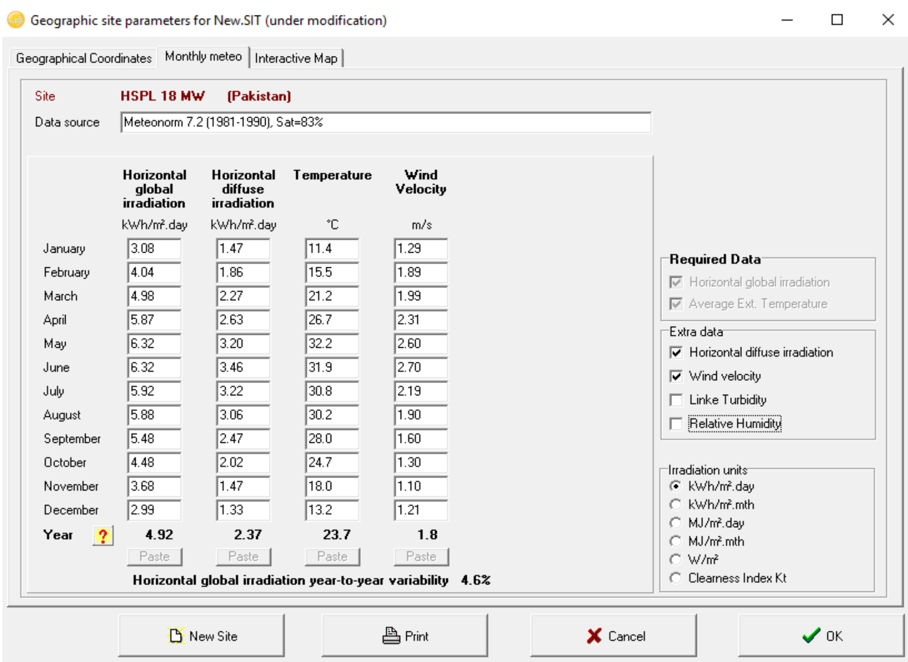

Figure 26: Geographical site parameters: Meteorological data

The meteorological data in Figure 26 provides important values such as the global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI), temperature, wind velocity, linked turbidity and relative humidity for computation of energy generation. The software also allows for selection of site from an interactive map. Figure 27 shows the interactive map pointing the actual site of the existing power plant.

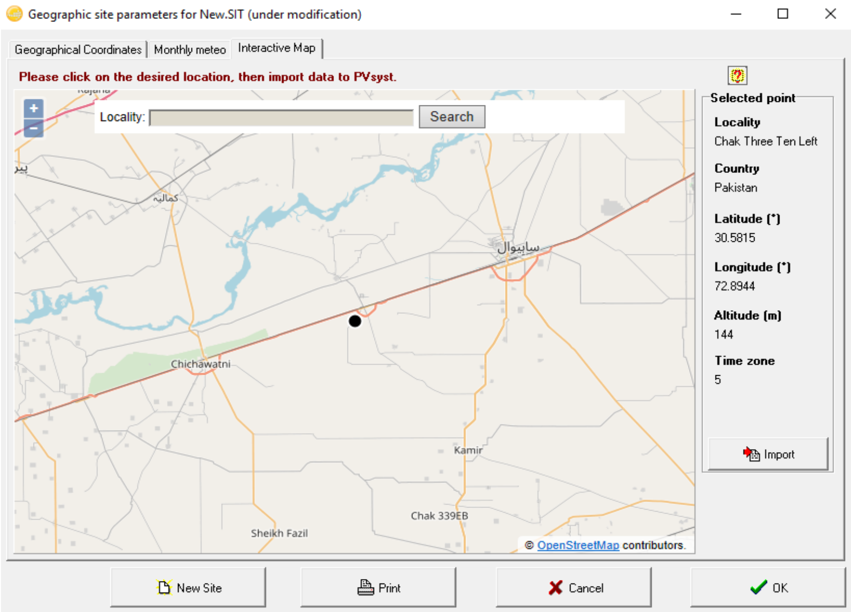

Figure 27: Geographical site parameters: Interactive Map

After all geographical parameters are detailed, orientation of the power plant is defined. Axis tilt, axis azimuth angle, minimum and maximum phi (rotation) angles are input as per the actual power plant design specifications, as shown in Figure 28.

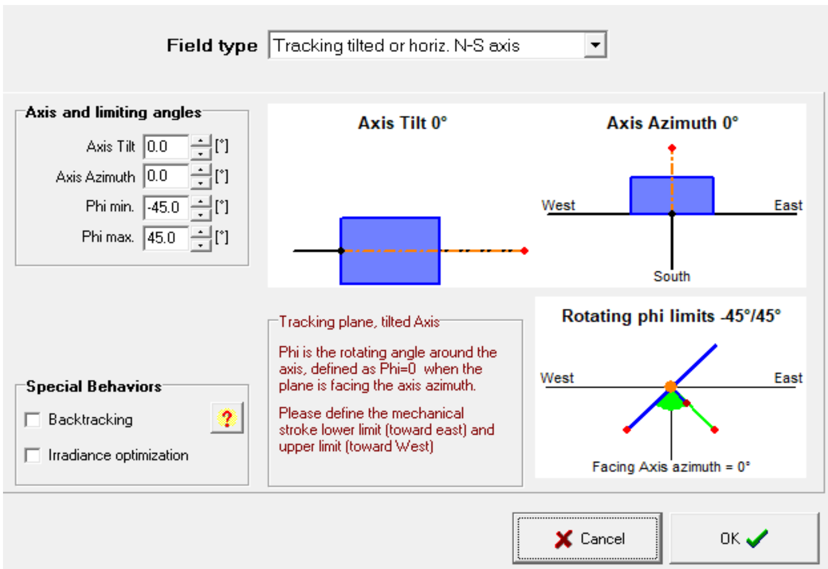

Figure 28: Power plant orientation

The simulation software provides various options to select from in terms of Field type. As per the actual power plant field type it has been selected as "Tracking, tilted or horizontal N-S axis". Following options are provided by the drop-down menu of field types by the software, as shown in Figure 29.

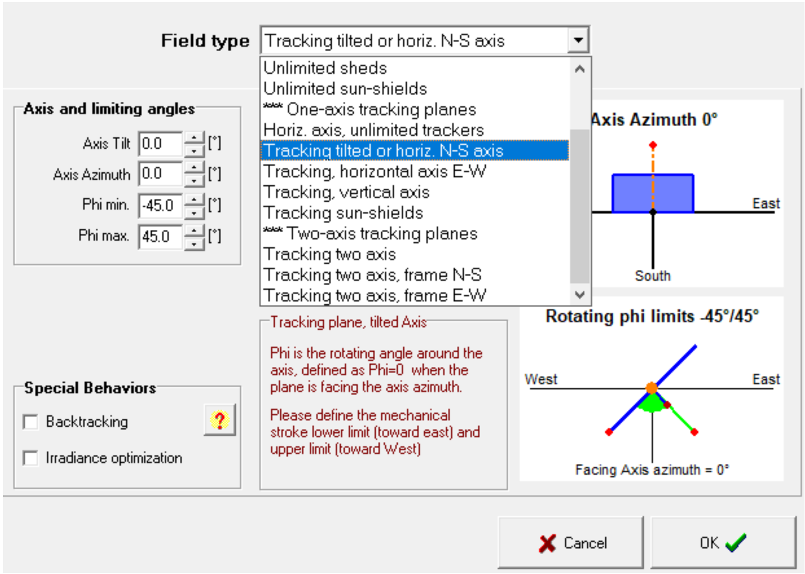

Figure 29: Power plant field types

Next key step is to input the main system parameters. In the PV array section, planned power is inserted which is 18,000 kW_p followed by selection of PV modules and inverters (as listed in Table 6) installed on the power plant from the software database. Number of inverters are input as per actual installed inverters and the software automatically calculates the number of modules in series and number of strings in the power plant. Actual PV modules and inverters used at the plant have been used for the simulation studies. Figure 30 shows the simulation software interface to input the main system parameters.

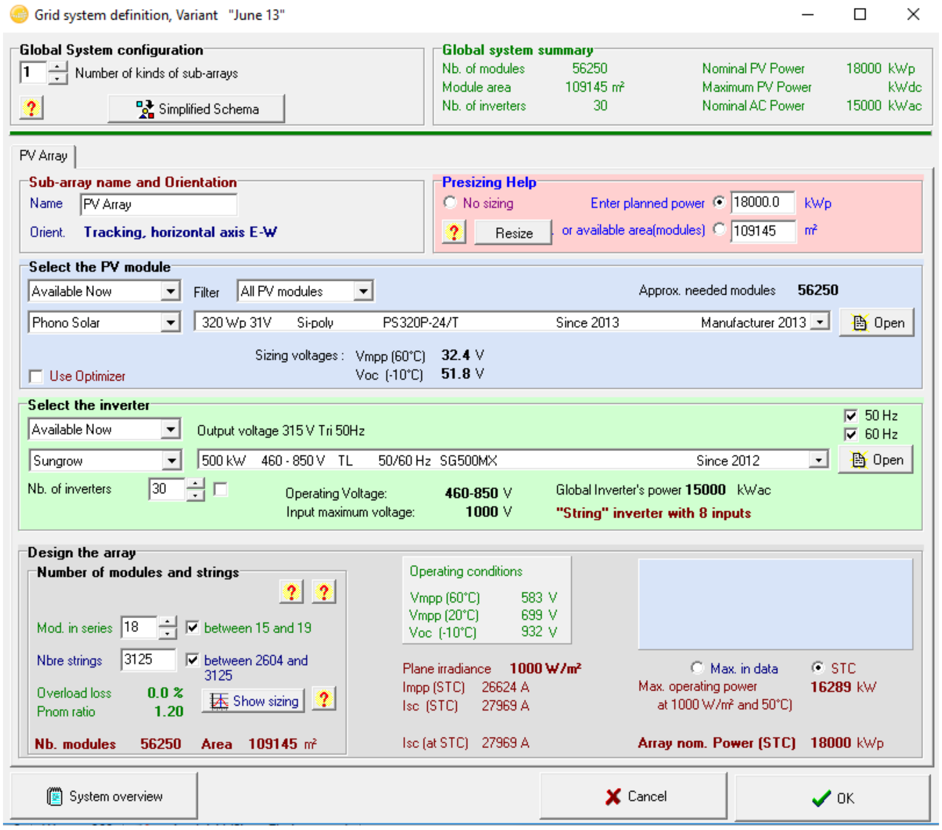

Figure 30: Power plant main system parameters

Now the losses in the power plant are input in the system as represented in Figure 31. Using a screen similar to Figure 31, PVsyst allows to input thermal parameter (field thermal loss factor), ohmic losses, module quality, LID, mismatch loss, soiling loss, IAM losses, auxiliaries (self-consumption at power plant), ageing, plant unavailability and spectral correction (changes in solar spectrum due to scattering and absorption in atmosphere) in the simulation of the power plant.

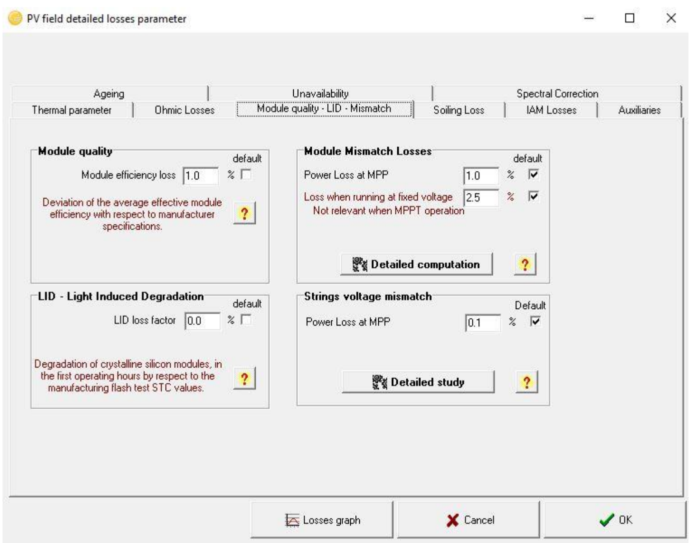

Figure 31: Power plant detailed losses

After inserting the losses, near shading diagram of modules is created. Direction of the plant and distance between successive rows, which is 7 meters in the actual plant, is replicated in the simulation software as shown in Figure 32.

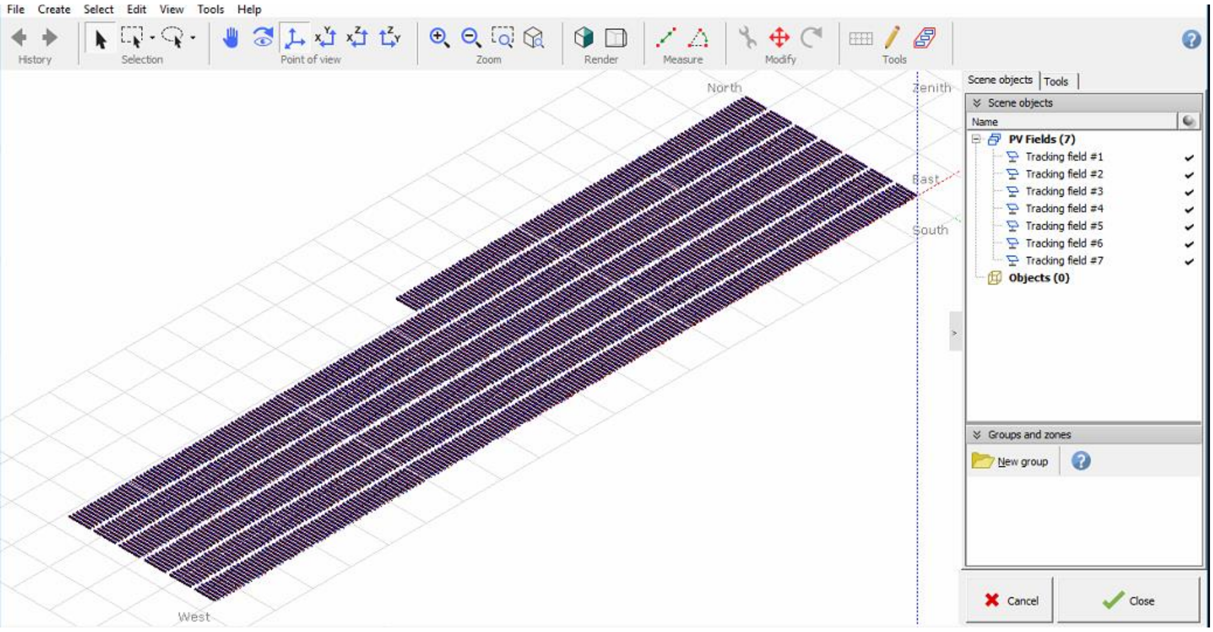

Figure 32: Near Shading diagram

When all the simulation parameters are in order and a simulation is performed a green bar appears on the middle of the home screen stating" Simulation done" as represented in Figure 33. If there are any problems in simulation, a red line appears instead, stating the problem. Furthermore, all input parameters turn green when the simulation is correctly performed.

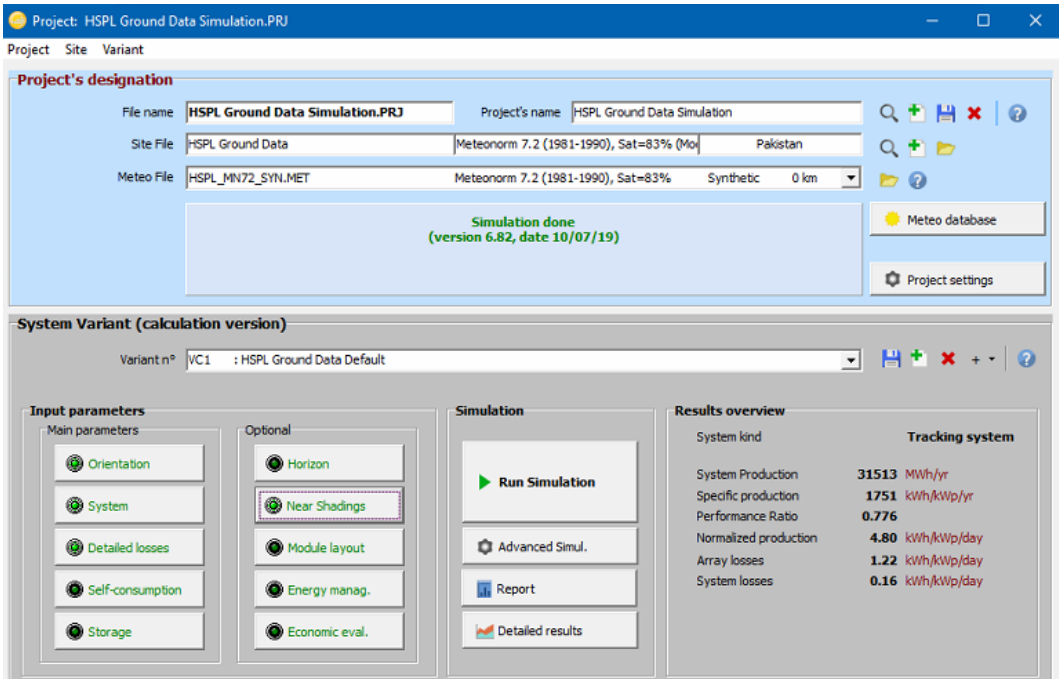

Figure 33: Simulated version of software main screen

An overview of the results showing the energy production, specific production, performance ratio, normalized production, array losses and system losses appears on the right side. A report of the simulation can be received by pressing the report tab and detailed results can be checked, which allow to compare various parameters such as the meteo data with energy production, etc.

A comprehensive software simulation report for one of the various simulations performed, detailing simulation parameters, near shading, main results and losses diagram has been presented in Annexure 1. Main results' section includes figures, which present simulated results of the monthly energy production and monthly performance ratios. A table presents the monthly values of global horizontal and diffused horizontal irradiations, ambient temperature, global horizontal irradiations incident on collector plane, effective energy at the output of array and energy injected to the grid. Finally, the loss diagram section provides a chart with detailed losses taking place at the plant site. It is pertinent to mention that the efficiency at STC mentioned in the losses diagram is the efficiency of solar PV modules provided by the manufacturer.

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 values, 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 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 13 shows the values of losses considered in four cases whereas Table 14 presents the energy output of the power plant in for each case simulated and with three different weather data sets.

Table 13: 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 14: 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	
		MWh	MWh	MWh	MWh	MWh
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	

An interesting insight was found as the results in Table 14 were compiled. 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 site losses and all-weather data sets is listed in Table 15. Percentage differences have also been listed to get a better idea of both the over and underperformance of the power plant. Figure 34 presents the differences pictorially.

Table 15: Plant output comparison with simulated results of different 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

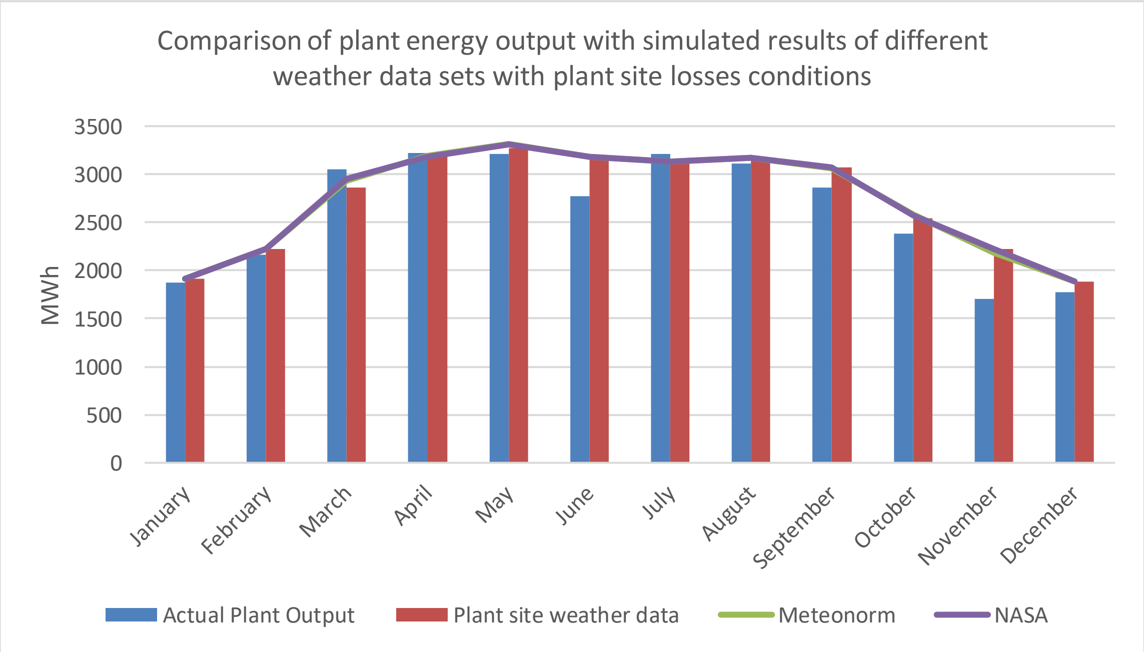

Figure 34: Difference between actual plant output and software simulated results

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 feasibility 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 16 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).

While comparing Table 16, it can also be seen that all major underperforming months in both cases of baseline scenario (present and recommended) are similar i.e. June, September, November and December, which signifies the need of detailed operations and maintenance documentation and remedies during such times. Section 5.2 elaborates further on this topic.

Table 16: Plant energy output comparison with simulated results for current baseline and 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**

For these two key simulated results the performance ratio of the plant has also been compared to determine authenticity of the simulations performed.

From the results in Table 17, it can be seen that the power plant is operating close to or at even having a slightly better annual performance ratio than that one predicted by simulation considering plant site weather data and plant site losses condition are simulated. In conclusion this validates the results of the simulation performed.

Table 17: Performance Ratio comparison of actual power plant and simulated results for current baseline and recommended baseline

Months	**Actual Plant Energy Output**	**PVsyst Simulated Results**	
		Meteonorm + Default Losses Condition	Plant site weather data + Plant site losses condition
		Present Baseline Scenario	**Recommended Baseline Scenario**
	PR (%)	**PR (%)**	**PR (%)**
January	85.43	84.6	86.5
February	85.38	83	84.8
March	80.43	80.2	79.3
April	79.71	78.3	79.8
May	77.84	71.5	76.7
June	78.98	72.8	78.6
July	81.1	77.6	79.2
August	80.28	78	79.7
September	82.31	78.3	80
October	82.05	74.5	80
November	79.95	75.7	83
December	83.69	83.1	85
Average	**81.43**	**78.13**	**81.05**

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 18 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 18: 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**
January	1,873	1,911	1,931
February	2,159	2,226	2,249
March	3,048	2,858	2,985
April	3,216	3,208	3,192
May	3,208	3,271	3,359
June	2,774	3,184	3,221
July	3,207	3,129	3,164
August	3,113	3,175	3,211
September	2,861	3,067	3,102
October	2,387	2,539	2,605
November	1,704	2,224	2,189
December	1,778	1,886	1,905
Annual	**31,328**	**32,678**	**33,113**
Difference	**MWh**	**1350**	**1785**
	%	**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 19 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 19: 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
2021	1,351,000	14.3961	194,491	175,042
2022	1,351,000	14.3961	194,491	175,042
2023	1,351,000	14.3961	194,491	175,042
2024	1,351,000	14.3961	194,491	175,042
2025	1,351,000	14.3961	194,491	175,042
2026	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
2029	1,351,000	6.0422	81,630	73,467
2030	1,351,000	6.0422	81,630	73,467
2031	1,351,000	6.0422	81,630	73,467
2032	1,351,000	6.0422	81,630	73,467
2033	1,351,000	6.0422	81,630	73,467
2034	1,351,000	6.0422	81,630	73,467
2035	1,351,000	6.0422	81,630	73,467
2036	1,351,000	6.0422	81,630	73,467
2037	1,351,000	6.0422	81,630	73,467
2038	1,351,000	6.0422	81,630	73,467
2039	1,351,000	6.0422	81,630	73,467
2040	1,351,000	6.0422	81,630	73,467
2041	1,351,000	6.0422	81,630	73,467
2042	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 20.

Table 20: 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
2021	1,786,000	14.3961	257,114	231,403
2022	1,786,000	14.3961	257,114	231,403
2023	1,786,000	14.3961	257,114	231,403
2024	1,786,000	14.3961	257,114	231,403
2025	1,786,000	14.3961	257,114	231,403
2026	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
2029	1,786,000	6.0422	107,914	97,122
2030	1,786,000	6.0422	107,914	97,122
2031	1,786,000	6.0422	107,914	97,122
2032	1,786,000	6.0422	107,914	97,122
2033	1,786,000	6.0422	107,914	97,122
2034	1,786,000	6.0422	107,914	97,122
2035	1,786,000	6.0422	107,914	97,122
2036	1,786,000	6.0422	107,914	97,122
2037	1,786,000	6.0422	107,914	97,122
2038	1,786,000	6.0422	107,914	97,122
2039	1,786,000	6.0422	107,914	97,122
2040	1,786,000	6.0422	107,914	97,122
2041	1,786,000	6.0422	107,914	97,122
2042	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 also 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 any problems in five months where power plant has underperformed i.e. June, September, October, November and December, but comparing results of Table 10 and Table 15 we can assess that most corrective maintenance activities have been performed on *trackers* in the months where there has been major underperformance. Table 21 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 21: Plant underperformance vs Corrective maintenance

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 22 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 [7]. Fourth column next to the ‘Requirement’ column, 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 also determine the actual amount of losses generated at various areas of the plant.

Table 22: 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:

- **Baseline for Comparison**

While comparing the energy output of power plant with simulated results, 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.

- **Losses Measurement**

Actual losses taking place at the power plant such as soiling, ohmic losses, module quality, mismatch, all must be measured and documented. Moreover, an effort to reach the minimum losses as documented in literature review must be aspired to achieve.

- **Predictive Maintenance**

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.

- **Automated Plant Diagnosis**

Similarly, 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.

- **Measurement of Key Performance Indicators (KPIs)**

As per literature review and review of operations and maintenance at the plant site, measurement of following KPIs on the power plant should be conducted as a minimum requirement, recommendation and best practice:

i. Minimum Requirement (Intervention time and Response time),
ii. Recommendation (Mean time between failures, Inverter specific losses, Inverter specific efficiency, Module soiling losses, Energy based availability),

iii. Best practice (Temperature corrected performance ratio, Energy performance index, Uptime).

- **Cable Repair**

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**

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.

- **Site Selection for Power Plant**

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.

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Anenexure 1: PVsyst Simulation Report

PVSYST V6.82		25/10/19	Page 1/5

Grid-Connected System: Simulation parameters

Project :	**HSPL Ground Data Simulation**			
Geographical Site	**HSPL Ground Data**		Country	**Pakistan**
Situation	Latitude	30.58° N	Longitude	72.89° E
Time defined as	Legal Time	Time zone UT+5	Altitude	144 m
	Albedo	0.20		
Meteo data:	**HSPL**	Meteonorm 7.2 (1981-1990), Sat=83% - Synthetic		

Simulation variant :	**HSPL Ground Data Default**			
	Simulation date	10/07/19 13h19		

Simulation parameters	System type	**Tracking system**		
Tracking plane, tilted Axis	Axis Tilt	0°	Axis Azimuth	0°
Rotation Limitations	Minimum Phi	-45°	Maximum Phi	45°
	Tracking algorithm	Astronomic calculation		
Trackers configuration	Nb. of trackers	1300	Identical arrays	
	Tracker Spacing	7.00 m	Collector width	2.02 m
Shading limit angles	Phi limits	+/- 73.0°	Ground cov. Ratio (GCR)	28.9 %
Models used	Transposition	Perez	Diffuse	Perez, Meteonorm
Horizon	Free Horizon			
Near Shadings	Linear shadings			
User's needs :	Unlimited load (grid)			

PV Array Characteristics				
PV module	Si-poly Model	**PS320P-24/T**		
Original PVsyst database	Manufacturer	Phono Solar		
Number of PV modules	In series	18 modules	In parallel	3125 strings
Total number of PV modules	Nb. modules	56250	Unit Nom. Power	320 Wp
Array global power	Nominal (STC)	**18000 kWp**	At operating cond.	16289 kWp (50°C)
Array operating characteristics (50°C)	U mpp	612 V	I mpp	26624 A
Total area	Module area	**109145 m²**	Cell area	98561 m²
Inverter	Model	**SG500MX**		
Original PVsyst database	Manufacturer	Sungrow		
Characteristics	Operating Voltage	460-850 V	Unit Nom. Power	500 kWac
Inverter pack	Nb. of inverters	30 units	Total Power	15000 kWac
			Pnom ratio	1.20

PV Array loss factors				
Array Soiling Losses			Loss Fraction	1.5 %
Thermal Loss factor	Uc (const)	29.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
Wiring Ohmic Loss	Global array res.	0.39 mOhm	Loss Fraction	1.5 % at STC
LID - Light Induced Degradation			Loss Fraction	2.0 %
Module Quality Loss			Loss Fraction	0.8 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Strings Mismatch loss			Loss Fraction	0.10 %
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Param.	0.05
Unavailability of the system	1.3 days, 5 periods		Time fraction	0.4 %

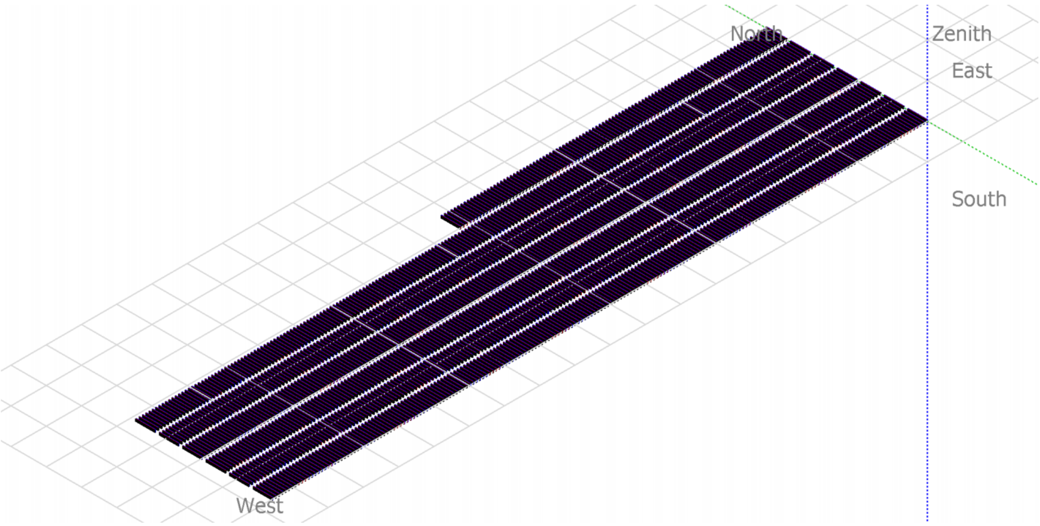
Grid-Connected System: Near shading definition

Project : **HSPL Ground Data Simulation**

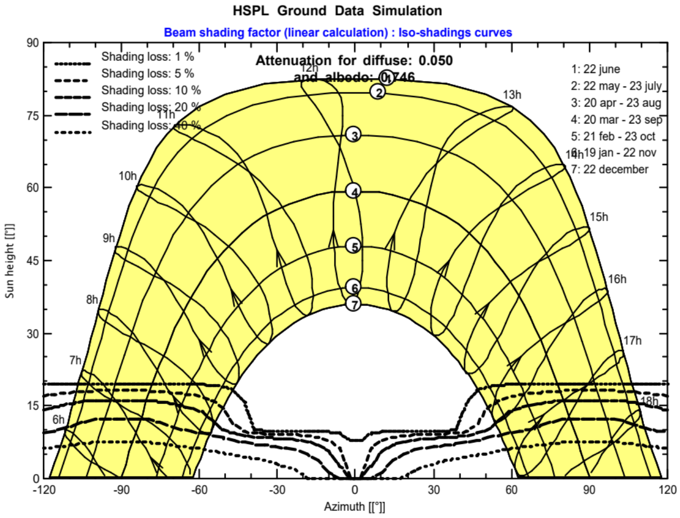
Simulation variant : **HSPL Ground Data Default**

Main system parameters	System type	**Tracking system**		
Near Shadings	Linear shadings			
PV Field Orientation	tracking, tilted axis, Axis Tilt	0°	Axis Azimuth	0°
PV modules	Model	PS320P-24/T	Pnom	320 Wp
PV Array	Nb. of modules	56250	Pnom total	**18000 kWp**
Inverter	Model	SG500MX	Pnom	500 kW ac
Inverter pack	Nb. of units	30.0	Pnom total	**15000 kW ac**
User's needs	Unlimited load (grid)			

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram



Grid-Connected System: Main results

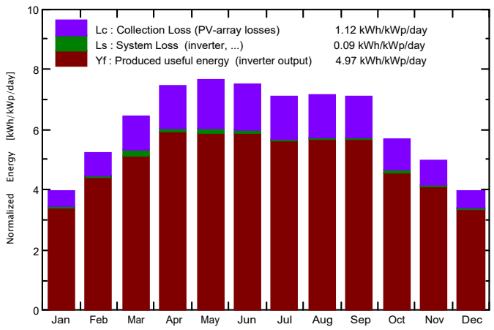
Project : **HSPL Ground Data Simulation**

Simulation variant : **HSPL Ground Data Default**

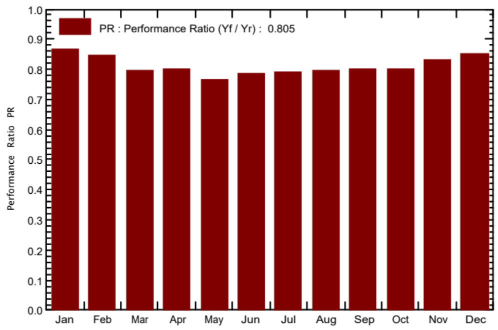
Main system parameters	System type	**Tracking system**		
Near Shadings	Linear shadings			
PV Field Orientation	tracking, tilted axis, Axis Tilt	0°	Axis Azimuth	0°
PV modules	Model	PS320P-24/T	Pnom	320 Wp
PV Array	Nb. of modules	56250	Pnom total	**18000 kWp**
Inverter	Model	SG500MX	Pnom	500 kW ac
Inverter pack	Nb. of units	30.0	Pnom total	**15000 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**32678 MWh/year**	Specific prod.	1815 kWh/kWp/year
	Performance Ratio PR	80.46 %		

Normalized productions (per installed kWp): Nominal power 18000 kWp



Performance Ratio PR



HSPL Ground Data Default
Balances and main results

	GlobHor kWh/m²	DiffHor kWh/m²	T_Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray MWh	E_Grid MWh	PR
January	95.6	45.5	11.37	122.8	113.8	1934	1911	0.865
February	113.1	52.1	15.46	145.8	135.8	2251	2226	0.848
March	154.4	70.3	21.17	200.2	186.9	2986	2858	0.793
April	176.1	79.0	26.66	223.3	209.8	3250	3208	0.798
May	195.8	99.3	32.16	237.0	223.2	3374	3271	0.767
June	189.7	103.9	31.95	225.2	211.5	3222	3184	0.786
July	183.6	99.9	30.81	219.4	206.0	3165	3129	0.792
August	182.3	95.0	30.21	221.4	208.0	3212	3175	0.797
September	164.5	74.0	28.02	212.9	199.2	3102	3067	0.800
October	139.0	62.5	24.75	176.3	165.1	2613	2539	0.800
November	110.4	44.0	18.01	148.8	137.4	2261	2224	0.830
December	92.6	41.1	13.24	123.3	113.2	1908	1886	0.850
Year	1796.9	866.6	23.69	2256.4	2109.9	33276	32678	0.805

Legends:

GlobHor	Horizontal global irradiation	GlobEff	Effective Global, corr. for IAM and shadings
DiffHor	Horizontal diffuse irradiation	EArray	Effective energy at the output of the array
T_Amb	Ambient Temperature	E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane	PR	Performance Ratio

Grid-Connected System: Loss diagram

Project : **HSPL Ground Data Simulation**

Simulation variant : **HSPL Ground Data Default**

Main system parameters	System type	**Tracking system**		
Near Shadings	Linear shadings			
PV Field Orientation	tracking, tilted axis, Axis Tilt	0°	Axis Azimuth	0°
PV modules	Model	PS320P-24/T	Pnom	320 Wp
PV Array	Nb. of modules	56250	Pnom total	**18000 kWp**
Inverter	Model	SG500MX	Pnom	500 kW ac
Inverter pack	Nb. of units	30.0	Pnom total	**15000 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year