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Research Article

Evaluation of Energy Production and Energy Yield Assessment Based on Feasibility, Design, and Execution of 3 × 50 MW Grid-Connected Solar PV Pilot Project in Nooriabad

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The installation of 3 × 50 MW (150 MW DC) large utility scale solar power plant is ground based using ventilated polycrystalline module technology with fixed tilt angle of 28° in a 750-acre land, and the site is located about 115 km northeast of Karachi, Pakistan, near the town of ThanoBula Khan, Nooriabad, Sindh. This plant will be connected to the utility distribution system through a national grid of 220 kV outgoing double-loop transmission line. The 3 × 50 MW solar PV will be one of the largest tied grid-connected power projects as the site is receiving a rich average solar radiation of 158.7 kW/h/m^2/month and an annual average temperature of about of 27°C. The analysis highlights the preliminary design of the case project such as feasibility study and PV solar design aspects and is based on a simulation study of energy yield assessment which has all been illustrated. The annual energy production and energy yield assessment values of the plant are computed using the PVSYST software. The assumptions and results of energy losses, annual performance ratio (PR) 74.73%, annual capacity factor 17.7%, and annual energy production of the plant at 232,518 MWh/year are recorded accordingly. Bear in mind that reference recorded data indicates a good agreement over the performance of the proposed PV power plant.

1. Introduction

Pakistan is experiencing an acute shortage of electricity and multifaceted energy crisis of about 7000 MW since many years, which is approximately 1/3 of the peak demand during extreme periods. This shortfall is the result of the failure of the GoP which had no investment planning to expand the power system capacity and to meet the power growth demand for more than a decade in the energy sector [1, 2]. In order to fill the gap of energy crises today, the GoP has tasked the local, provincial governments to set up new renewable energy power projects such as solar, wind, and biomass in order to provide a requisite institutional framework to end the shortage of severe energy demand. These energy shortages are imposing large costs on the country's economy, which is estimated around 2 percent of the GDP annually [3]. In May 2003, AEBD was established as the sole representing agency of the GoP; it took key roles to facilitate, promote, and develop renewable energy projects in Pakistan. With the permission of AEDB, the first phase of 100 MW was commissioned and energized into the national grid in 2014 named as Quaid-e-Azam Solar Park [4]. According to the report of the Pakistan Economic Survey 2014-15 by the Ministry of Finance, the GoP would be inducted into 10400 MW through solar, wind, coal, and hydropower by the end of 2017 [5]. For this purpose, the GoP prepared the national power policy through AEDB which allows energy departments from the local provinces and attached departments to issue the LOIs for all based IPPs to construct the solar PV power plants in remote areas. In order to remove the certain risk in private business investment and generate energy in a fast track system, IPPs are encouraged to set up PV pilot projects in the public and private sectors and given monetary incentives [6]. In addition, GoP will issue the guarantee letter in terms of IA to IPPs or IPPPs so that production of electricity from the solar power plant will be purchased by WAPDA and CPPA or K-Electric through standard EPA or PPA contract after energizing the plant into the national grid utility [7].

In order to improve the environmental condition, save ozone, and to decrease the emission of CO_2/0.6 kg on per kWh into the atmosphere [8, 9], the 3×50 MW solar PV pilot project has been proposed as one of the renewable energy projects in Pakistan with IPP mode and will operate on a BOO business model. In this case, a 3×50 MW solar PV project, LOI (land: 750-acre area), was issued by provisional GoS, and therefore, grid interconnection studies were approved by NTDC. The Upfront FIT was determined by NEPRA in 2014 due to the project's financial closure which took several months to fetch up and yet certain time was required for EPC work to kick off the construction phase [10]. The total rough cost of this project is estimated around 150 million USD based on the financial proposal of the International EPC contractor. In consequence, a full rollout of such a project could be envisaged. In addition, load shedding would be eliminated immediately with a clean source of electricity, reducing the burden on the already stretched grid.

The main groundbreaking targets in this paper were that we contributed to the research work on PV plant sustainable accessibility and feasibility study, including site and land survey, and compared meteorological data, weather cast, temperature, equipment selection, and design layout of PV system such as the primary and secondary design solutions. We computed the plant initial performance analysis based on annual system yield assessment report, plant loss factors, performance ratio, capacity factor, and estimated total output energy production yearly based on degradation factor. The software used was PVsyst V6.47 for sizing and data analysis of complete PV system's simulation and AutoCAD for the drawings [11].

The novel portion of the project is the selection of the equipment including eBOP and cBOP part based on the analysis of the meteorological database. In literature review of the manuscript, we identified the research gap on solar radiation assessment resources using the different weather station databases and compute the yearly production using PVsyst model to judge the capability of existence of the project. Hence, this paper provides the knowledge of technical proposal to the potential energy developers for the large-size PV pilot projects before setting up the plant. This study also provides how to improve the energy harvest and maximize generation by selecting reliable equipment selection and design solution. The obtained data could be used as guidelines for the application of large-size solar PV plants in other countries within a similar nature [9].

2. Project Profile

In South Asia, solar energy is viewed as most promising for the sun peak hour countries such as Pakistan, located in different climatic conditions such as tropical and humid. Every day, the country receives an average of about 19 MJ/m^2 of solar energy, and solar power potential available is 5.3 kWh/m^2/day. Based on this, Pakistan has favored projects that utilized solar energy and backed up some energy for the 43% of the total population who live without access to electricity in Pakistan [12]. To cope with these demands, we have studied the development of the 150 MW DC solar project in this regard.

Table 1: The coordinates and elevation are provided.

Weather database	Latitude (degree)	Latitude (degree)	Elevation (m)
Meteonorm 7.1 [2001–2010]	25°19.2N	68°0.42E	110

This study is also based on the 150 MW DC project that facilitates the interconnection study by using the utility, energy production assessment, and yield output of the electricity per year. These are three 50 MW solar projects located around 115 km northeast of Karachi, Pakistan, near the town of Thano Bula Khan and Nooriabad, Sindh, side by side on the same parcel of land with a combined installed DC capacity of 150 MW DC. The PV arrays will be connected to a single interconnection point and each 50 MW DC project is identical. Therefore, dividing the energy production estimates by three projects of 50 MW size (3×50 MW) will provide the estimation of energy production of total 150 MW DC and evacuation into the national grid.

In this paper milestone, we also used other comparative statements which match their PV system characteristic parameters and show model superiority such as focus on performance analysis, energy yield assessment of the PV power plant, and general production. These relative works are given as a reference study in the following references [9, 11, 13–17] which are cited in this paper. These references [9, 11, 13–17] reviewed the similar studies of the following project advantages and characteristics such as PV power plant data and model approach, project profile estimate electricity yield, parameters of the site and PV power plant, site solar resource summary, local climate analysis, and PV energy production based on uncertainty and degradation evaluation.

2.1. Site Location and Land Coordinates. According to the land coordinates, the solar power plant site is located at longitude 68°4.2′, north latitude 25°19.2′, and elevation is approximately 110 m above sea level in Table 1. It is rich in solar energy resources based on the land coordinate status; the land coordinates information is given in Figure 1.

2.2. Meteorological Data for Proposed Site. In order to observe the energy yield of the solar system, meteorological data of the PV power plant under consideration is required [18]. The energy efficiency of PV system depends on the real

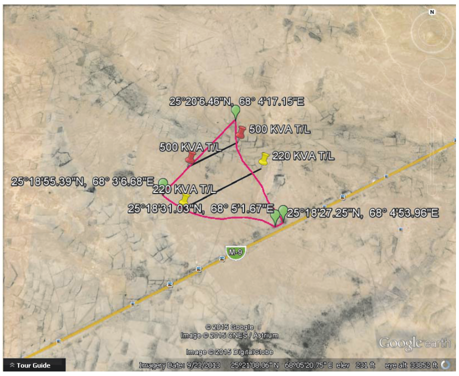

Figure 1: Land coordinates on Google map at the proposed solar site.

meteorological data based on the local climate condition and availability of solar radiation. Therefore, two meteorological databases are used to estimate and determine the solar radiation and temperature information at the proposed site. Pakistan climate for the solar radiation has potential value because the project site is located nearby Karachi city, the solar resources are wildly available, and the average maximum radiation in Karachi between September and February is 550 W/m^2 [4].

2.2.1. Meteonorm Database. Meteonorm 7.1 weather database has obtained irradiation and temperature data from the ones listed in Table 1. The meteonorm results are based on the extrapolation of data from a weather station located 105 km from the project. The irradiation data, as its name implies, has an uncertainty of 11% and with an interannual variability of 4.5%. The average monthly values of the global horizontal and temperature from meteonorm database are analyzed in Table 2 [13]. In the absence of an on-site monitoring station, the analysis of influences of the distance is through irradiation data sources which, when consulted, present several drawbacks. When compared to a high-quality on-site monitoring station, the data sources are lacking accuracy in terms of spatial distance, spatial resolution, or temporal resolution. Please note that there is no measured solar radiation data from the solar radiation monitoring system within 25 km of the project site, and we extracted data from 105 km away from the project site according to the Pakistan Meteorological Department and the relevant department is aware of this fact and is relying on the satellite data to establish solar resource for the feasibility studies [19]. The following facts and figures are given below.

(1) There is no measured irradiation data near the project site. In such case, data from surrounding available databases have been considered.

(2) NASA-SSE predicts irradiation data at the project site; however, the data is unrefined in spatial resolution with relatively high uncertainty (10%).

(3) Meteonorm results are based on the extrapolation of the data from a weather station located 105 km from the project site given that irradiation data has an uncertainty of 11% and with an interannual variability of 4.5%.

(4) SolarGIS data are provided at the project site using satellite data interpolated by GeoModel algorithm which typically has an uncertainty between 3.5% and 7.0%. The irradiation data for the project site has an estimated uncertainty of 6.0% with a calculated interannual variability of 3.4%.

(5) The error rate of the distance between the weather station and the project site is based on values of uncertainty and with an interannual variability as discussed in the above points 3 and 4.

Table 2: Monthly values of Meteonorm 7.1 [2001–2010] sat = 56% database.

Month	Global irrad. [$kWh/m^2{\cdot}mth$]	Diffuse [$kWh/m^2{\cdot}mth$]	Temper. [°C]	Wind vel. [m/s]
January	126.5	44.1	17.8	2.09
February	128.0	57.9	21.0	2.39
March	170.3	78.4	26.0	2.60
April	182.0	88.8	29.5	3.30
May	198.5	98.4	32.5	4.40
June	198.1	97.8	32.6	4.80
July	168.8	100.8	31.7	4.90
August	160.7	97.7	30.4	4.49
September	169.2	81.0	29.8	3.90
October	159.2	63.4	28.8	2.31
November	130.9	45.4	23.7	1.70
December	112.1	47.6	19.2	2.00
Year	**1904.3**	**895.3**	**26.9**	**3.2**

2.2.2. Solar GIS Database. We procured SolarGIS irradiation and temperature data from GeoModel which includes 15 years of meteorological history at the project site. Table 3 presents the average monthly values of the global horizontal irradiation (GHI) and ambient temperature obtained from SolarGIS for the project location including the period of record. From this database, the interannual variability of the project site was calculated to be 3.4%. SolarGIS data are provided on the project site using satellite data interpolated by GeoModel algorithm which typically has an uncertainty between 3.5% and 7.0%. The irradiation data for the project site has an estimated uncertainty of 6.0% with a calculated interannual variability of 3.4% [13].

2.3. Construction Scope. The whole construction works for this project mainly including the civil and electrical construction phase and their foundation section as well as the following items are mandatory such as project planning, facility installation and engineering, water supply and drainage, plant roads, pipeline installation, firefighting, complex building, and substation-related services. The construction work shall end at the 220 kV main transformer HV outgoing

Table 3: Monthly values of GHI and temperature from Solar GIS.

Period	Month	GH [kWh/m^2]	Temperature [°C]
	January	134	18.5
	February	153	22.7
	March	197	26.0
	April	215	32.3
	May	227	34.2
	June	204	33.7
1999–2013	July	180	33.7
	August	179	31.1
	September	179	31.1
	October	172	30.0
	November	136	25.8
	December	122	20.5
	Year	**2098**	**28.3**

line. The technical components of the solar power plant are properly selected and manually matched at their datasheets. The connection and a number of panels and centralized inverter are chosen with appreciate to nominal power and advocated operation values of currents and voltages [13]. The following main technological components of a grid-connected solar PV plant which mainly consists and properly selected to be equipped for the installation are given below.

(i) Installed capacity DC: 150 MWp

(ii) Type of solar cell: polycrystalline silicon module

(iii) PV arrays: 150 nos.

(iv) PV array size: 150001 kWp

(v) 300 Wp PV modules: 500004 nos.

(vi) Inverter: 500 kW AC, 300 units

(vii) Main transformer 132 kV, 2 units

(viii) Step-up transformer 22 kV–1000 kVA, 150 units

(ix) 22 kV assembly line: 5 loops

(x) 220 kV outgoing line: 2 loops

In the grid-connected PV power generation system, the system maximum working voltage of DC side mainly depends on the inverter's maximum DC voltage and the rated voltage of a circuit breaker on the DC circuit. However, the working voltage of equipment is related to the equipment working environment and altitude; since the project site is located at a lower altitude area and the surrounding air is relatively dry, the equipment selection and design shall use grade I filthy conditions. The grade I filthy condition depends on the feasibility of the site based on the temperature of the equipment to maintain the protection level and operating condition. The manufacturers designed the electrical equipment and set the equipment-working voltage based on the working environment and altitude. Due to the fact that the 3 × 50 MW project site is located at lower altitude area and air around is relatively dry, the equipment selection and design shall use grade I filthy conditions which means that equipment selection design has to consider the conditions of elevation and grade I pollution/environment conditions. Hereby, level 1 environment condition is an important factor for designing and selection of electrical equipment according to the project atmospheric condition such as temperature, wind, clouds, and precipitation.

3. Design Layout of Photovoltaic Plant

The construction design of the PV power plant is incorporated with the primary and secondary designs. The primary design contains total cBOP civil works, and secondary design contains total eBOP electrical works.

3.1. Primary Design. Primary design includes the total cBOP civil work, such as civil foundation, design of solar panel support structure, support of distance/angle, and module mount structural design system.

3.1.1. Design of Solar Panel Support Structure. The support of solar energy photovoltaic matrix can be installed in two types: fixed or tracking. Because the PV module support structure requires different encapsulations according to the local climate condition, the fixed system features a simple structure with convenient installation, debugging, management, and maintenance. Tracking systems do not only need to collocate an automatic tracking mechanism with increased system investment but the installation, debugging, management, and maintenance are also relatively complex. However, the advantage of tracking in terms of increase in power generation is clear. Therefore, an exercise in optimization definitely helps in making the right selection. The selection of support installation type depends on the local climate conditions, solar panel dimension, installation cost, operation and maintenance cost, power generation volume, and power purchase price of grid. The design of support of solar panel has to not only meet the excellent structural and anticorrosive performance requirements but should also be inclined according to the latitude of construction venue to maximize power generation. Most projects are seeking minimum power generation cost. Therefore, the maximum power generation volume is the main objective. Different elevation systems lead to different power generation volumes in various months. According to the operational features of project equipment, the overall dimension of polysilicon solar panel is 1650 × 990 mm. According to the meteorological data and project's requirements, the support and solar panel are required to bear a limit wind speed of 45 m/s. After general consideration, the support of solar energy photovoltaic matrix shall be installed at a fixed angle. In light of this, we have done our due design calculations to propose the most optimum design. According to the local climate conditions, the support has an inclination angle of 28° in the north-south direction.

3.1.2. Design of Distance/Angle Support System. The incident angle of the sun in dissimilar latitude is different. The

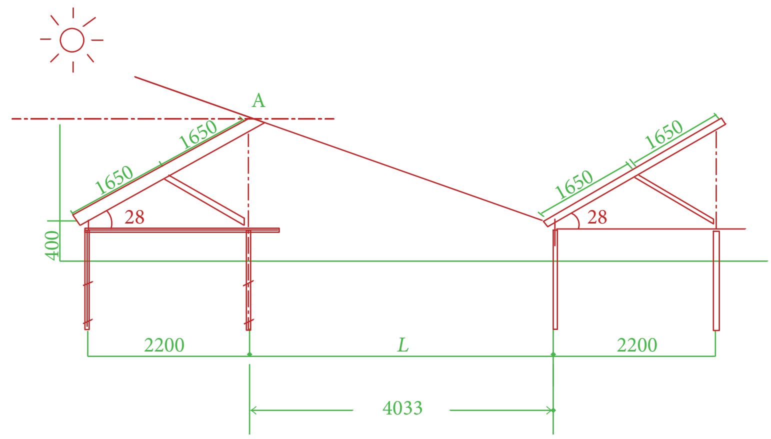

Figure 2: Support distance of PV mounting structure from the ground to the sun.

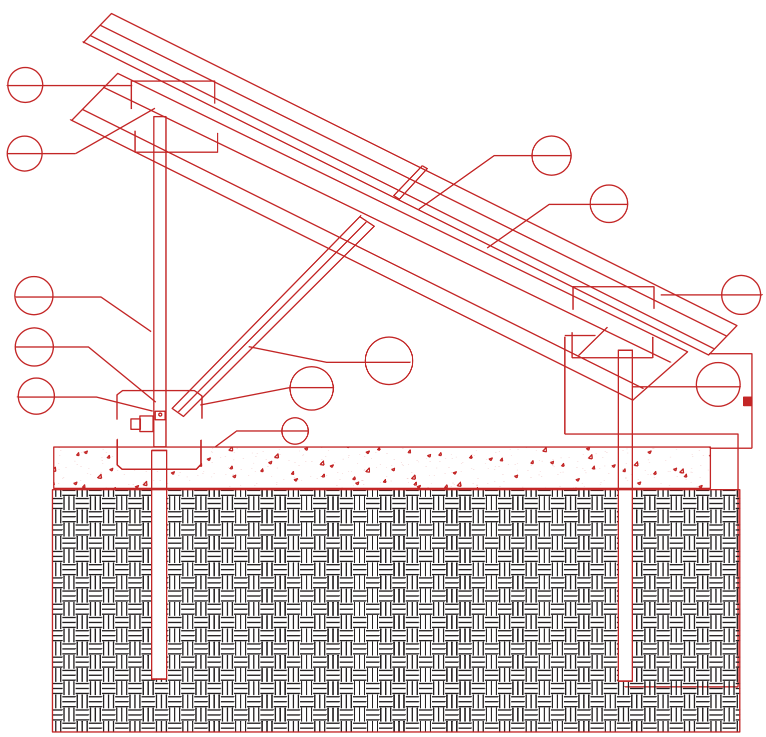

Figure 3: Support structure of solar energy photovoltaic panels.

calculation of support distance of PV is by mounting the structure from the ground to the sun at an inclination best tilted to an angle of 28° based on the geographic coordinates (east longitude 28°4.2′ and north latitude 25°19.2) of the 3 × 50 MW project site in Figure 2. After a general calculation in conjunction with the proposed site size, the optimized value of "L" is as follows: $L = 2.80$ m. This PV pilot project uses the latest technology for tilting of solar panels [13].

3.1.3. Module Mount Structure Design System. The support of solar panels is according to the national standard for steel section structure. The surface is treated by the hot-dip galvanization process to guarantee an excellent anticorrosive coating on the structure. The structure is fastened using stainless steel bolts to guarantee the support to take on 45 m/s wind speed load. The panel installation is equipped with 2 cm of wind gap to ensure the stability of the structures as shown in Figure 3.

3.1.4. PV Array Design. PV array designing requires PV string calculation. The equipment of the solar array system are given in Table 4. This project plans to use 300 Wp polycrystalline silicon modules. The working voltage of the modules and inverter's DC input voltage range must be considered when calculating the serial number of the modules. Also, one needs to consider the working voltage, temperature coefficient of the modules, temperature coefficient of open circuit voltage, and reasonable optimization of the serial number, so that the system can work within the range of maximum power track voltage in various circumstances, thereby gaining maximum power output. The PV module operating and design parameters such as temperature, loss coefficient, open-circuit voltage, short-circuit current, maximum power point voltage, maximum power point current, and module area have an adverse consequence on the performance of photovoltaic modules [14]. The lesser the temperature of the photovoltaic module is put off, the greater the impact on the performance level and increases of the efficiency such that PV performance takes an inverse relation with PV module temperature [20]. Besides efficiency of PV, modules depend on the operating temperature and the power density of the solar radiation as well as environmental conditions and seasons of the year [15, 21]. If the PV module's temperature increases, the efficiency shall decrease linearly, at STC conditions [22]. The inverter DC input voltage is 1000 V and MPPT voltage range is 450 V–820 V; therefore, 20 modules per string shall be the best option. The JA Solar-manufactured PV module parameters are given in Table 5.

Table 4: Description of solar array system.

Name	Specification	Quantity	Remarks
Inverter	500 kW 2 sets	1	Data
Step-up transformer	S11-1000 kVA, 22 ± 2 × 2.5%/ 0.315/0.315 kV	1	Data
Combiner box	HL1601B	12	15 A, fuse

Table 5: Detail of PV module parameters.

NOCT	Data	Electrical parameter	Data
Max. power	217.80 W	Rated max. power at STC	300 W
Open circuit voltage	42.31 V	Open circuit voltage	45.20 V
Max. power voltage	33.77 V	Max. power voltage	36.41 V
Short circuit current	6.93 A	Short circuit current	8.73 A
Max. power current	6.53 A	Max. power current	8.24 A
Condition	20°C, 1 m/s	Module efficiency	15.48%

3.2. Secondary Design. Secondary design includes the total eBOP equipment such as electrical system and installation of inverter, combiner box, step up transformer, AC and DC cables, feeder cabinet, PT, SVG wiring cabinet and substation, and interconnection work to the grid.

3.2.1. PV Plant Electricity and Main Electrical Wiring. The PV plant electricity is a station power booster through which one set of 22 kV–1000 kVA is oil-immersed to double split to step down from 22 kV section bus to 22 kV to 0.4 kV. This main electric wiring is planned to be in 22 kV single bus mode of connection, according to the requirement of OTS and project specification, and two loops of 220 kV outgoing line shall be configured. There are altogether 5 loops of 22 kV AC collection feeder lines with a capacity of 150 MW DC designed.

The total installed capacity of the PV power plant at Nooriabad shall come to 150 MWp, 300 Wp polycrystalline silicon modules shall be used, and the total number shall be 501000 pieces; the mounting structure installation shall adopt the fixed type. PV arrays will be divided into 150 subarrays with 1 MW capacity, each array incorporates about 3340 pieces of modules along with 12 sets of combiner boxes which shall be 16 to 1 type, and the output side of the combiner boxes will connect to the DC distribution cabinets and 500 kW inverters inside the integrated inverter room; then, the output side of the inverters shall be evacuated through one set of 22 kV–1000 kVA oil-immersed double split step-up transformer; totally, 150 sets of the 22 kV step-up transformers shall be used. Every 12 or 13 nos. step-up transformers are going to be connected with one 22 kV switchgear cabinet (namely feeder cabinet); correspondingly, a total 12 sets of feeder cabinets shall be installed. Except for the feeder cabinet, the HV room also has 6 outgoing cabinets, 6 PT cabinets, 6 SVG wiring cabinets, 6 grounding transformers, 6 station transformer cabinets, and 6 section cabinets which are arc suppression coil wiring cabinets. The power can be evacuated through 220 kV substation LV side with 1 circuit of 22 kV outlet line to be sent out to the power grid.

3.2.2. Inverter Description. This central inverter mode is deemed as being highly efficient and reliable for large-scale photovoltaic power generation system. The type of model inverter used is TC500KH. The following inverter description is given in Table 6.

3.2.3. kV System Design. This plant shall design a total of 150 nos. 22 kV step-up transformers; every 12 nos. of the transformer output brings together and connects to the 22 kV bus bar and shall have 2 circuits of 22 kV feeder line and one circuit outgoing line in its entirety.

3.2.4. The Design of Inverter and Step-Up Transformer. The PV power plant incorporates a total of 150 nos. 1 MWp units; specs of grid-connected inverter shall be 2 × 500 kW. The step-up transformer for subarrays shall be three-phase oil-immersed fully sealed power transformer. Each power unit shall set up a 1000 kVA/22 kV oil-immersed double split winding step-up transformer.

3.2.5. SCADA Networking System. The scope of a computer monitoring system is a network security monitor for this project to study the seasonal variations in PV plant output. The SCADA shall be allocated in a control room in the complex building, and the following tasks shall be determined—meteorological station inverter enclosure, inverter performance, combiner boxes and strings, transformers, AC collection and interconnection, DC system

Table 6: Detail of inverter parameters.

Electrical input (DC) parameter	Data	Electrical output (AC) parameter	Data
Max. power	618 kW	Rated output power	500 W
Max. voltage	1000 V	Rated voltage range	270–350 V
Voltage range	450–1000 V	Grid voltage	315 V
MPP voltage range	500 V–820 V	Rated current	916 V
Max. current	1236 A	Grid frequency	50 Hz/60 Hz
Max. number of DC inputs	10	Power factor	0.9 lag-0.9 lead, adjustable

and UPS system, alarming signal of communication equipment and power, fire alarm system, booster station SVG adopting SF6 air density, and hotbed and moisture alarming signal. The SCADA monitoring system shall be able to connect the following intelligent equipment such as an information management system of the whole substation, DC and UPS systems applied, fire alarming and firefighting system, computer desperation-preventive locking system, safety monitoring system, and electricity charging system.

3.2.6. Grid Interconnection. The project collection substation includes 2 × 200/22 kV–50 MVA main power transformer which includes a primary and a redundant power transformer for each 50 MW block for a total of two (2) power transformer. Two (2) additional transformers are considered in anticipation for a future expansion block of 50 MW. The project's point of interconnection (POI) is a tap at the 220 kV transmission line between Jamshoro and KDA-33. The project collection substation will be interconnected via a utility-owned 10 km-220 kV transmission line. The energy meter is currently set to be located after the site transformers and before the utility transmission line and thus assumed that the transmission line losses are borne by the utility and not the power producer company in this study.

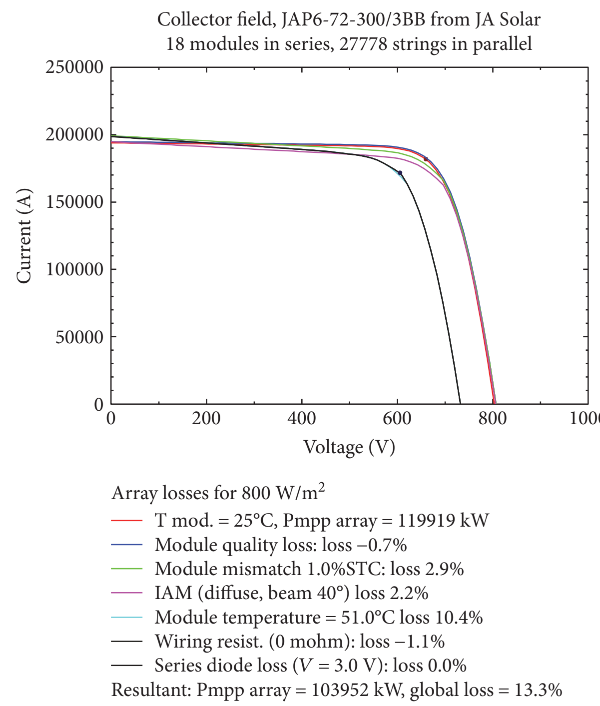

Figure 4: Simulation results of PV array behavior for each loss effect of JA Solar module.

4. PV System Energy Production Assessment Methodology

4.1. The Process of Estimating Solar Power Generation Typically Involves Several Steps [14]

(i) Determination of the solar climate conditions, primarily the global and diffuse irradiation on the horizontal plane, should be carried out.

(ii) Calculation of irradiation on the tilted plane is using the known global and diffuse horizontal irradiations. Transposition is the calculation of incident irradiance on a tilted plane from horizontal irradiation data. This is calculated separately for each irradiance component such as diffuse beam and reflector. The diffuse component is typically calculated using the Perez model or the Hay model. The beam component transposition involves a geometrical transformation that accounts for the module and solar angles. The reflective or albedo component is evaluated as a given fraction (the "albedo coefficient") of the global irradiance, weighted by the angle between the horizontal and the PV plane.

(iii) An assessment of the irradiation losses due to optical effects and near shading, using the known layout of the PV plant (PV module dimensions and geometrical arrangement, orientation, row distances, etc.) and the model of the plant surroundings. This enables the calculation of the usable irradiation.

(iv) Calculation of the final energy delivered at the output of the inverters: the electrical simulation takes into account the properties of the PV modules (output power, irradiation performance, partial shading affects temperature behavior, etc.) and the inverters (conversion efficiency, partial load, etc.) and losses in the electrical wiring.

Table 7: Using 3 × 50 MW parameters for the simulations.

(a)

System type	Specification	Data
Grid-connected unlimited load	Software project	PVsyst V6.47, 3 × 50 MW solar PV power project in Nooriabad
	Data sources	Meteonorm 7.1 [2001–2010] Sat = 56%
	Land coordinate legal time	Longitude 68°4.2, north latitude 25°19.2′, Altitude 70 m time zone TU+5

(b)

PV system	Model	Pnom	Quantity
PV modules	Model JAP6-72-300/3BB	300 W	27778 strings of 18 modules in series, 500004 total
PV array	Nb. of modules 500004	150001 kWp	
Inverter	Model TC 500 KH	500 kW ac	Nb. of units 300.0, Pnom total: 150000 kW AC
		Area, 969206 m^2	
		System production 232518 MWh/year	

(v) The yearly power degradation and the uncertainty analysis are used to calculate the expected energy production over the plant lifetime at different probabilities of surplus.

4.2. Loss Factors. The net energy produced by the PV plant (MWh/year) is obtained from the incident global irradiation on the tilted plane in Figure 4, following the loss factors which are calculated, applied, or estimated during the simulation such as far shading, near shading, soiling/snow losses, angular losses, irradiance level losses, temperature losses, module quality losses, module mismatching losses, ohmic wiring losses (DC), and inverter losses [13].

4.2.1. Other Losses. We also estimate other losses due to a variety of effects:

(i) Wiring losses (AC network) consist of ohmic losses of the AC network on account of the medium voltage network connecting the inverter cabinets. This loss can be precisely assessed if a detailed electrical design is made available.

(ii) Transformer losses may be due to the fact that the transformer can only be precisely assessed with more information on the transformer or during the eventual technical due diligence process for the project.

(iii) Plant availability figure is calculated after a review of the proposed O&M contract (particularly the plant availability guarantee or performance guarantee) during the eventual technical due diligence process for the project.

(iv) Grid availability losses: in modern electrical grids, the unavailability is kept to a minimum value.

5. Performance Parameters

To evaluate the performance parameters of solar PV plant such as energy efficiency, yield factor, performance ratio, and capacity factor are defined by IEC 61724:1998 Standard and International Energy Agency (IEA) [9, 16, 23–32].

5.1. Array Yield. The array daily output energy of the plant is computed with nominal solar generator power P to generate array DC energy; E_a is called array yield, which referred to the nominal power [kWh/kWp/day].

$$Y_A = \frac{E_a}{P_o}. \quad (1)$$

5.2. Reference System Yield. The Y_r (reference system yield) defines the solar radiation resources, location, and orientation of PV array, monthly and yearly wise depending on variability. Y_r is numerically equal to the incident energy in the array plane, expressed in [kWh/m^2/day].

If G is equal to 1 kW/^{2}, then Y_r is the number of solar radiation in units of kWh/m^2.

$$Y_r = \frac{\text{kWh/m}^2}{1\text{kW/m}^2}, \qquad Y_r = \frac{H_t}{G_o}, \quad (2)$$

where H_t is the total horizontal irradiance on array and G_o is the global irradiance at STC (W/m^2).

5.3. System Yield Factor. System yield factor referred as the final yield is the system daily useful energy and the nominal power unit is [kWh/kWp/day].

$$Y_f = \frac{E_{ACout}}{P_{max}, \text{STC}}. \quad (3)$$

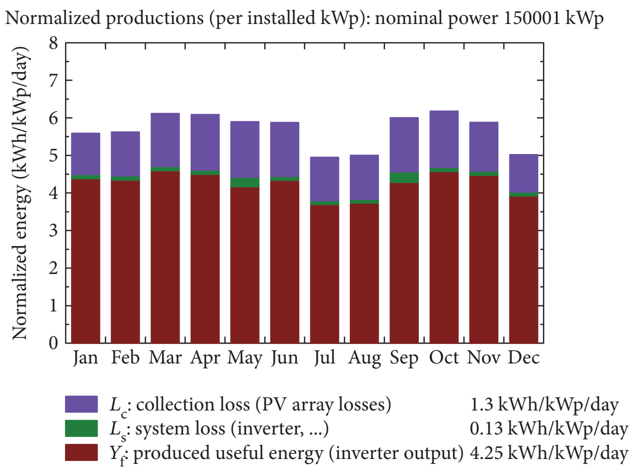

Figure 5: Monthly graph of normalized production (per installed).

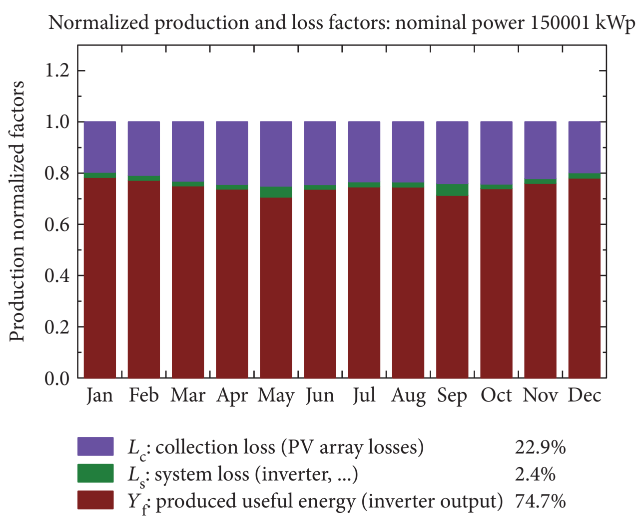

Figure 6: Monthly graph of normalized production and loss factor.

E_{ACout} is the amount of electrical energy generated by the solar PV solar plant and P_{max}, STC is the total installed power of solar modules [17].

5.4. Availability Factor. To define the availability factor A_F of the PV power plant, which requires the plant to produce the electricity over a certain time period, A_F is divided to the amount of the time in the evaluated period [33].

$$A_F = \frac{T_{output}}{T_t}. \quad (4)$$

5.5. Capacity Factor. To consider the capacity factor, solar plant life span can be calculated. The plant capacity factor is the key factor used to calculate the monetary values of the financing structure for the whole plant. The following formula is given below [16]

$$C_f = \frac{\text{estimated energy production } Y_f}{\text{installed capacity} \times 24 \text{ hours} \times 365 \text{ days}}. \quad (5)$$

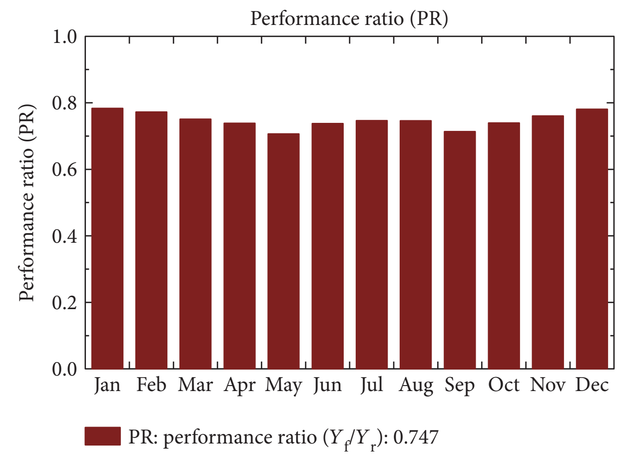

Figure 7: Monthly graph of performance ratio of the plant.

5.6. System Efficiency. In PV system efficiency, items included the inverter efficiency η_{inv} and PV module efficiency η_{PV}.

Inverter efficiency and PV module efficiency are given below [21].

$$\eta_{inv} = 100 * \frac{E_{DC}}{H_t} * S\%,$$
$$\eta_{PV} = 100 * \frac{E_{AC}}{E_{DC}\%}. \quad (6)$$

5.7. Performance Ratio. The performance ratio (PR) falls between relations of yield factor of the PV plant divided by the reference yield (system yield) as illustrated in [9, 23, 32]. Usually, performance ratio and module efficiency of PV modules decreased with the increase of solar irradiance and high module temperature [21]. It presents the total losses such as panel degradation, temperature, soiling, transformer, inverter, system availability, and grid connection in the system when converting from nameplate DC rating to AC output [15].

$$PR = \frac{Y_f}{Y_R}. \quad (7)$$

The performance ratio (PR) is an international measure for describing the level of the utilization of an entire PV system. The PR is the fraction of useful energy (at the feed-in point) in the nominally producible energy volume, which results from the module surface area, the module efficiency (according to the data sheet), and the irradiation incident on the module surface. The PR is nondimensional and is a parameter that enables comparison between PV plants at different locations and orientations. The PR is calculated during the simulation process, by multiplying the abovementioned loss factors [13].

Given the overall PR factor, the total energy delivered is calculated as follows:

$$E_{AC} = \frac{PR(\%) G_{INC} P_{STC}}{100 I_{STC}}. \quad (8)$$

Table 8: New simulation variant balance and main results.

	GlobHor kWh/m	Temp Amb. C	GlobInc kWh/m	GlobEff kWh/m	Earray kWh	E_Grid kWh	EffArrR %	EffSysR %
January	126.5	17.76	173.3	164.2	2089776	20373453	12.44	12.13
February	128.1	20.98	157.5	148.9	18709171	18242204	12.26	11.95
March	170.1	25.96	189.6	178.9	21867831	21352410	11.90	11.62
April	182.0	29.41	182.7	172.0	20736061	20236994	11.71	11.43
May	198.3	32.44	182.8	171.6	20553243	19376725	11.60	10.94
June	197.4	32.58	176.3	165.4	19995150	19617989	11.70	11.42
July	168.8	31.63	153.4	143.8	17641961	17184777	11.75	11.55
August	160.6	30.30	155.0	145.7	17814786	17347500	11.85	11.54
September	169.4	29.83	180.1	169.7	20524945	19271874	11.76	11.04
October	159.5	28.67	191.5	181.2	21759705	21251333	11.72	11.45
November	130.7	23.64	176.4	167.0	20618588	20128108	12.06	11.77
December	112.1	19.20	155.6	147.3	18720953	18234173	12.41	12.09
Year	**1903.4**	**26.89**	**2074.4**	**1955.8**	**239840162**	**232517541**	**11.93**	**11.57**

In the formula qualification parameters,

(i) E_{AC} (kWh/year) is the system yield;

(ii) P_{STC} (kW) is the real installed power (at STC conditions);

(iii) G_{INC} (kWh/m^2) is the irradiation on the inclined plane;

(iv) I_{STC} (1 kW/m^2) is the irradiance (at STC conditions).

6. Results of Energy Yield Assessment and Discussion

6.1. Energy Yield Assessment Results and Discussion

6.1.1. Influencing Factors of Power Generation. The key factor of influencing the power is system efficiency, and the main factor of system efficiency is low efficiency caused by dust and rain cover, temperature caused low efficiency, and module series dismatch caused the efficiency reduction and power loss, DC and AC part cable power loss and power loss of transformer, and so forth.

6.1.2. The Result of PVSyst Simulation Is as Follows. The most commonly used model within the PV industry is the "one-diode" model which is nonlinear and implicit. The hourly calculations are required and best performed with the aid of software packages. There are several software packages which use the "one-diode" model. We used the PVsyst V6.47 software package along with internal tools to calculate energy loss factors for the proposed PV plant and deals with grid-connected, stand-alone, pumping and DC-grid PV systems [11]. The design software named PVSyst is used for this project, which can ensure that power supply mode is beneficial for the annual maximum power generating, through the angle adjustment, irradiation quantity minimum loss simulation and calculation. The solar power plant's site is located at longitude 68°4.2′, north latitude 25°19.2′; it is rich in solar energy resources based on simulation results. The best angle for bracket installation is 28°; thus, we can compute the capacity as given in Table 7 below. The main simulation results of the system production are produced energy 232518 MWh/year and specific prod. 1550 kWh/kWp/year as well as performance ratio PR 74.73% is found.

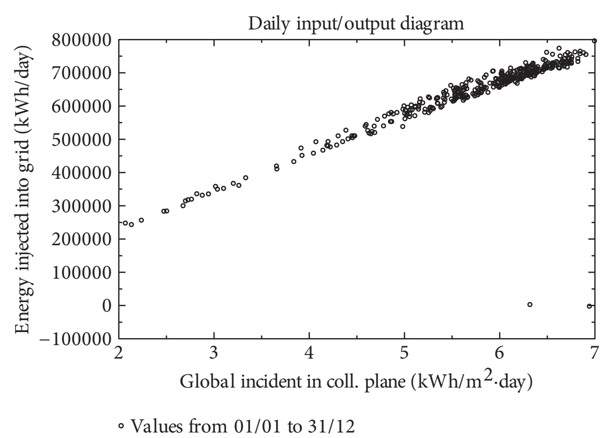

Figure 8: Daily input and output of energy injected into the grid.

6.1.3. Normalized Production. This simulation is the first year operation of PV plant, and normalized production (per installed kWp) of monthly graph is shown in Figure 5 based on nominal power of 150001 kWP (150 MWp). We obtained the array capture losses ($L_C = Y_r - Y_a$), L_C value [collection loss (PV array losses)] is 1.3 kWh/kWp/day, and $L_S = Y_a - Y_f$ value (system loss from the inverter side) is recorded 0.13 kWh/kWp/day while the Y_f value (produced useful energy from inverter output side) is recorded 4.25 kWh/kWp/day accordingly. Based on loss factor, the normalized production parameters' recorded values L_C,

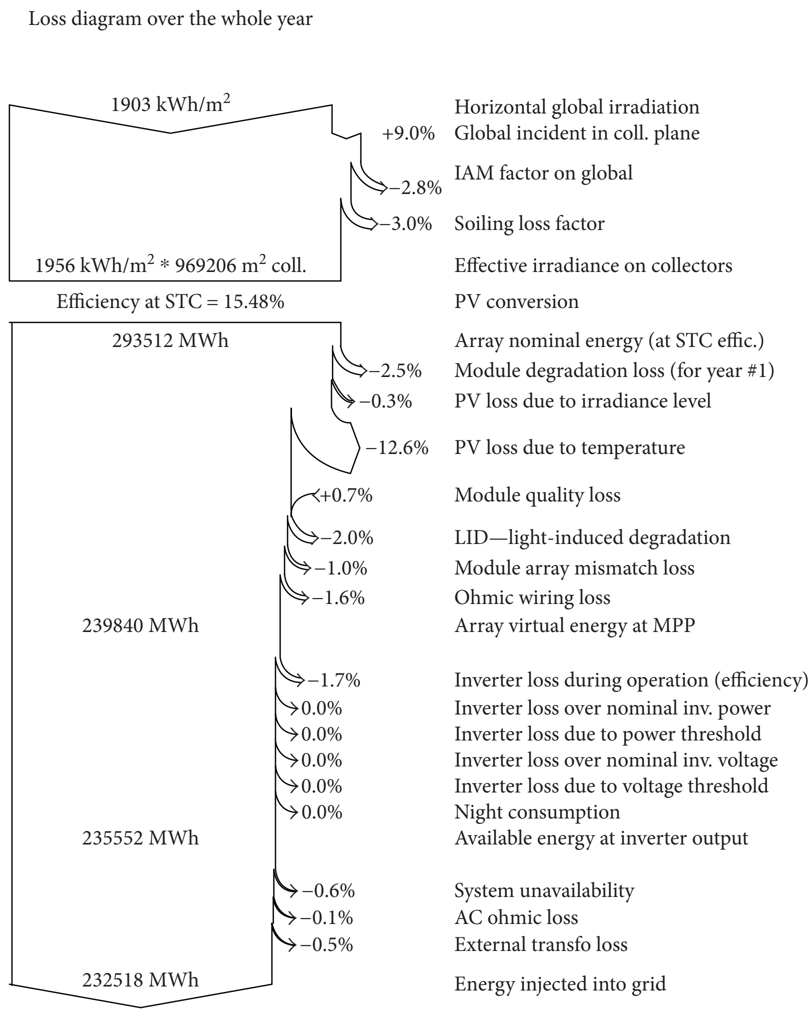

Figure 9: Simulation results of losses of the system annually.

L_S, and Y_f obtained 22.9%, 2.4%, and 74.7%, respectively, as shown in Figure 6 [18].

6.1.4. Performance Ratio (PR). Keeping in view the performance ratio (PR) which causes the plant availability at the highest levels is by far the most the important parameter of PV power plant. Based on the calculated values with the PVsyst simulation results, the performance ratio of 3×50 MW solar power plant is determined at PR 74.73%, which shows that 25.27% energy generated through the solar panels is lost in the system losses. We computed that the monthly performance factor average PR of the plant is 0.747 as shown in Figure 7, through which we can observe the plant performance and plant behavior—whether solar equipment is in good shape. The performance ratio (PR) shows the performance of the PV modules at outdoor conditions as compared to their performance under STC. During the summer, the PR of PV panels procure some due to high-temperature factor, but in winter, PR loss is less in a monthly graph as shown in Figure 7 [34]. Generally, PR values come based on system losses and depend on the site spectrum, technology, and sizing of the system but

Table 9: Monthly average output based on manual calculation.

Month	Coll. plan $kWh/m^2 \cdot day$	Average monthly output (ten thousand kW)
January	5.74	2137.95
February	5.69	1914.23
March	6.14	2286.94
April	6.06	2184.33
May	5.86	2182.64
June	5.78	2083.40
July	4.88	1817.63
August	4.93	1836.25
September	6.01	2166.30
October	6.20	2309.28
November	5.93	2137.47
December	5.14	1914.47
Total	5.70	24970.89

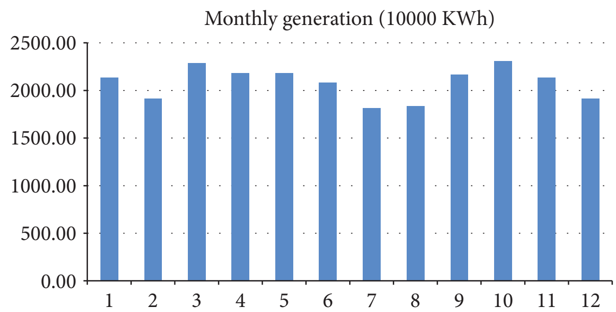

Figure 10: Monthly output production generation.

Table 10: Power generating prediction and net output [10000 kWh/year] for one-year period.

Year	Degradation factor	Expected attenuation rate	Expected output per year (ten thousand kWh)
1	2.500%	2.500%	24970.89
2	0.625%	3.125%	24346.62
3	0.625%	3.750%	24190.55
4	0.625%	4.375%	24034.49
5	0.625%	5.000%	23878.42
6	1.000%	6.000%	23722.35
7	1.000%	7.000%	23472.64
8	1.000%	8.000%	23222.93
9	1.000%	9.000%	22973.22
10	1.000%	10.000%	22723.51
11	0.625%	10.625%	22473.81
12	0.625%	11.250%	22317.74
13	0.625%	11.875%	22161.67
14	0.625%	12.500%	22005.60
15	0.625%	13.125%	21849.53
16	0.625%	13.750%	21693.46
17	0.625%	14.375%	21537.40
18	0.625%	15.000%	21381.33
19	0.625%	15.625%	21225.26
20	0.625%	16.250%	21069.19
21	0.625%	16.875%	20913.12
22	0.625%	17.500%	20757.06
23	0.625%	18.125%	20600.99
24	0.940%	19.065%	20444.92
25	0.935%	20.000%	20210.19
Total	20.00%		558176.91
		Average	22327.08

sometimes soiling and dust factors also affected the losses in PR behavior as well.

6.1.5. Balance and Main Results. As referring to Table 8, we computed that the following value of the one-year horizontal global irradiation is 1903.4 kWh/m and global incident energy on the collector plane annually is 2088.3 kWh/m. The total energy determined from the output of the PV array is 239840162 kWh and one-year efficient E array/rough area found is 11.93% as well as annual efficient E system/rough area obtained 11.57% accordingly. The total input-output energy injection to the grid is shown in Figure 8.

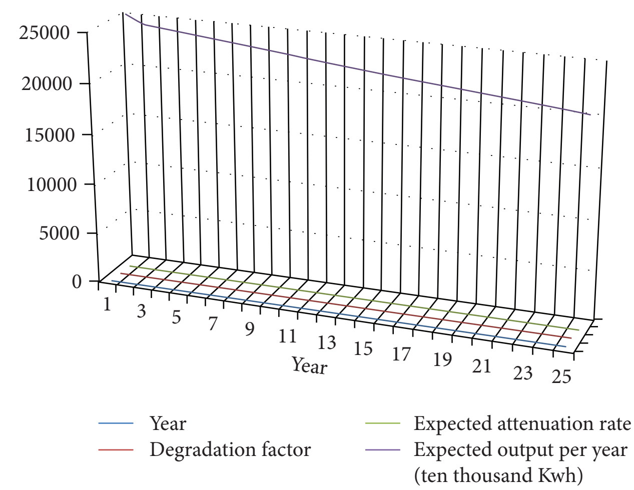

Figure 11: Expected output capacity generation 25 years.

Table 11: The financial figures.

Item	Value
Total project cost	150 million USD
Project construction type	EPC work
Project type of business model	Build-operate-ownership (BOO) basis
Project lender	Local banks
Equity shares	30% from project owner and 70% from lender (local bank)
Tariff agreed with power purchase agreement	US 14.00 cents/unit
Annual generation per 50 MW	74500 MW/year
Project life	25 years
IRR—without CRE revenue	17.16%
IRR—with CRE revenue	17.26%
Payback (term)	6-7 years

6.1.6. Loss Diagram. We estimated the energy losses over the whole year for the PV facility and results are shown in Figure 9 for the project under study. The loss factors can be assumed as losses for module quality, soiling, mismatch, cabling, inverter efficiency, transformer, system availability, and grid availability and parasitic (equipment power consumption) [15, 16]. The horizontal global irradiation is found 1903 kWh/m^2 and the effective irradiation on the collector plane is 1956 kWh/m^2. The solar energy incident on the solar PV panels will convert into DC electrical energy. The final energy injected into the grid is 232518 MWh after all loss behavior.

Table 12: Breakdown eBOP's list of 3×50 MW solar project.

Number	Materials	Specs & type	Unit	Quantity	Remarks
1	Modules	300 Wp	Each	50001	Ploy crystal
2	Mount structures	Steel structure, 150 MWp	Set	13360	Fixed, 28°
3	Combiner box	16 to 1	Each	1500	15 A fuse isolating
4	Integrative inverter	500 kW AC	Set	300	Isolating transformer excluded
5	22 kV box-type transformer	S11-1000/500/5000 kVA $22 \pm 2 \times 2.5\%$/0.315/0.315 kV	Each	150	
6	Arc suppression earthing transformer	400 kVA/22 kV/0.4 kV, arc suppression coil 1200 kVA	Each	6	Dry type
7	SVG	22 kV, −10 ~ +10 MVar	Each	6	Step-down type
8	Switchgear	Ir = 1250, 2500 A, Ib = 31.5 kA (4 s), (3 s)	Each	40	
9	220 kV main transformer	SFZ11-50000/220, $220 \pm 8 \times 1.25\%$/22 kV	Set	6	220 kV main transformer
10	220 kV main transformer spacing interval	Outgoing line spacing interval and PT		2	—
11	Breaker	type: LW36-220, breaker, Ie = 2000 A, Ib = 50 kA		6	//
12	Double earthing isolator	type:GW4-220D(W) (double), 1250 A-125 kA		6	//
13	Current transformer	10P40/10P40/10P40/10P40/0.5S/0.2S, $2 \times 600/5$ A		36	//
14	Single earthing isolator	GW4-220D (W) (single), 2000 A-125 kA		6	//
15	Secondary equipment line protection and surveillance	Item	1		
16	Civil engineering building	Support equipment foundation, the fittest	Item	1	
17	Cable	AC/DC type, fiber optic	Set	1	Roll bundle double 100
18	Monitoring system	SCADA/PLCs	Set	1	Mbps industrial Ethernet network structure
19	Substation	AIS (air-insulated switchgear)	Set	1	220 kV line grid POI

After the PV conversion, the nominal array energy is 293,512 MWh/year. The efficiency of the PV array is 15.48% at standard test condition (STC), and array virtual energy is obtained 235840 MWh. After the inverter loses the available energy, the inverter output obtained is 235552 MWh and energy injected into the grid finally calculated is 232518 MWh.

6.2. Calculation of Electricity Production. The 3×50 MWp PV power station project is expected to have a capacity of 249708900 kWh in the first year, and the average daily output of 693635.833 kWh is determined. Table 9 presents the monthly archived average outputs based on manual calculation, and Figure 10 shows the monthly output production generation (10000 kWh) in graph plot.

6.3. Power Degradation and Production. The degradation factors based on the performance of the PV module manufacturer's warranty are typically pessimistic, and a more realistic approach should be based on both the track record and existing information regarding each technology and/or PV module supplier. For that purpose, we had taken the crystalline silicon technology track record into consideration. Ideally, module degradation could be further investigated during the technical analysis due to the diligence process for the project and the analysis of the specific references by the module manufacturer. The performance of PV modules decreases under the dust effect on the module surface, thus causing the significant degradation. Therefore, PV modules also require regular cleaning to minimize the degradation factor [35]. We considered the PV module technology track record, based on the review; we applied a linear degradation factor of 2.5% to account for the first year due to long-term mechanisms but degradation process of PV is considered for a period of 25 years. The PV degradation losses can reach 5% with a lifetime of 20-year warranty [16, 36].

The degradation factor at the end of single year has been applied at the beginning of the same year based on a pragmatic approach. As shown in the results, the expected attenuation rate for each single year is presented in Table 10 as well as the resulting values for a one-year period, with the corresponding expected output also presented in Table 10. From manual calculation, the solar power is expected during

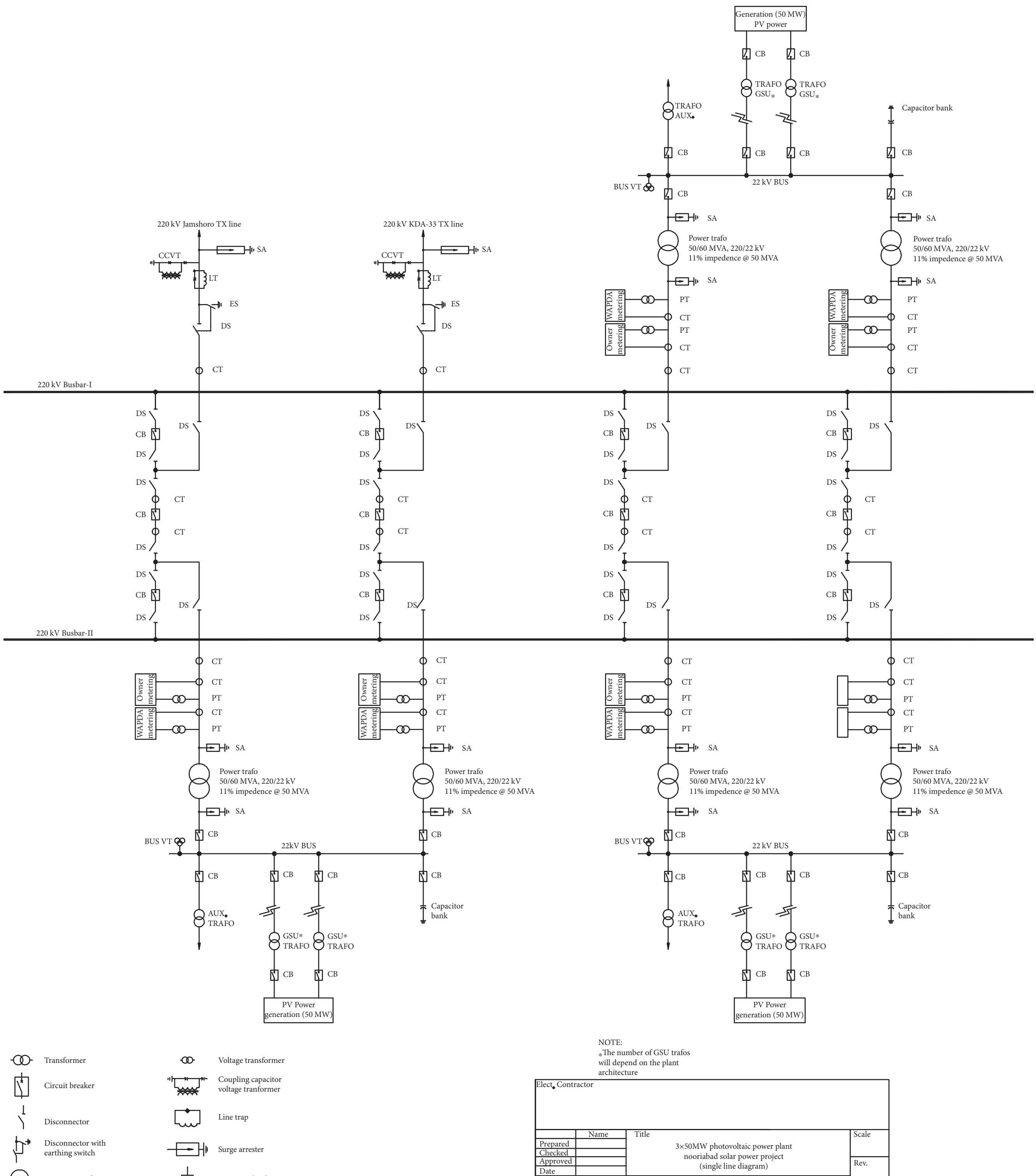

Figure 12: Main single line diagram (SLD) of 3 × 50 MW PV project.

the construction period, in which 25 years construction capacity is shown in Table 10 [13].

From Table 10, for the 3 × 50 MW, the total expected generating capacity from the photovoltaic power stations in 25 years is 558176.91 ten thousand kWh; the average annual output is 22327.08 ten thousand kWh (223,270 MWh/year), according to the degradation factor based on expected attenuation rate; hence, we investigated the graph plot for the expected output capacity generation yearly as shown in Figure 11.

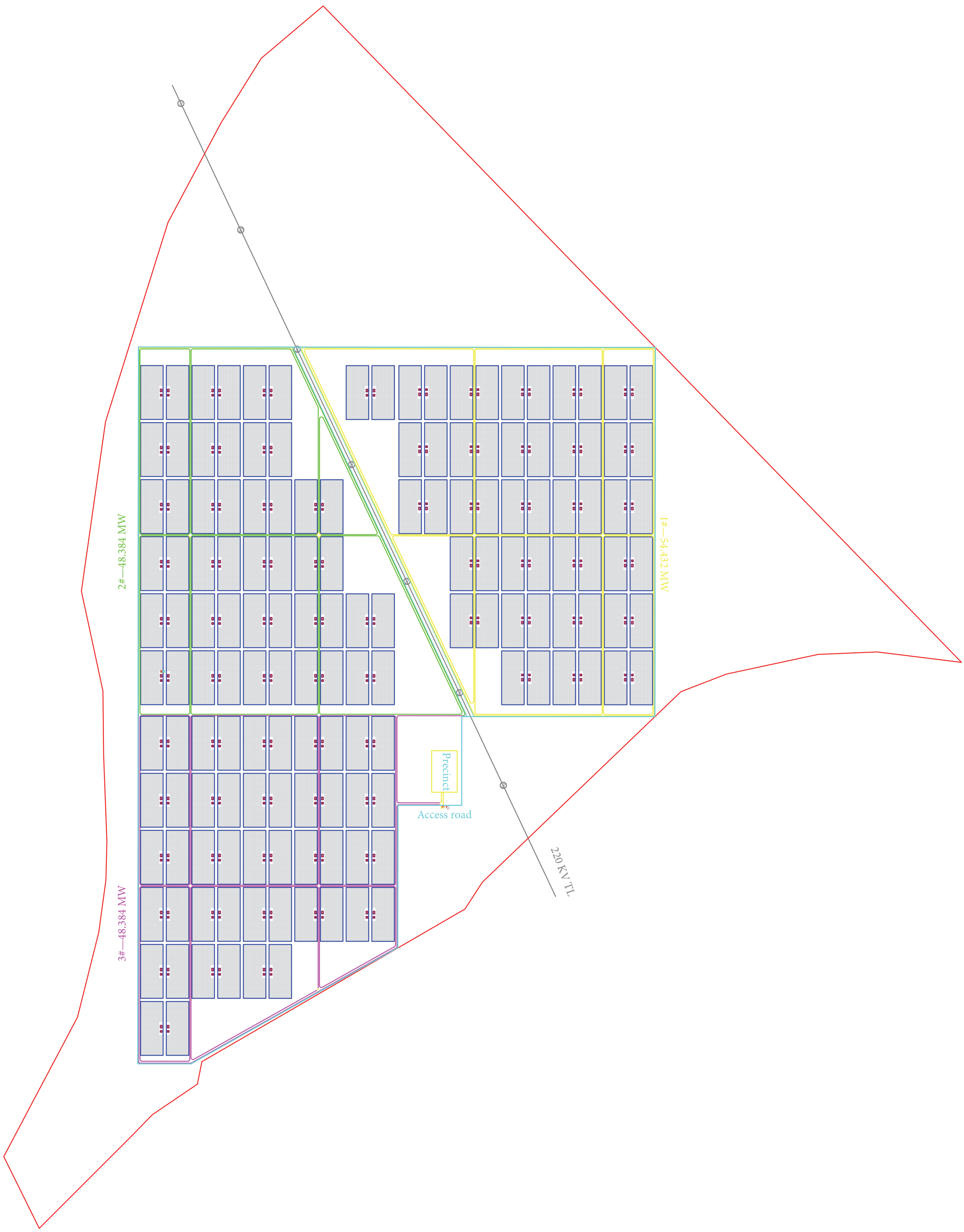

Figure 13: 3 × 50 MW PV project overall drawing layout.

7. Payback and IRR

From the financial feasibility report, the total EPC cost of the project is 150 million USD and IRR is an important financial index factor for financial model of 3×50 MW solar projects. Based on the analysis of the financial model, equity IRR of 3×50 MW is about 17.16% without CRE revenue and 17.26% with CRE revenue and NEPRA has allowed 17% RoE (IRR based) net of 7.5% for the development of renewable energy base IPPs. The internal rate of return (IRR) reveals the rate of return from NPV cash flows which received from a solar investment $EPV_c - EPV_p = 0$ which means that payback analysis takes into account only first costs and energy savings at present cost. The payback will be completed in 7 years according to the lender/bank term sheet. If we reduce the O&M cost, IRR can change from 17.6% to 22.70% which is lower than the benchmark rate of return and yet the project is still achievable [10, 37]. The project financial figures are given in Table 11.

In our project, the IRR baseline structure meets the following considerations.

$$\begin{aligned} &\text{FIT} \times \text{output generation} > \text{income}, \\ &\text{development work} + \text{EPC work} + \text{financial model} > \text{total cost}, \\ &\text{financial index} = \text{income} + \text{total cost} > \text{IRR}_{\text{index}}. \end{aligned} \tag{9}$$

8. Conclusions

This study provides an insight to investigate the energy yield assessment for 3×50 MW PV pilot project based on large-scale turnkey development solar projects in Pakistan. This experience is reasonable in achieving the preliminary evaluation of the project proposal and feasibility benefits to the independent power producers for future renewable energy projects. The assumptions, results, and conclusions of this study have deduced that the proposed project is favorable for commercial operation. The following conclusions summarize the main findings of the works.

(i) Average annual energy production of the plant is recorded based on simulation (232518 MWh/year).

(ii) Average annual energy production of the plant is recorded based on manual calculation (223270 MWh/year).

(iii) Average annual performance ratio of the plant is recorded (PR 74.73%).

(iv) Average annual capacity factor is computed (17.7%).

These findings show that the plant will be operated with a good amount of PR and CF and will serve as feeding energy to the grid station at maximum available percentage. The plant operational performance data is not available to validate these results. The operational data can be computed after completion of the civil construction and during the O&M period based on O&M yearly progress report. But the site is receiving a good amount of solar radiation to acquire the current data in less uncertainty percentage by weather station databases. Thus, the project will combat climate change by reducing CO_2 emissions by about 3 lakh tons upon the project completion. The integration of 3×50 MW (150 MW DC) has obligated the technical and commercial requirements of energy policy in Pakistan and CPPA as a buyer of the electrical energy and shall receive 50% of the revenues from carbon credits generated by the owner's project. Through this additional production of the 232,518 MWh/year from the 3×50 MW PV plant, the energy deficit in Pakistan shall reduce and its GDP percentage shall increase by a lump sum as well.

Appendix

A. The eBOP Breakdown List

The eBoP solutions are capable to support a large scale deployment turnkey projects for renewable applications and integral issue for the EPC contractor to solve diagnoses with its versatile and robust solutions. The eBOP (electrical balance of plant) is a system of whole project covered secondary design (electrical system) such as power train, auxiliary system, and high-voltage substation with full scope of engineering and design. The title project breakdown electrical equipment's list is given in Table 12.

B. Main Single Line Diagram

In Figure 12, the main single-line diagram is showing an electrical system analysis for the 3×50 MW PV power plant in which main components of the electrical system and power distribution path are designed.

Overall drawing layout: the total land area is 2699324 m^2, and the planned installed capacity is 150 MWp DC. The solar power station incorporates 500001 pieces of 300 wp PV panels as shown in the Figure 13. The project of the road is width of 4 m and the turning radius is 6 m.

Note that the designing of overall plant layout and single-line diagram is approved by ISO and NTDC under their code of standards.

Nomenclature

PV:	Photovoltaic
PR:	Performance ratio
MPPT:	Maximum power point tracker
CF:	Capacity factor
GoP:	Government of Pakistan
GoS:	Government of Sindh
AEDB:	Alternative Energy Development Board
LOI:	Letter of intent
IPPs:	Independent power producers
IPPPs:	Individual private power producers
IA:	Implementation of agreement
WAPDA:	Water and Power development Authority
CPPA:	Central Power Purchasing Agency
kV:	Kilovolt

K-E: Karachi Electric Pvt. Ltd
KDA-33: Karachi Development Authority-33
EPA: Energy purchase agreement
PPA: Power purchase agreement
NTDC: National Transmission Dispatch Company
COD: Commercial operation date
EPC: Engineering, procurement, and construction
BOO: Build, operate, ownership
NEPRA: National Electric Power Regulatory Authority
FIT: Feed-in-tariff
LC: Letter of credit
LV: Low voltage [V]
HV: High voltage [V]
eBOP: Electrical balance of plant
cBOP: Civil balance of plant
OTS: On the side
MVA: Mega volt amp [VA]
MW: Megawatt [W]
MPPT: Maximum power point tracking
GlobleHI: Horizontal global irradiation
E_{ACout}: Energy generated by the solar PV [W]
P_{maxSTC}: Total installed power of solar modules [kW]
P_{STC}: Real installed power (at STC condition) [kW]
G_{INC}: Irradiation on the inclined plane [kWh/m^2]
I_{ST}: Irradiation on (at STC condition) [kWh/m^2]
η_{inv}: Inverter efficiency (%)
η_{PV}: PV module global efficiency factor (%)
PT: Pass-thru type cabinet
SVG: Static var generator
OTS: On the side (owner side)
SCADA: Supervisory control and data acquisition
UPS: Uninterruptible power supply
POI: Point of interconnection
GDP: Gross domestic product
KDA-33: Karachi Development Authority-33
STC: Standard condition
P_o: Nominal power at STC [W]
L_{C}: Array capture loss
L_{S}: System loss from the inverter side
Y_{f}: Array yield [kWh/kWp/day]
Y_{a}: Array yield [kWh/kWp/day]
Y_{r}: Reference yield [kWh/m^2/day]
H_{t}: Total horizontal irradiance on array plane [Wh/m^2]
G_o: Global irradiance at STC [W/m^2].

Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this paper.

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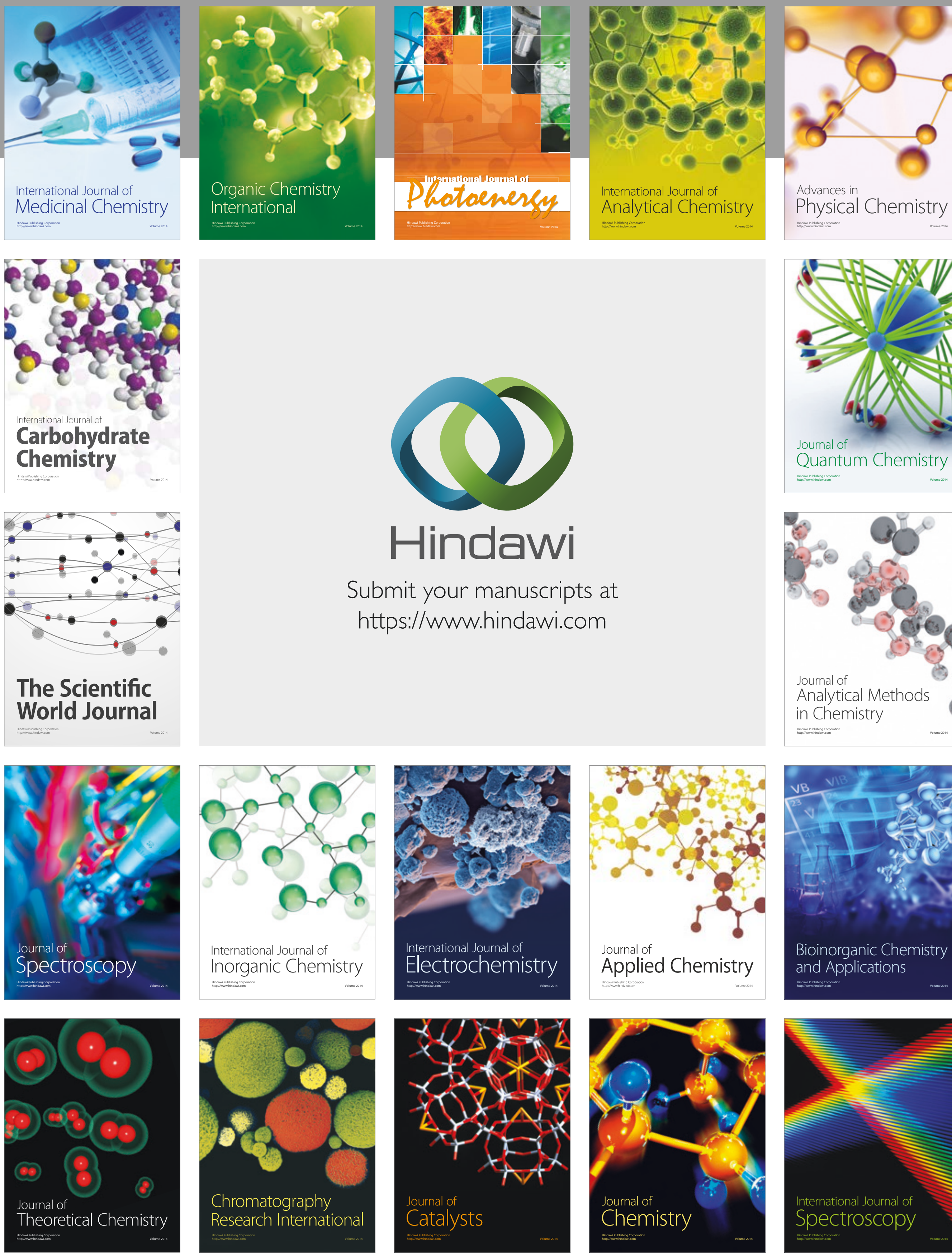
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