Feasibility Analysis of 100kW Grid Connected PV System: A Case Study at Karachi

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***Abstract*—The city of Karachi, with its ever growing population and an immense solar potential through rooftop solar photovoltaic (PV) system in urban areas is proving to provide a propitious investment opportunity for both domestic and industrial sectors. This is leading towards trends of moderate to small scale electricity production through solar power in many areas of city, with applications ranging from industrial processes to meeting the typical household electrical requirements. In conformance with this shifting tendency for attaining sustainable power generation, this paper aims to present the theoretical and practical aspects behind the working of a 100 kW roof-mounted PV system at Sindh Industrial Trading Estate (SITE) Area, Karachi. The analysis follows a systematic procedure, highlighting the key aspects of the working components and overall system design. It also includes the detailed study of output production and its comparative analysis with the local solar potential which was obtained through PVsyst software. Lastly, system contribution towards Greenhouse Gas (GHG) reduction is also discussed.**

***Index Terms*—Karachi, PV, roof-mounted, grid connected, SITE, GHG reduction**

I. Introduction

Karachi is hailed as the metropolis of Pakistan with its immense contribution towards economic activities and its influence on the overall development of the country. The demand of the electricity supplied can be deduced from the fact that lately more than 63% areas of Karachi do not suffer from load shedding. In actuality, this 63% area is bigger than more than hundred cities of this world. The installed power generation capacity of 2,431 MW depends heavily on the processing of fossil fuels [1]. Since the previous two decades, Karachi has faced a drastic increase in urbanization sprawl. This has led towards an ever increasing population and an incredible shortfall of electricity supply. Conventional electric power systems have failed to cater for this sudden surge in power demand due to its dependency on large based-load power plants [2]. The large gap between requirement and provision of energy owing to occurrence of faults in power distribution system leads to increased load shedding hours [3]. It is imperative that principal reliance for sustainable power production should be based on renewable energy sources. As evident from the practices in developed cities, large-scale renewable setups involving wind and solar energy are much more preferable and have promising impacts on the power systems [4]. In this respect, based on NASA's Surface Meteorology and Solar Energy (SSE) database, Karachi receives an annual average direct normal irradiance (DNI) of 6.20 kWh/m^2/day [5].

Due to such enormous availability of solar potential throughout the year, there is an immense scope for rooftop PV installation setups for millions of urban households of the city. It is pertinent to mention here that Karachi possesses a significant benefit of a privately-run power utility, leading to a much easier process initiation of integrating solar power in the grid system [6].

Several significant country specific descriptive studies have been conducted on applications of PV system and associated issues with it [7]. In contrary to the dynamic nature of wind turbine, PV installation is stationary and is independent of strong towers and extensive cooling systems. Perhaps the most profound appeal of this technology lies upon the fact that it is environmentally friendly and lead to comparatively lesser production of any greenhouse gases [8]. Complexity wise, two types of variations in PV systems are observed, namely "stand-

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alone or off-grid" PV systems and "grid connected or on-grid" PV systems [9]. Off grid systems serves as the sole provider of power to supply building loads. On-grid PV system comes with options of either supplementing system loads through drawing energy from the grid in case of increase power demand or selling of surplus electricity supply to a utility company. The latter version of PV system is more complicated in design and is similar to the one which will be discussed in coming sections of this paper. This particular approach is not dependent on the availability of expensive storage battery systems.

This research paper aims to provide a working model of a medium sized PV system which can be adapted to the power requirements of any industrial or commercial applications in case of occurrence of power failure or load shedding. With reference to the current energy scenario of Karachi, it is essential that small to moderate setups of PV system are to be built and encouraged.

II. Material and Methods

Majority of the previous research relating to the PV system working and performance analysis relies extensively upon software applications such as MATLAB/Simulink, PVsyst, Homer and RET Screen to name a few [10]. Following the similar popular approach, a substantial portion of the test results and analytical findings were done through the use of PVsyst software, version 6.44. Analytical descriptive study of the solar conditions and PV module system was also done after comprehensive study of the working of PV plant systems [11].

The analysis follows a systematic procedure, beginning with the description of location and climatic conditions relevant to solar energy production. A brief analytical description of relevant solar parameters is also given. Analytical considerations relating to the working of PV module systems are addressed, subsequently followed by the description of technical and design specifications of the selected module. Significance of inverter use and selection and relevant associated performance parameters are then briefly discussed. A considerable portion of analysis is devoted to the explanation and demonstration of the schematic layout of the PV system with respect to the string distribution, panel distribution, service provider and customer side section. Summary of the effective solar energy availability and electricity output production is covered in the results and discussion section, with some emphasis on the cost incurred upon the development and running of PV plant and contribution towards environment preservation.

III. Description of Selected Location and Site Survey

A. Study Area Location

Sindh Industrial Trading Estate (SITE) location was established in 2001 at Karachi, Sindh, Pakistan. It lies in western part of city with geographical coordinates of latitude 24.9°N and longitude 67.0°E. SITE is reputed to be the oldest and the largest designated Industrial Area of Pakistan, spanning over 4,700 acres ($19km^2$) of land. It contains approximately 2,400 factories to date [12]. Fig. 1 shows the aerial 3D view of the selected location. The installed solar panels can be viewed form the figure as well.

Figure 1. Satellite imagery through Google Earth of SITE area, Karachi (ROI: Region of Interest) [13].

B. Site Survey Analysis

An extensive site survey analysis for determination of load demand and capacity distribution was conducted as part of a feasibility study of the solar PV system. The findings of the survey are summarized by Fig. 2.

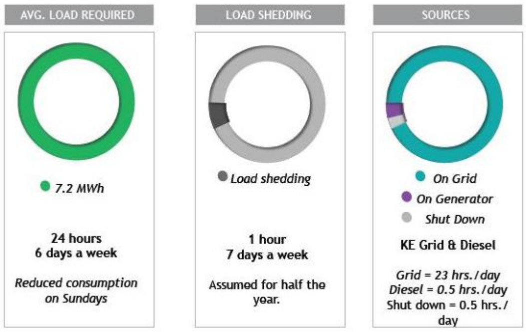


Figure 2. Results of site survey analysis

It is observed that average load requirement amounts to 7.2MWh, with comparatively reduced consumption on weekdays, particularly Sunday when most of the industries are closed. Load shedding serves as a major deterrent to continuous production with duration of around 1 hour for every weekday. This leads to shut down period of approximately 30 minutes per day, resulting in moderate to substantial losses in production. This implies that there is significant scope for the development of a PV solar powered project, covering the shutdown period due to load shedding.

IV. Analysis and Description of Solar Conditions

A. Monthly Optimum Tilt Angle

The monthly best tilt angle can be determined according to the following equation provided in literature [14].

$$\beta = \phi - \delta \tag{1}$$

where,
β= Tilt angle of solar cell modules (degrees)
ϕ=Latitude of site (degrees)
δ= Declination angle of location (degrees)

Declination angle for the Northern Hemisphere can be calculated by:

$$\delta = 23.450 \sin\left[360\left(\frac{284+n}{366}\right)\right] \tag{2}$$

In (2), n denotes the recommended day of year. Application of the above formulae and PVsyst software yields the value of 24 °tilt angle for our system.

B. Radiation on Collector Tilted Surface

For each calendar month in a year, average daily solar radiation on horizontal surface H, in J/m^2, can be expressed by [15]:

$$H = H_0 K_T \tag{3}$$

where
K_T: fraction of the mean daily extraterrestrial radiation,
H_0: Mean daily extraterrestrial radiation (J/m^2)

In a similar manner, H_T, in J/m^2, which is average daily radiation on the tilted surface can be expressed by:

$$H_T = RH = RH_0 K_T \tag{4}$$

Taking into account the beam, diffuse and reflected components of the radiation incident on the tilted surface directed towards equator, R fraction can easily be estimated.

In case of isotropic diffuse and reflected radiation, R can be expressed by (5). The p symbol denotes the ground reflectance and H_d is the diffused radiation in J/m^2.

$$R = \left(1 - \frac{H_d}{H}\right) R_b + \left(\frac{H_d}{H}\right)\left(\frac{1+\cos(\beta)}{2}\right) + p\left(\frac{1-\cos(\beta)}{2}\right) \tag{5}$$

where,

$$\frac{H_d}{H} = 1.39 - 4.027K_T + 5.531K_T^2 - 3.108K_T^3 \tag{6}$$

R_b in (5) indicates the ratio of the monthly average beam radiation on the tilted surface to that on a horizontal surface for one month. Being a complex quantity, it is dependent upon atmospheric transmittance which further depends on the atmospheric cloudiness, water vapor presence and further other factors. Additionally, it can be estimated to be the ratio of the extraterrestrial radiation on the tilted surface to that on horizontal surface for the month by (7) [15]:

$$R_b = \frac{\sin(\delta)\sin(\phi - \delta)\left(\frac{\pi}{180}\right)(w'_s) + \cos(\delta)\cos(\phi - \delta)\sin(w'_s)}{\sin(\delta)\sin(\phi)\left(\frac{\pi}{180}\right) + \cos(\delta)\cos(\phi)\sin(w_s)} \tag{7}$$

where,

$$w_s = \cos^{-1}\left(-\tan(\phi)\tan(\delta)\right) \tag{8}$$

$$w'_s = \min[w_s, \cos^{-1}(-\tan(\phi - \beta)\tan(\delta))] \tag{9}$$

C. Description of Solar Path Diagram

After substituting the relevant geographical parameters in the PVsyst software module, a solar path diagram was obtained from the meteorological data generated by the software. Fig. 3 shows the respective solar paths obtained for specific period of months.

Fig. 3 contains month to month meteorological information obtained from MeteoNorm 7.1 Station (Synthetic) of Karachi. With an altitude of 18 m, it can be observed that the location receives an ample coverage of sun trajectory over a period of year. The solar path is most pronounced for the month of June and spans a considerable distance. The minimum distance of span occurs in the month of December.

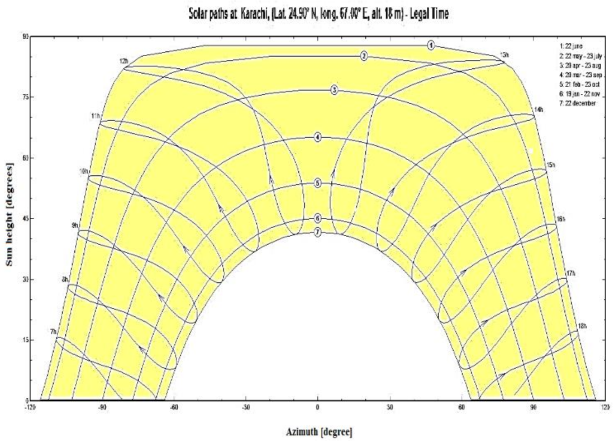


Figure 3. Solar path at SITE Karachi using PVsyst software

D. Determination of Monthly Solar Insolation Conditions

In addition to the solar path diagram, a detailed description of solar irradiation experienced by the area was also obtained. The relevant numerical data is summarized graphically in Fig. 4. The highest value of average ambient temperature is recorded as 31.09 ℃ in the month of June.

The temperature values showed an increasing trend till June after which it declined gradually. The values of solar radiation are observed to vary proportionally with ambient temperature. Maximum values of global horizontal irradiation and global incident irradiation are observed to occur at the month of May and October respectively.

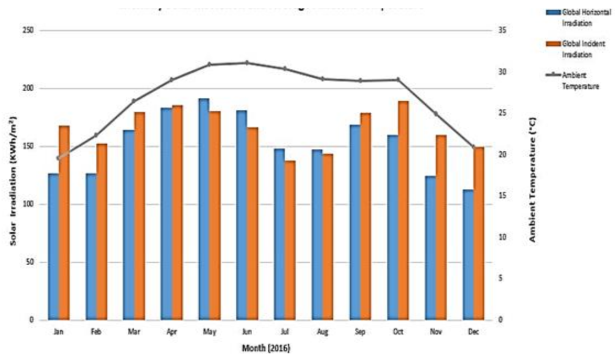


Figure 4. Graphical description of monthly solar insolation and ambient temperature

E. Description of Collector Plane Orientation

In consideration to the space availability and enhancing the working efficiency of the overall system, several important parameters relating to the orientation and layout of collector planes were determined. These are summarized in Table I.

TABLE I. COLLECTOR PLANE CHARACTERISTICS

Parameter	Value
Tilt Angle	24°
Azimuth Angle	0°
Pitch	6.60m
Collector Width	3.00m
Shading Limit Angle (Gamma)	17.55°
Occupation Ratio	45.5%
Number of sheds	5

Dimensions of the aluminum frame for solar collector plane are summarized in Fig. 5.

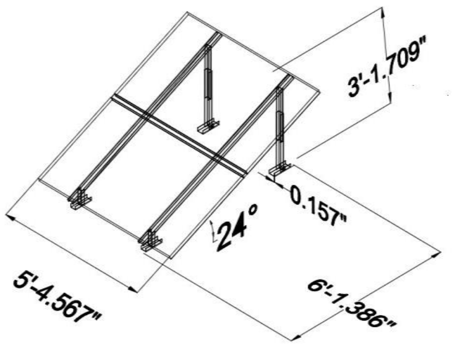
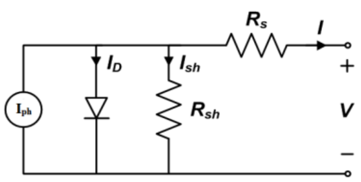


Figure 5. Dimensions of aluminum frame

V. ANALYSIS AND DESCRIPTION OF SOLAR MODULE

A. Analytical Modelling of a Photo Voltaic Module

The basic design of a typical module consists of multiple tiny cells grouped in the shape of an array [16], [17]. The type of cell used is a p-n junction constructed from a semiconductor material (mostly silicon). Exposure to solar radiation leads to the generation of electron hole pairs inside the cell. Owing to the internal electric field of cell, these electron hole pairs experiences a drift motion [18]. This results in a flow of current when the cell terminals are shorted. If the cell circuit is in open state, any current produced is shunted through a diode connected in parallel with the cell [19]-[21]. The equivalent circuit of a PV array and graphical display of voltage versus current characteristics is given by Fig. 6.



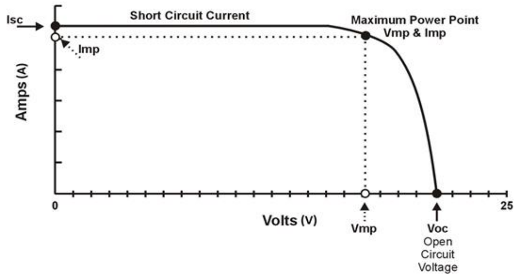


Figure 6. Equivalent circuit diagram and IV characteristics of a solar cell

Equations (10)-(16) were observed to be prevalent in application for mathematical modelling of a PV module [22], [23].

$$V_t = \frac{KT_{op}}{q} \tag{10}$$

$$I_{rs} = \left(\frac{I_{sc}}{e^{\frac{V_{oc}q}{KCT_{op}N}}}\right) - 1 \tag{11}$$

$$I_{sh} = \frac{(V+I_{rs})}{Rsh} \tag{12}$$

$$I_{d} = \left(e^{\frac{V+I_{rs}}{NV_tCN_s}} - 1\right) I_s N_p \tag{13}$$

$$I = I_{ph}N_p - I_d - I_{sh} \tag{14}$$

$$V_{oc} = V_t \ln\left(\frac{I_{ph}}{Is}\right) \tag{15}$$

$$I_{ph} = G_k[I_{sc} + K1(T_{op} - T_{ref})] \tag{16}$$

where,
G_k: Ratio of solar irradiance
V_t: Thermal voltage (V)
K: Boltzmann's constant (1.38E-23 J/K)
q: Charge of an electron (1.6E-19 C)
T_{ref}: Reference temperature (25 ℃)
I_d: Diode current (A)
V_{oc}: Open circuit voltage (V)
I_{sc}: Short circuit current (A)
T_{op}: Operating temperature (℃)
R_{sh}: Shunt Resistance (Ω)
I_s: Diode saturation current (A)
K1: Change in panel I_{sc} per ℃ at temperatures other than 25 ℃ (A/ ℃)
I_{ph}: Photocurrent (A)
I_{rs}: Diode reverse saturation current (A)
I: Module output current (A)
I_{sh}: Shunt current (A)
V: Output voltage from the module (V)
I_s: Diode saturation current (A)
N: Diode ideality factor
C: Quantity of cells in a module
N_s: Quantity of modules in series
N_p: Number of modules in p

B. Description of Selected PV Module System

For our system, it is preferred to use the polycrystalline type of PV module of model no TP 660P-250. This is due to the variation in daily temperature conditions of the region which will lead to performance decline if monocrystalline type of PV module is used. Another major reason for this selection is the high conversion efficiency and performance displayed by the model. Compared with the Talesun recommended efficiency of 15.4%, the system is currently working at an efficiency of 14.4%. Table II presents the major technical characteristics of the PV module [22].

TABLE II. SPECIFICATIONS OF PV SYSTEM

S. No	Item	Parameter	Unit
1	PV Material	Poly-Si	
2	Manufacturer	Talesun Solar (Zhongli)	
3	Module	TP660P	
4	Quantity of Modules	400	unit
5	Module Area	649	m^2
6	Cell Area	584	m^2
7	Cell Arrangement	6x 10 (60)	cells
8	Power Production	0.25	kW
9	Total Power Capacity	100	kW
10	Maximum Power (P_{max})	250	W
11	Power tolerance	0 to +3	%
12	Module Efficiency (η%)	15.4	%
13	Rated Voltage(V_{mpp})	30.5	V
14	Rated Current (I_{mpp})	8.22	A
15	Open Circuit Voltage (V_{oc})	37.6	V
16	Short Circuit Current (I_{sc})	8.97	A
17	Maximum Reverse Current (I_R)	15	A
18	Maximum System Voltage (U_L)	1000	V
19	Temperature Coefficients (Power (P_{mpp}))	-0.45	% / ℃
20	Voltage (V_{oc})	-0.35	% / ℃
21	Current (I_{sc})	0.05	% / ℃
22	NOCT	45±2	℃
23	Weight	20	kg
24	Module Dimension (LxWxH)	1,640x990x40	mm
25	Cell Dimensions (LxWxH)	156x156	mm
26	Operating Temperature	-40 to +85	℃

Standard Test Conditions (STC) used for measurement include irradiance of 1000 W/m^2, air mass coefficient (AM) of 1.5 and cell temperature of 25℃. Fig. 7 and Fig. 8 presents the electrical performance and IV characteristic of the proposed PV module system [22]. It is to be noted that the green colored graphical plot represents the actual persisting characteristic of the proposed PV system.

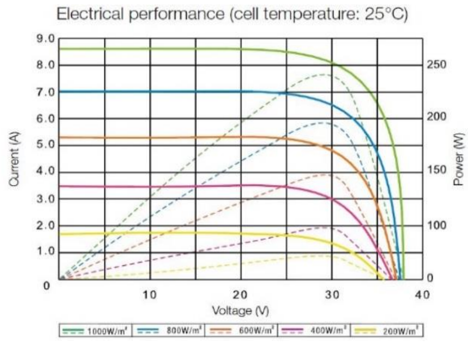


Figure 7. Graphical display of electrical performance

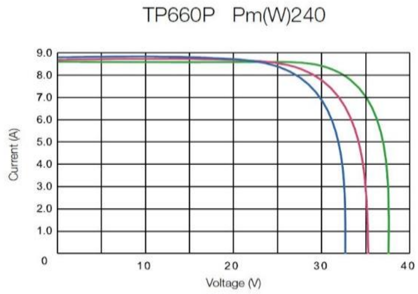


Figure 8. Graphical display of IV characteristics

VI. DESCRIPTION OF SELECTED INVERTER

Inverters are essentially used for provision of energy supply to grid system from PV modules. Their functioning includes conversion of DC current from PV system in to an Alternating Current (AC). This process serves as a common basis of all grid linked inverters which is subsequently achieved in a very efficient manner without the need of any rotating elements. On connection in parallel to the utility power grid, the output for alternating current from the inverter flows directly into the distribution circuit, which is in turn linked to the public distribution utility grid. In this particular PV system, four inverters module TRIO-20.0/27.6-TL-US (ABB solar inverters) are considered for supplying energy to grid. The reason for selection of ABB central inverter model was due to its power point tracking (MPPT) algorithm. Such level of highly efficient power converter design means that nominal power of 110 kW_{ac} can be obtained from the selected inverter type [23], [24]. The operating and design performance parameters of the inverter are summarized in Table III [23].

TABLE III. INVERTER SYSTEM SPECIFICATIONS

Inverter Code: TRIO-27.6-TL-OUTD			
S. No	Item	Parameter	Unit
1	Nominal Output Power	27,600	W
2	Maximum Output Power	30,000	W
3	Rated Grid AC Voltage	480	V
4	Total Quantity	4	unit
5	Total nominal power	110,000	W
6	Efficiency (Max/CEC)	98.2 / 97.5	%

	Input Side (DC)		
	Item	**Parameter**	**Unit**
1	Quantity of independent MPPT channels	2	unit
2	Maximum useful power for single MPPT channel	16,000	W
3	Absolute maximum voltage (V_{max})	1000	W
4	Start-up voltage (V_{start})	360 (adj. 250-500)	V
5	Full power MPPT voltage range	520-800	V
6	Operating MPPT voltage range	200-950	V
7	Maximum usable current (I_{dc} max) for single MPPT channel	30.9	A
8	Maximum short circuit current (I_{sc} max) per MPPT channel	36	A
	Output Side (AC)		
	Item	**Parameter**	**Unit**
1	Type of grid connection	3Ø/4W + Ground	
2	Default range of operating	422-528	V
3	Extended adjustable voltage range	240-552	V
4	Nominal grid frequency	60	Hz
5	Adjustable range of grid frequency	57-63	Hz
6	Continuous current	36	A_{RMS}
7	Contributory fault current (@ 1 cycle)	42.72	A_{RMS}
8	Power factor	>0.995 (adj. ±0.8, or ±0.9 for active power >27.6kW)	

VII. Schematic Layouts of PV System

A. General Layout Description

The total roof area available for PV system installation is approximately 1338m^2 with dimensions of 29.26 m x45.72 m respectively. The pitch distance is constantly maintained between any two individual array units. Fig. 9 shows the top view of the roof layout. The staircase is indicated by red circle at the bottom right of the diagram.

Figure 9. Lay out of PV system (top view)

B. String and Inverter Wise System Distribution

Electrically connected multiple photovoltaic modules in series results in photovoltaic string. On the other hand, an array is usually comprised of a mechanically integrated assembly of modules or strings to produce an integrated DC system. The current of an individual string or array should comply with the limits of the inverter [23].

Fig. 10 shows the layout of string distribution with respect to inverter. It can be observed that the entire system consists of 20 strings. Inverter 1 and 2 are each connected to 4 strings and a single string have 20 panels in total. Inverter 3 and 4 have a total of 6 strings each.

It is to be noted that each string is shown in different color with a specific number assigned for ease of identification and performance recording purpose

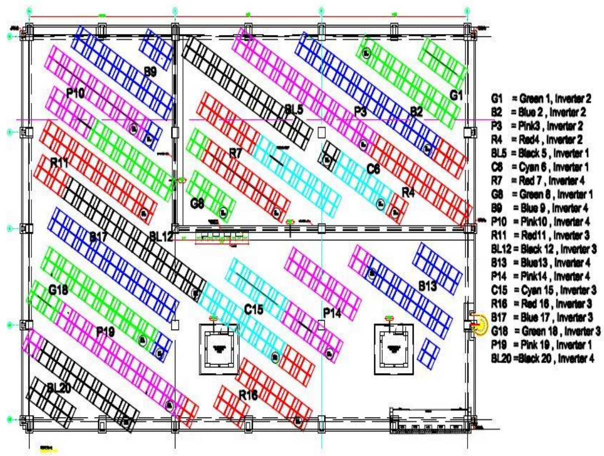


Figure 10. Schematic layout of inverter wise string distribution

C. AC Wire Layout of Proposed System

Fig. 11 describes the 3D orientation of the ac wire from the inverter system to the main distribution board. The total length of wire amounts to approximately 100 m. Grid wiring termination is of copper material with wire gauge dimension ranging from 6 AWG-4 AWG.

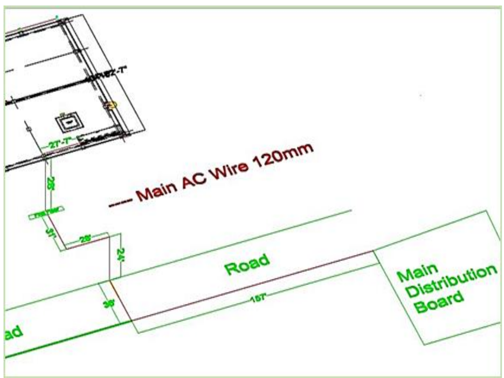


Figure 11. AC wire layout of system

VIII. Output Characteristics of the PV System

A. Effective Solar Irradiation on Collector Plane

From Fig. 12, monthly variations in effective solar irradiation can be viewed. These results are obtained through simulation using PVsyst software and take in to account the losses occurring due to shading and array incidence effect. For this system, the b_o parameter value is calculated to be 0.05 which is utilized in IAM factor determination. It can be observed that the highest value of effective global irradiation occurs around October.

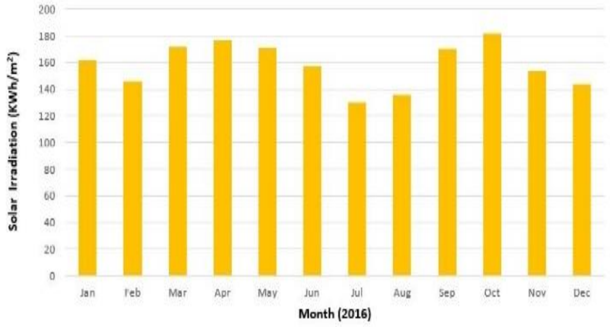


Figure 12. Effective global irradiation at collector plane

B. Single Line Diagram of Proposed Grid Connected System

After finalizing the design and operating parameters of the entire system, a single line diagram was prepared for determination of components in both the service provider and customer section of power generation. Details of the major components and their respective performance parameter are summarized in Fig. 13.

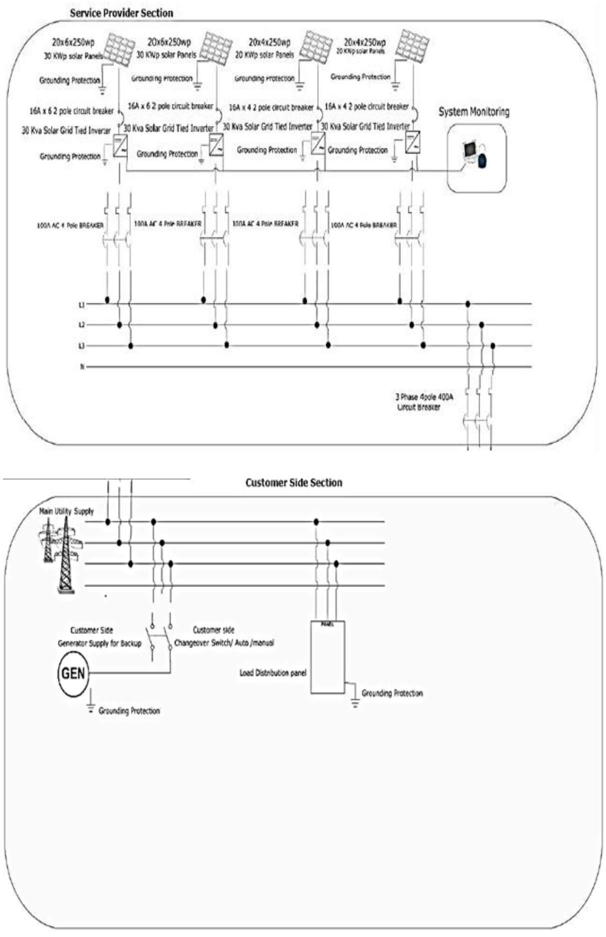


Figure 13. Single line diagram of the grid connected PV system

C. Extracted Energy and Associated Percentage Efficiency

The results of the expected monthly output energy from array and energy being supplied to grid were calculated through PVsyst software and are summarized in Fig. 14. In addition, percentage efficiency of energy conversion by PV array and system output efficiency is also highlighted. A similar trend for variation is observed in both the graphs of efficiency with the highest values recorded in January. In October, highest occurring values were observed for both energy output characteristics.

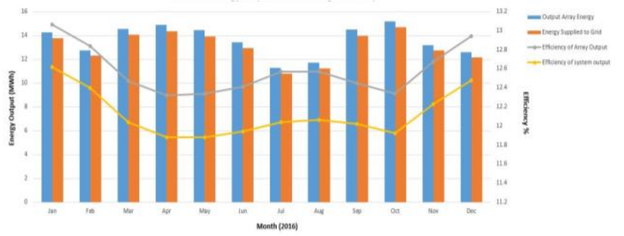


Figure 14. Output energy produced and percentage conversion efficiency

D. Month-Wise Output Production Results

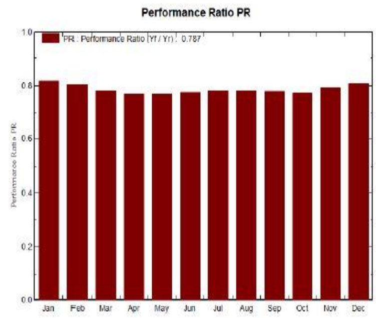
Table IV displays the electricity production in kWh generated during a specific month since the commencement of system working on 6 June, 2016. The production data is obtained from month of June to September.

TABLE IV. MONTHLY OUTPUT PRODUCTION

S. No	Month	Generation (kWh)
1	June	9,348.57
2	July	8,922.47
3	August	9,353.51
4	September	12,365.31

E. Determination of Performance Ratio and Normalized Production Units

Calculation of performance ratio and normalized production of electricity was done through PVsyst software analysis through inputting of relevant present solar conditions and power requirement parameters in module. The results obtained are summarized in Fig. 15. The average annual performance ratio was found out to be 0.787 with the highest value of 0.8 recorded in January. No abrupt shift in the performance ratio was observed throughout the year. For normalized production output, highest value of 4.75 kWh/kWp/day was recorded in April. Monthly collector and system losses can also be observed.



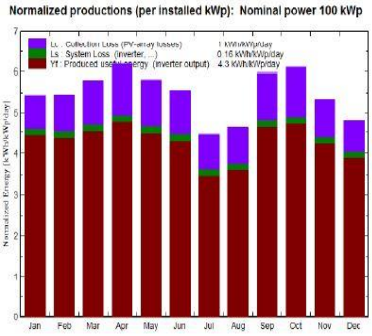


Figure 15. Graphs of performance ratio and normalized output production

F. Occurrence of Losses in PV System

An annual loss diagram was obtained for determination of different losses and the extent of their contribution. Fig. 16 shows the loss diagram for the upcoming year of production. Highest losses were observed to occur at PV section due to temperature. Lowest value of losses occurred in inverter section of the PV system.

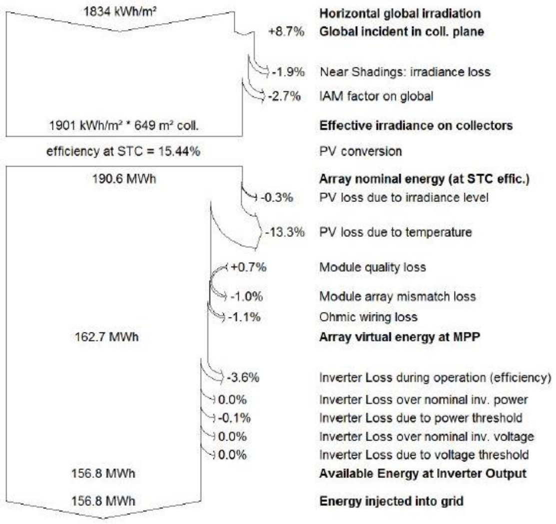


Figure 16. Annual loss diagram of PV system

IX. System Cost and Reflection of Environment Contribution

A. Description of Completed Payment

Table V summarizes the different phases over which payment is made and individual contribution of each payment delivery. The total costs incurred in this project amounts to approximately PKR 13.2 million.

TABLE V. Detail of Payment for Project

Payment Mode	Contribution (%)	Amount (PKR)
Mobilization	25	3,300,000
Shipment at premises	40	5,280,000
Completion of Installation	25	3,300,000
Dues after 3 months of testing and commissioning	10	1,320,000

B. Unit Cost Variation with Increase in Production Year

Fig. 17 describes the graphical trend obtained for unit cost with increasing year of production. It is observed that as cumulative power produced increases per year, cost per unit of solar power declines rapidly. This result is a positive indicator of a successful investment for production of electricity power. The total estimated life of this project is about 25 years.

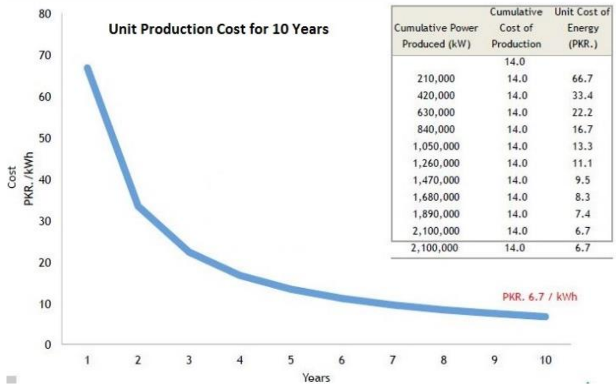


Figure 17. Graph of variation in unit production cost with time

C. Contribution to Environment Preservation

To date, with cumulative output production of 41,831.36 kWh, the solar powered plant application has resulted in saving of 5,630 kg of coals. An equivalent oil consumption of 24.59 barrels is also saved. This affirms its significant contribution towards greenhouse gas emission reduction and preservation of fossil fuels.

The real time picture of installed PV module system is shown in Fig. 18. Particular attention is paid on complying with the maintenance schedule of the components as directed by the company and industrial regulations. This ensures that the system operates nears its optimum condition leading to an increase in production efficiency.

Figure 18. View of installed solar arrays

X. Conclusion

A comprehensive feasibility analysis is discussed in this paper with particular emphasis on design methodology and output results of the system. Previous literature was reviewed prior to this study and the applicable principles derived are mentioned at relevant places. A substantial part of plant working is summarized through tabular and graphical data for ease of understanding and deduction of results. In view of the obtained results, the significant scope of the conduction of this study is evident and it is hoped that this work would be beneficial for future solar projects development local to Karachi. The future work may include expansion of project for generation of around 500 kW owing to increasing demand of electricity and popularity of solar projects.

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