Chapter 6

Comprehensive Design Aspects and Performance Assessment of On grid solar 500 kWp PV plant

6.1. Introduction

In today’s world, solar power plants and assisted technologies are growing as green and imperishable option for national energy security. “On-grid rooftop solar” (OGRTS) power plants are believed to be a potential source for catering to peak loads of industrial and infrastructure sectors. One such OGRTS plant with 500 kWp capacity is designed and installed at National Metallurgical Laboratory in Jharkhand state of India. In this work, methodologies and tools used for optimal plant design, engineering, and project management activities are elaborated for OGRTS plant citing the site-specific conditions. Critical aspects of project feasibility analysis for defining the electricity utility scenario, shadow analysis, solar radiation analysis, electrical SLD for power distribution along with power evacuation strategies are discussed by correlating the data obtained from the plant site.

Engineering installation aspects to be followed during the project execution along with material management aspects are also discussed for optimising the capital cost of the project. The technical and commercial analysis of the designed plant carried out with PVSYST©V6.63 predicts the effective energy output to be 652.79 MWh and net apparent energy for grid as 621.76 MWh and compared with real time generation data. For a span of 25 years, Greenhouse gas emissions are calculated as 13212 t of CO_2 reduction with 44 t of reduction for every monthly billing cycle. Energy cost from this OGRTS plant is found to be ₹4.44/kWh as compared to ₹12.50/kWh from local grid. With commercial viability and associated sustainability, this OGRTS plant is found out to be a lucrative option for enhancing environmentally friendly industrialisation and greatly helps in energy policy formulation.

The present work discusses the optimal designing and engineering issues related to supply, installation, testing, and commissioning of 500 kWp OGRTS system installed in the industrial city of Jamshedpur. Critical aspects of project feasibility analysis for defining the electricity utility scenario, shadow analysis, solar radiation analysis, electrical SLD for power distribution along with power evacuation strategies are discussed by correlating the data obtained from the plant site. In addition, an attempt is made in the form of engineering drawings, flow charts along with techno-economic analysis for a broader insight into the utility and solar sector. Performance parameters of the designed plant, simulated through PVSYST© V6.63 is compared with the actual generation data to get the idea of energy output, performance ration and capacity factors.

6.1.2. Site details and overview

OGRTS power plant studied in the present work is for CSIR-National Metallurgical Laboratory, Jamshedpur which is in the Indian state of Jharkhand. The geographical location of the proposed site identified with (Latitude and longitude in degree) 22.778°N, 86.204°E with MSL 159 m is shown in **Figure 6.1**. Average wind speed for this site location is 6.3 mph.

Figure 6.1- Top view of site for PV plant.

Feasibility analysis is the most crucial engineering aspects for the installation of OGRTS power plant. Many tools are available for deciding the feasibility factor of a particular site for solar installation. In Green field solar power plant projects, the design engineer has flexibility for deciding the verticals starting from basic equipment layout to point of power delivery. This flexibility offers the options to maximise the power production by efficient designing of the plant and for the planning of project capital and expenditure costs [118] to arrive at the precise power purchase agreement.

With the progression and advancements in the solar sector, transition from green field to brownfield solar rooftop projects, many factors need to be checked and considered for efficient designing and effective floor space utilisation. Besides, precise feasibility analysis will cut down the unforeseen installation costs and helps in the timely execution of project. There has been an effort here to develop a generic methodology consisting of various tools used for feasibility analysis of OGRTS power plant. For this, the authors proffered a framework as shown in **Figure 6.2** flow chart.

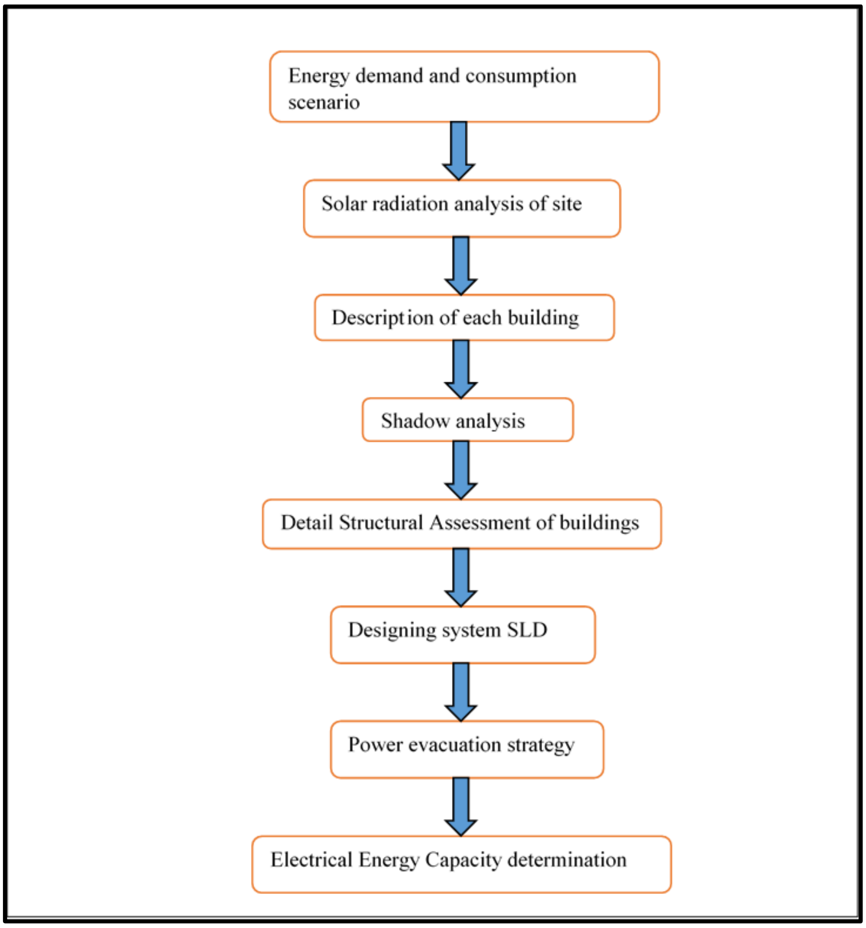


Figure 6.2- Flow chart for feasibility aspects for OGRTS plant

6.2. Detailed Methodology for feasibility analysis

Tools used for feasibility analysis are discussed and methodology for analysis is enumerated with the detailed description. These tools can be used effectively for ascertaining critical aspects of engineering like project funding, material estimation, manpower management, and project planning activities including supply, installation, commissioning, and testing. In addition, tentative OGRTS plant size along with wattage output per sq.m area can be obtained from the proposed tools.

6.2.1. Energy demand and consumption scenario

Electricity demand shows the rate of electricity consumption and denoted by kilowatts (kW). Kilowatt-hours (kWh) is the unit used to measure electricity consumption and represent the total quantity of power used within a specific time period. The current scenario of energy demand from OGRTS plant installation site chosen was ascertained. Energy demand for the past 1 year is analysed and connected load and operating load of the building with demand factor is calculated.

Calculation of daily, monthly, and yearly average load will give the idea of energy consumption pattern. Once the energy consumption pattern of the consumer is established, critical loads with high demand factor were identified as per standard power system tools. Technical details of diesel generator kVA, output current rating, operation philosophy, and connection to auto mains failure panel (AMF) along with its emergency load sharing details in the past year are noted and taken into consideration. Automatic power factor compensation panel (APFC, for maintaining unity Power factor) feeding point to low tension panels is to be noted for retrofitting. The tentative annual energy consumption pattern of the system is mentioned in **Table 6.1**.

Table 6.1- Electrical energy consumption scenario at the site

Month	Monthly Consumption (kWh)	Maximum Demand (kW)	Apparent power (kVA)	Power Factor	Daily consumption (kWh)
January	57110	203	206	0.985	1842
February	57440	242	252	0.958	2051
March	69250	369	369	1.000	2234
April	101860	478	478	0.999	3395
May	122120	494	496	0.996	3939

June	109460	511	512	0.997	3649
July	120190	448	449	0.998	3877
August	108910	436	440	0.991	3513
September	115630	428	429	0.999	3854
October	95470	394	397	0.995	3080
November	78670	269	270	0.996	2622
December	75400	256	260	0.987	2432

Annual variation of maximum demand as shown in **Figure 6.3a** indicates that the peak occurs in the month of May-June. **Figure 6.3b** shows the monthly consumption data for the year 2023. It was observed that monthly consumption is more in the 2nd and 3rd quarters of the year hitting the maximum in May and minimum in January. It is found that metallurgical pilot operations and process HVAC (heating, ventilation and air conditioning) systems, which are mainly intermittent nature loads attributed to these changes in energy consumption. Hence, this OGRTS plant can be potentially designed for meeting these peak loads.

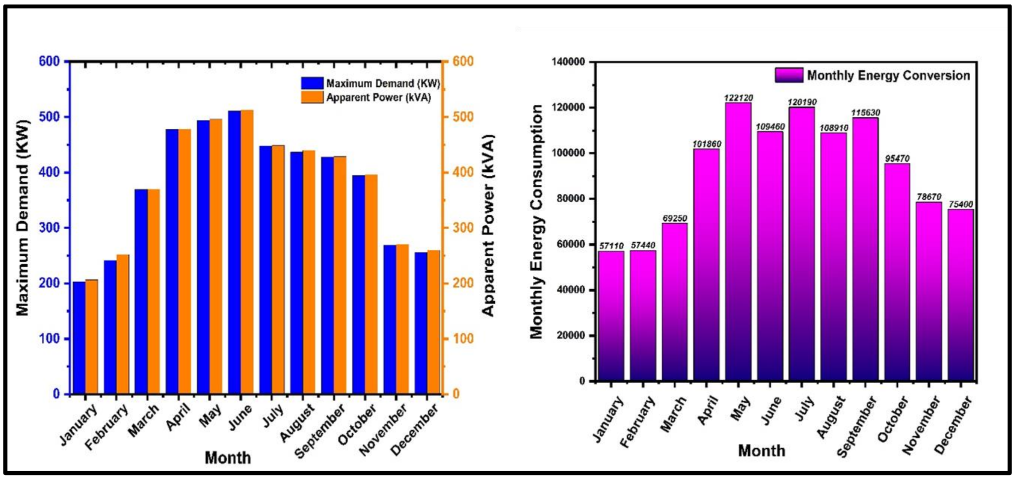


Figure 6.3- (a) and (b): Maximum Demand and Monthly consumption data for the year 2023.

6.2.2. Solar radiation analysis of the proposed site

Amount of incoming solar radiation is the key factor in designing the OGRTS plant. This radiation analysis was done with solar irradiance data available for the proposed site location. Site co-ordinates along with MSL and elevation of the building are key aspects for the analysis. In this study, the database from ISRO & MNRE has been taken for analysis and the detailed observations are mentioned below. The behavior of sunshine duration and global solar radiation of site was found by the methodology of long term site averages with 14 years of data.

It is evident and proved fact that solar irradiation will vary as per geographical location and with seasonal variations through the year. Hence a detailed analysis is needed to ascertain the engineering aspects of plant and its installation capacity. This analysis was carried with statistical data of solar calculator developed by ISRO [119]. **Table 6.2** indicates the average temperatures of the site along with key indices AEP, CUF, DNI and DHI, which are well above the average values of entire peninsular India. Necessary details confirming the kWh/m^2 are also depicted for detailed design.

For the proposed site, solar insolation data in kWh/m^2 is collected for the last 14 years and average insolation was calculated with respect to each month. For the past decade, insolation in 2010 is found to be highest with 1814 kWh/m^2 and the year 2013 is with the lowest insolation of 1413 kWh/m^2. This study indicates highest average insolation at OGRTS plant site is received mostly in second and third quarters of each year, which is in-line with the requirement of the consumer.

Table 6.2- Site-Specific Data for OGRTS plant

S.no	Description	Details
1	Latitude/Longitude	22.778 ºN, 86.204 ºE
2	State/District/Taluk	Jharkhand/ Jamshedpur
3	Day Length (Min/Max)	10.60/13.40 hours
4	Avg. Temp. (Min/Max)	20.1 ºC/31.6 ºC
5	Global Horizontal Irradiance	1684 kWh/m^2/year
6	Annual Global Insolation	1619 kWh/m^2/year
7	Annual Energy Production (AEP)	1296110 kWh/m^2
8	Capacity Utilization Factor (CUF)	14.8%
9	Direct Normal Irradiance (DNI) [120]	1184 kWh/m^2/year
10	Diffused Horizontal Irradiance (DHI)	812 kWh/m^2/year
	Source: NIWE (MNRE) Statistics	

The Sun's position is determined by the solar azimuth angle. Horizontal coordinate defines the azimuth angle in a direction with reference to altitude angle in **Figure 6.4a** obtained from ISRO solar calculator [VEDAS]. Sun path can also be traced for finding out maximum and minimum insolation value for a specific coordinate. Site specific annual day length plot is shown in **Figure 6.4b** indicating potential availability of source for estimating the generation.

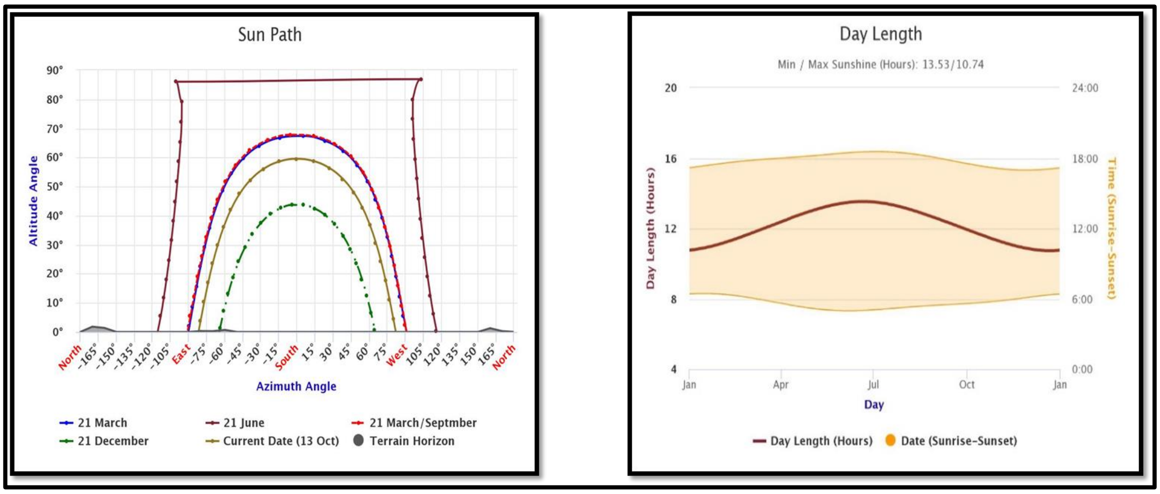


Figure 6.4 (a) and (b): Trace of Sun path at the site and Annual day length

6.3. Description of site condition

For detail engineering designing of the plant, survey of the site was carried out and key details of each building, i.e. type of roof, the height of roof from ground level (+0.00 mm), the orientation of the building, roof health, inclination of roof, chances of the level of soiling of PV panels, the distance between existing LT panel to proposed PV panels are measured.

Details and type of parapet walls for mounting protocols, shaded and un-shaded area and positioning of beams and columns have also been taken for detail design assignment. These details are expected to help in estimation of free floor space area and address the design issues pertaining to base frames, number of inverters, cable routing, panel sizing and injection points. Roofs with major inclinations/odd shapes, soiling issues were avoided for finalising the space layout. At each stage, tilting angle and orientation of PV array towards south direction are evaluated and addressed suitably. Sufficient number of water supply points along with drain lines is ensured for periodic cleaning of PV panels.

Different parts of the building are considered for installation in this case. Blocks with complete North side orientation, obstructions and self-shaded areas are not considered. Tentative roof area available for installation activity and plant layout is decided based on above conditions.

6.3.1. Structural Assessment of buildings

Most of the civil structures used in this study are aged more than 50 years and structurally old. Simply supported concrete RCC roof with 125 mm thickness are used in these structures and are designed for imposed uniform load-bearing capacity of 500 kg/m^2. This load-bearing capacity of the roof is expected to decrease with ageing and probable cracks in the structure. As per the calculation for the solar module support structure, imposed load on the roof for module mounting position is determined to be 18-25 kg/m^2 (including panel dead weight, mounting structure weight etc.). Preliminary structural analysis of the roof has been done to evaluate the load-carrying capability. Portions of the roof where visible cracks and degradations are marked were left blank as a safety measure. For major structural issues, Non-Destructive Testing analysis report may be considered before mounting the PV panels. **Figure 6.5a-b** shows a few roof sites where analysis was carried.

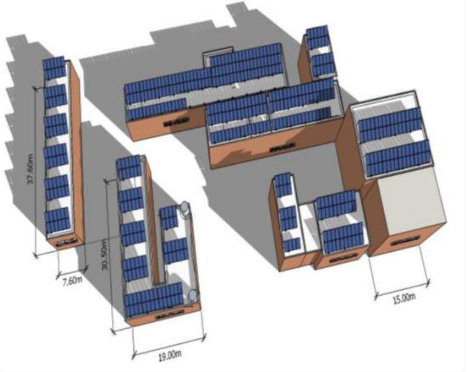
Figure 6.5- (a) and (b): proposed installation site roof photographs.

6.3.2. Shadow analysis

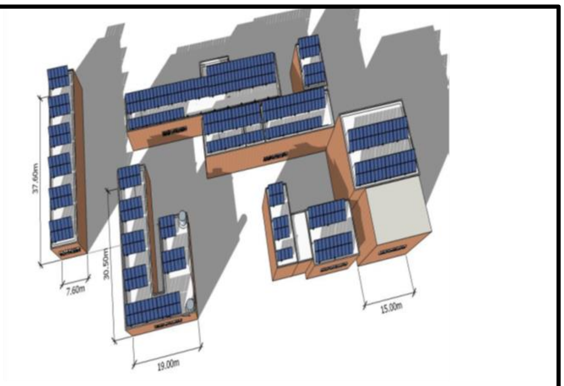
Shadow analysis investigates the reduction in PV panel performance by reducing output generation due to artificial factors generated by shadow cover of rows and columns in an array of solar panels. There are many experimentations works on the shadow effects upon PV panel performance, due to building and solar panels arrays [121]. From the results of shadow analysis, it is possible to tune the various installation parameters so as to achieve optimum utilisations of available resources [122].

The orientation of the building plays a key role in shadow analysis. For a linearly shaped building, the effect of shadowing is observed to below when compared to buildings with interconnecting walkways built in periphery. Besides, the effect of shadow cover was studied for each particular building with respect to sunrise and sunset. Similarly, the shadow patterns for the months of January and July are analysed for ascertaining the change in shadow position to finalise array layout. In **Figure 6.6a-h,** Building-1 and Building-2 areas are shown for shadow analysis using Sketchup© software. This analysis was done for all proposed areas of installation. For ease of drawing representation, the structural portions considered here for explanation are shown in two parts.

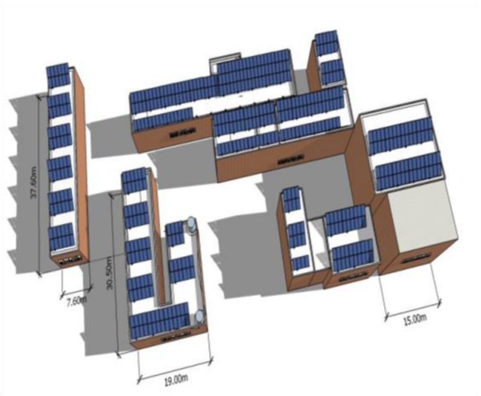
After entering the details of PV panel orientation, shadow analysis details will give the input for modifications in layout and can maximize the utilization of floor space area. The occurrence of shadows and generation losses for different seasons has been calculated and panel orientation is selected with probability of minimum generation loss.



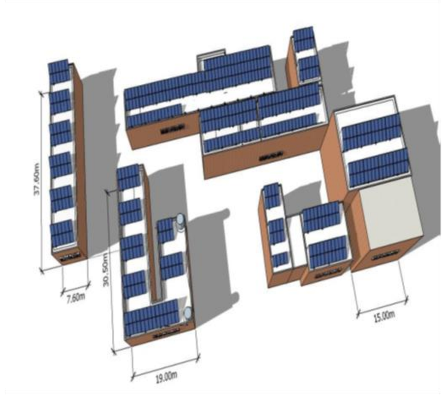
(a) Building 1 (179.4 kWp)/Month- January, Time: 09:00AM



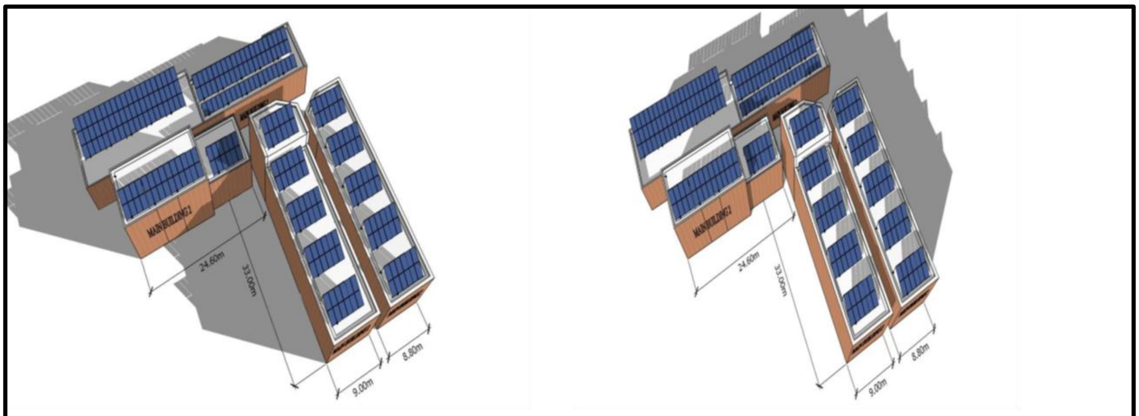
(b) Building 1 (179.4 kWp)/Month-January, Time- 05:00 PM



(c) Building 1 (179.4 kWp)/Month- July, Time: 09:00AM

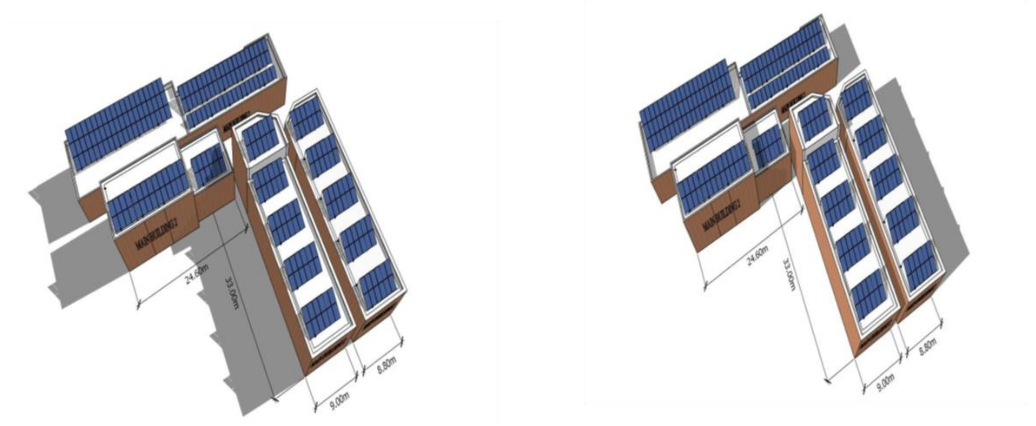


(d) Building 1 (179.4 kWp)/Month- July, Time: 05:00PM



(e) Building 2 (91 kWp) /Month- January, Time: 09:00AM

(f) Building 2 (91 kWp) /Month- January, Time: 05:00PM



(g) Building 2 (91 kWp) /Month- July, Time: 09:00AM

(h) Building 2 (91 kWp) /Month- July, Time: 05:00PM

Figure 6.6- (a-h): Shadow analysis for Building 1 and Building 2 for different months and time

6.3.3. Power evacuation strategy & Feeding point analysis

Before deciding the feed point and power evacuation strategy, Single Line Diagram (SLD) of the system was prepared and electrical energy distribution scenario of each area was identified. This diagram shows the main connections and arrangement of the system sub-components along with their ratings and power flow directions.

Figure 6.7- (a) and (b) Sub distribution panels considered for solar installation

SLD showed in **Fig. S12** indicates 6.6 kV, 400 Amps feeder input for mains power from local grid ring mains system. 6.6 kV HT panel is placed at the ring mains entry for the distribution to individual transformers. There are two numbers of 500 kVA transformers with primary circuit fed from HT panel and the outgoing LT secondary is connected to panels showed as sub-distribution panel A, B, C and D as shown in **Figure 6.7a-b**.

Each electrical panel is facilitated with two numbers of incomers with bus coupler for feeding the downstream loads in the event of a failure in either transformer. From individual panels of A, B, C and D local distribution panels are feeding to loads at various locations. Above figure shows the structure of a local distribution panel. A dedicated HT feeder is connected to a 500 kVA transformer for feeding critical loads. Feeding points from solar inverter modules is designed for panel A and C through an individual AC distribution board (ACDB). Local metering facility for feed power is connected in this ACDB.

Feeding points are decided by keeping in view the minimum distance from inverter panel to ACDB panel, and utility industrial loads. In the event of grid power failure, the reference voltage to solar inverter becomes zero and OGRTS plant will not be in functional mode. Hence, as a safety measure and to feed emergency loads of building, electrical connection between Diesel generator AMF panel to LT panel should be given at downstream point of solar power feeding. While connecting feeder to industrial loads, utility loads with maximum kW/kVA and demand factor are considered on priority basis, for maximum utilisation of generated power. In the event of a reduction in power fed by OGRTS system to utility loads, power from the local grid is pumped to the system. During surplus power generation from plant in lean demand period, excess power is fed back to the local grid through Transformer primary. This philosophy was finalised and followed for reaping maximum benefit from OGRTS power plant.

6.4. Engineering Design aspects

6.4.1. Panel Layout designing of the system based on feasibility analysis

Array layout of a solar pant is the engineering drawing which indicates the positioning of the PV modules with respect to the available floor space area. This layout is prepared by taking beam positions of building as a reference, aiming to transfer the panel loading on the roof directly to the building columns. Module mounting structure for this plant is designed for 1 × 4, 2 × 4, 2 × 6, and 3 × 4 configurations having 2,4,6,6 numbers of legs and 4,8,12,12 numbers of PV modules respectively. This selection was done based on the available floor span and to minimise the self-shadow on the subsequent row mounting structures.

Similarly, String layout drawing indicates module interconnection cable, main string cable and loop string cable and its termination at the array junction box (AJB). DC output power from these junction boxes is fed to inverter input. Proper cable scheduling with corresponding cable tagging will ease the identification of faults during plant operation.

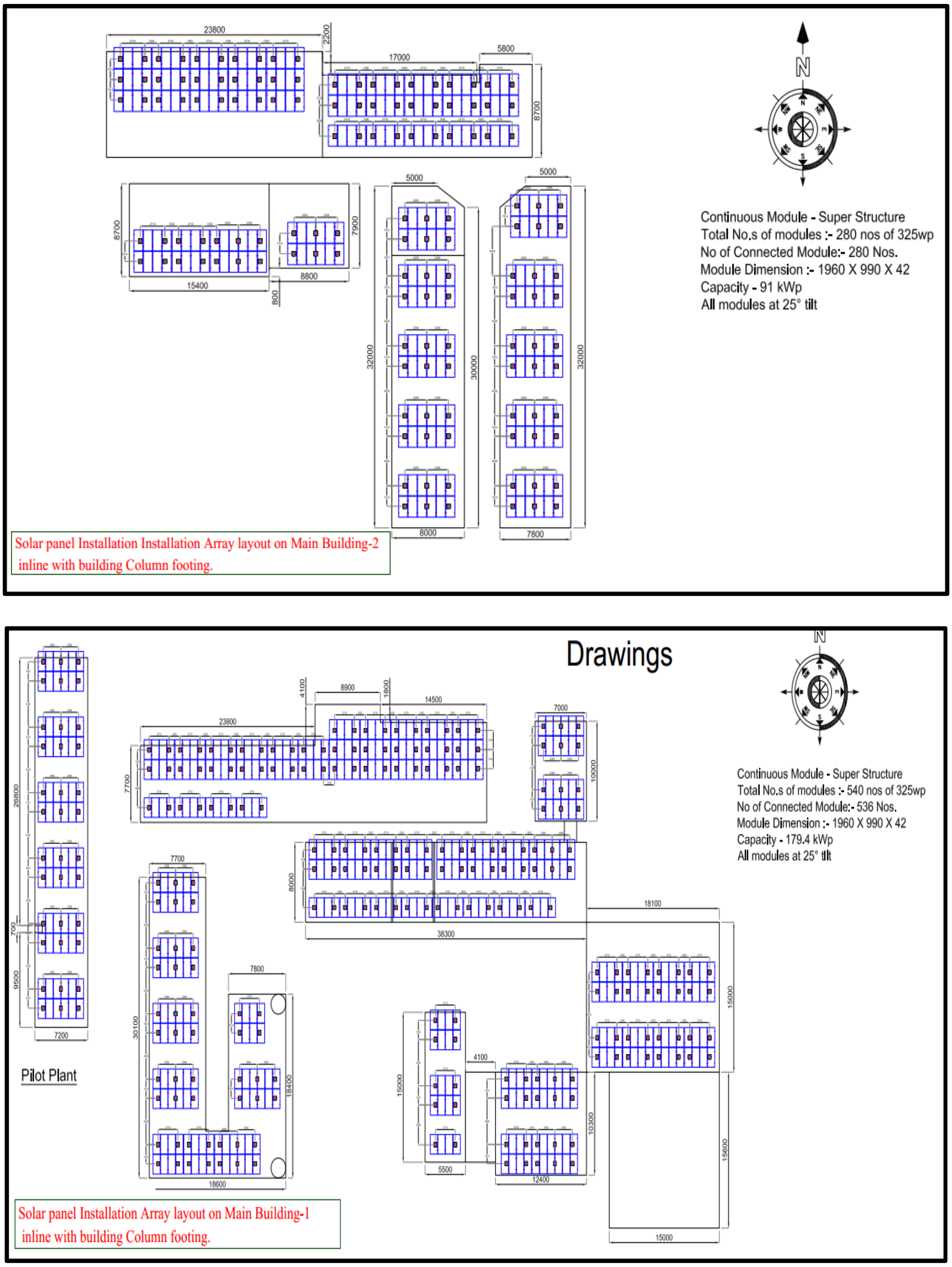


Figure 6.8- (a) and (b): Array layout drawing for Building 1 and 2

Array layout was prepared for the entire installation floor space and cross-checked with the beam alignment. **Figure 6.8a-b** indicates the typical PV array layout drawing for the portion of building-1 and 2. After identifying the beams of the building, module footing was adjusted in the periphery to beam and accordingly the spacing between array rows are positioned. PV module dimension is portrayed as 1960 × 990 × 42 mm and this array arrangement houses 540 numbers of PV modules each rated 325 W, installed at a tilt angle of 25^o amounting to 179.4 kWp as shown for building-1.

Similarly, for building-2, 280 numbers of PV modules are proposed summing to 91 kWp capacity. Such array layouts have been prepared for all proposed areas as per literature [123]. It is found that around 9 sq.m. roof area is required for each unit of kWp solar installation. For finalising the array arrangement drawing, inputs from feasibility analysis are considered.

Electrical string layout is shown in **Fig. S13 (a) and (b)** indicate the tentative electrical cable routing along with sizes. The positioning of array junction boxes with cable entry and exit routing is also shown. Legend in the drawing shows the description of cables along with the symbol. Different sizes of cables are used for main string, loop string cables and module interconnection. U-PVC (unplasticized polyvinyl chloride) conduit routing with AJBs are indicated for connection to upstream Inverter and further distribution. String layout and array layout are design engineering activities which are considered to be pre-installation requisites of OGRTS plant.

6.4.2. On-grid PV system designing and sizing

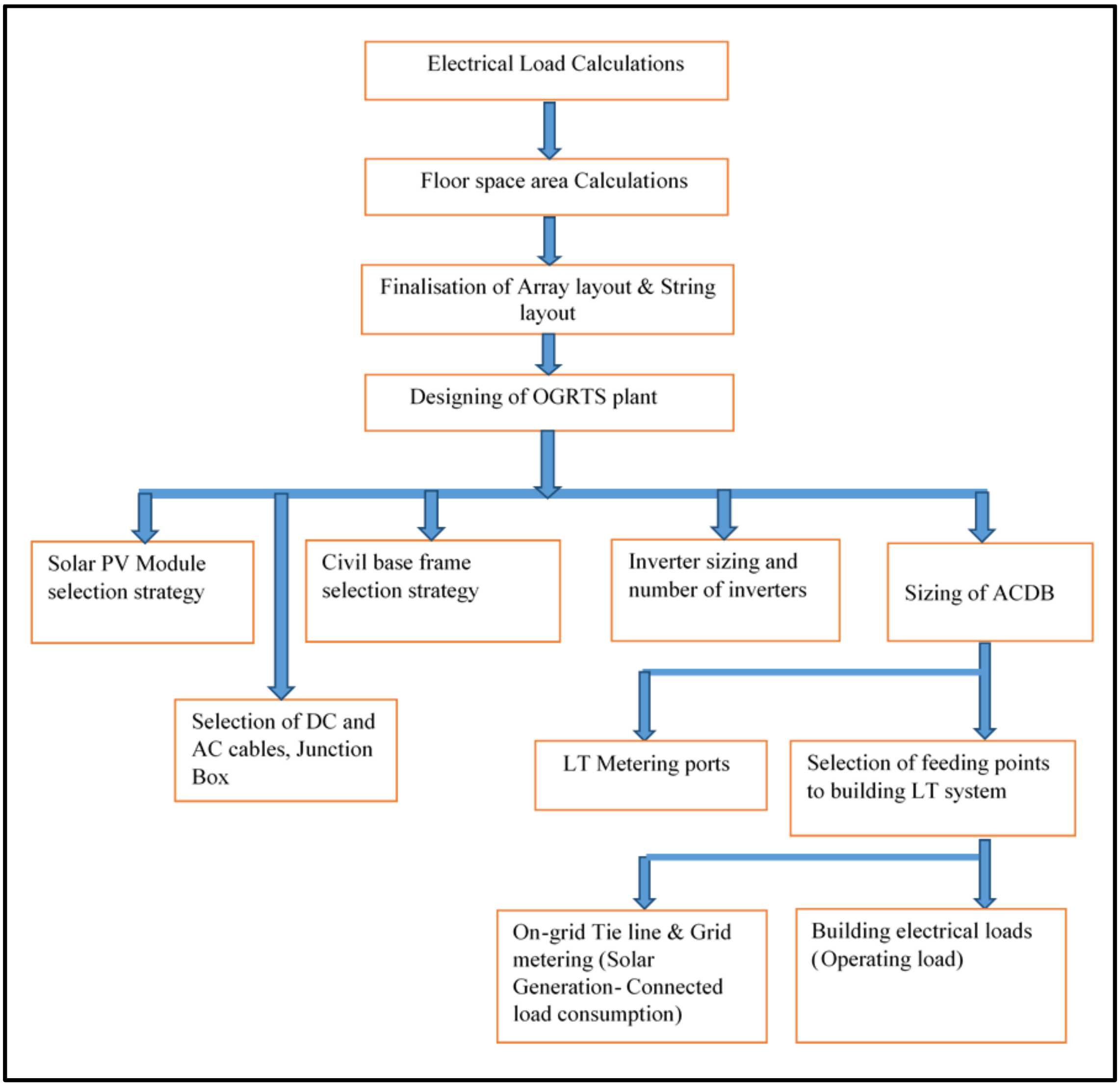


Figure 6.9- Flow chart for OGRTS power plant sizing and design

Detailed designing of the OGRTS system was done based on the feasibility analysis which is the vital aspect and authors have proposed the flowchart in **Figure 6.9** as a generic solution to maximise the energy generated within the fixed building periphery. This design is mainly based on Solar module selection, total number of modules to be used, Inverter sizing, number of inverters, selection of DC and AC cables, Junction boxes, civil base frame module selection and number of modules, sizing of ACDB and selection of feeding points to building LT system. Out of the above, the decision on technicalities of solar modules, inverters, cables, and ACDB is project-specific activity and the rest are site-specific activities. Proper designing and sizing tools should be used in designing the capacities of these components of the system. Tools in PVSYST© V6.63 software are used in this case for validating the design analysis of the OGRTS plant. An overview of each element is presented here.

6.4.3. Solar PV Module selection strategy

The Photo Voltaic (PV) modules are the heart of the plant which converts solar energy into electricity. PV panels are made up of PV cells, in which silicon is the most commonly used material. Silicon-based solar cells which are commonly in use show the efficiency in the range of 15-25%. Technological and manufacturing costs are high in the case of these high-efficiency materials. PV module has different characteristics in the lines of wattage per module, operating V-I characteristics, cell efficiency, performance in different radiation levels, rate of degradation, production and maintenance cost etc.

Selection of a specific PV module to a particular project is made based upon the design ratings which essentially includes plant capacity, space availability, maximum voltage and current requirement, inclination angle, module efficiency, V_{oc}- I_{sc} and weight. Selection of the PV module is purely a technical aspect related to project objective and is site-specific. The useful life for PV modules chosen in this plant is 25 years.

Table 6.3- Technical particulars of selected solar PV module

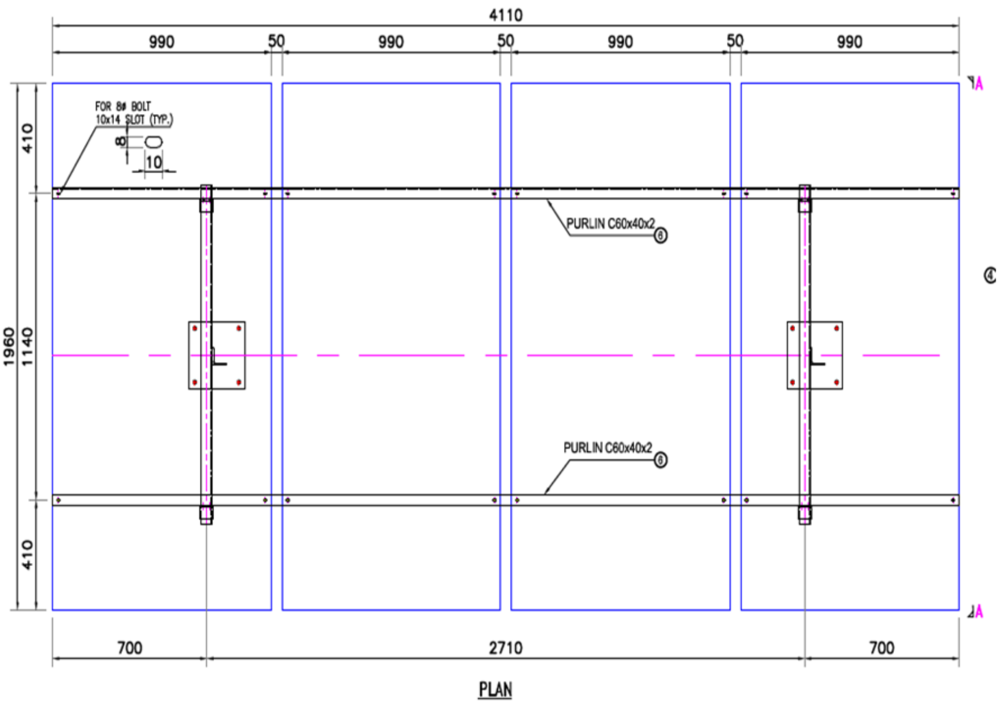
Electrical parameters of Solar PV module			Operating Conditions & Module characteristics	
(STC)		(NOTC)		
P_{max} (watt)	325	242	Maximum System voltage (IEC)	1000 V
V_{max}(V)	37.30	34.60	Series fuse rating Imax	20 A
I_{max}(A)	8.42	6.99	Limiting reverse current I_{Lmax}	20 A
V_{oc}(V)	46.00	42.70	Operating T ^{o}C	-40^{0} to 85^{0}
I_{sc}(A)	9.20	7.46	Static load	5400 Pa
Type	Polycrystalline PV		Dimensions mm	1960 × 990 × 42
Total cells	72		Weight of module Kg	23
Efficiency	16.75		Cable compatibility	MC4, 4 Sq.mm.
Configuration	12 × 6		Glass	3.5 mm
*Standard Test Conditions (STC) **Normal Operating Cell Temperature (NOTC)				

It can be inferred that power delivered by a solar cell is the product of current and voltage. Power curve can be obtained by tracing voltage generated from open circuit condition to short circuit condition for a specific insolation value. In open circuit condition, where the current is minimum and voltage generated across terminals is maximum, the corresponding voltage is called open-circuit voltage (V_{oc}). Similarly, during short circuit condition, the voltage generated across the cell is minimum and current flowing is maximum and this current flown is known as short circuit current (I_{sc}). At one particular point, for the product of current and voltage measured, power generated reaches its maximum value and is referred to as “Maximum point of power” (MPP). Thus, this MPP is the key point in designing and selecting a solar PV module and the OGRTS plant.

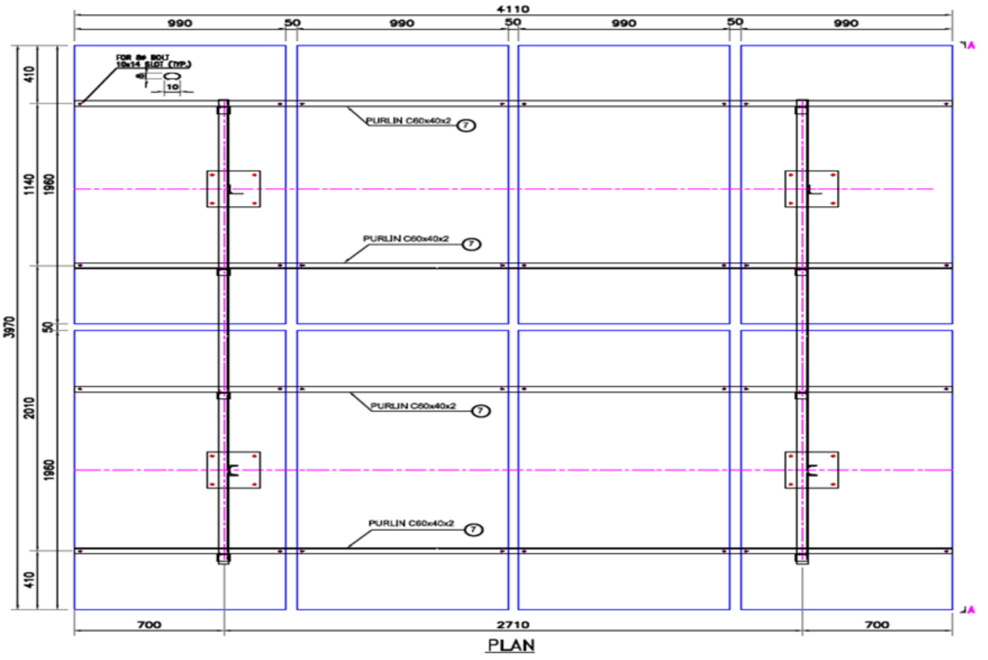
Table 6.3 shows the technical particulars of the selected PV module. V-I characteristics of the selected PV module is considered for finding maximum power output of 330 W, indicating maximum voltage at abscissa of 37.40 V and maximum current at ordinate 8.83 A.

6.4.4. Mounting structure (civil base frame) selection strategy

The mounting structure is the support structure used for resting the PV panels. Flat PV panel with 23 kg self-weight with 1960 × 990 × 42 mm dimensions is selected here. These panels are mounted to a fabricated channel which fixes onto a civil base frame. Fixed type mounting structure design is considered here due to its maintenance-free operation and cost-effectiveness, compared to tracking type mounting structures. Layout drawings for mounting structures are prepared for entire floor space by ascertaining the guidelines of operations and maintenance.



1×4 module structure



2×4 module structure

Figure 6.10- (a) and (b): Elevation view of 1×4 and 2×4 module mounting structure

Four types of module structures are used in this project out of which, elevation views for 1 × 4 and 2 × 4 types are shown in the **Figure 6.10a-b**. Different dimensions of structures can be selected as per selected PV module general arrangement drawing.

6.4.5. Inverter sizing and number of inverters

The PV modules' DC power is transformed into AC power by the inverter. Irrespective of plant size, inverters play a crucial role in the conversion of DC power generated by solar string. Typically for solar power projects, based on the application and feasibility of site, five categories of inverters are in generic use. For projects up to 1 MW, string inverters are used which are connected to DC power output from sub-strings. Central power electronic Inverters are capable of handling input more than 500 kW, used in greenfield solar installations greater than 1 MW capacity. Battery type inverters find application in off-grid systems. Micro inverters are generally used for the optimization of output from PV modules and hybrid inverters are for multi-mode type utilities.

The power produced at the output terminals of the PV module is in DC mode. In this plant, a total of 8 numbers of string inverters with different capacities are used. Selection of an inverter and technical detailing is also a vital factor in efficient utilization, conversion and transmission of power generated in the system [124]. After finalizing the string layout, inverter positioning is decided and accordingly design calculations are done to arrive at the technical requirements of the inverter. Inverter rating mainly based on the DC input operating voltage and maximum DC power [125,126]. **Table 6.4** shows the technical details of an inverter selected for our plant.

Determining the maximum and minimum PV module numbers to be connected in series in a single string will help in proper selection and designing of inverter capacity. With the wide varieties of inverters available, there lies a flexibility to calculate the number of PV modules to be connected in each string so as to match the maximum current rating of inverter. Based on feasibility analysis of space availability, all arrays/sub-arrays connected in the module can be finalized initially and then accordingly inverter sizing can also be done. While designing the system it is essential to maintain the Inverter Loading Ratio within prescribed limits[127].

During plant operation and commissioning trails, it was observed that in the event of UV (Under Voltage) from grid mains, inverter gets a temporary shutdown as a safety measure [128]. After grid power resumes, inverter will prompt for high open-circuit voltage. As a safety protocol to the inverter, voltage generated due to “switching on” the inverter module should be less than the maximum DC input voltage from the strings connected to the inverter, which may otherwise damage the inverter. This is one of the common observations in the OGRTS plant, found during commissioning trails.

Table 6.4- Technical details of grid tied solar inverter.

INPUT (DC)		OUTPUT (AC)	
Max. DC Power	37.5 kWp	Rated Output Power	30 kVA
Max. Input Voltage	1000 V	Maximum Output Power	33 kVA
DC Voltage Range	200 - 1000 V	Rated Output Current	45.5 A
Start-up Voltage	>250 V	Max. Output Current	50 A
Start-up Power	40W	Inrush Current	150 A / 100 μs
MPPT Voltage Range	200 - 1000 V	Nominal AC Voltage	3 Ph, 415 V
Nominal DC Voltage	600 V	AC Voltage Range	320-480 V
Total Input Current	60 A	Nominal Frequency	50 Hz

Maximum Short Circuit I	36 A	Frequency Range	45 Hz - 55 Hz
DC Disconnection Switch	Yes (Inbuilt)	PF at Rated Power	Unity
Unbalanced Input (%)	33 / 67	Harmonics	<3% at P rated
Maximum Efficiency	98.50%	DC Injection	<0.5% at I output
Euro Efficiency	98.20%		

6.4.6. Balance of System

Balance of system refers to all subsystems of plant starting from the selection of ACDB, cables, LT metering ports, array junction boxes, communication system, metering system with real-time interfacing used for plant data recording. Regulations pertaining to meter locations are followed as per stipulated norms. Chemical earthing pits and lightning arrestors are placed as per design calculations. Twenty numbers of chemical earthing pits with copper bonded rod of 3000 mm length, 17 mm diameter was installed with graphite based mineral compound. Four numbers of pole type lightning arresters are mounted by maintaining at least 1 met distance above PV modules.

6.5. Philosophy for the number of PV modules

The designer can calculate the minimum number of modules that needs to be connected in a series string by $V_{min} = (V_{mp} + ((T_{High} + T_{Rise} - T_{Stc}) \times (V_{mp}Coef \times V_{mp}/100)))$ [129]. Datasheet of PV module gives the above data and is shown in **Table 6.5**. In this case study, 8 numbers of inverters are used in the system. This calculation depends upon the specification of inverter module to which the strings are connected.

Table 6.5- PV module parameters and coefficients

V_{mp}	T_{High}	T_{Rise}	T_{Stc}	$V_{mp}\,Coef$	V_{oc}	T_{Low}	$V_{oc}\,Coef$
37.3	45	47	25	-0.41	46	-40	-0.3

Where, V_{min} = 27.05 V, deration factor is 12% or 0.88

V_{min} = 27.05*0.88 = 23.80 V

Maximum DC input voltage of Inverter = 1000 V

Start or strike voltage of the inverter = 250 V

V_{oc}, V_{mp} are open circuit, maximum power point voltages and $V_{mp}\,Coef$ and $V_{oc}\,Coef$ are temperature coefficients of module.

Minimum no. of modules in series= 250/23.80 = 10.5

Maximum Number of modules in series can calculated by formula $V_{max} = V_{oc} + ((T_{Low} - T_{Stc}) \times (V_{oc}Coef \times V_{oc}/100))$. Where, V_{max} = 54.97 V.

Maximum DC input voltage of Inverter = 1000 V

Maximum Number of modules in series = 1000/54.97 = 18.19

Number of modules should be less than 18 and more than 10. Hence 17 modules are selected in this specific string.

Table 6.6 indicates the input to PVSYST$^{©}$ V 6.63, wherein the number of PV panels in the series is selected as 17 and strings in parallel calculated as 8 numbers. The number of PV panels in series will decide the voltage rating input to inverter and the number of loop strings decide the current rating. Hence no of strings in a circuit is the ratio of maximum inverter current rating to the current rating of each string. Selected inverter rating can be cross-checked by $0.8 \times P_{pv} < P_{inv} < 1.2 \times P_{pv}$, where, P_{pv} is DC power generated by array. P_{inv} is the inverter rated power [130].

Table 6.6- Input loop for Subarray in PVSYST© V 6.63

Sub-array "Pilot Plant & MB1 A2				
Number of PV modules	In series	**17**	In parallel	**8 strings**
Total number of PV modules	Nb. modules	**136**	Unit Nom. Power	**325 Wp**
Array global power	Nominal (STC)	**44.2 kWp**	At operating cond.	**41.1 kWp (50°C)**
Array operating characteristics (50°C)	U_{mpp}	**601 V**	I_{mpp}	**68 A**

6.6. Engineering Installation aspects

6.6.1. Civil works for structure

For OGRTS system installation, civil base frame for module mounting as per layout drawings finalised in section 5.2.2 were grouted upon the building roof. In structures made prior to project execution, major drillings for anchoring or puncturing the rooftop is not allowed due to risk of water seepage/logging. In this case, implementation was carried out with four types of the mounting configurations viz. 1 × 4, 2 × 4, 2 x 6 and 3 × 4 base frame modules. The figure below shows the plan view for 1 × 4 and 2 × 4 module structure. Two-dimensional view of the rafter, leg along with inclination angle is shown in **Figure 6.11a-b**.

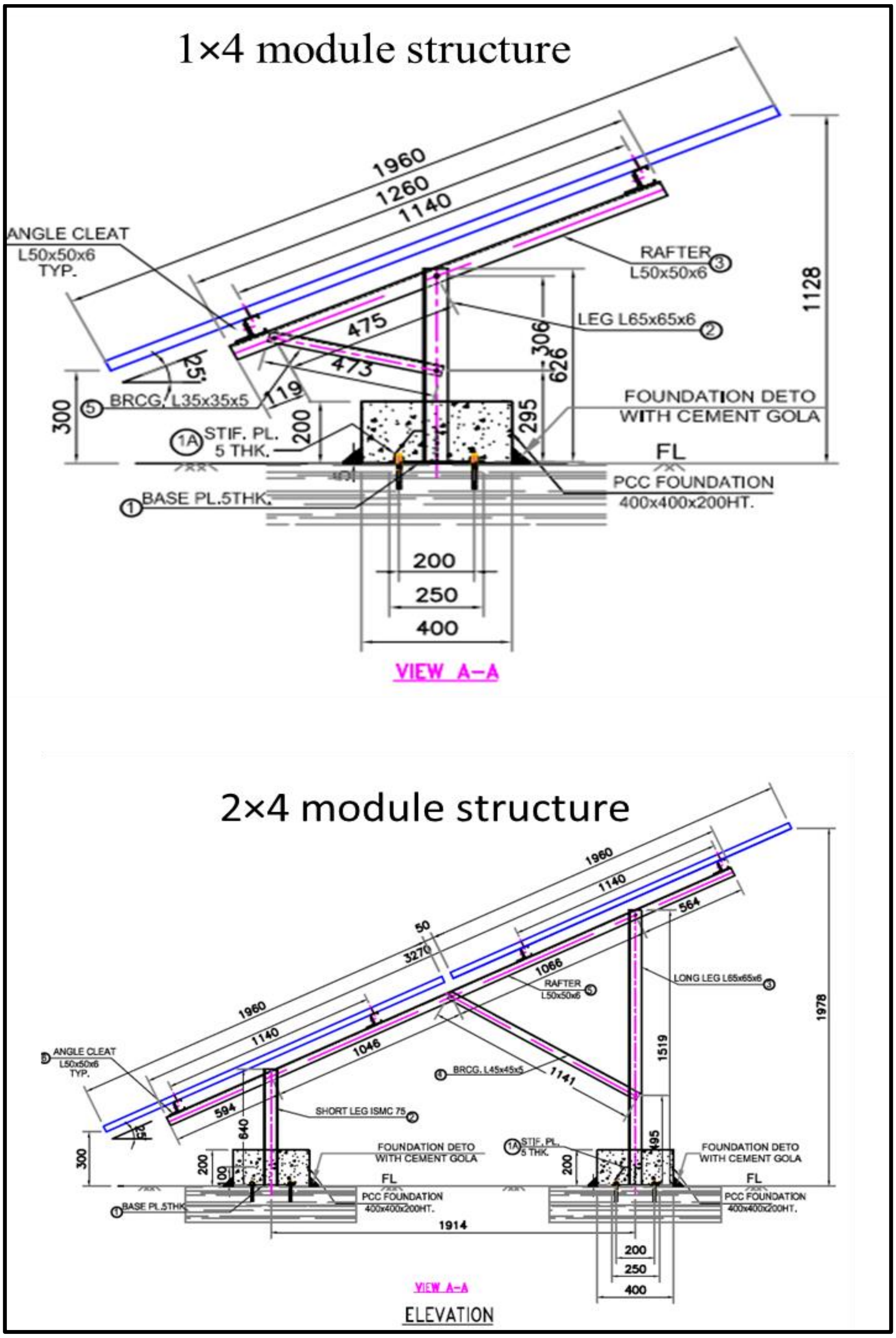


Figure 6.11- (a) and (b): Section drawing of module mounting structure

Foundation along with section details are designed and cross-checked with STAADM© software for structural safety, by taking dead load and wind loads at the site into consideration. Mounting on parapet walls is avoided in this case. Details of anchor fastener for a typical leg of mounting structure are shown in **Fig. S14**. M10 × 113 anchor bolts are selected for this purpose. 400 × 400 × 200 mm Plain cement concrete blocks are casted here for leg mounting.

6.6.2. Project planning activity chart

The work was carried out as per a pre-planned work schedule and the actual work schedule is shown in **Table 6.7**. **Figure 6.12** gives a diagrammatic representation indicating the contribution of different activities on the total project execution time.

Table 6.7- Work schedule chart for OGRTS plant

Work schedule	Sub Work	Time taken (weeks)
Site feasibility		2
Preliminary estimation		2
Basic Design & Engineering		4
Bill of quantity (BOQ) Preparation		2
Tender finalisation		7
Detail design and equipment selection		4
Detail BOQ preparation		2

Design and drawing approval		1
Supply Schedule to the site (as per finalised BOQ)	Module Mounting Structure	16
	PV Module	
	Cable & Electrical Accessories	
	Inverters	
	ACDBs	
	Civil items	
Plant Construction	Site preparation	16
	Civil works & fabrication	
	Vertical Post Installation	
	Racking Installation	
	Module Installation	
	Electrical Wiring	
	Inverter Installation	
	Feeding points with ACDBs	
	Installing Monitoring & Control System	
	Testing & Commissioning	

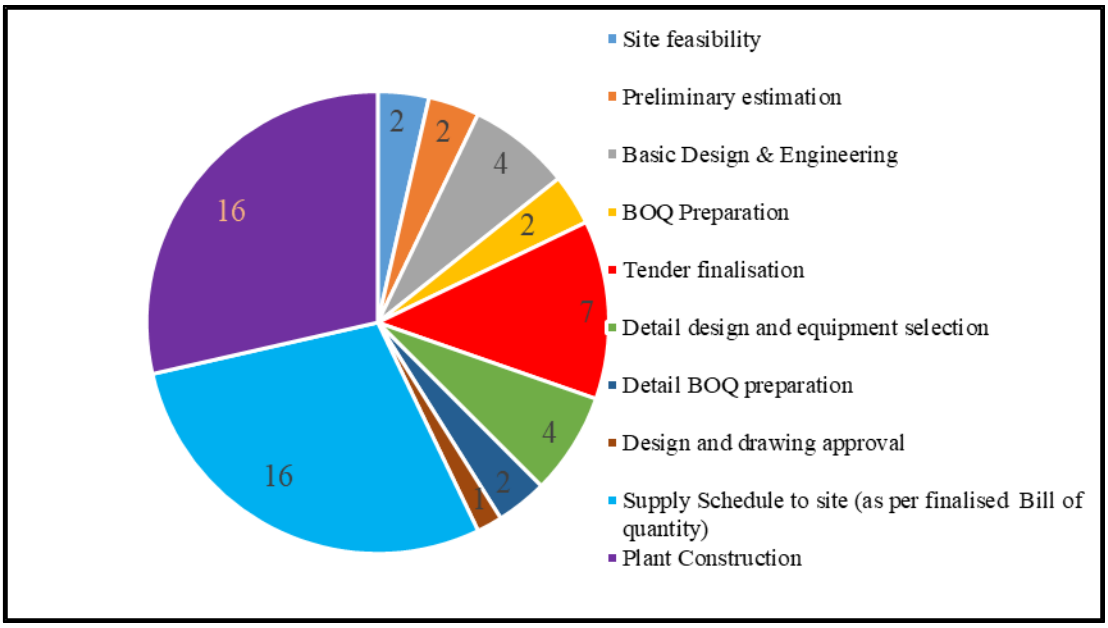


Figure 6.12- Pie chart of project work schedule

6.6.3. Electrical layout and OGRTS SLD

Designing electrical SLD gives an idea of power flow from PV module to end loads. A portion of Electrical SLD with three numbers of inverters is shown in **Fig. S15** for discussion, indicating all interconnection cables, ACDBs and PV modules. PV modules are connected in series with a designed number of parallel strings which are connected to nearby branch connector with 1R × 1C × 4 sq.mm DC cable.

DC cables of 1R × 1C × 6 sq.mm size, electrolytic multi stranded tinned copper flexible conductors as per IEC 60228 class 5 type are used for connecting branch connector to the array junction box. Surge protection device and fuse units installed in AJB for protection and these cables are terminated on the inverter input. Output terminals of inverter modules are connected to ACDB with 1R × 4C × 35 sq.mm AC cable and then through billing meter box, power is fed to solar feeding points in designated LT panels. DC cables are routed such that voltage drop in the loop should not exceed 2% [131].

6.7. Technical Analysis of the OGRTS system

Technical analysis of this OGRTS plant is carried out with PVSYST©V6.63 and the simulated data is compared with real time generation data. Design and engineering analysis was done in the simulation with the inputs of feasibility analysis, selection and operational philosophy obtained from previous sections to get precise simulation parameters.

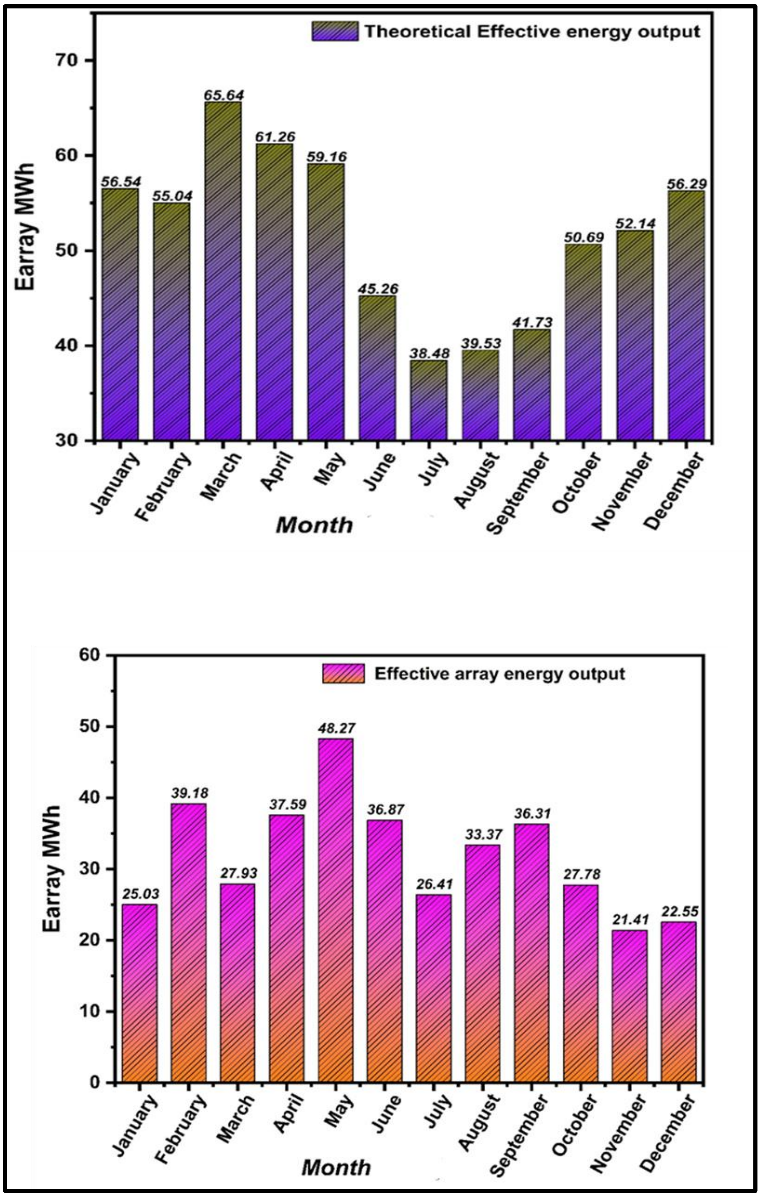


Figure 6.13- (a) and (b): Theoretical and actual energy output of PV plant

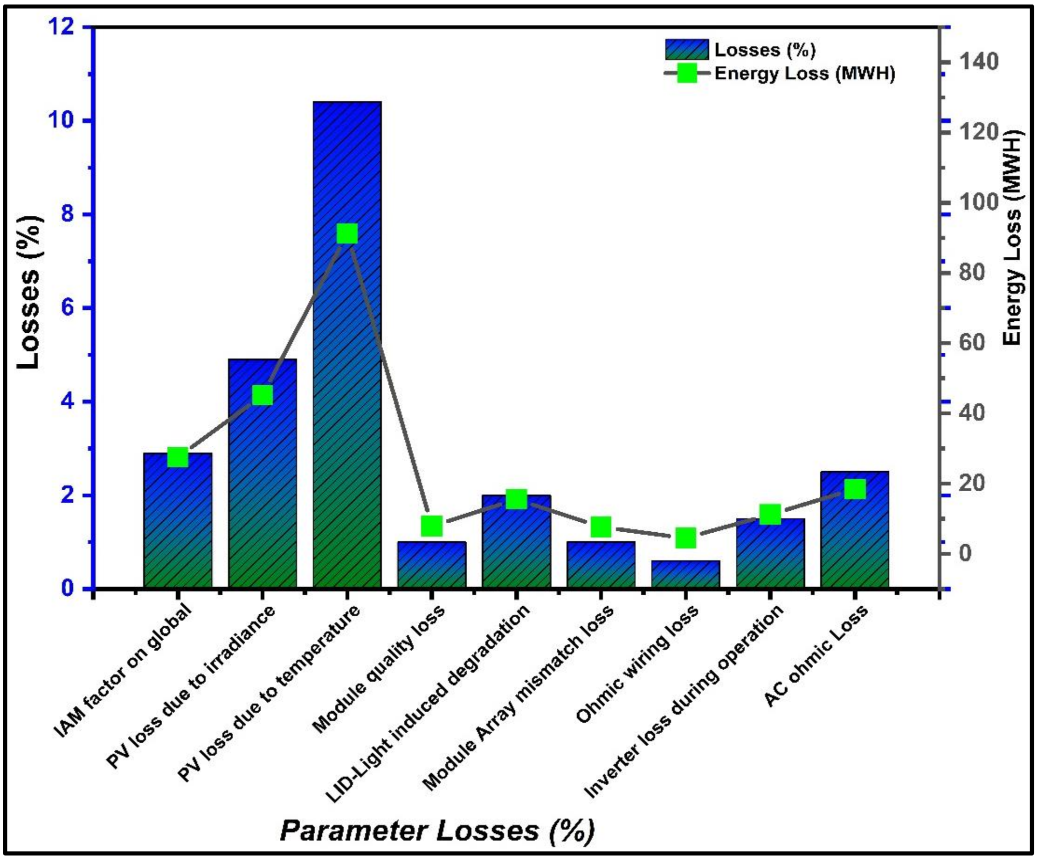


Figure 6.14- Parameter losses of PV plant

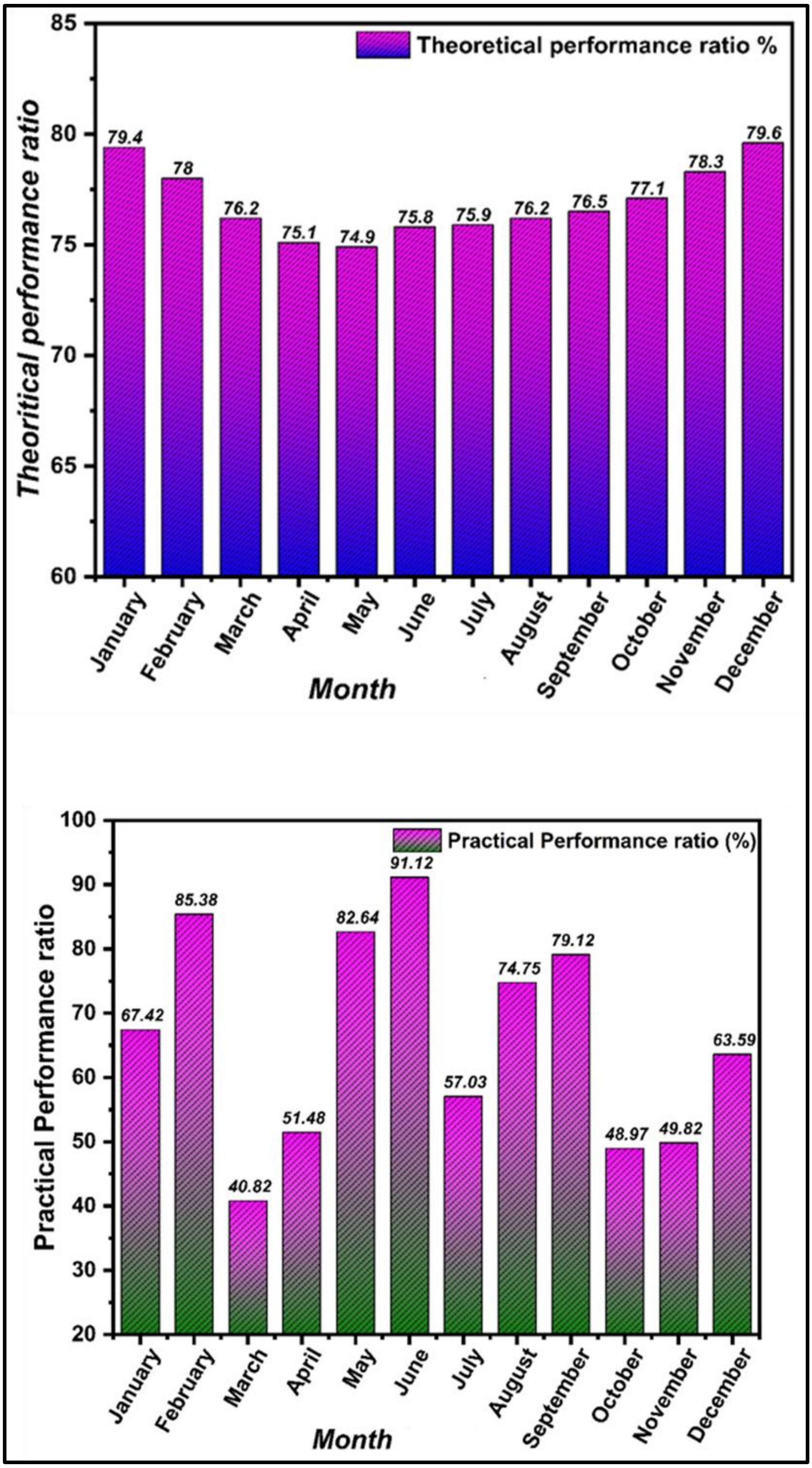


Figure 6.15- (a) and (b): Theoretical and actual performance ratio of PV plant

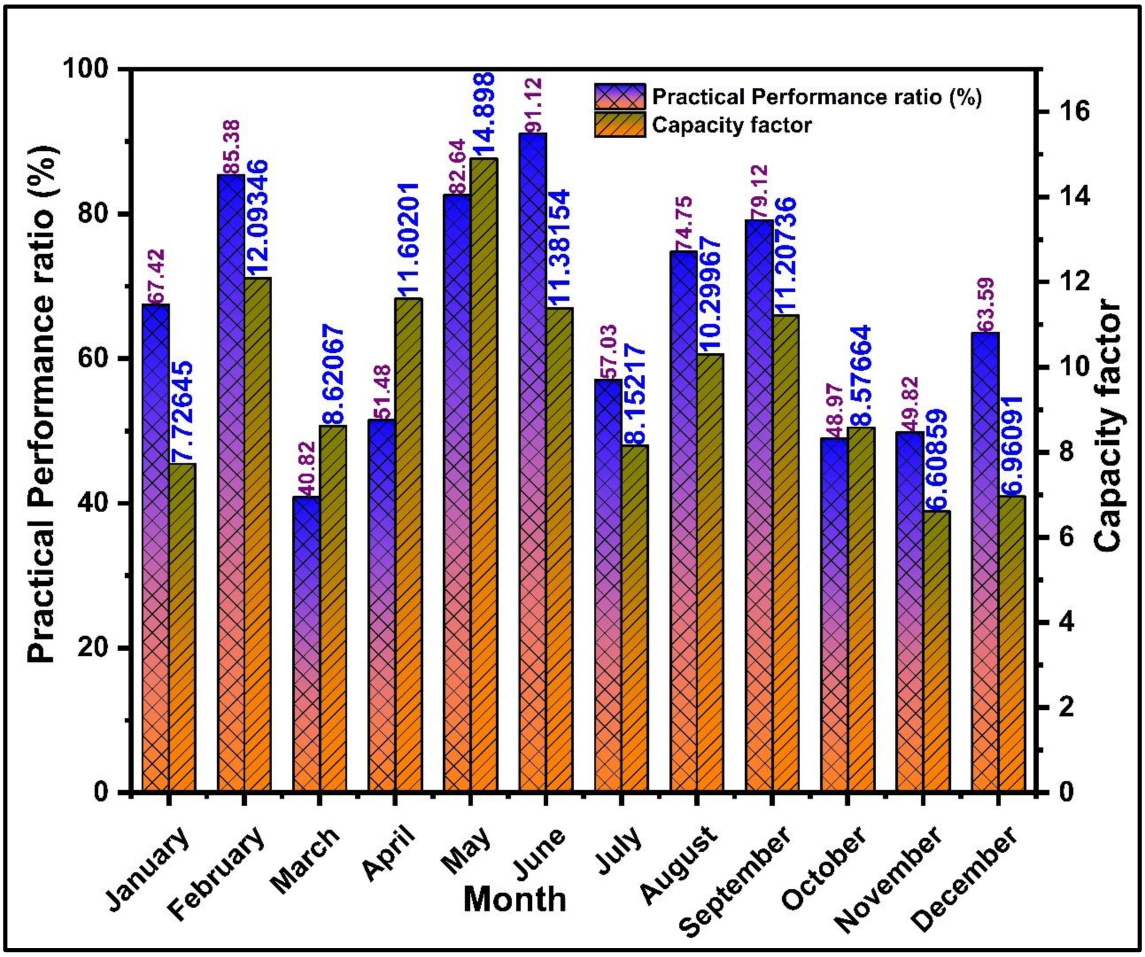


Figure 6.16- Practical performance ratio and Capacity factor of PV plant

Latitude and longitude (in degrees) 22.778°N, 86.204°E has to be fed as inputs for analysis with a tilt angle of 25^0. Details of each sub-array connected PV modules are entered in PVSYST©V6.63 by defining the number of PV modules connected in series and parallel strings. Quantity and sizing of inverters were carried out as per PV plant SLD. This analysis indicated the effective energy at the output of the array in MWh for all the months.

Figure 6.13a-b shows theoretical energy output from simulation to and actual energy output of PV plant, which gives insights into actual production values of the plant by taking parameter losses into consideration as shown in **Figure 6.14**. It was observed that the month of November perceived a lowest value 21.4 MWh of effective energy output and highest for the month of May with the value of 48.27 MWh.

The performance ratio is the measurement of the quality factor for a PV plant. The performance ratio is looked upon as a merit factor and figure of quality. It is a dimensionless quantity and denoted in percentage which establishes the relation among actual energy and theoretical energy output. **Figure 6.15a-b** shows theoretical and actual performance ratio of PV plant for this location. It is observed that theoretical performance ratio is varying from 0.75 to 0.8 whereas actual performance ratio is observed varying between 0.4 to 0.9 based on the actual solar insolation. **Figure 6.16** shows the comparison of performance ratio along with capacity factor of the plant, showing the capacity factor varying from 6 to 14.

$$\text{Performance ratio} = \frac{Actual\ energy\ reading\ of\ plant\ out\ put\ in\ \text{kWh}}{Calculated\ \text{nominal plant output in kWh}}$$

Performance ratio is a figure of merit showing the proportion of the energy available for utility loads after eliminating energy losses (conduction losses, thermal losses etc.). The ideal value of PR is 100% and is not reachable at a predefined efficiency of a PV module because of inherent operational losses (like thermal losses).

Literature shows Solar PV plants are operating with a performance ratio of 0.75-0.8 [132,133]. PVSYST$^{©}$V6.63 simulation resulted annual Effective energy output is calculated to be 652.79 MWh at array terminal and apparent annual energy available to the grid is 621.76 MWh with a performance ratio of 0.77. For the life span of 25 active years, 13212 t of CO_2 can be reduced in totality. Capital cost for the project based on detailed design estimates to be ₹ 2.48 crores which includes operations and maintenance costs for 10 years. Specific energy cost is calculated as ₹ 49.81 of Wp power generated.

With the annuity interest rate 8% per annum for 10 years along with 3% inflation rate, the total project is costing to ₹ 3.7 crores. Energy cost for one unit of power consumption (1 kWh) is calculated to ₹ 4.44, which is financially viable solution compared to the current tariff of ₹ 12.50 from the grid. Results obtained from this study can be used as reference values for the state of Jharkhand, India.

6.8. Summary

Solar energy power plants are increasingly emerging for catering peak loads of industrial as well as commercial infrastructure sectors across the world. With the advantage of its geographical location, India is ideally situated to get continuous sun irradiance all year long. For the location of Jamshedpur (Latitude and longitude in degree) 22.778°N, 86.204°E, Jharkhand state in India, all design aspects are enumerated for 500 kWp OGRTS plant. PVSYST©V6.63 simulation revealed that annual effective energy output to be 652.79 MWh at array terminal and apparent annual energy available to the grid is 621.76 MWh.

With a performance ratio of 0.77, designed PV plant is capable of generating at a monthly average capacity of 51.82 MWh. Based on actual generation scenario, effective energy output is found to be maximum in the month of May (48.27 MWh) and minimum in the month of November (21.4 MWh), with actual performance and capacity ratios calculated varying between 0.4 - 0.9 and 6-14 observed in various months of the calendar year. For the life span of 25 active years, 13212 t of CO_2 can be reduced due to this PV plant.

Hence, OGRTS plants are very well suitable for meeting peak loads of a wide range of industries present in steel city of Jamshedpur. Besides, the cost of one-unit solar power (1 kWh) arrives to be at ₹ 4.44 from this plant, as compared with the tariff of ₹ 12.50 supplied by the grid from power distribution companies. It is also found that proper engineering and designing will improve plant efficiency and brings down the installation area requirement of 9 sq.m per 1 kWp. Accurate feasibility analysis and following project management methodology will reduce the associated costs of the project. Hence such OGRTS plants prove to be a financially feasible option for the industrial city to encourage industrialisation.