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Structuring, Costing and Maintaining a Solar PV System

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ABSTRACT

This paper is the study on setting up a solar PV system plant and rooftop system in the northern hemisphere of India. It includes brief explanation on structure, calculations based on the approximated data collected from the 5MW plant and maintenance required to get the maximum efficiency of the plant. However many locations around the world have years of weather records that will provide average data which is sufficient for designing a PV systems and if no long term data exists for the chosen site, in that case the availability of sun light and the amount of sunshine can also be estimated with the help of available equipments.

Introduction

Solar energy on the earth in direct or indirect form is the source of nearly all other energies i.e. Wind energy which uses air that is created by sunrays heating the surface of earth and the rotation of the earth, Hydropower depends on the evaporation of water by the sun, and its coming back to the Earth as rain to provide water in dams. Photovoltaic devices (solar cells) directly convert the incident solar radiation into electricity, which are noise free because of no moving parts, pollution free that makes them vigorous, reliable and long lasting. As per the study conducted by Einstein and Plank, light may be viewed as consisting of "packets" or particles of energy, called photons which can be used to produce electricity, the phenomenon is called Photoelectric effect [1]. The key characteristics such as the spectral content of the incident light, the angle at which the incident solar radiation strikes a photovoltaic module, the radiant energy and power density from the sun. This paper is divided into sections explaining study and approximate calculations for setting up a PV system.

The solar irradiance at the earth's surface depends on the parameters like atmospheric effects including absorption and scattering, the variations in the atmosphere such as water vapor, clouds, and pollution, latitude of the location that means the season of the year and the time of day. Atmospheric effects have several impacts on the solar radiation at the earth's surface. The important effects for photovoltaic applications are: reduction in the power due to absorption, scattering and reflection. Due to greater absorption or scattering of some wavelengths there can be change in the spectral contents of visible sunlight. Whereas the diffused/indirect components in the solar radiation are due to local variations in the atmosphere (such as water vapors, clouds and pollution) produces reflection [1-3].

The light that we see every day is only a fraction of the total energy emitted by the sun incident on the earth. The sunlight is a form of electromagnetic radiations and the visible light that we see is a small subset of the electromagnetic spectrum. The PV modules need photons of visible light in direct or indirect to convert it into electrical power.

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Properties of Light and PV cells

Solar radiation can be useful either through solar photovoltaic route or solar thermal route. Solar radiations strike earth's surface at a particular time and place called Insolation. The total insolation striking the earth on a clear day is about 1000W/m^2. However many other factors determine how much sunlight will be available at a given site.[2]

In PV system design it is essential to know the amount of sunlight available at a particular location at a particular time. The two common methods which characterize solar radiations are Solar Radiance (or radiation) and Solar Insolation. The solar radiance is an instantaneous power density in units of kW/m^2 whereas the solar insolation is total amount of solar energy received at a particular location during a specified time period unit kWh / (m^2 day). Whereas the solar radiations power incident on a PV module depends on the power contained in the sunlight and the angle between the module and the sun [3]. Normally optimum tilt angle is the latitude of the location, so in order the sun rays fall perpendicular to the module surface.

Properties of Light

Some important terms which we use working on the properties of light/ solar radiations on solar modules.

Air Mass

It is the path length which light takes through the atmosphere normalized to the shortest possible path length (that is, when the sun is directly overhead). The Air Mass is = 1/ Cos θ where θ is the angle from the vertical (zenith angle)). The standard spectrum outside the earth's atmosphere is called AM 0, because at no stage does the light pass through the atmosphere. Whereas when the sun is directly overhead, the Air Mass is 1 and at the angle θ = 48.2 degree, the Air Mass is 1.5. For standard test conditions of Cells and Modules, the AM is considered 1.5.

Local Solar Time (LST)

It is defined as when the sun is highest in the sky i.e. twelve noon is called local solar time (LST). Local time (LT) usually varies from LST because of human adjustments such as time zones and daylight saving while we always consider local solar time for all the calculations related to modules [4],[5].

Solar Declination

Despite the fact that the Earth revolves around the sun, it is simpler to think of the sun revolving around a stationary Earth.

Peak Sun Hour:

Peak Sun hour is an equivalent measure of total solar irradiation in a day given in 1 KWhr / m^2.

Elevation Angle

The elevation angle / altitude angle is the angular height of the sun in the sky measured from the horizontal. It varies throughout the day.

Azimuth Angle

The azimuth angle is the compass direction from which the sunlight is coming. At solar noon, the sun is always directly south in the northern hemisphere and directly north in the southern hemisphere.

Properties of PV Cells

Absorption coefficient

The absorption coefficient determines how far into a material, light of a particular wavelength can penetrate before it is absorbed.

Module circuit Design

The voltage of a PV module is usually chosen to be compatible with a 12V battery. An individual silicon solar cell has approximate voltage of 0.6V under 25 °C and AM1.5 conditions. This gives an open-circuit voltage of about 21V under standard test conditions (STC), and an operating voltage at maximum power and operating temperature of about 17 or 18V. A typical module has 36 cells connected in series mostly.

Mismatch Effect

Mismatch losses are caused by the interconnection of solar cells or modules which do not have identical properties. When one solar cell is shaded while the remainder in the module are not, the power being generated by the "good" solar cells can be dissipated by the lower performance cell rather than powering the load. This in turn can lead to highly localized power dissipation and the resultant local heating may cause irreversible damage to the module.[6] Thus the output of the entire PV module under worst case conditions is determined by the solar cell with the lowest output. Large mismatches are most commonly caused by differences in either the short-circuit current or open-circuit voltage. With short-circuit current mismatch, severe power reduction can take place, if the poor cell produces less current than the maximum power current of the cells in good condition, the high power dissipation in the poor cell can cause irreparable damage to the module [7]. Whereas with open-circuit voltage mismatch the overall current from the PV module is unaffected. At the maximum power point temperature, the overall power is reduced because the poor cell is generating less power.

Hot Spot heating

If one shaded cell in a string reduces the current through the good cells, causing the good cells to produce higher voltages that can often reverse bias the bad cell. Bye pass diodes are used to reduce this effect.

Structure and operation of PV cell

Structure of PV Cell modules

Silicon PV modules consist of a transparent top surface, an encapsulant, a rear layer and a frame around the outer edge as shown in the figure:1[4][9] .In most modules, the top surface is glass, the encapsulant is EVA (ethyl vinyl acetate) and the rear layer is known as Tedlar, which provides durability to PV modules.

The top surface have high transmission of light in the wavelength range of 350x10^{-9} m to 1200 x10^{-9}m. The reflection from the front surface must be low. An encapsulant is used to provide union between the solar cells. Followings are the characteristics of the rear surface of the PV module, that it should have low thermal resistance and that it must prevent the ingress of water or water vapors. A final structural component of the module is the edging or framing of the module.

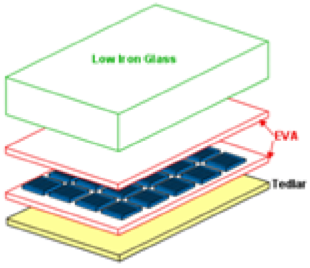

Figure 1

The operation of a solar cell is based on the generation of light-generated carriers that implies generation of current, large voltage across the solar cell and dissipation of power in the load. Efficiency of a Solar Cell plays a very important role in the operation of PV cell, which is defined as the ratio of energy output from the solar cell to input energy from the sun determined as the fraction of incident power which is converted to electricity [8]. This is the commonly used parameter to compare the performance of one solar cell to another where terrestrial solar cells are measured under AM1.5 conditions at a cell temperature of 25°C and Irradiance 1000 Watt /Sq mt. For example if a one Sq. mt. cell produces 150 Watt peak at STC condition then the efficiency of the cell is 15%. One method to increase the efficiency of a solar cell is to split the spectrum and use a solar cell that is optimized to each section of the spectrum known as tandem cells. For the solar collectors or cells which are flat, global horizontal irradiance (GHI) is important. For solar collectors or cells which are concentrating, direct normal irradiance (DNI) is important. The module data which is provided on the back side of each module is shown below at Standard Test Condition (STC) and at Nominal Operating Cell Temperature (NOCT)

Module Data

Electrical Data @ STC	**REC 240PE**
Nominal Power - Pmpp (Wp)	240
Watt Class sorting (watt)	0/+5
Nominal Power Voltage- Vmpp (V)	29.9
Nominal Power Current- Impp (A)	8.04
Open Circuit Voltage- Voc (V)	37
Short Circuit Current- Isc (A)	8.60
Module Efficiency (%)	14.50
Electrical Data @ NOCT	**REC 240PE**
Nominal Power - Pmpp (Wp)	176
Nominal Power Voltage- Vmpp (V)	27.30
Nominal Power Current- Impp (A)	6.45
Open Circuit Voltage- Voc (V)	34.10
Short Circuit Current- Isc (A)	6.96
Normally operating Cell Temp (deg C)	47.9
Temperature related Data	**REC 240PE**
Temp Coefficient of Pmpp	-0.43 % / deg C
Temp Coefficient of Voc	-0.33 % / deg C
Temp Coefficient of Isc	0.074 % / deg C
Operating Temp range	-40 to + 80 Deg C
Warranty	10 yr product warranty
Performance Warranty	25 yr linear warranty

Selection of Components for Solar PV System

Following are the basic key components with their parameters required to setup a PV system [2],[3]

1. Land & Infrastructure	**2. Silicon Solar Modules**
•Location and Availability of land. •Land topology. •Distance from Substation. •Resistivity of land. •Availability of portable water. •Hardness of the soil. •Shading. •Flora & fauna. •Assessment of radiation at the location.	•Crystalline PV Modules. Mono Crystalline Silicon Modules. Poly Crystalline Silicon Modules. •Thin Film PV Modules. Amorphous Silicon Modules. Tandem Junction Modules.
3. Solar Module Parameters	**4. Mounting Structure**
•Cost. •Efficiency. •Availability. •Product Warranty. •Power output Warranty. •System Voltage. •Open Circuit Voltage. •Max Power point Voltage. •Max Power point Current. •Weight. •Performance Ratio.	**Fixed Tilt** •Single Axis Tracking. •Dual Axis Tracking. •Tracking technology. •Distance between the rows. •Design strength. •Power required for tracking operation. •Additional gain due to tracker. •Warranty on Structures. •Guarantee against additional gain.
5. DC Cabling and Connectors	**6.String Combiner Boxes**
•Size of cable (4 mm & 6 mm). •Specification of Cables, viz. FRLS, UV resistant etc. •Wiring of DC cables. •Avoid looping. •Parallel and Series connections. •Lying of DC cables. •Different types of Connectors. •DC Loss Calculation.	•Various Components of a SCB. •Terminal Blocks / Connectors. • Surge Protection Devices (SPD). •Fuse Blocks. •Current sensors. (Hall effect sensor / Resistive Sensor). •DC Switch / Circuit breaker. •DC Copper Cable.
7.Inverters*	**8.Batteries**
The other parameters related to inverters are: Suitability of Rated AC power. •Max DC voltage. •Range of Max. Power point Temperature • Higher output AC voltage. •Infield starting power requirement •Power Consumption in ideal state at night. •Power consumption during operation.	The parameters of concern regarding the batteries are as follows: •Depth of discharge (DOD) of battery •Voltage and the ampere-hour (Ah) capacity of battery. •Number of days of autonomy.**
9.HVAC cabling and Control Panels	**10.Transformers**
•Different type of conductors. •Size of the cable and cable loss. •Requirement of SCADA control panels. •Battery pack/ Battery charger. •Accuracy class of CT/PT. •Cable route marking. •Cable sleeve fixing.	The parameters for the Three winding transformers are as follows: •Max Efficiency at low loads. •Usage of good quality cores. •Low operation losses. •Low no load loss: •% age load at max efficiency. •Cable Connectivity. •Evacuation Transformer. •Cost per MW..
11.Monitoring System	**12.Weather Station**
Different type of Interfacing. •Data transfer through vendor site. •Data acquisition and transfer through own network. •Monitoring parameters. •String monitoring. •Alarms and Costing •Control through PLC(Programmable logic controllers).	•Pyranometer or Pyrheliometer. • Type of Thermopile. • Type of Cell. •Temperature sensors. •Wind vanes. •Humidity Sensors

* Two types of inverters are generally used named as String Inverters and Central Inverters are used depending upon the scale of the plant. For MW plant the string and central inverters both are used while for small scale plants central inverters are more efficient.

* *The battery capacity for a given load can be determined as Watt Hr Storage= (Daily watt hr consumption X Days of Autonomy)/ (Inverter Efficiency* Depth of discharge) Battery Capacity (in Ah) = Watt Hr Storage / Battery voltage/ Battery efficiency No of Batteries= Total Amp hr / Amp hr per battery.

Cost Of Solar Pv Project Without Land Cost					
Sr. No	**Particulars**	**Nos**	**per unit cost**	**Cost per MW (Rs in lakhs)**	**Total cost (Rs in lakhs)**
Cost of land & boundary wall etc					
1	Cost of land (in Acres)	4	0	0	
2	Conveyancing charges	15%		0	
3	Boundary wall (mt)	600	0	0	
4	Site development	1	0	0	
	Sub Total			0	0
Plant & Machinery					
5	Modules	1000	45	45000	45000
6	Inverters	1	9000	9000	9000
7	Module mounting structures	0.3	80000	24000	24000
8	Cables & connectors	1	8000	8000	8000
9	SJB	12	0	0	0
10	Lightning arresters	1	4000	4000	4000
11	Transformer & HT panels	1	0	0	0
12	Evacuation line	5	0	0	0
	Civil Construction				
13	Inverter & control Room (Sqft)	1750	0	0	
14	Trenches	1	0	0	
15	Internal roads	1	0	0	
	Sub Total			0	0
16	SCADA	1	0	0	0
17	Metering panels	1	0	0	0
18	Misc approvals etc	1	0	0	0
				0	90000
	Cost of Project without land cost				90000

Cost Of Solar Pv Project With Land Cost					
Sr. No	**Particulars**	**Nos**	**per unit cost**	**Cost per MW (Rs in lakhs)**	**Total cost (Rs in lakhs)**
Cost of land & boundary wall etc					
1	Cost of land (in Acres)	4	400000	1600000	
2	Conveyancing charges	15%		240000	
3	Boundary wall (mt)	600	2000	1200000	
4	Site development	1	500000	500000	
	Sub Total			3540000	3540000
Plant & Machinery					
5	Modules	10,000,00	38	38000000	38000000
6	Inverters	2	2500000	5000000	5000000
7	Module mounting structures	55	80000	4400000	4400000
8	Cables & connectors	1	2800000	2800000	2800000
9	SJB	12	80000	960000	960000
10	Lightning arresters	10	50000	500000	500000
11	Transformer & HT panels	1	6000000	6000000	6000000
12	Evacuation line	5	1200000	6000000	6000000
	Civil Construction			63660000	
13	Inverter & control Room (Sqft)	1750	1600	2800000	
14	Trenches	1	300000	300000	
15	Internal roads	1	500000	500000	
	Sub Total			3600000	3600000
16	SCADA	1	2000000	2000000	2000000
17	Metering panels	1	200000	200000	200000
18	Misc approvals etc	1	2000000	2000000	2000000
				4200000	
				75000000	75000000
	Cost of Project without land cost				71460000

Basic Calculations Based On Approximated Data

For the calculation of azimuth angle and elevation angle of solar modules following calculations are required [9].

Calculating Azimuth Angle for solar modules

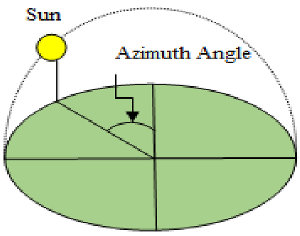

Figure 2

$$\cos\phi_s = \frac{\sin\delta - \sin\alpha_s \sin\varphi}{\cos\alpha_s \cos\varphi}$$

Where

ϕ_s is the solar azimuth angle

α_s is the solar elevation angle, $\sigma_s = 90° - \theta_s$.

h is the hour angle, in the local solar time.

δ is the current declination of the sun.

φ is the local latitude.

Calculating Angle of Elevation for solar modules

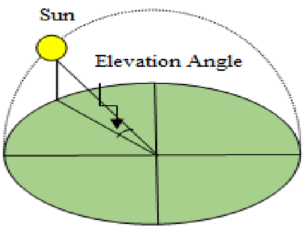

Figure 3

$$\sin\alpha_s = \cos h \cos\delta \cos\varphi + \sin\delta \sin\varphi$$

Where

α_s is the solar elevation angle, $\sigma_s = 90° - \theta_s$.

h is the hour angle, in the local solar time.

δ is the current declination of the sun.

φ is the local latitude.

Declination Angle

$$\delta = -23.44° * \cos\left[\frac{360°}{365}(N + 10)\right]$$

Calculating Inter Row spacing distance

$$D' = \frac{h}{\tan\alpha}$$

$$D = D' * \cos(180 - \emptyset)$$

$$\sin\alpha_s = \cos h \cos\delta \cos\varphi + \sin\delta \sin\varphi$$

Where

α_s is the solar elevation angle, $\sigma_s = 90° - \theta_s$.

h is the hour angle, in the local solar time.

δ is the current declination of the sun.

φ is the local latitude.

Thus the solar modules are installed in rows which causes shadow falling on the modules installed behind. We cannot have shadow free module spacing throughout the period of sun shine. Decide on solar window, which is the time during which you do not want any shadow on the modules caused due to modules installed on the front side.

The "backtracking" feature in a tracking system is to avoid morning and afternoon shading of PV modules by neighbouring tracker rows when several trackers are installed side-by-side. Shading losses are more that the loss due to different angle of incidence of solar rays on the module [9]. Thus the required angle for the tracker is reduced to avoid, any shadow on the module.

Solar window is decided, based on the space available for installation of solar panels.

Normally for solar window ,the period during 8am to 4 pm is considered in locations near to equator and the period during 9am to 3pm is considered in locations away from equator on the day of 21st December of the year, if the location is in northern hemisphere. This date is chosen, since on this day, the sun is in the southern hemisphere and is far away from the location in the northern hemisphere. This day will cause longest shadow of any object situated in the northern hemisphere.[10]

Calculation of inter row spacing of different solar windows shown at latitude: 41.21 deg

Solar Window	7AM to 5PM	8AM to 4PM	9AM to 3PM
Length of the Module (mts.)	1.66	1.66	1.66
Tilt (angle in degree)	41	41	41
Tilt angle in Radian Height (h)	0.72	0.72	0.72
Longest shadow assessment			
Solar Inclination(α)	0.7	5	13.8
Solar Azimuth(ϕ_s)	57.8	52.7	41.7
Distance(D)	89.13	12.45	4.43
Distance between array (D)	47.47	7.54	3.31
Ratio of distance to height	43.57	6.92	3.04

Comparison of angles from solar path diagram and formula

Solar Window	7AM to 5PM	8AM to 4PM	9AM to 5PM
Declination Angle	-23.44		
Hour Angle	45	60	75
Sine of angle of elevation	0.3974	0.228	0.0309
Angle of elevation	23.416	13.176	1.775
Cosine of Azimuth angle	- 0.70717	-0.5778	-0.4625
Azimuth angle	135	125.3	117.54
Height of module	0.75	0.75	0.75
Length of long shadow	1.73	3.2	24.2
Distance between rows	1.22	1.85	11.18
Elevation based on sun path chart	23.6	13.4	1.9
Azimuth based on sun path chart	134.8	125.6	117.5

In case of modules being installed in the southern hemisphere, 21nd June is normally taken, since the longest shadow will be caused on this day.

Once the solar window is decided, one can find out the azimuth angle as well as elevation of sun on that day and time. All the calculations presented above, assumes that the site is located in the northern hemisphere. The same calculations can be done for locations in southern hemisphere, by taking the same data for 21st June.

Degradation of Solar Cells

Light Induced Degradation

C-Si solar cells fabricated on Czochralski (CZ) wafers exhibit light-induced degradation (LID) of the cell performance. This effect is generally ascribed to boron-oxygen (B-O) defects in the wafer and is accompanied by a reduction in the minority-carrier lifetime in the bulk of the wafer [11]. There is an initial rapid decay of all cell parameters (within a few minutes), followed by a slower degradation. In general, all cell parameters experience a reduction. Under 1-sun at 25°C, it takes about 72 hours for complete light-induced degradation.

Potentially Induced Degradation

The cause of PID is mainly due to high voltage stress, high humidity as well as high temperature. The degradation depends on the polarity and the extent of potential between cell and ground which is determined by the actual configuration of the PV system. Lower quality silicon or comparably high concentration of crystal defects seems to increase the tendency of PID [12]. There are different parameters having a large impact on PID but the Anti Reflection Coating deposition was seen to have a crucial role in not only influencing but actually preventing PID on cell level. It also shows that by using suitable combination of Refractive Index and thickness of ARC, PID can be completely prevented on cell level. Negative earthing can also reduce the voltage stress, thereby reducing the PID effect.

Transparent Oxide Coating (TCO) Corrosion

Even after a small period of operation, it is being observed that degradation occurs in the TCO layer in certain thin film modules[13]. The study showed that a-Si and CdTe thin film solar cells are mostly affected.TCO corrosion occurs on the edge of the PV module as a result of the reaction of moisture with sodium that is contained in the glass cover. As a result, the TCO becomes milky and the conductivity reduces and subsequently efficiency[14]. This is prevented by negative grounding the PV array using grounding kit, which the positively charged sodium ions are repelled from TCO. This prevents corrosion. Penetration of moisture is prevented through improved sealing of the module edge.

Maintenance of Solar System

Maintaining the solar system require the following check [16]

•Crimping of Cables on DC side of converters.
•Check for any shading due to any object or dust on the modules by visual inspection.
•Checking the module for hotspots with infrared camera.
•Laying of Cables: Check visually and by Meggar for any faults before setting in position for use.
•Faults in Jointing Kits.
•Faults in modules of SCADA.
•Checking of string voltage and string current regularly.
•Current checking with respect to current irradiance level.
•Checking input DC power and output AC power of Inverter.
•Changing of Silica Gel in the breather of Transformer.
•Cleaning of Inverters & Fan filters.
•Fixing of RF ID tag.
•Check for inverter data using inverter software.
•Check for battery charger & battery bank condition.
•Working out maintenance schedule and follow the same & keep all records.

Conclusion

This paper briefly addresses the technical and economic aspects of setting up a photo voltaic solar plant at commercial and rooftop levels. Northern hemisphere is chosen for the approximate calculation at latitude of 41.21 degrees. This study can help to reduce the everyday struggle for electricity at peak load durations and can also meet the storage capacity of national grids. The stored electricity can be consumed in case of blackout in summer and during other difficult situations. The degradation and maintenance of PV modules are very important aspects discussed above plays very important role in the overall efficiency of the solar system.

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