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A METHODOLOGY FOR ATTAINING PROXIMITY TO ACTUAL SOLAR ENERGY YIELD ON-ROOF

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ABSTRACT

There is a wide scope of generating several kilo Watts of electrical energy on the roof area of various building constructions by installing Solar Photovoltaic power generation systems. Energy yield analysis will be performed by existing simulation software's to estimate the possible energy generation at the site, however the estimated energy may not be produced in actual due to non-consideration of certain inputs. The proposed paper presents a methodology for attaining proximity to actual solar energy yield by on-roof solar PV systems accounting the best fit site constraints. The approximated deviation error in annual energy yield and kWp power generation attained with respect to actual possibility using only software based simulation can be compensated by using the proposed methodology for PV Module allocation. The proposed methodology could become reference guide for on-roof solar power plant design and erection engineers.

Keywords: On-Roof Area, Power Conditioning Unit, PV Array, PV Module, Solar Photovoltaic Power Generation

I. INTRODUCTION

Electrical energy became essential commodity in the present day lively hood. There is a rapid demand for its generation both by conventional and renewable energy resources. To address the environmental concerns and for overall economic development of the country, addition of major renewable sources of energy and transition from conventional energy systems to those based on renewable energy resources became necessary. Among several renewable energy resources, solar is identified as the main source for reliable power generation. In terms of cost of energy the solar photovoltaic (PV) plants located in high solar radiation zones will have a greater economic and logistical advantage.

In addition to on ground sitting, on-roof placement of solar PV power generation system (SPVPGS) became an added advantage for developing Solar PV power systems. The roofs of residential and commercial complexes, government organizations, housing societies, community centers, private institutions can be utilized for installing [1] SPVPGS. Educational institutions contribute major portion of on-roof area feasible for establishing SPVPGS. Also if PV based power generation is carried out, a portion of load demand of respective institute can be met and the electrical energy consumption can be saved to the extent possible. In addition during excess generation and non consumption hours it can also be fed to the grid.

The grid connected on-roof SPVPGS generates electricity at the consumption center, thereby contributes to reducing the network losses of the distribution licensee. The electricity generation meets the demand and supply gap. In grid connected on-roof system, the DC power generated from Solar PV module is converted to AC power using power conditioning unit and is fed to the grid depending on the capacity of the system installed. Present status of Indian grid connected roof top program as on 19th March 2015 is depicted in Table I.

Table I

Present Status of Indian Grid Connected Roof Top Program as on 19-03-2015

S. No	Description	Solar PV Capacity
1	Estimated Potential of Solar Roof Top in India	124 GW
2	Solar Roof Top Projects sanctioned in India	358.43 MW
3	Solar Roof Top Installed	41.239 MW

In India, Andhra Pradesh (AP) state is one of the suitable locations for installing solar power plants [2]. In AP annual sunny days are about 300, with solar insolation of 5 to 6 kWh/m². Solar power plants can be easily connected to the grid due to the availability of widespread electric-grid network and also due to growing energy demand in the State.

II. SCHEME OF SPVPGS

The basic arrangement of grid connected on-roof SPVPGS is shown in Fig. 1. It includes the following stages, namely PV arrays, power conditioning unit and the load.

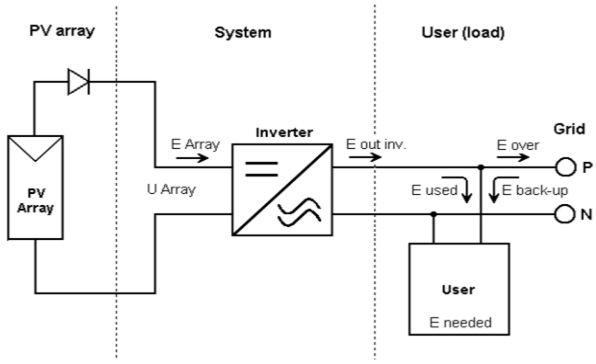

Fig.1. Schematic Diagram of SPVPGS

The first stage consists of PV array, through which the sun light is converted into the power and is fed to the inverter through diode. The function of diode is to avoid the reverse power flow. The power obtained from the PV modules is in the form of DC.

The second stage consists of power conditioning unit with inverter as major equipment. Inverter is used to convert the DC power into AC power with desired voltage and frequency. In general the DC power is converted into the AC power because most of the loads are operated with AC voltage, while the other operates with DC voltage.

The converted AC power at the inverter can be utilized by user directly or can be pumped to the grid.

2.1 Selection of PV Modules

For a particular kilo Watt peak (kWp) and voltage rating, the selection of PV modules depends up on the module area and weight. However a compromise can be made with respect to module weight. If module area of selected make is comparatively less than other makes, more number of modules can be accommodated within less area. In this case HBL POWERSYTEM LTD make 250Wp PV module is considered.

2.2 Selection of Inverter

Based up on the estimated kWp power generation, the inverter rating is chosen. The capacity and quantity of inverters are estimated based on the equalized power distribution. It is recommended to utilize the shadow areas of the trees and building profiles on the roof of the blocks for positioning power conditioning units or inverters.

III. DESIGN OF SOLAR PV POWER GENERATION SYSTEM

Considered project site is one of the hotspot regions in AP located at 13.6^{O}N and 79.3^{O}E, with a daily horizontal irradiation about 5.12 kWh/m^2. On the available on-roof area about 8446.16 m^2, a solar PV power generation system is designed and modeled.

3.1 On-Roof Area Estimation

The area estimation is the main criterion in order to place sufficient number of PV modules and inverters for the purpose of power generation. The project site has fourteen individual building blocks. So by utilizing the on-roof area of these building blocks an efficient solar energy can be grabbed by placing SPVPGS. By performing on-roof area measurement by surveying, it has been found that the gross total available on-roof area at the project site is 8446.34 m^2. Certain portion of on-roof block area is left free for concerning the possible shadow un-certainties and for facilitating corridor or walk way spacing during erection and maintenance activities and then the net area is calculated. It has been estimated that the net on-roof area that can be utilized effectively for placement of SPVPGS after considering the above mentioned constraints is 7140.01 m^2.

3.2 Allocation of PV Modules- A Novel Methodology

On-roof area of the project site is divided into fourteen blocks and each block is subdivided into number of possible block segments within which a sector of SPVPGS can be allocated.

The methodology proposed for allocating the PV modules is listed below:

1. Consider the segments in each block.
2. Measure the length, width of each segment and calculate the total segment area.
3. Identify the corridor spacing and calculate the area that enables for walk-way during erection and maintenance.
4. Subtract the corridor area from total segment area. This leads to the net area of the segment which is convenient for allocating the PV modules.

5. By using PVsyst simulation software, obtain the possible number of PV modules that can be accommodated within the net segment area and also the possible kWp generation.
6. Now cross check step 5, by performing regular module allocation method.
7. In regular module allocation method, two possibilities for PV module placement based on the length and width alignment of modules with respect to segment dimensions should be dealt.
8. First possibility is attained by checking the alignment of length of the PV modules with length of the segment and width of the PV module with width of the segment. For this possibility net area required and number of PV modules that can be placed should be estimated. This possibility can be referred as P1 possibility.
9. Second possibility is attained by checking the alignment of width of the PV modules with length of the segment and length of the PV modules with width of the segment. For this possibility also net area required and number of PV modules that can be placed should be estimated. And this possibility can be referred as P2 possibility.
10. Among the above two possibilities the one which accommodates more number of modules for the net specified segment area may be considered as the best possibility and can be considered as the suggested module segment combination for allocating the PV modules.
11. Then calculate the possible kWp power generation for each block segment in the block, by using the suggested PV modules.
12. Step 11 can be cross checked by comparing the possible kWp power generation for each segment in the block (under standard, minimum and maximum temperature conditions) using PVsyst simulation software.

In this case the suggested PV module combination in all the block wise segments is attained using the above methodology.

3.3 Array Sizing and Allocation

To increase their utility, a number of individual PV cells are interconnected together in a sealed, weatherproof package called a PV module. To achieve the desired voltage and current, modules are wired in series and parallel into what is called a PV array. The flexibility of the modular PV system allows designers to create solar power systems that can meet a wide variety of electrical needs. A single PV module can be erected on a four pole structure. But PV array consists of number of modules and hence it is preferable to erect the PV array on a multi-pole structure that arms all the modules.

PV array size depends up on the area of the segment, and the suggested module matrix combination. In the considered project site, PV arrays are modeled in such a way that each segment consists of at least one array, and as the total number of segments are 133, the minimum number of possible arrays is also 133. Each array is coded by considering a walk-way path that starts from block-1 towards block-14.

To overcome the possibility of shading uncertainties, minimum array to array distance is calculated based on the profile view of one array as shown in Fig.2. From this figure array hypotenuse length, array length, array horizontal length and array vertical length are calculated. Based on these values minimum array to array distance required is estimated.

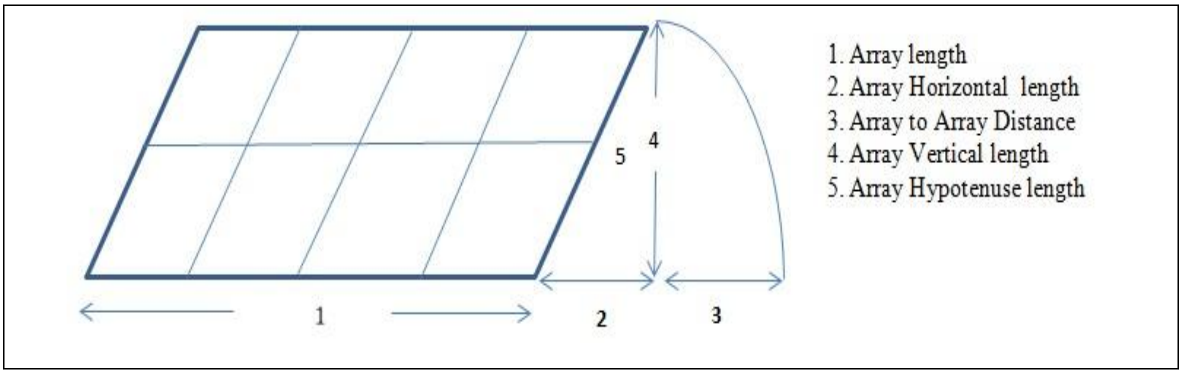

Fig.2. Profile View of One Array

Array hypotenuse length and array length are calculated by considering possibilities which are discussed in the section III (B). If the possibility is P1, hypotenuse length is obtained by adding the lengths of each module in a column and array length by adding widths of the modules in a row. If the possibility is P2, hypotenuse length is obtained by adding the widths of each module in a column and array length by adding the lengths of each module in a row.

As the project site is at northern hemisphere region, to capture the maximum solar insolation, PV array shall be positioned by a tilt angle about 18.6^{o} and is to be directed in such a way that it always faces the south direction aligned with east to west axis. In this case the suggested array sizing in all the block wise segments is attained by adopting the above procedure.

3.4 String Sizing

String is a series combination of more than one solar PV modules that are combined to increase the voltage level. It is sized based on the total number of PV modules that can be accommodated in the site area and the equalized voltage generation withstanding capability. Based on the site constraints and estimated possible number of PV modules that can be accommodated in an array matrices, it has been found that number of PV modules that can be connected in series forming a string is 19, with a total voltage generation withstanding capability of 590 V. It has also been verified by using PVsyst simulation software. There by total number of PV modules in an array or combination of arrays is divided in to 19 and is connected in series forming a string. The left over modules in an array, after string formation, is combined to the next array for devising another string. By these process a total of 207 strings are formed using 3933 PV modules out of total estimated 3939 PV modules. The remaining six modules are considered extra. Each string consists of one string terminal set and is connected to String Monitoring Box (SMB).

3.5 Inverter Sizing

The output terminals of SMBs will be connected to the inverters. The sizing of inverter and number of inverters depends up on the DC voltage and power distribution by the group of terminals arrived from the SMBs. As there are 14 SMBs, their output terminals are grouped to equalize the voltage distribution and balance the DC power input to the inverters. For equal distribution of power to the inverters, 14 output terminals from the SMBs are enhanced to 16 output terminals without exceeding the power handling capacity and are divided in to four groups to feed four inverters of capacity 257 kW each.

3.6 Array Voltage Sizing

Based on the inverter selected with specified make, PV array voltage is sized. Power sizing characteristics of inverter by the manufacturer of AD ANSALDO SISTEMI is shown in the Fig.3. At standard temperature condition (STC) the nominal PV array power is found to be 984.2 kWp and nominal inverter power to be 1028 kWp. At 60 ^{0}C the minimum Vmpp voltage is occurred and at 20 ^{0}C the maximum Vmpp voltage is occurred. There by it can be understood that, with increase in temperature, voltage produced gets reduced.

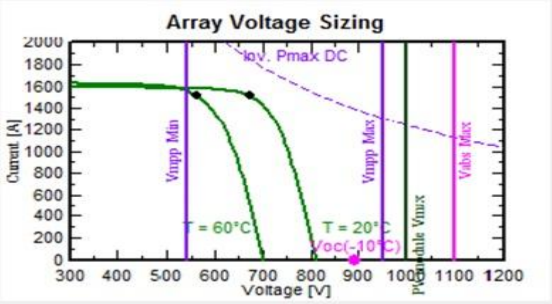

Fig.3. Array Voltage Sizing

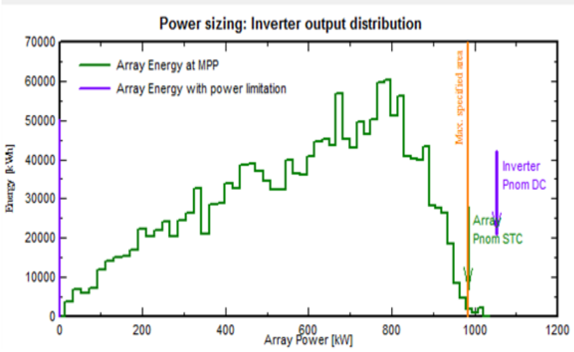

Fig.4. Inverter Output Distribution

Inverter output distribution is shown in the Fig.4. It is a plot against the variation of array energy (kWh) with array power (kW).The green color represents the array energy at maximum power point (MPP) and the blue color represents the array energy with power limitation. At STC the array nominal power is acquired at maximum specified area. From the graph it can be observed that, the inverter output distribution is high about 60 MWh at around 800 kW.

IV. ELECTRICAL EQUIVALENT CIRCUIT OF PROPOSED SPVPGS

The electrical performance of a PV module can be approximated by enhancing single diode lumped circuit model with the parametric variation. The single diode lumped circuit model is the most common model used to predict energy production in PV cell [3, 4]. In the single diode model, a current source is connected in parallel to a diode, and with equivalent series resistance R_S and equivalent shunt resistance R_{SH} [5]. A shunt diode connected across the current source represents the diffusion current through the p-n junction of each PV cell. The series resistance affects the cell operation mainly by reducing the form factor. For simplicity only a single diode is represented in view of PV module.

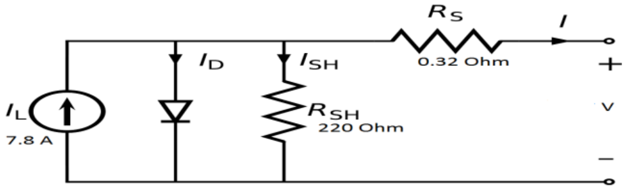

Fig.5. Equivalent Circuit of Single 250Wp Solar PV Module

A single 250Wp solar PV module considered for carrying out the case project can be represented by an equivalent circuit consisting of 7.8A current source, 220 Ohm of shunt resistance and 0.32 Ohm of series resistance as shown in Fig.5.

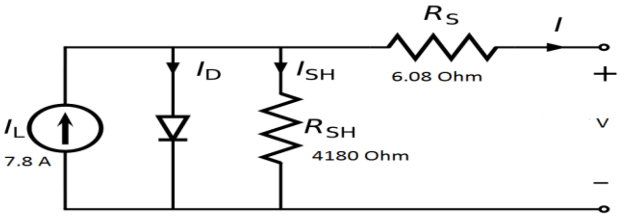

Fig.6. Equivalent circuit of single PV module string

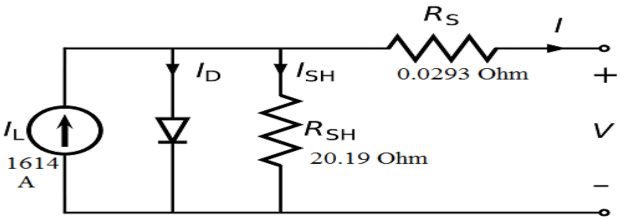

Fig.7. Equivalent circuit of proposed solar PV generation system

The equivalent circuit of a single solar PV string developed in the carried out case project is shown in Fig.6. In this case a string is attained by connecting 19 solar PV modules in series. The string equivalent circuit consists of current source of 7.8A, shunt resistance of 4180 Ohm and series resistance of 6.08 Ohm.

The equivalent circuit of proposed SPVPGS is shown in Fig.7. The proposed SPVPGS consists of 207 strings connected in parallel. And the corresponding equivalent circuit consists of a 1614 A current source, 20.19 Ohm shunt resistance and 0.0293 Ohm series resistance.

V. RESULTS AND DISCUSSIONS

Depending up on the availability of net on-roof area the total possible power generation is estimated using PVsyst- V6.32 simulation software.

The proposed On-Roof SPVPGS would utilize vacant area of 7140.01 Sqm and could produce about 984.2 kWp possible power generation. The SPVPGS is estimated to cost Rs.583.902 lakhs based on the normative cost of Rs.612 lakhs per MW adopted by CERC Suo-motu order dated 7th January 2014[6]. As the On-Roof area is readily available the cost component against land procurement becomes zero.

Variation in the estimated area with and without corridor spacing at the project site is shown in Fig. 8.

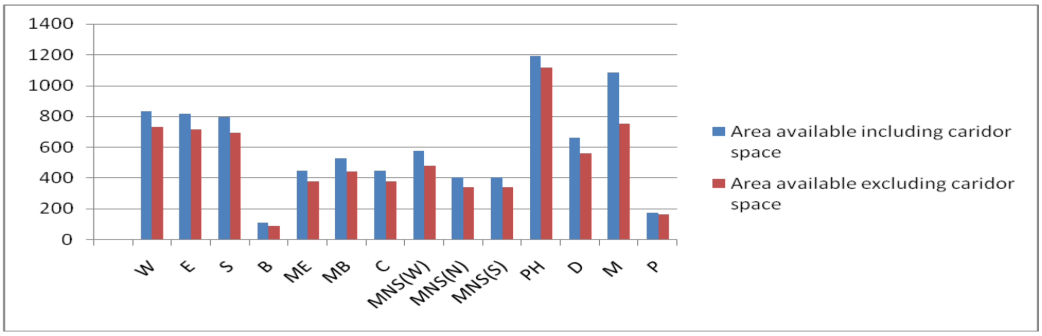

Fig.8. Variation in the Estimated Area with and Without Corridor Spacing

The net on-roof area is estimated by dividing the available area into flat area and segmented area for ease in PV array sizing and is shown in Table II.

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TABLE III

On-roof area is estimation

S. No	Block	Block Flat Area (m^2)	Block Segment Area (m^2)	Net Roof Area (m^2)
1	W	375.5	354.3	729.8
2	E	425.4	286.76	712.16
3	S	608.93	80.14	689.07
4	B	84.5	0	84.5
5	ME	364.22	11.5	375.72
6	MB	430	11.5	441.5
7	C	364.22	11.5	375.72
8 To 10	MNS-W,N,S	931.5	0	1147
11	PH	1118	0	1118
12	D	475	82.42	557.42
13	M	750	0	750
14	P	160	0	160
				7140.89

On-roof area contribution and corresponding estimated kWp power generation of various blocks is shown in Figures 9 and 10 respectively. From the Fig.9 it can be observed that MNS-W,N,S blocks shares maximum on-roof area and could generate maximum kWp power. However from Fig.10, PH block individually can generate maximum kWp power.

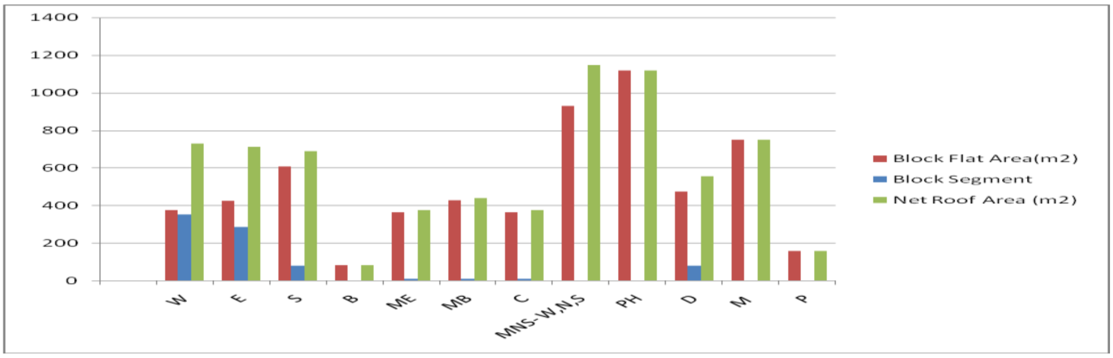

Fig.9. On-Roof Area of Various Blocks in the Project Site

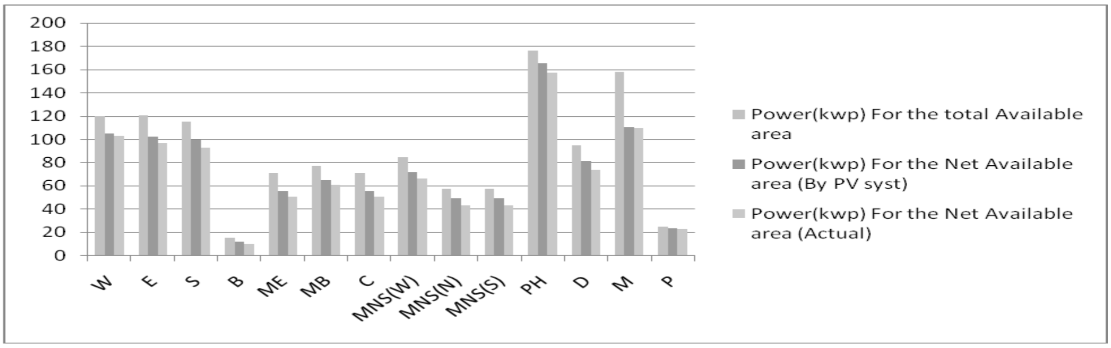

Fig.10. Estimated kWp for the Net Roof Area

Block wise estimated annual energy yield for considered net on-roof area is shown in Fig.11 and from that figure it can be found that PH block contribute about 233.4 MWh/annum.

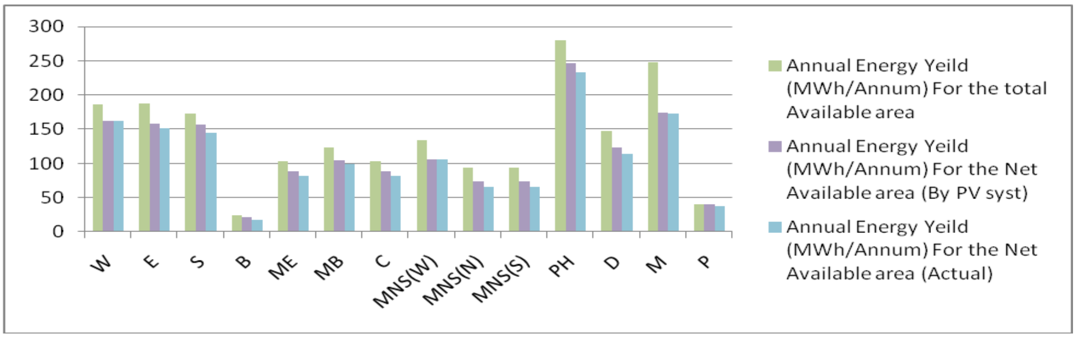

Fig.11. Annual Energy Yield for the Net Area

The power balance configuration of the proposed Solar PV Power Generation system is shown in Table III.

TABLE IIIII

Power balance configuration of the proposed SPVPGS

S.No	Name of block	No. of array junction boxes	No. of string terminal sets	Starting point of the SMB	Place of inverters	Connected terminals of SMB to the inverter	Input current for the inverter(Amps)	Input power to the inverter (KWp)
1	P	3	4	M1				
2	E	12	21	M2				
3	S	16	19	M3	IR1	1,M2,M3,M4	397.8	245.5
					IR2	4-2,M5,M6,N	397.8	242
4	M	12	24	M4,M5				
5	B	1	2					
6	W	15	22	M6,M7				
7	ME	9	10	M8				
8	MB	9	13					
9	C	9	11	M9				
10	MNS(S)	5	9	M10				
11	MNS(W)	8	14	M11	IR3	,M9,M10,M1	405.5	247.75
					IR4	-2,M12,M13,	413.4	249.5
12	MNS(N)	5	9					
13	PH	20	33	M12,M13				
14	D	9	16	M14				
		133	**207**	**14**	**4**		**1614.5**	**984.75**

Estimation of block wise number of modules, kWp and MWh/annum is tabulated in Tables IV, V and VI.

TABLE IVV

Estimation of Block wise number of modules

S.NO	Name of Blocks	Area available including caridor space	Area available excluding caridor space	No of modules		
				For the total Available area	For the Net Available area (By PV syst)	For the Net Available area (Actual)
1	W	830.8	727.8	480	415	412
2	E	817.81	712.76	483	405	389
3	S	791.83	689.53	460	395	372
4	B	105	84.5	62	49	42
5	ME	446.12	375.77	286	221	204
6	MB	524.96	441.16	308	260	244
7	C	446.12	375.77	286	221	204
8	MNS(W)	575.4	476.5	340	286	265
9	MNS(N)	402	335.4	231	197	174
10	MNS(S)	402	335.4	231	197	174
11	PH	1192.5	1118	703	660	630
12	D	658.62	557.42	380	321	296
13	M	1081	750	630	443	440
14	P	172	160	100	94	91
		8446.16	**7140.01**	**4980**	**4164**	**3937**

TABLE V

Estimation of Block wise kWp power generation

S.NO	Name of Blocks	Power(kwp)		
		For the total Available area	For the Net Available area (By PV syst)	For the Net Available area (Actual)
1	W	120	104.9	103
2	E	121	102.3	97.25
3	S	115	99.8	93
4	B	15.5	12.5	10.5
5	ME	71.5	55.4	51
6	MB	77	65.1	61
7	C	71.5	55.4	51
8	MNS(W)	85	71.8	66.25
9	MNS(N)	57.8	49.6	43.5
10	MNS(S)	57.8	49.6	43.5
11	PH	176	165.3	157.4
12	D	95	81.6	74
13	M	158	110.8	110
14	P	25	23.8	22.8
		1246.1	**1047.9**	**984.2**

TABLE VI

Estimation of Block wise annual energy yield

S.NO	Name of Blocks	Annual Energy Yeild		
		For the total Available area	For the Net Available area (By PV syst)	For the Net Available area (Actual)
1	W	186	162.5	161.5
2	E	187.2	158.3	151.3
3	S	172.7	156.4	144.3
4	B	23.78	20.82	16.81
5	ME	103.7	88.15	81.3
6	MB	123	103.8	98.61
7	C	103.7	88.15	81.3
8	MNS(W)	134	106.4	105.3
9	MNS(N)	93.24	73.71	65.56
10	MNS(S)	93.24	73.71	65.56
11	PH	279.6	245.8	233.4
12	D	147.3	123.3	113.3
13	M	247.7	174.5	173.1
14	P	39.59	40	38.16
		1934.75	**1615.54**	**1529.5**

In Table IV, the measured area is in square meters. From the tables IV, V and VI, it can be observed that for the net available on-roof area of the individual blocks considered, the estimated annual energy yield obtained by performing only software based simulation is 1615.54MWh, whereas by using the novel methodology proposed for allocating the PV modules and performing the simulation, it is 1529.5 MWh. The approximated deviation error about 5.62% in annual energy yield and 6.47% in kWp power generation with respect to actual possibility is attained using only software based simulation and can be compensated by the proposed methodology for PV module allocation.

VI. CONCLUSIONS

By considering one of the hotspot regions in Andhra Pradesh located at 13.6 ^{O} N and 79.3^{O} E, with a daily horizontal irradiation of 5.12 kWh/m^2 annual energy yield analysis is performed for proposed on-roof solar PV power generation system. On the available on-roof area about 8446.16 m^2, a SPVPGS is designed and modeled by considering novel methodology proposed for allocating the PV modules and found that approximated deviation error about 5.62% in annual energy yield and 6.47% in kWp power generation with respect to actual possibility can be compensated. Thereby the proposed methodology could become reference guide for on-roof solar power plant design and erection engineers.

Thus out of the total 8446.16 Sqm available on-roof area at considered project site, 7140.01 Sqm can be effectively utilized for Solar Power Generation. And for that net area, 984.2 kWp power can be produced and can yield 1529.5 MWh per annum , if the proposed novel methodology for allocating the PV modules is considered and designed solar PV power generating system is implemented. The generated energy can effectively meet the present load demand at that site and can even feed to the nearby grid.

VII. ACKNOWLEDGMENTS

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