Electrical Performance of Off-Grid Solar Photovoltaic (PV) Array System: An Annual Experimental Study for Comparative Assessment

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Abstract:- With the growing solar photovoltaic(PV) electricity generation technology in the rural-urban areas of developing countries, on field performance investigation of the solar photovoltaic generator system has become an essential activity. Developing countries are still lacking in the availability of necessary test equipment and other facilities in all the places due to cost constraints. Hence, a simplified convenient economical alternative is needed to monitor on field array performance. In this communication development of an experimental computational model for comparative assessment of annual technical performance of existing solar photovoltaic (PV) array /sub arrays based on electrical energy output and power conversion efficiency is presented. This communication presents field experience of existing on field stand-alone photovoltaic (SAPV) array system by evaluating and assessing annual electrical performance of solar photovoltaic array system with its individual component sub arrays, on the basis of measured on field experimental observations carried out in clear days of each month during a year. With the developed mathematical computational model experimentally calculated actual electrical performance results have been presented with respect to the estimated rated performance results obtained at nominal rating of parameters as specified by manufactures at standard test conditions (STC). Further for more realistic assessment measured on field actual PV array performance results have been compared with respect to its maximum (potential) performance results that are estimated for existing actual on field measured environmental conditions.

Keywords: Solar Photovoltic power,Electrical output,Electrical Efficiency,On-field PV array system, Performance assessment

1. Introduction

In the developing countries, solar photovoltaic system has emerged as most promising as a future energy technology. There still present constraints, and the problems that need to be evaluated from the economic, technical, operational and institutional point of view. Installation and knowing performance of a some small to medium capacity photovoltaic (PV) units is very necessary.

In a solar PV array, solar PV modules are connected in parallel and/or series to get desire output power. For engineering handiness, a PV array can be divided into number of sub arrays. Rated specifications of PV modules are specified at standard test conditions (STC) but these STC conditions do not correspond to what is typically experienced by PV modules under on field PV operation [1]. Jae-Hyun Yoo [2] pointed out that PV arrays output changes with environment remarkably, the output power of PV arrays changes with different temperatures and illumination.

Willeke [3] studied that solar conversion efficiencies of commercially available modules of crystalline silicon are typically in the range of 10–16%. More refined cell designs having efficiencies at the higher side of this range. Wang Lu at el. [4] pointed out that with the increased potential of voltage, efficiency potential of thin crystalline solar cells can be achieved. The outdoor performance evaluation of the PV array is an important action that is not only assign the efficiency and PV module performance but also explore the imperfect and unusual of the PV system. The evaluation result can also be used as the database in adjustment and maintenance of PV generator. Rely solely on STC data can lead to an over calculation of the power production.

Durisch at el. [5] discussed that for correct product selection and precise prediction of electrical energy production it is necessary to have reliable understanding of different PV generators performance under real outdoor operating environmental conditions. Though PV modules are considered very trustworthy as electrical energy generator but outdoor results indicates that the modules can degrade or fail in a number of ways. Boonmee at el. [6] evaluated 5 kW_p PV system at Rajamangala University of Technology Suvarnabhumi with the help of data obtained data monitor system and standard apparatus or IV Checker. Result exhibited that the both data give the difference of average array efficiency about 1 %.

This paper presents on field annual performance evaluation and comparative assessment of solar PV array and its individual component sub arrays. Experiments have been conducted on a typical stand-alone photovoltaic array system installed at IIT Delhi, India during a year. With the help of on field measured experimental parameters and simplified mathematical model developed for evaluating daily, subsequently monthly and then yearly performance indices electrical energy output and actual power conversion efficiency of PV array and its constituent sub arrays have been determined. Actual experimentally calculated yearly performance indices have been shown with respect to the estimated nominal rated/maximum performance indices. Further nominal rated performance indices at STC have been corrected for existing on field experimental environmental conditions i.e. PV operating temperature and incident solar intensity to obtain more practical on field maximum performance indices for more realistic and effective performance assessment.

2. A Stand-alone PV system: on field experience

Fig.1 presents the experimental setup installation of existing stand- alone photovoltaic (SAPV) array system at IIT Delhi, India. This stand-alone PV system(SAPV) of 2.32 kW_p is constituted with, two sub arrays of rating 1.2kW_p and 1.12kW_p each as shown in Fig.2 and Fig.3 respectively. PV sub array1 consists of 16 modules of rating 75W_p each (Siemens Make, 15 years old) ; short circuit current (I_{sc})= 4.8 A; rated current 4.4 A ; open circuit voltage (V_{oc}) =21.7V; rated voltage 17.0V with an effective area of 0.605 m^2 and PV sub array2 consists of 32 modules of each rating 35 W_p each (CEL Make, 25 years old); short circuit current (I_{sc})= 2.35 A; rated current 2.1 A ; open circuit voltage(V_{oc})=20.5V; rated voltage 16.5V with an effective area of 0.4 m^2 .The modules are made of 36 monocrystalline silicon cells per module. The photovoltaic modules are mounted on a fixed metal supporting structure. The different array elevation angle caused different incident solar intensity on PV array and power output [7]. On the basis of latitude of place, New Delhi, the frame is placed at fixed tilt of angle at which the average yearly energy is maximised. The power generated by solar modules is stored in battery bank of 360Ah, 48V which consist of set of 16 d.c. batteries of rating each 6V and 180Ah-10h. An inverter of 3kVA is employed for running a.c. equipment. For monocrystalline silicon cell temperature coefficient β has been considered 0.45% / °C [8].

Fig.1: Stand- alone Solar PV array system setup at IIT Delhi, India

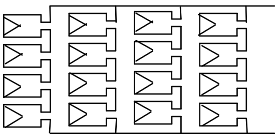

Fig. 2: Arrangement of solar PV modules (Siemens) in Sub array1

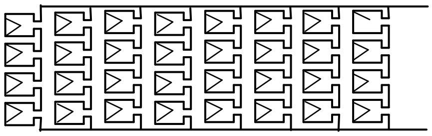

Fig. 3: Arrangement of solar PV modules (CEL) in Sub array2

1.1. Outdoor Monitoring

Data were sampled for each hour during whole experimentation. For each month two sets of experiments have been carried out. In each month number of clear days has also been recorded.

For example experimental observations on standalone photovoltaic array/sub arrays measured on typical clear day of December (winter) and April (summer) at solar energy park, IIT Delhi. (INDIA) have been shown by Table 1 and Table 2 respectively.

Table 1. Experimental observations of standalone photovoltaic array measured on Typical clear day of December (winter) at solar energy park, IIT Delhi

	Subarray1			Subarray2					
Time (hour)	Short circuit current I_{sc} (Amp)	Open circuit voltage V_{oc} (Volts)	Solar Intensity I_1 (W/m^2)	Short circuit current I_{sc} (Amp)	Open circuit voltage V_{oc} (Volts)	Solar intensity I_2 (W/m^2)	Ambient air temp. T_{amb} (°C)	PV operating Temp. T_{OT} (°C)	Average solar intensity I_{ave} (W/m^2)
10:00am	3.6	75.4	230	2.2	72.5	220	16.0	20.7	225
11:00am	4.4	75.3	270	2.5	72.4	240	17.5	22.8	255
12:00pm	5.4	74.3	340	3.7	72.4	360	18.5	25.8	350
1:00pm	5.1	74.2	310	3.2	72.3	330	19.0	25.7	320
2:00pm	4.9	74.1	290	3.0	72.4	300	20.0	26.1	295
3:00pm	4.0	73.2	250	2.4	70.8	250	20.5	25.7	250
4:00pm	3.0	73.1	200	2.1	70.4	200	19.0	23.2	200

Table 2. Experimental observations of standalone photovoltaic array measured on typical clear day of April (summer) at solar energy park, IIT Delhi

Time	Subarray1 Short circuit current I_{sc}	Subarray1 Open circuit voltage V_{oc}	Subarray1 Solar intensity I_1	Subarray2 Short circuit current I_{sc}	Subarray2 Open circuit voltage V_{oc}	Subarray2 Solar intensity I_2	Ambient air temp. T_{amb}	PV operating temp. T_{OT}	Average solar intensity I_{ave}
(hour)	(Amp)	(Volts)	(W/m²)	(Amp)	(Volts)	(W/m²)	(°C)	(°C)	(W/m²)
8:00am	4.2	71.5	350	2.5	68.5	340	32.0	39.2	345
9:00am	6.4	71.4	520	3.8	68.4	510	32.5	43.2	515
10:00am	7.5	71.4	600	4.4	68.4	600	33.0	45.5	600
11:00am	10.2	71.4	790	6	68.4	790	34.0	50.4	790
12:00pm	11.9	71.3	890	6.8	68.3	890	35.0	53.5	890
1:00pm	11.8	71.3	880	6.7	68.3	880	35.0	53.3	880
2:00pm	10	71.3	760	5.8	68.3	760	34.0	49.8	760
3:00pm	7.6	71.5	610	4.5	67.8	610	33.5	46.2	610
4:00pm	5.4	71.4	420	3.2	67.4	420	32.0	40.7	420
5:00pm	3.2	71.2	190	1.9	64.9	190	31.5	35.5	190

During sun shine hourly observations of solar intensity on both sub arrays, ambient temperature, operating temperature, and I_{sc} for sub array1 and sub array2 ,battery voltage , V_{oc} for sub arrays have been measured during experiment conduction with the help of transportable calibrated solari meter (least count 20 W/m² and accuracy of ±2% of measured solar radiation reading), calibrated mercury glass thermometer (least count 1°C with accuracy ±10% of reading (or ±0.1°C), infrared thermometer (with 0.1°C least count and ±1% accuracy) and clamp meter (with 0.001V,0.1A least count and ±1% accuracy) respectively for the whole day.

3. Computational model of experimental data analysis for annual performance evaluation

Based on experimentally measured parameters technical performance of solar PV array with its individual component sub arrays can be evaluated in terms of electrical energy output and electrical efficiency. Periodic measurement of individual sub arrays parameters are helpful for characterising the performance of individual component sub array and can be necessary to distinguish which components are responsible for general performance problem. There are various methods used in industry to estimate performance, which are complicate and complex to use and needed detailed data. Some times it becomes important to obtain monthly and annual on field energy performance of PV array system in a most simplified way using less complicated experimental setup and parameters to provide information on the quality, general performance and associated problem of installed setup.

There is a need to develop a simplified approach to evaluate approximate monthly and annual performance of PV array system. Present paper provides a simplified method of monthly and annual performance evaluation. Here we have considered average no. of days in each month for climatic conditions of New Delhi which are the useful for PV power generation. We can consider the useful PV power generation under clear sky conditions (not in cloudy skies) (Nayak and Tiwari 2008). Normally, for a clear day sun shine hours to be available for useful power generation have been considered six hours or more than 6 hours per day.

In this section using experimentally measured parameters first daily performance index such as electrical energy output and electrical efficiency of PV array and each sub arrays are computed, further monthly indices for particular month are calculated by multiplying the daily value with the number of clear days in that particular month and finally by adding all monthly performance over a year, annual performance has been calculated. Developed expressions can also be applied to calculate daily, monthly and yearly performance indices of any other kind of PV array system having component sub arrays.

PV module/array technical performance is mainly depends upon solar intensity and temperature of PV module [9]. Short circuit current (I_{sc}) obtained from PV array/sub arrays is a linear function of incident solar radiation. The short circuit current, I_{sc}, increases with increasing insolation intensity due to the increase in the number of photons generating the photo current [10]. PV Open circuit voltage (V_{oc}), depends logarithmically on solar intensity [11] and small variation in V_{oc} during the day can be caused by temperature changes and cloud cover. Parameters as open circuit voltage (V_{oc}) and short circuit current (I_{sc}) of PV sub arrays are continuously monitored and measured hourly since morning to evening during a whole day of experimentation in order to calculate total daily hourly output of electrical energy and electrical efficiency from PV array and sub array [12]. Degradation or failure can also detected by using these continuously monitored and measured hourly parameters.

In Eq. (1) average daily electrical power output in a particular nth month (n=1, 2, 3….12) $\left(\mathrm{E}_{PVarray}\right)_{daily,n}$ is multiplied with the number of clear days in that month (D_n) in order to calculate the approximate monthly electrical energy of n$_{th}$ month i.e. $\left(\mathrm{E}_{PVarray}\right)_{monthly,n}$

$$\left(\mathrm{E}_{PVarray}\right)_{monthly,n} = \left(\mathrm{E}_{PVarray}\right)_{daily,n} \times D_n \quad (1)$$

Average of daily electrical energy output of PV array measured for typical clear days in nth month has been taken as PV array ave. daily electrical energy output for that nth month.

To calculate approximate annual electrical energy output, monthly electrical energy output over a year are added. Eq. (2) express the annual electrical energy output from existing PV array, which is the sum of annual electrical energy output obtained from PV sub array1 and PV sub array 2.

$$\left(\mathrm{E}_{PVarraay}\right)_{annual} = \sum_{n=1}^{12}\left[\left\{\sum_{hourly}\left(FF\times V_{oc}\times I_{sc}\right)_{subarray1}\right\}_n \times D_n\right] + \sum_{n=1}^{12}\left[\left\{\sum_{hourly}\left(FF\times V_{oc}\times I_{sc}\right)_{subarray2}\right\}_n \times D_n\right] \quad (2)$$

Where, I_{sc} is Short circuit current, V_{oc} is Open circuit voltage; FF is fillfactor for sub array.

Similarly separate annual electrical energy output from PV sub array 1 and sub array 2 can also be expressed. If investigational data is measured for typical clear days of every month in a year to obtain average daily performance then more approx. conversion efficiency of PV array can be evaluated by taking the ratio of total annual electrical energy output from PV array and total incident solar energy measured on PV sub array 1 and sub array 2 all through a year. Power conversion efficiency of PV array on the basis of annual performance $\left(\eta_{PVarray}\right)_{annual}$ has been developed as Eq. (3).This Eq. has been developed with the help of hourly measured observations on both sub arrays during typical days of nth month and subsequent monthly calculations over a year.

$$\left(\eta_{PVarray}\right)_{annual}=\frac{\sum_{n=1}^{12}\left[\left\{\sum_{hourly}\left(FF\times V_{oc}\times I_{sc}\right)_{subarray1}\right\}_n\times D_n\right]+\sum_{n=1}^{12}\left[\left\{\sum_{hourly}\left(FF\times V_{oc}\times I_{sc}\right)_{subarray2}\right\}_n\times D_n\right]}{\left[\left(\sum_{n=1}^{12}\left(I_1\right)_n\times D_n\times A_{subarray1}\right)+\left(\sum_{n=1}^{12}\left(I_2\right)_n\times D_n\times A_{subarray2}\right)\right]} \quad (3)$$

Where, $\left(I_1\right)_n$ is sum of daily hourly measured solar intensity over the PV sub array1 of area $A_{subarray1}$, calculated for a clear day in nth month, (W/m^2). $\left(I_2\right)_n$ is sum of daily hourly measured solar intensity over the PV sub array 2 of area $A_{subarray2}$ calculated for a clear day in nth month, (W/m^2). Here, $A_{subarray1}$ is obtained from area of PV module multiplying with no. of PV modules in sub array1, $A_{subarray2}$ is obtained from area of PV module multiplying with no. of PV modules in sub array2. If parameters are measured for more clear days in a month then average value is considered. To evaluate power conversion efficiency of sub array 1 the ratio of output energy of PV sub array1 and incident solar energy to sub array 1 is taken, similarly sub array2 power conversion efficiency is evaluated by taking the ratio of output energy of PV sub array2 and incident solar energy to sub array2.

4. Computational model for estimating potential / maximum annual performance indices

Assessment of electrical energy output and conversion efficiency of PV array and sub arrays at rating provided by manufacturer at STC are useful to predict the rated PV performance at initial design and installation phase. During on field operating conditions PV technical parameters depends on solar intensity and PV operating temp. Increase in the PV operating temperature reduces array max. Energy output and PV electrical efficiency measured at STC. In this regard transformation of these maximum performance indices from STC (given nominal rated conditions) to existing field environmental conditions(i.e. outdoor operating temperature and solar intensity) become more realistic while studying the on field PV performance and other possible improvement in PV system.

4.1 Annual maximum/rated electrical energy output evaluation for existing onfield environmental conditions

To calculate Approx. PV array monthly maximum/rated electrical energy output $(\xi_{rated})_{annual}$, PV array peak/rated power (P_m) is multiplied with ave. daily equivalent hours of full sun shine h_{EFS_n} calculated for distinctive clear days of n$_{th}$ month during experimentation and number of clear days in that particular month (D_n). Eq. (4) presents addition of all obtained twelve months max. Energy output of PV array/sub arrays over a year to calculate max. Annual energy output from PV array/sub arrays

$$(\xi_{rated})_{annual}=\sum_{n=1}^{12}\left[P_m\times h_{EFS_n}\times D_n\right](4)$$

Where, P_m is peak power from array that is considered at standard test conditions (STC) as given by manufacturer. The standard test condition (STC) is defined to have a standard solar spectrum of 1000 W/m^2 solar intensity, this intensity is represented under clear mid-day condition (air mass = 1.5), cell temperature 25C inside the module, and solar irradiance normal to the module front surface [13].

There are approximately 12 hours between sunrise and sunset and during winter or monsoon the sun does not shine at peak intensity of 1kW/m^2 because of haze, cloud and the atmosphere reduces solar intensity. Here, h_{EFS_n} is defined as the equivalent no. of hours per day, with solar intensity equalling 1kW/m^2 that gives the same energy received from sunrise to sunset. Equivalent hours of full sun shine (h_{EFS_n}) for a typical day of month can be obtained by the integration of the area under the graph of daily hourly variation of incident solar intensity on a unit area of PV array or sub arrays, this provides total energy from sun received by unit area in kWh/m^2 on same day. Power output of a PV module decreases linearly with increase in PV operating temperature, T_{OT} [14]. There is need to consider PV operating temperature in order to correct the performance indices of PV arrays obtained for the standard rated temperature (25°C) to the performance indices obtained at onfield actual environmental conditions such as onfield measured PV operating temperature(T_{OT}). Maximum PV array/sub arrays electrical energy output $(\xi_{\max})_{annual}$ is calculated at existing environmental conditions (i.e. experimentally obtained PV operating temperature and solar intensity) and can be expressed by Eq.(5).

$$(\xi_{\max})_{annual} = \sum_{n=1}^{12}\left[P_m \times h_{EFS_n} \times D_n \times \left\{1-\beta(T_{OT_n} - T_{STC})\right\}\right] (5)$$

where, β is temperature coefficient, T_{STC} is STC reference temperature, T_{OT_n} is the daily mean of PV operating temperature calculated for typical clear days of nth month of a year. Eq. (6) expresses production factor on the basis of annual performance which can be determined from the ratio of actual array yield calculated from annually measured investigational results and maximum/rated annual array yield estimated with existing environmental conditions for a particular location.

$$Production\_Factor(PF) = \frac{Actual\_yield}{potential\_yield} = \frac{\left(E_{PVarraay}\right)_{annual}}{(\xi_{\max})_{annual}} (6)$$

4.2. Maximum electrical energy efficiency estimation on annual basis with existing environmental conditions

An expression to calculate PV array power conversion efficiency or electrical efficiency at STC $\left(\eta_{stc}\right)_{PVarray}$ has been developed as Eq. (7), where existing PV array consists of two sub arrays [22]. Same developed formula can be modified for calculating power conversion efficiency or electrical efficiency of two component sub arrays1 and sub array2 individually.

$$\left(\eta_{stc}\right)_{PVarray} = \frac{\left(FF \times Voc_m \times M_s \times Isc_m \times M_p\right)_{\text{subarray1}} + \left(FF \times Voc_m \times M_s \times Isc_m \times M_p\right)_{\text{subarray2}}}{\left[\left(I_p \times A_{\text{subarray1}}\right) + \left(I_p \times A_{\text{subarray2}}\right)\right]} (7)$$

where, V_{oc_m} is module open circuit voltage , I_{sc_m} is module short circuit current , M_s indicates no. of series modules in a sub array and M_p represents no. of parallel strings of series connected modules in a sub array. FF is fill factor, I_p peak solar intensity of 1000 W/m^2. All these parameters are provided by manufacturer specifications and that are measured at STC

To obtain more realistic assessment nominal rated value of electrical efficiency obtained at STC can further be transformed for actual existing PV operating temperature conditions calculated for each month during a year. For temperature corrected PV electrical efficiency a conventional linear expression was developed to illustrate the significance and consequence of including the effects of PV operating temperature in the power conversion efficiency [15, 16]. On the basis of average of daily PV operating temperature obtained for typical clear days of n^{th} month estimated max. power conversion efficiency of PV array with temperature correction for n^{th} month $(\eta_{max})_{OT_n}$ is expressed by Eq.(8).

$$(\eta_{max})_{OT_n} = \eta_{STC}[1-\beta(T_{OT_n} - T_{STC})] \quad (8)$$

where, η_{STC} is the PV array/sub arrays electrical efficiency calculated for standard test conditions(STC), PV operating temperature varies with existing environmental conditions depends on ambient temperature and incident solar intensity on PV array for a given location [17,18]. Eq. (9) expresses the maximum electrical efficiency with PV operating temperature correction on the basis of annual performance. This has been obtained by taking the average of all estimated maximum electrical efficiency of PV array/sub arrays with temperature correction for n^{th} month during a year.

$$(\eta_{max})_{annual} = \frac{\sum_{n=1}^{12} \eta_{STC}[1-\beta(T_{OT_n} - T_{STC})]}{12} \quad (9)$$

5. Experimental results and discussion

To calculate various performance indicators of 2.32kW$_p$ PV array and its constituent sub array1: 1.2 kW$_p$ and sub array2: 1.12 kW$_p$, experimentally measured data for typical clear days of every month during a year have been used. To calculate electrical efficiency and energy output, PV array experimental field observations generally use the traditional method like measurement of V_{oc}, I_{sc}, T_{amb}, I_t.

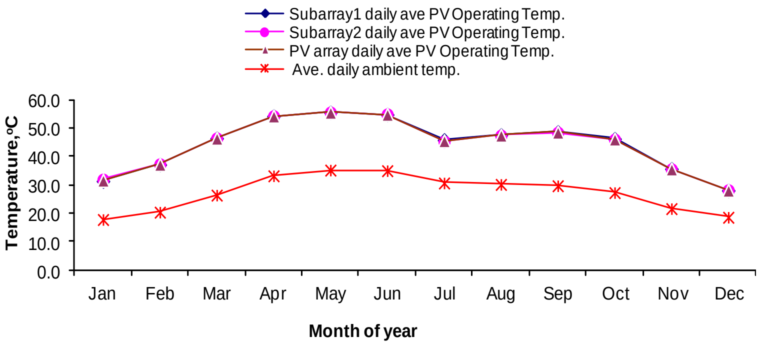

Fig. 4: Monthly variation of average daily ambient and PV operating temp. operating

Fig.4 exhibits the monthly variation of average daily ambient air temperature and PV operating temperature for entire PV array and sub arrays measured during typical clear day of experimentation in each month over a year. In installation of PV array both component sub arrays have been placed adjacent to each other at same height. PV array maximum PV operating temperature was found 43.3°C at 12:00 noon when ambient air temperature was measured 31°C and solar radiation was 590W/m^2. Main factors that are responsible for the variation in PV operating temperature are variation in ambient air temperature and solar intensity incident on PV array. Hourly performance of existing standalone photovoltaic array/sub arrays in terms electrical energy output and electrical efficiency for typical clear days in every month were evaluated with the help of hourly measured experimental parameters of PV array.

By constant monitoring of the parameters I_{sc} and V_{oc} of PV module or array, it is possible to spot immediately any degradation/failure in module or array technical performance. On the basis of daily received solar energy, equivalent hours of full sun shine (h_{EFS}) for existing PV array/sub arrays are evaluated for each month. For on field PV array/subarrays Table3 presents the solar energy received on daily basis and calculated equivalent hours of full sunshine (h_{EFS}). Area calculated under the graph of hourly variation of solar intensity on given PV array/sub arrays for a typical day is integrated for total solar energy received by the unit PV area on that day and that was used to calculate equivalent hours of full sun shine (h_{EFS}).

For experimental calculation of monthly and then annual electrical energy output and electrical efficiency of existing PV array and its individual sub arrays, mathematical Eq. (2) and Eq. (3) have been used. Table 4 shows calculated monthly performance analysis of existing PV array and its individual subarrays. Observation has been made that actual electrical efficiency or power conversion efficiency of PV sub array2 (CEL make) was considerably lower than the actual electrical efficiency or power conversion efficiency of PV sub array1 (Siemens make). This was caused mainly due to the high degradation losses in CEL modules of sub array2 with installation age and long term exposure of PV modules. Maximum actual onfield electrical efficiency of Sub array1 and Sub array2 and entire PV array have been experimentally calculated 8.96% and 4.07% respectively in the December month. It has been observed from the recorded data that electrical efficiencies obtained during summer were found lower than the electrical efficiencies obtained during winter season due to higher temperature and insolation available which in turn cause higher PV operating temperature. These observations are in agreement with the observation made by Kalogirou, 2001 [21].

Table 3. Daily received solar energy and evaluated equivalent hours of full sunshine (h_{EFS}) for existing PV array/subarrays

For a clear day of month	Ambient air temp.	Daily received Solar energy on subarray1	Daily received Solar energy on subarray2	Daily received Solar energy on PV array	Equivalent hours of full sunshine for subarray1	Equivalent hours of full sunshine for subarray2	Equivalent hours of full sunshine for PV array
	°C	Wh/m^2	Wh/m^2	Wh/m^2	hours	hours	Hours
Jan	17.9	2710	2810	2760	2.7	2.8	2.8
Feb	20.4	3830	3850	3840	3.8	3.9	3.8
Mar	26.4	5150	5130	5140	5.2	5.1	5.1
Apr	33.3	6010	5990	6000	6.0	6.0	6.0
May	35.3	5810	5790	5800	5.8	5.8	5.8
Jun	35.1	5650	5660	5655	3.9	3.7	3.8
Jul	30.7	3890	3745	3817.5	3.9	3.7	3.8
Aug	30.2	4470	4415	4442.5	4.5	4.4	4.4
Sep	29.7	4870	4800	4835	4.9	4.8	4.8
Oct	27.3	4250	4150	4200	4.3	4.2	4.2
Nov	21.7	3200	3160	3180	3.2	3.2	3.2
Dec	18.6	1890	1900	1895	1.9	1.9	1.9

Table 4. Monthly performance analysis of existing PV array and its individual subarrays

Months	No. of clear days in each month	Subarray1 electrical energy Output En_1 (monthly) (kWh)	Subarray2 electrical energy output En_2 (monthly) (kWh)	PV array electrical energy output En (monthly) (kWh)	Subarray1 electrical efficiency η_1 (monthly) (%)	Subarray2 electrical efficiency η_2 (monthly) (%)	PV array electrical efficiency η (monthly) (%)
Jan	22	47.12	27.52	74.64	8.23	3.48	5.47
Feb	25	72.54	42.76	115.30	7.89	3.47	5.36
Mar	29	101.37	63.19	164.56	7.07	3.32	4.93
Apr	28	112.51	62.59	175.10	6.96	2.92	4.65
May	30	116.88	65.34	182.22	6.98	2.94	4.68
Jun	25	93.17	54.06	147.23	6.87	2.98	4.65
Jul	16	39.55	30.79	70.34	6.62	4.01	5.16
Aug	17	57.89	36.27	94.16	7.94	3.78	5.57
Sep	23	84.60	53.75	138.35	7.87	3.80	5.56
Oct	25	81.09	51.62	132.71	7.95	3.89	5.65
Nov	22	60.67	34.95	95.63	8.98	3.93	6.11
Dec	20	32.51	19.80	52.30	8.96	4.07	6.16
(Annual)	282	899.90	542.64	1442.53	7.69	3.55	5.33

Total annual electrical energy output of entire Stand alone photovoltaic (SAPV) array of 2.32 kW_p was calculated 1442.53kWh/year with Eq.(1). Performance values evaluated during the experiment have already incorporated the effect that caused by PV operating temperature as measured parameters V_{oc} and I_{sc} are temperature dependent. Production factor of 2.32kW_p PV array and its component sub array1 (Siemens) and sub array2 (CEL) were calculated 0.552, 0.665 and 0.431 respectively by using Eq.(6).

On the basis of daily and subsequently monthly performance during a year, actual electrical efficiency or power conversion efficiency of sub array1 (Siemens) ,sub array2 (CEL) and of entire PV array of 2.32 kW_p has been calculated 7.69% ,3.55% and 5.33% respectively by using Eq.(3) with standard deviation of 0.764 , 0.409 and 0.505, respectively. Although the measured actual electrical efficiency of sub array1 of PV array is obtained high but reduction in electrical efficiency of entire PV array is due to low value of measured electrical efficiency of sub array2. These measured power conversion efficiency or electrical efficiency includes the effect of PV operating temperature and degradation losses due to modules aging.

5.1 Comparative representation of annual performance

To obtain comparatively reliable effective performance assessment of existing PV array/sub arrays nominal rated performance indices on the basis of annual performance are obtained at STC for maximum annual electrical energy output and for maximum power conversion efficiency using Eq. (4) and Eq. (7) respectively and these indices have been corrected for actual on field experimental conditions obtained during experimentation using Eq. (5) and Eq. (9) respectively. Eq. (8) has been used to estimate max. Electrical efficiency for every month during a year. Fig.5 depicts the values of experimentally calculated annual electrical energy output in comparison of estimated annual maximum electrical energy output with existing environmental conditions for individual sub array1, sub array2 and entire PV array respectively.

Similarly, Fig.6 clearly indicates the obtained annual outdoor experimental performance of electrical efficiency of PV array and its constituent sub arrays in comparison with standard nominal rated performance and environmental temperature corrected nominal rated performance. From the presented array/sub arrays investigation it is apparent that the calculated indices of technical performance such as electrical annual energy output, power conversion efficiency and production factor for Sub array2: 1.12kWp (CEL) were obtained quite less (a) compare to sub array1 (Siemens) performance indices and (b) compare to maximum performance indices for same sub array2 estimated with existing environmental conditions during the experiment. It is understandable that reduction in overall performance of entire PV array is essentially due to the underperformance of sub array2.

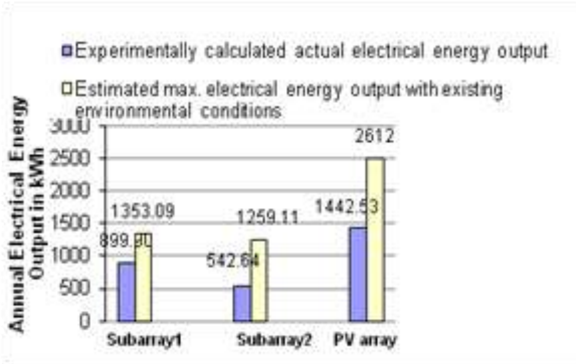

Fig.5. Annual electrical energy output of solar PV array and

Its individual sub arrays

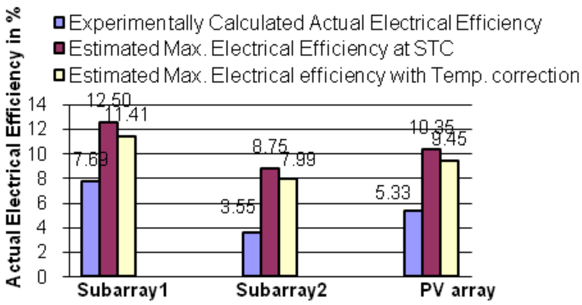

Fig. 6: Comparative representation of experimentally calculated onfield electrical efficiency of PV array and its individual sub arrays

6. Conclusions

There is a need of a suitable simplified method for evaluating and comparing the annual electrical energy provided by a PV array in actual on field conditions in comparison with the expected potential energy. This comparison of technical performance is required without delay after installation to validate initial system technical performance, in addition to over the long-term performance as the system exposed to actual field conditions or ages. At present there are varieties of methods used in industry for estimating performance. The most general method to estimate performance is to use software programmes that apply an hourly simulation. These software programs normally utilize long term meteorological data. It is often not practical of direct measurement of the array I-V characteristics on regular interval because of the cost associated with the testing effort, in the developing countries especially.

Most of performance assessment methods found in literatures for on field evaluation of standalone PV array system performance are either complex to use or needed detailed data or usually limited to economic performance evaluation. As presented in paper alternative can be implemented with simplified computational model for array performance evaluation with comparative assessment approach and monitoring procedure in conjunction with on field measured values of array/sub arrays open circuit voltage and short circuit current , solar intensity, ambient and PV operating temperature. Present model evaluates more approximate on field performance of PV array with its individual constituent sub arrays in a simplified way. On the other hand outdoor onfield performance results can be helpful in deriving recommendations for recovering and improving solar photovoltaic generators and to realize doing well PV systems.

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