International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878 (Online), Volume-8, Issue-1, May 2019

Optimal Sizing of a Stand-alone PV System for Remote Area of India

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Abstract*: At present, either the standalone solar photovoltaic (PV) renewable energy system or the hybrid solar-wind power system with storage is one of the most powerful solutions for isolated bucolic areas, distant from utility grid. These papers analyze the analysis based of a stand-alone (SA) solar PV project on Mayurbhanj district in Odisha. A stand-alone PV system with 1.38 KWP is set up to generate electricity for local residents in the remote rural area. The meteorological data for Mayurbhanj has been taken for acquiring results generated for one complete year. Energy balancing, overall system energy utilization ratio and some performance factor and the energy consumption of complete PV system are estimated on monthly basis. Monitoring the long-term system evaluation makes the system to perform a detailed evaluation of the operating performances.

Index Terms*: Performance evaluation, Stand-alone system with battery, Isolated bucolic area, Normalized parameters, Performance Ratio.

I. INTRODUCTION

The rural electrification drive of the Centre has not been completely helpful in improving the situation in Odisha. Ironically, over 36.78 lakh households in the electrified villages are living without power. The number of un-electrified villages has, though, come down from 3,860 to 579. Of these, 275 villages will be supplied electricity through off-grid measures, but the lack of access to a large number of households to electricity is a point of major concern [1]. As per the status report of the Ministry of Power, 2,555 villages have been electrified in the last three years and work is in progress in 400 others. Intensive electrification works are underway in 75 villages of Rayagada district, 73 in Kalahandi and 53 in Mayurbhanj. Mayurbhanj district has larger number of uninhabited villages which is around 118.

Since, currently Odisha is having one of the most non-electrified villages in the country. Amongst 11 major States such as Bihar, UP, Rajasthan, MP, Jharkhand and Assam, there is highest number of non-electrified villages in Odisha. **To** ensure development, every home requires access to clean, efficient and safe sources of energy [2,4]. Electricity is a part of modern day life and is one of the key factors of production. However, it is produced by use of natural resources such as wind, water, coal and solar energy and most of the State's investment has not yet reached many poorer sections of rural Odisha.

In what lays bare the glaring infrastructure deficiencies in school education system, more than 40,000 government-run primary and upper primary schools in the State are yet to be electrified. Of the 30 districts, Mayurbhanj district in northern part of the state languish at the bottom in the list of un-electrified schools with 3,346 schools not connected to power supply. To meet out these challenges, Odisha will have to make various efforts to electrify its villages, as the children only read about electricity from books.

Odisha had 3,474 unelectrified villages as on 1 April, 2015, as per the Rural Electrification Corporation (REC) monthly report of 28 February, 2018. According to the Grameen Vidyutikaran (GARV) portal, managed by the power ministry, claimed that all the remaining 2,093 villages had been electrified on 28 April, 2018 but still Odisha has 579 uninhabited villages.

In this paper, SA PV system [3] Mayurbhanj is designed to generate the result for one complete year, and the data was evaluated regarding inverter and PV array performance. The performance of the PV system was analyzed with respect to generalized parameters. Following options are possible:

i. Last mile connectivity and power connections in all non-electrified homes in rural areas.

ii. Solar Photovoltaic (SPV) based standalone system for non-electrified homes located in remote and inaccessible villages/habitations, where grid extension is not possible or cost-effective.

iii. Last mile connectivity and power connections in all remaining financially poor non-electrified homes in urban areas.

II. SYSTEM DESCRIPTION

The 1.38 kW_P PV array consist total amount of 4 modules (in series 1 module, in parallel 4 string) Model:TSM-345DD14A9II) total module area 7.8m^2. For an inclined angle of 30^o, each PV panels are situated in a predetermined direction on the south side. A stand alone system [5] with batteries has been designed with seasonal modulation for average 6.2 kWh/Day and global 2279 kWh/year daily household consumers. Fig. 1 shows the typical layout of stand-alone system.

Revised Manuscript Received on 30 May 2019.
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Battery model is CELL Li NCA, battery pack has 1624 units (14 cells in series x 116 in parallel) to provide a 50 volts nominal storage voltage with nominal capacity of 293 Ah. Discharging minimum SOC is 10 %.The un-electrified villages of Mayurbhanj district, Odisha involved in this study. At present, around 60 residents on the village area are being considered.

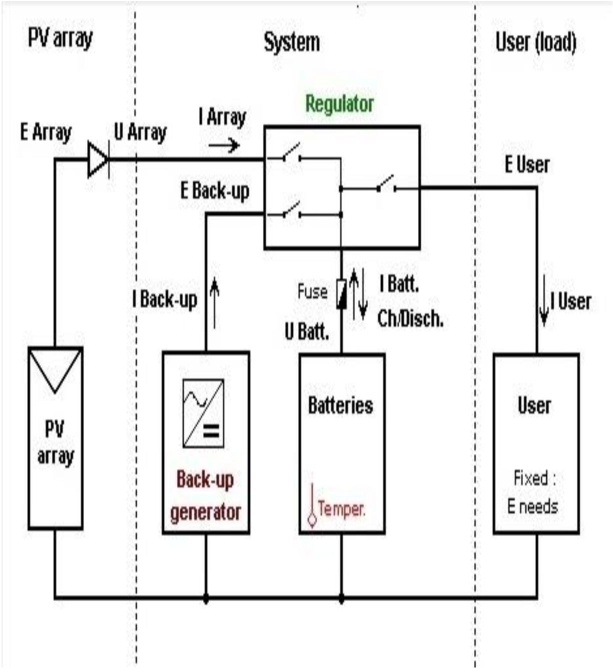

Fig. 1.Typical layout of a stand-alone system [7].

III. GEOGRAPHICAL AND METEOROLOGICAL DATA

When considering geographical site are being considered then the monthly meteorological data of diffuse irradiation, horizontal global irradiation, wind velocity and ambient temperature are specified at the equal time. Information can be automatically generated per hour from the monthly values of parameters like global radiation like global radiation and temperature when the site is confirmend. The location of this project for study is chosen to be at Mayurbhanj, Odisha. The system performance is characterised on the basis of array output, battery characteristics [8] and energy usage. The weather data for the place Mayurbhanj, Odisha is listed in Table 1. Where the variables are as follows:

TABLE I
METEO AND INCIDENT ENERGY

Month	GlobHor kWh/m^2	DiffHor kWh/m^2	T_Amb °C	GlobInc kWh/m^2	DifSInc kWh/m^2	Alb_Inc kWh/m^2
January	136.4	48.24	18.91	183.5	57.10	1.827
February	142.0	46.70	22.51	175.2	53.08	1.902
March	177.6	57.47	26.82	194.7	61.58	2.379
April	186.3	68.46	28.72	181.2	67.52	2.495
May	189.1	78.88	28.62	166.7	73.25	2.516
June	140.4	83.92	28.20	121.8	75.47	1.876
July	126.2	86.26	27.39	112.3	78.04	1.689
August	122.5	80.17	27.08	113.5	74.34	1.641
September	123.3	74.85	26.51	123.0	72.62	1.651
October	140.4	59.97	24.74	162.4	63.96	1.881
November	130.2	48.89	22.22	171.2	56.68	1.744
December	130.8	43.37	19.39	184.3	52.38	1.752
Yearly count	**1745.2**	**777.16**	**25.10**	**1889.8**	**786.01**	**23.353**

GlobHor: Global irradiation on the horizontal plane. This is our meteo input value,

GlobEff: “Effective” global irradiation on collectors means after optical losses, like (distant and near shadings, soiling losses).

GlobInc: Incident global irradiation,

DiffHor: Horizontal diffuse irradiation,

DiffSInc: Incident diffuse irradiation (from sky) in the collector Plane,

T_Amb: Ambient temperature,

WindVel: Wind velocity,

Alb_Inc: Incident albedo irradiation in the collector plane.

E_Avail: Available Solar Energy (=Y_f),

EUnused: Unused energy (battery full) (=L_u),

E_User: Energy supplied to the user (or ESol),

E_Load: Energy need of the user (Load),

SolFrac: Solar fraction (ESol/ ELoad),

EArray: Energy produced by the PV array (=Y_a),

IAM: The optical losses. Which are considering more details with additions to the variant, will result in more arrays for far and near shadings, soiling etc.

IV. SYSTEM PERFORMANCE ASSESSMENT TECHNIQUE

The performance ratio (PR) is the rate of the energy effectively produced, which would be generated, if the system was constantly working at its nominal Standard Test Conditions (STC) efficiency. The performance of the system is judged by battery bank, PV array and entire PV plant. Analysis of overall system evaluation can be done in the context of generalized parameters [9] and energy efficiency index (efficiencies/ratio). Generalized performance parameters are used as the basis for comparing the performance PV systems.

TABLE II
NORMALIZED PERFORMANCE COEFFICIENTS

Month	Y_r kWh/m^2.day	L_u	Y_u kWh/kW$_P$/day	L_c	Y_a kWh/kW$_P$/day	L_s	Y_f kWh/kW$_P$/day	PR
January	5.92	0.000	5.92	0.870	5.05	0.382	4.67	0.788
February	6.26	0.000	6.26	1.068	5.19	0.437	4.75	0.759
March	6.28	0.000	6.28	1.182	5.10	0.325	4.77	0.760
April	6.04	0.000	6.04	1.147	4.89	0.244	4.65	0.770
May	5.38	0.000	5.38	0.977	4.40	0.367	4.03	0.750
June	4.06	0.000	4.06	0.674	3.39	0.306	3.08	0.759
July	3.62	0.000	3.62	0.571	3.05	0.280	2.77	0.765
August	3.66	0.000	3.66	0.607	3.05	0.233	2.82	0.771
September	4.10	0.000	4.10	0.686	3.41	0.278	3.14	0.765
October	5.24	0.114	5.24	1.011	4.23	0.401	3.83	0.730
November	5.71	0.075	5.71	1.002	4.70	0.448	4.26	0.746
December	5.95	0.000	5.95	0.892	5.05	0.302	4.75	0.799
Yearly count	**5.18**	**0.016**	**5.18**	**0.889**	**4.29**	**0.333**	**3.96**	**0.764**

These indicators relates to the kWh/kW$_P$/d (simplified as ‘h/d’) energy for the nominal power PV array. Table II gives the normalized performance coefficients.

Performance ratio (PR) is the factor through which one can assess the plant performance, indicating how the plant is behaving. There are two basic parameters [10] to calculate the performance ratio:

1. **Reference Yield (Y_r) –** A parameter relating to energy generation if the system is at all times operating at “nominal” efficiency, calculated under STC of PV modules. This is expressed in [kWh/m^2/day].
2. **Final System Yield (Y_f)** – The usable part of the energy obtained from the overall PV system and is a yield, carried to the load per kilowatt peak of installed PV array.

The following relations are required to estimate the above mentioned normalized parameters.

$$\text{Performance Ratio} = \frac{Y_f}{Y_r} \qquad (1)$$

$$\text{and } Y_f = \frac{E}{P_o}, Y_r = \frac{H}{G} \qquad (2)$$

where, E = Net energy output in kWh

P_o = Installed PV array in kW

H = Total plane irradiance in kW/m^2

G = PV reference irradiance in kW/m^2

The array yield Y_a which is defined as the number of hours/day, the array has to work at its nominal power P_0, in order that the system can contribute to the same quantity of energy which is actually measured in practice. The losses mainly include the two parts:

$$\text{Array capture losses } (L_c) = Y_r - Y_a \qquad (3)$$

$$\text{System losses } (L_s) = Y_a - Y_f \qquad (4)$$

The study being carried out, the data of one complete year considers to evaluate the energy performance of the PV system. Unused energy (L_u), when system is saturated. Normalized potential PV production, Y_u (battery never full) is in kwh/kW$_P$/day.

$$\text{Normalized unused energy} (L_u) = Y_r - Y_a \qquad (5)$$

V. STAND-ALONE SYSTEM SIZING

A. *Load analysis*

System configuration must first define user's first and foremost prerequisites. In SA systems, energy usage is based on daily, monthly or annual use. For every load, the energy is used for the immediate load order, for the required load order, the required energy and operating time for each load is necessary.

If the system includes AC load, then an inverter is required to change the DC voltage provided by an array or battery in the AV voltage. Choosing Inverter [11], many factors need to be considered. The peak watt hour of all AC loads should meet the inverter's power output. Inverter sizes are generally slightly larger than the demand for AC load for possible future load expansion. Inverter performance usually ranges from 80% to 95%.

This place has been taken up at Mayurbhanj, Odisha, where the monthly cost of the load is measured and most of the loads are considered stable during any month. Loads include home equipments and solar pumps, wherein the appliances are composed by TV, fan, fridge, mobile and lamps. Every day the electricity demand is received and the total needs that are required at different times of the year vary, the monthly weighting analysis is considered in this scheme. Total daily energy consumption is 5549Wh/day and total monthly energy is 166.5kWh/month for 60 Stand-by consumers.

B. *Battery sizing*

Following considerations are important:-

i. Requested autonomy

The essential autonomy of the desired nature is defined as the duration which can support the use of the battery without separating load. This whole battery charge occurs in the state and has been considered for a long time.

TABLE III
BATTERY OPERATION AND PERFORMANCES

Month	U_Batt V	SOCmean	SOC_End	EffBatI %	EffBatE %
January	51.5	0.476	0.549	97.0	95.0
February	51.6	0.482	0.627	94.5	93.0
March	51.8	0.503	0.489	94.1	96.6
April	51.5	0.472	0.179	93.9	99.9
May	50.2	0.353	0.285	94.3	92.4
June	50.2	0.352	0.360	94.3	92.8
July	50.1	0.342	0.413	94.2	93.1
August	49.8	0.318	0.325	94.2	95.5
September	50.0	0.333	0.313	94.5	94.6
October	51.5	0.474	0.476	94.6	92.0
November	52.3	0.542	0.681	94.5	90.9
December	52.7	0.585	0.423	94.5	98.2
Yearly count	**51.1**	**0.436**	**0.423**	**94.5**	**94.5**

Large autonomy demands for increased battery bank, which increases cost as well as complicated to sustain, but decreases the depth of discharge (DOD) and hence for the battery [12,13] it is advantageous. This is considered for four days.

ii. *Probability of Loss of Load (PLOL)*

This is one solution during one year that the PV module cannot fulfill the demand for load percentage. They can be present due to system failure. During the shaping process, PLOL [21] allows determining the desired size [14] for battery capacity given by the PV array. PLOL is controlled by autonomy and rebellion. In most practical SA systems, there is a 5% decrease in the probability of three to five days of autonomy. For the study taken into consideration, autonomy has been fixed for four days and PLOL is 5%.Figure 2 shows PLOL in terms of the PV power.

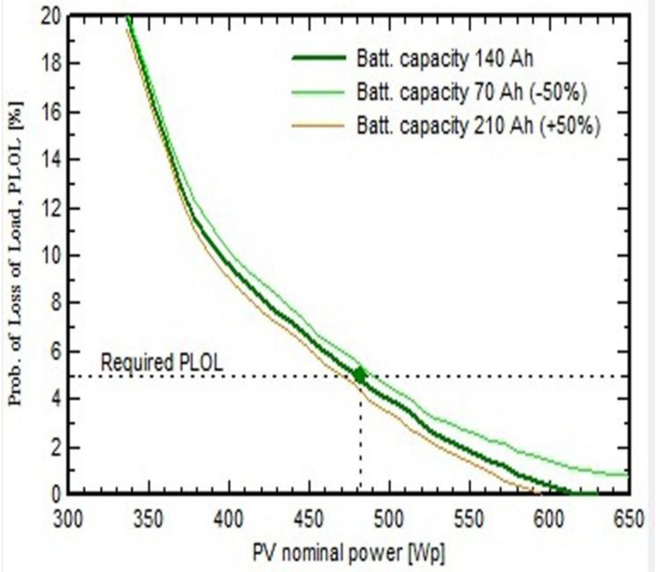

Fig. 2.PLOL as function of the installed PV power.

By the following equation the desired battery output can be calculated by loads and autonomy.

$$B_{out} = \frac{E_{daily} + T_a}{V_{dc}} \qquad (6)$$

Where, E_{daily} is energy consumption on daily basis and T_a is the autonomy, V_{dc} is DC voltage. The battery operation and performance variants are shown in Table III and Table IV has battery sizing parameters. The meaning of the different variables is following:

U_Batt: refers to average battery voltage,

SOCmean: is the average State of Charge (SOC) throughout the period,

SOC_End: a parameter referring to State of Charge at last part of time interval,

EffBatI: Battery current charge/discharge efficiency,

EffBatE: Battery energy charge/discharge efficiency.

TABLE IV
BATTERY SIZING PARAMETERS

Daily energy consumption	5549 Wh
DC system voltage	50V
Autonomy	4days
Battery voltage	3.6V
Battery capacity	293Ah
Number of batteries in series	14
Number of strings in parallel	116
Total number of batteries	1624

C. *PV array sizing*

Array sizes [17,19] designed carefully to power the battery and to provide adequate power over loads. When the current output is running, the first array is calculated by DC voltage and then the energy. However, after asking for a battery charge, it is mandatory that the current calculation is higher than the original because the battery charging efficiency is always less than 100%. The charging capacity for most batteries is from 85% to 95% [18] and the final output is then calculated using the following equation:

$$I = \frac{E_{critical}}{\eta_B \times V_{dc} \times t_{psh}} \qquad (7)$$

Where, $E_{critical}$ is consumption of daily energy for critical month, η_B is the efficiency of charge battery, V_{dc} is the voltage of the system and t_{psh} is the hour of peak sun for the critical design month. The rated voltage of the array can be calculated by:

$$V_{rated} = 1.2 \times V_{dc} \times \{1 + [C_{\%v} \times (T_{\max} - T_{ref})]\} \qquad (8)$$

Where, $C_{\%v}$ is the coefficient, T_{max} is the operating temperature of maximum module, and T_{ref} is the reference temperature. Battery sizing parameters are given in Table V. Where V_{mpp} is maximum power point voltage at reference temperature usually STC = 25^0C, Voc is open circuit voltage, Impp is maximum power point current and Isc is short circuit current.

TABLE V
ARRAY SIZING PARAMETERS

$V_{mpp}(60^0C)$	32.8V
$Voc(-10^0C)$	51.9V
Plane irradiance	1000W/m^2
Impp(STC)	36.2A
Isc(STC)	38.5A
Array nominal power (STC)	1.4kW$_P$

VI. RESULTS AND DISCUSSION

General information about system behavior Daily input / output figure is given in Figure 3. For every day, simulation was conceived as a global event radiation in an effective power and collector plane on the output of the array. It is thought that PV DC output power is dependent on the line at the solar radiation level. Ideally, it must be almost a straight line which is slightly saturated for large radiation values and plateau indicates overload (full battery) operation. The system output is 2058 kWh / year and the specific product is 1491 kWh / kWp / year which is the energy divided by the nominal power of the array (Pnom from STC), which is the display of system capacity, adverse conditions (site location, orientation, weather conditions) . Performance ratio is 76.4%, which indicates system quality, indirectly being indirectly.

TABLE VI
BALANCES AND MAIN RESULTS

Month	GlobHor kWh/m^2	GlobEff kWh/m^2	E_Avail kWh	EUnused kWh	E_User kWh	E_Load kWh	SolFrac
January	136.4	179.3	204.8	0.000	210.8	210.8	0.947
February	142.0	171.0	189.9	0.000	190.4	190.4	0.965
March	177.6	189.5	206.8	0.009	204.2	204.3	1.000
April	186.3	175.8	192.2	0.000	197.7	197.7	0.974
May	189.1	161.1	178.6	0.009	204.3	204.3	0.844
June	140.4	117.5	133.5	0.019	166.6	166.5	0.766
July	126.2	108.2	124.2	0.000	172.2	172.0	0.689
August	122.5	109.6	124.3	0.009	172.2	172.0	0.701
September	123.3	119.1	134.4	0.000	181.6	181.5	0.715
October	140.4	158.3	176.5	4.891	187.6	187.5	0.873
November	130.2	167.0	137.8	3.116	181.5	181.5	0.971
December	130.8	179.9	204.9	0.000	210.8	210.8	0.965
Yearly count	**1745.2**	**1836.3**	**2058.0**	**8.053**	**2280.1**	**2279.1**	**0.874**

Table VI given the overall yearly value and monthly values of main variables. The complete value of year can be a sum, like the irradiation or energies. Reference incident energy (Y_r) is 5.18kWh/m^2.day which is shown in Fig.4

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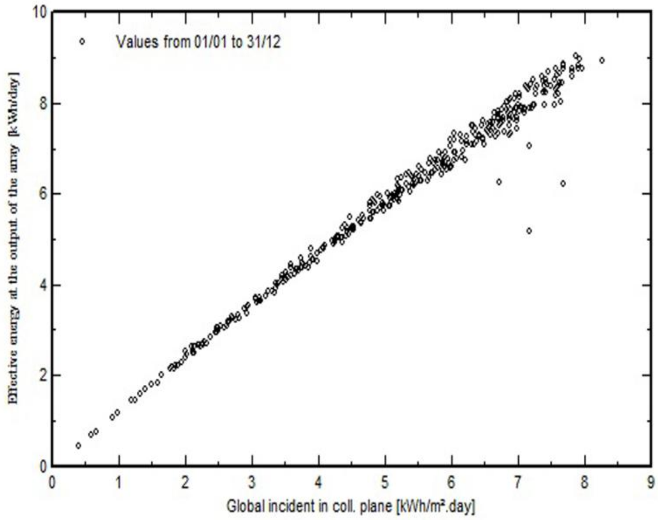

Fig. 3.Daily Input/Output diagram.

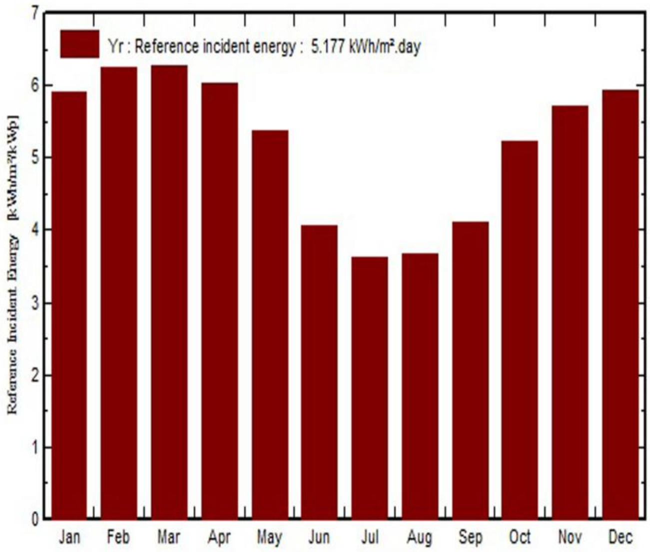

Fig. 4.Reference incident energy in collector plane.

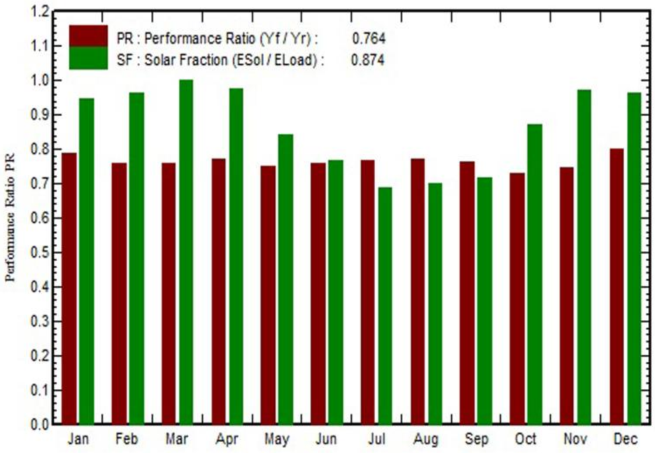

Fig. 5.Performance Ratio and Solar Fraction.

PR and solar fraction for the proposed stand alone system are depicted in Fig.5. The monthly graphs shown in Fig.6 and Fig.7 are expressed in units described by "Normalized Performance Index". By "Joint Research Center" (JRC), these parameters have been identified for the standardized report of PV system performance and they are now defined in the international IEC61836 norm.

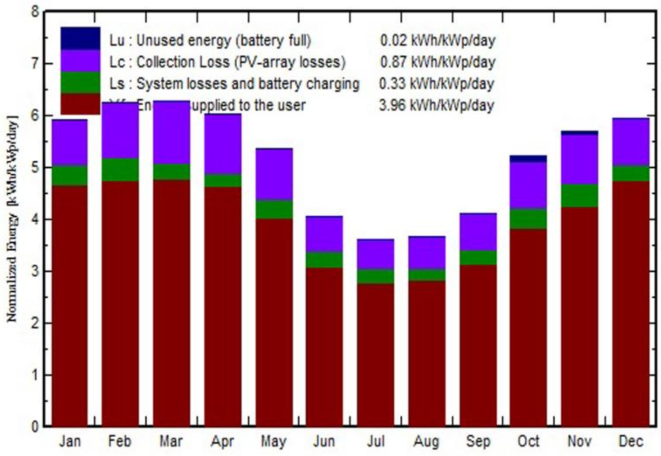

Fig. 6.Normalized productions (per installed kWP): Nominal power 1380WP.

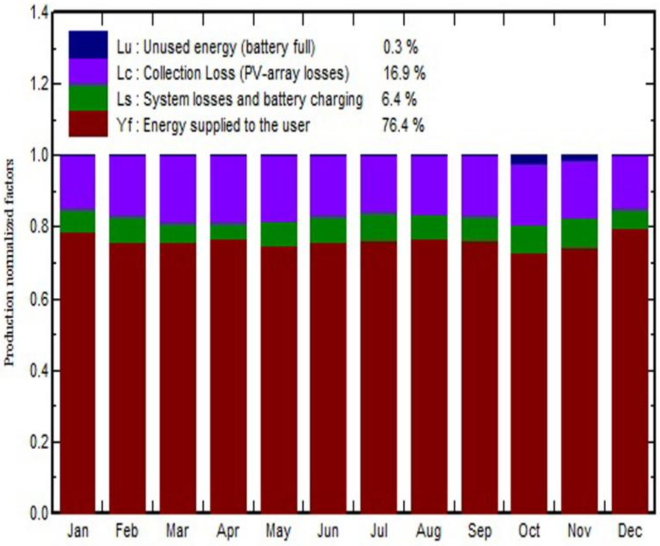

Fig. 7.Normalized productions and Loss Factors: Nominal power 1380WP.

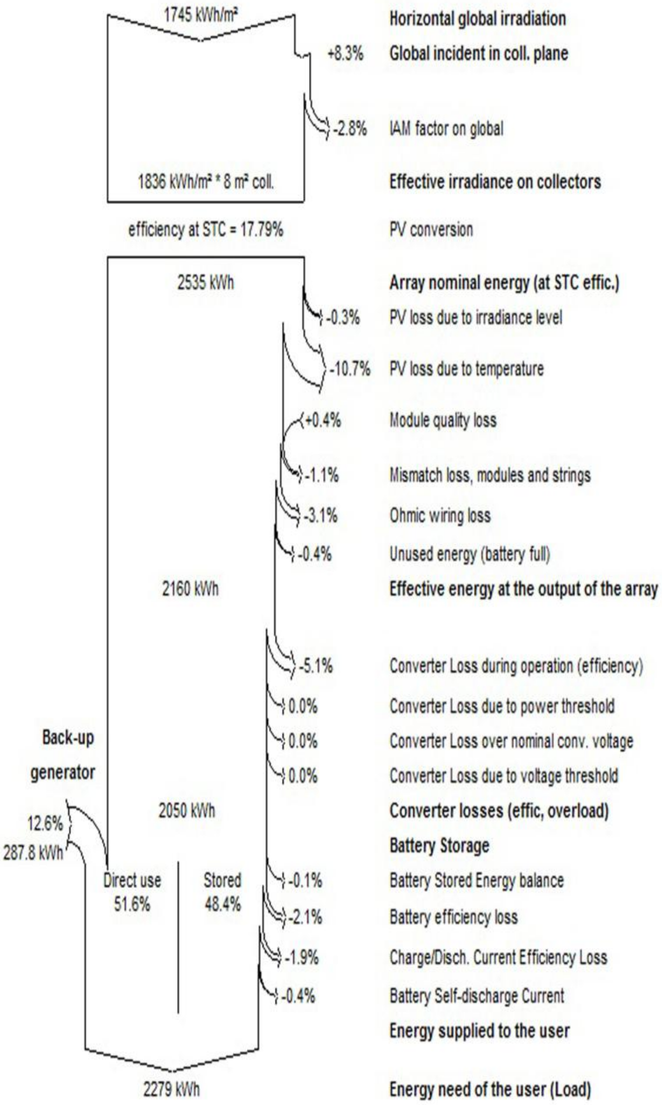

Fig. 8.Loss diagram over the whole year.

Figure 8 provides a significant and insightful look into the quality of the PV system design, by identifying the main source of the losses, which shows the loss diagram. A loss diagram can be estimated for the entire year or for each month so that the seasonal effects of specific losses can be assessed. Loss of the array global effective irradiation and the array MPP (maximum power point) on STC begin with a rough evaluation of nominal energy using nominal efficiency. Also considering the environmental variables, it gives the details of the PV model behavior. In the SA system, the system performance emphasizes the use of array output, battery specificity and energy. Figure 9, Daily Array shows the output power. SA systems a loss diagram, highlights battery usage, which is part of the energy effectively, transferred through the battery. It is important to reduce the battery life (number of battery / discharge cycle). All losses have been described percentages of previous power values. The nominal energy of the array is 2535 kWh, which would assume different types of losses like the set value of the configuration.

These designs are based on critical months and with autonomy; Battery capacity must be selected in order to meet any specific load requirements, to ensure that unused power loss is shown in large amounts. The last power of the load is 2297kWh, the entire system shows the efficiency of 89.9%.

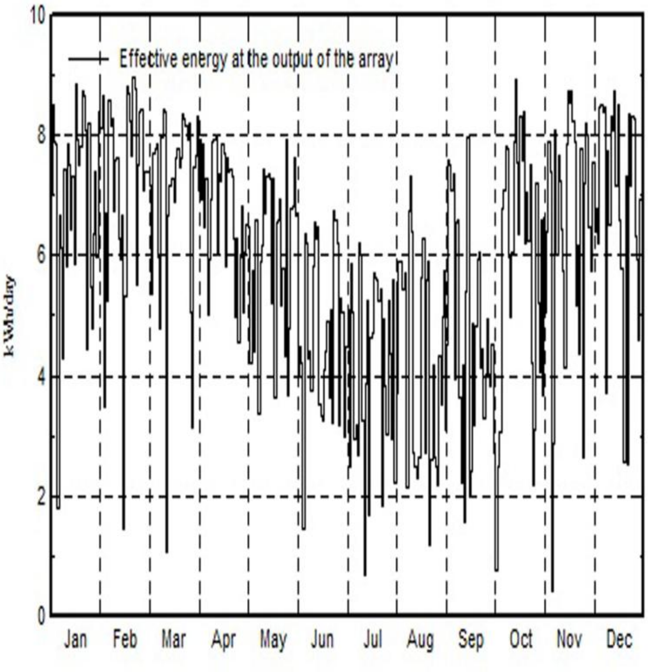

Fig. 9.Daily array output energy.

VII. CONCLUSION

In this paper, the standalone solar PV system operation performance is completed with various aspects of full year; Such as the overall system performance of the battery bank, PV array and SA PV system. Selecting the type of system based on the place because either the SA system is used for either a different area or away from the grid. Summarize the following facts:

1) Total system production is 2058 kWh/yr and specific production is 1491kWh/kWp/yr.

2) Normalized production is 3.96kWh/kWp/day and performance ratio is 0.764. These values are satisfactory.

3) System losses are 0.33 kWh/kWp/day and array losses are 0.89 kWh/kWp/day.

4) Efficiency of the system is 89.9%.

The data of the system taken into consideration is collected for a full year and analyzes the battery efficiency of the battery, PV array and the entire PV system. The results of long-term system monitoring with evaluation help system detailed inspection of operating performance, which also provides significant references to future applications of solar photovoltaic.

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