The Journal of CPRI,
Vol. 10, No. 2, June 2014 pp. 345-354

System Efficiency (non-module) Considerations in the Sizing Solar Photovoltaic Plants

Siddhartha Bhatt M*

This paper presents a review of the energy efficiency in solar photovoltaic (SPV) systems with special reference to quantification and improvement of non-module system efficiency. The system efficiency (also called as performance ratio) is composed of photopic efficiency (losses in light energy before actually interacting with the SPV cell surface) and electrical efficiency (losses in electrical energy output generated by the module and before it is used by the load). Non module system efficiencies of operating SPV plants range between 54.93 % to 70.16 % with an average value of 62.32 % and standard deviation of 4.57 %. System efficiency considerations are important in design of power plants for given end user loads. If the calculations are on the basis of kW_{peak}, a typical 100 kW_{peak} system gives a peak output of 50-65 kW at the load point due to system efficiency and also lowering of module efficiency due to non-standard operating conditions. System efficiency excludes auxiliary power (2-4 % of the generated power), losses in battery (~20 %) due to storage component loss of energy generated due to non-availability of the grid (for grid tied systems) and stochastic incident radiation loss (~16 %). System efficiency presents possibilities of improvement to 75-80 % level through improved system design and improved operation and maintenance practices.

Keywords: *Solar Photovoltaic, System Efficiency, Photopic Efficiency, Electrical Efficiency, Module Efficiency, Stochastic Efficiency.*

1.0 INTRODUCTION

SPV cell efficiencies are limited by the Stockley-Quieser (SQ) limit of 31 % without concentration and 41 % under concentration [1]. The overall efficiency of SPV cells and components constructed out of them, viz., modules, panels, arrays and plants can be increased by improvement in the cell and associated system efficiency through improvement in photopic and electrical efficiency.

Presently, SPV systems are used in three configurations:

- Off grid power generation systems with battery energy storage for autonomy.
- Grid connected systems without battery energy storage operating in the anti-islanding mode.
- Grid connected systems with battery energy storage for islanded operation during grid failure periods.

Energy losses are occurring in the SPV systems because of inability to capture the total light input, generation-load mismatch and down-the-line electrical energy drop in the system. Energy storage in batteries results in drop in efficiency by ~20 % points of the quantum of energy stored due to charge-discharge cycle losses. In the off grid and battery storage off grid periods, when the battery banks are fully charged and there is no

*Energy Efficiency & Renewable Energy Division, Central Power Research Institute, Sir CV Raman Road, Bangalore-560080, India.
Mobile : +91 9448459587, E-mail : msb@cpri.in

load, the SPV generation cannot be utilized and gets wasted. In the grid connected mode without battery storage, during a network failure, the SPV generation is not utilized. These also result in system losses but in the review is restricted to system inefficiencies and not loss of generation due to bulk energy mismatch. Stochastic losses refer to reduction in incident solar radiation from atmospheric disturbances and cloud cover with reference to the value in a clear and fully sunny sky.

Baltus *et al.* (1997) have measured SPV system losses, represented them through a Sankey's diagram and introduced the concept of Performance ratio (PR) as the ratio of the measured overall system efficiency to the module efficiency [2]. The PR is measured to be in the range of 0.612 to 0.737.

Modeling system losses in SPV systems, Mermoud (2012) [3] has classified system losses into optical, array and electrical losses and quantified these. Electrical yield improvement in SPV modules is through computation and minimization of the optical losses [4]. The concept of avoidable losses due to faults has been proposed and measured to be in the range of 3.6 % to 58 %. Avoidable losses have been identified in the optical system (shading) and electrical circuit (inverter shut down, system isolation, etc.) [5] and represented the percentage of the system losses which could be easily avoided during system operation.

System efficiency has been used as a basis for sizing of SPV system and has been modeled the system losses like shading, incident angle dependence, load mismatch, temperature effect on cells, array electrical limit losses [6,7]. The concept of system performance ratio has been brought out and quantified at 67 % for 421 sites over a period of 1995 to 1999 [7].

MPPT mismatch losses have been quantified in arrays. The effects of shading and string configuration have also been considered in the mismatch [8].

Losses due to accumulation of dust have been studied considering both masking as well as incident angle change in areas with rain and without rain [9]. The quantification of irradiance loss has been modeled for the whole day and shown to be as high as 14.8 % [9].

The system losses consisting of optical losses, electrical losses as well as due to MPPT tracking have been computed at 72 % [10].

Using loss factor model outdoor system performance of SPV has been evaluated for different types of cells like crystalline mono- and poly-silicon; and thin film [10].Shading losses in arrays have been worked out by Dorado et al. (2010) [11]

In this paper the efficiency improvement through system efficiency is presented. System efficiency is also known as performance ratio (in unit of p.u.).

2.0 OVERALL EFFICIENCY OF A SPV SSTEM

2.1 Overall Efficiency

The overall efficiency of a SPV system can be decoupled into module and system efficiency as,

$$\eta_{overallSPVsystem} = \eta_{module} x\, \eta_{system} \quad ....(1)$$

In other words the system efficiency is defined as,

$$\eta_{system} = \frac{\eta_{OverallSPVsystem}}{\eta_{module}} \quad ....(2)$$

Accurate determination of the module efficiency is of importance in the computation of system efficiency. Normally, modules are tested in sun simulators using xenon lamps. High accuracy sensors such as reflection type single long pulse flash lamps give accuracy of 1 %.

The system efficiency can be decoupled into photopic and electrical efficiency as,

$$\eta_{system} = \eta_{photopic} x \eta_{electrical} \quad ....(3)$$

The photopic efficiency is composed of the following losses which occur before the light gets converted at the cell level:

- Maximum irradiance level below 1 kW/m^2
- Shading
- String
- Sun-tracking
- Soiling of the glass cover with dust and dirt
- Module quality
- Reflection
- Angle of incidence
- PV module name plate DC rating

The electrical efficiency is composed of the following losses which occur after the electrical energy output is generated by the cell:

- Maximum power point tracking (MPPT)
- Tolerance of rated power variations due to variation in voltage, current, power factor, harmonic injection, power frequency, etc.
- Resistance/ohmic drop in components like wires, etc.
- Inverter losses
- Mismatch /calibration errors
- Overall DC-to-AC de-rating factor

The detailed definition, modeling and computation of the component efficiencies are brought out in several references [2, 3, 7]. In this paper a collective analysis of this data is attempted.

While the efficiencies give the conversion ratio they do not give the exact energy or power being generated over a time period for which the solar radiation data is required. By coupling the efficiency with the solar radiation data it is possible to estimate the energy generated and power over a period of time. The specific energy generation (SEG) is an index which combines the radiation data with energy efficiency.

2.2 Specific Energy Generation

The specific electrical energy generation (SEG): kWh/kW$_{peak}$ of installed module capacity at standard temperature and pressure (STP). The SEC is also being used by designers to guarantee minimum energy generated for a SPV installation.

$$Operating\ daily\ SEG\ \frac{kWh}{kW_{peak}} = \left[max\ daily\ solar\ rad\ \frac{kWh}{kW_{peak}}\right]_{rad} x\ \eta_{overall\ SPV\ sys} \quad ....(4)$$

$$Operating\ daily\ SEG\ \frac{kWh}{kW_{peak}} = \left[maximum\ daily\ SEG\ \frac{kWh}{kW_{peak}}\right] x\ \eta_{system} \quad ....(5)$$

The operating daily SEG is the inverse of the array to load ratio which is,

$$\frac{A}{L} ratio = \frac{1}{SEG} = \frac{kW_{peak}}{kWh} \quad ....(6)$$

The operating daily kWh/kW$_{peak}$ can also be represented in the form of daily plant load factor (PLF),

$$PLF = \frac{\text{kWh of energy output/day}}{kW_{peak} x24} \quad ....(7)$$

The index kWh/kW$_{peak}$ is nothing but (PLFx24). Suppose PLF is 20 % it is 4.8 kWh/kW$_{peak}$.

The SEG can be computed on probabilistic basis for different seasons.

2.3 Stochastic Losses

The importance of stochastic losses occurs because many designers provide guaranteed energy based on percentage of actual incident energy received. The actual incident energy is stochastic while maximum incident energy generated in a given location is deterministic. Firm performance guarantees are not provided and instead the guarantees are given as a percentage of the actual incident energy. If the stochastic efficiency is quantified and bound by predefined limits, the firm performance guarantees can be provided as the maximum radiation levels are deterministic. In other words, if the stochastic element is quantified as a percentage of the maximum value (deterministic), then the errors will be largely reduced.

Stochastic efficiency are given by,

$$\eta_{Stochastic} = \left(\frac{E_{actualincidentsolarradiation}}{E_{maximumincidentsolarradiation}}\right)_{year} \quad ....(8)$$

Stochastic losses are quantified and indicated but not possible to be controlled or reduced. Though uncontrollable, the quantification of stochastic losses is essential in arriving at the maximum possible generation from a given site over the year form providing performance guarantee and to decouple this from the system (non-module) losses.

The annual solar radiation (kW/m^2) data which represents the global radiation (sum of the diffused and direct components) is compiled as hourly average values for 12 points (0600 to 1800 hours) averaged over the month (for each given hour) for 35 years (1977-2012) (for each month). From 1959 till 1978 the data of Mani (1980) [12] is used. The subsequent data (1977 to 2012) is averaged along with the data up to 1978. In all, each set and grand average of the annual data can be represented by 144 values (12 daily values averaged over the month for 33 years x 12 months).

The long term monthly averaged variation of incident solar radiation (average over the whole day) is given in Figure 1. Considering the energy yield the operational year can be divided into three distinct phases:

- Summer season
- Monsoon (rainy) season
- Winter season

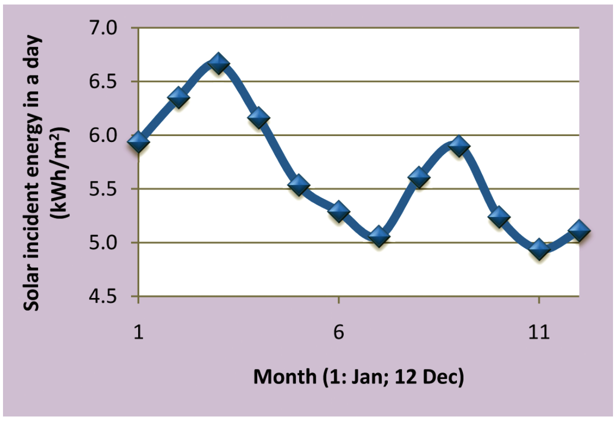

FIG. 1 VARIATION OF MONTHLY LONG TERM TIME AVERAGED SOLAR INCIDENT RADIATION (FOR A DAY) WITH MONTH FOR A TYPICAL TROPICAL REGION.

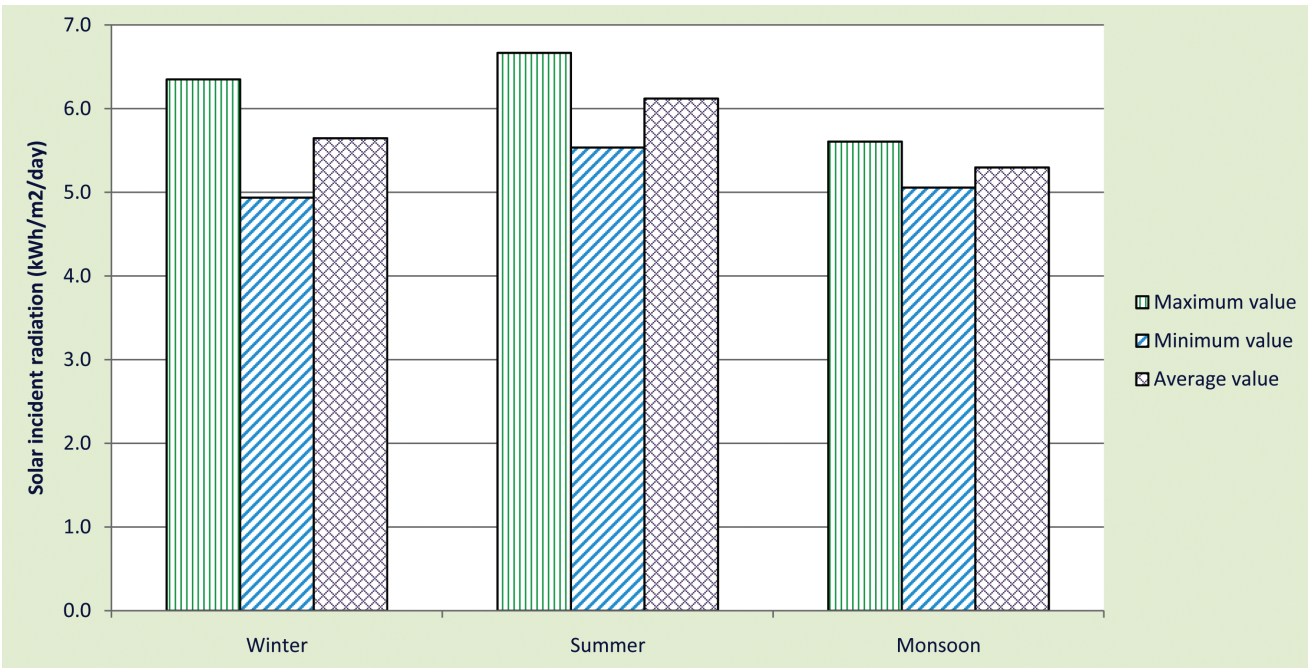

FIG. 2 VARIATION OF MONTHLY LONG TERM TIME AVERAGED SOLAR INCIDENTRADIATION (FORADAY) WITHSEASONFORATYPICALTROPICALREGION.

TABLE 1			
STOCHASTIC EFFICIENCY AND RANGE OF VARIATION IN THE TIME AVERAGED DAILY SOLAR INCIDENT RADIATION (AVERAGE OVER THE MONTH FOR THE WHOLE DAY)			
Sl. No.	**Particular**	**Unit**	**Value**
1	Maximum daily incident solar radiation	kWh	6.67
2	Minimum daily incident solar radiation	kWh	4.94
3	Average daily incident solar radiation	kWh	5.65
4	Total collectable energy	kWh	2434.55
5	Actual collectable energy	kWh	2053.71
6	Stochastic losses	%	15.64
7	Stochastic efficiency	%	84.36

The variation in the long term monthly average value (averaged over the whole day) for the three seasons is given in Figure 2. It can be seen that stochastic losses in solar incident radiation is 8.2 % in summer, 20.5 % during monsoon season and 15.4 % during winter. Table 6 gives variation in long term averaged daily incident solar radiation over the year for Bangalore. It can be seen that the average loss due to stochastic factors is 15.6 %.

To provide good visualization, the 10 s plots of solar incident radiation for the three seasons are shown in Figure 3.

3.0 RESULTS AND DISCUSSION

Table 1-3 give the module, photopic and electrical efficiencies of 10 systems studied. Table 4 gives the system efficiency and overall efficiency and Table 5 gives the analysis of the results of these 10 systems. The system efficiency does not take into consideration the battery storage efficiency, auxiliary power which is charged from the station transformer and loss of generation due to loss of grid availability (for grid tied systems only).Auxiliary power is generally required for air conditioning (cooling) of the inverter room, ventilation fans in the inverter room, plant lighting. Auxiliary power for a 1 MW plant is ~ 100 kWh/day which is 2 to 4 % of the plant output power. Charge-discharge efficiency of battery storage is 80 % for the quantum of stored energy.

TABLE 2											
PHOTOPIC EFFICIENCY OF TEN SPV PLANTS											
Sl. No.	**Particulars of Photopic efficiency**	**Efficiency (%)**									
1	Maximum irradiance level below 1 kW/m^2	95.4	95.5	95.4	95.5	99.05	97.0	95.5	95.4	95.4	95.4
2	Shading	96.5	94.4	99.3	98.0	94.4	97.0	96.0	99.0	99.0	100.0
3	String	97.5	97.5	97.5	97.5	97.5	97.5	97.5	97.5	97.5	94.4
4	Sun-Tracking	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0
5	Soiling of the glass cover with dust and dirt	99.05	97.9	99.05	97.0	99.07	98.0	99.05	99.05	98.0	95.0
6	Module quality	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8	96.8
7	Reflection	89.1	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0	96.0
8	Angle of incidence	94.0	94.0	94.0	94.0	94.0	94.0	94.0	94.0	94.0	94.0
9	PV module name plate DC rating	99.05	99.05	99.05	99.05	99.05	99.05	99.05	99.05	99.05	99.05
10	Photopic efficiency	**70.68**	**73.71**	**78.36**	**75.82**	**77.36**	**77.01**	**75.84**	**78.13**	**77.30**	**73.28**
	References*	[2]	[3]	[4]	[5]	[6]	[6]	[7]	[10]	[10]	[10]

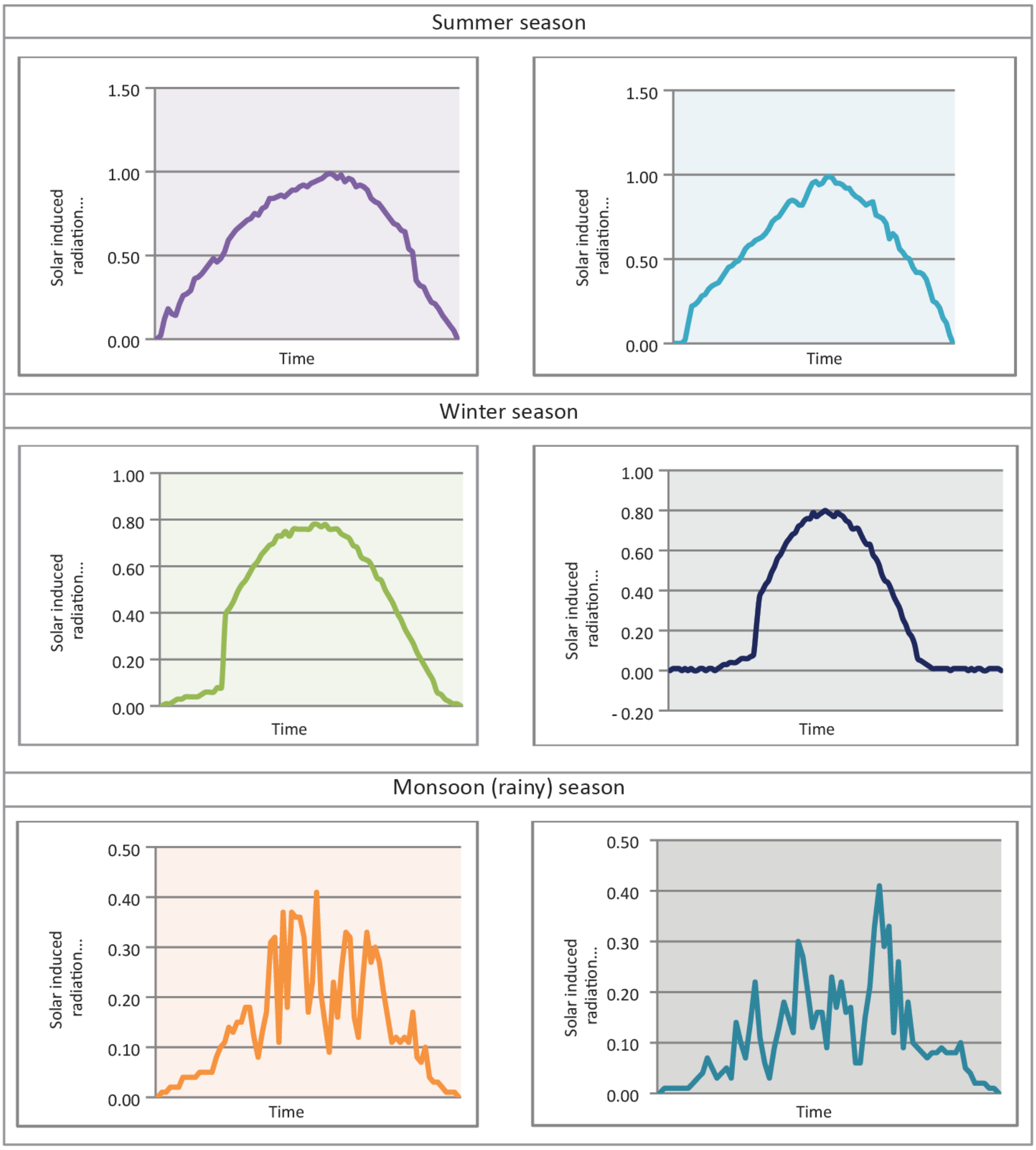

FIG. 3 PLOT OF 10 S VARIATION OF SOLAR INCIDENT RADIATION DURING THE SUMMER, WINTER AND MONSOON SEASONS

TABLE 3

ELECTRICAL EFFICIENCY OF TEN SPV PLANTS

Sl. No.	Particulars of Electrical efficiency	Efficiency (%)									
1	MPP-tracking	98.0	98.0	98.0	98.0	98.0	98.0	98.0	98.0	98.0	98.0
2	Tolerance of rated power range	96.0	96.0	96.0	96.0	96.0	96.0	99.0	96.0	96.0	95.0
3	Resistance (ohmic)	97.04	98.7	98.8	98.0	99.03	96.0	98.5	97.1	98.0	96.0
4	Inverter	90.3	93.1	90.3	93.0	99.06	92.0	94.0	99.08	90.0	92.0
5	Mismatch /calibration errors	95.0	97.9	95.0	95.0	99.02	95.0	91.0	99.02	99.02	98.0
6	Overall DC-to-AC de-rating Factor	99.23	99.23	99.23	99.23	99.23	99.23	99.23	99.23	99.23	99.23
7	Electrical efficiency	**77.71**	**83.98**	**79.12**	**80.83**	**90.68**	**78.33**	**81.12**	**88.93**	**81.53**	**79.96**
	References*	[2]	[3]	[4]	[5]	[6]	[6]	[7]	[10]	[10]	[10]

TABLE 4

MODULE EFFICIENCY OF TEN SPV PLANTS

Sl. No.	Particulars of fundamental module efficiency	Efficiency (%)									
1	Temperature	95.2	98.2	95.2	92.0	92.0	92.0	96.0	92.0	86.0	92.0
2	System availability	99.02	99.02	99.02	99.02	99.02	99.02	99.02	99.02	99.02	98.0
3	Ageing factor	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.0	99.5
4	Fundamental module conversion	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
5	Total fundamental module system efficiency	**13.35**	**13.77**	**13.35**	**12.90**	**12.90**	**12.90**	**13.46**	**12.90**	**12.06**	**12.83**
	References*	[2]	[3]	[4]	[5]	[6]	[6]	[7]	[10]	[10]	[10]

TABLE 5

OVERALL AND SYSTEM EFFICIENCIES OF TEN SPV PLANTS

Sl. No.	Particulars of overall SPV system efficiency	Efficiency (%)									
1	Photopic efficiency	70.68	73.71	78.36	75.82	77.36	77.01	75.84	78.13	77.30	73.28
2	Electrical efficiency	77.71	83.98	79.12	80.83	90.68	78.33	81.12	88.93	81.53	79.96
3	Total non-module system efficiency	**54.93**	**61.90**	**62.01**	**61.28**	**70.16**	**60.32**	**61.52**	**69.48**	**63.02**	**58.60**
4	Total fundamental module efficiency	13.35	13.77	13.35	12.90	12.90	12.90	13.46	12.90	12.06	12.83
5	Overall SPV efficiency	**7.33**	**8.52**	**8.27**	**7.90**	**9.05**	**7.78**	**8.28**	**8.96**	**7.60**	**7.52**
	References*	[2]	[3]	[4]	[5]	[6]	[6]	[7]	[10]	[10]	[10]

TABLE 6

ANALYSIS OF OVERALL AND SYSTEM EFFICIENCIES OF TEN SPV PLANTS

Sl. No.	Particulars of overall SPV system efficiency	Average	Maximum	Minimum	Standard deviation
1	Photopic efficiency	75.75	78.36	70.68	2.47
2	Electrical efficiency	82.22	90.68	77.71	4.39
3	Total non-module system efficiency	62.32	70.16	54.93	4.57
4	Total fundamental module system efficiency	13.04	13.77	12.06	0.47
5	Overall SPV system efficiency	**8.12**	**9.05**	**7.33**	**0.60**

Grid tied systems are characterized by absence of battery storage. However, due to power disturbance on the grid side, SPV Generation is also lost. In some case this can be partially used in battery storage.

System efficiency presents opportunities for improvement from 55-70 % to 75-80 % level through:

- Design improvements: advanced MPPT tracking systems, reduced tolerance bands of power output, improved inverter efficiency,
- Focused operation and maintenance: minimization of shading, cleaning of module surface, etc.

4.0 SYSTEM EFFICIENCY CONSIDERATIONS IN THE SIZING OF SPV PLANTS

The system efficiency plans a major role in the sizing of SPV plants. Modules of SPV plants are sized on one of the following criteria:

- Panel area (m^2)
- kW_{peak} of module output under STP conditions
- kW_{peak} at load end

The $P_{peak,\ load}$ delivered at the load end depends on whether module efficiency and non-module system efficiency is considered in the sizing. Installed capacity of the plants is generally sized based on P_{peak} delivered at the module output.

In many cases, the electrical power output at the module terminal under STP conditions is considered for calculations. In that case, the actual power output of the system at the load or user end gets reduced to the extent of the system efficiency as well as difference in STP and non STP module efficiency. For example a 100 kW_{peak}plant gives a maximum power output of 60-70 kW output at the load end.

This difference is due to the perceptional difference between the designer and the end user and could be resolved by considering the non-module system efficiency and non-STP module efficiency in the calculations to provide the power output at the end user terminal.

If the system efficiency as well as the non-STP module efficiency is taken into account, the SPV plant will have to be sized based on a much larger P_{peak} at the module output. The peak module output ($P_{peak,module}$) considering these factors is given by,

$$P_{peak,module} = \frac{P_{peak,load}}{\eta_{system} x \frac{\eta_{off-STPmodule}}{\eta_{STPmodule}}} \quad ....(10)$$

The peak power output of the module will have to be oversized to accommodate the system efficiency and deviation of module performance from STP conditions. In other words, it is tantamount to considering $P_{peak,load}$ as the starting point and work out the $P_{peak,module}$ backwards. In some cases, the photopic efficiency is absorbed in the sizing of $P_{peak,module}$but electrical efficiency is not. In that case $P_{peak,module}$will be oversized to the extent of the electrical efficiency.

Thus, it can be said that the non-module system efficiency plays a major role in avoiding de-rating of the actual panel output of a SPV plant.

5.0 CONCLUSIONS

The main conclusions of the study are as follows:

i. Overall efficiency of a SPV plant can be decoupled into module efficiency and non-module system efficiency. Non-module system efficiency is also termed as performance ratio (in unit of p.u.).Stochastic efficiency is also indicated to decouple the performance ratio from loss due to non-availability of the maximum solar incident radiation for the given site.

ii. Annual stochastic losses in solar radiation are around 15.6 %. The stochastic loss is 8.2 % during summer, 20.5 % during monsoon season and 15.3 % during winter. Though stochastic losses are uncontrollable they are essential for assessment of the annual energy generation from a plant. If these losses are evaluated, loss of energy generation from this factor can be quantified and losses higher than these can be ascribed to system (non-module) efficiency degradation. Otherwise, system efficiency degradation cannot be tracked accurately.

iii. While specifying SPV capacity, power output (kW_{peak}) must be specified either at the array output ($P_{peak,\ module}$) or at the load point($P_{peak,load}$). Though this looks trivial, overlooking of this factor has resulted in contractual disputes regarding the deliverable power output of SPV plants.

iv. The non-module system efficiency (range: 55 to 70 %, average value: 62.3 % and standard deviation 4.57 %) is a significant component and needs to be considered in the system sizing. If P_{peak} at the module output is considered as a basis for sizing, the finally installed plant will give a shortfall in P_{peak}. This also has contractual implication in projects.

v. If the kW_{peak} at the module output is considered under STP conditions then this has to be uprated to include non STP conditions. If P_{peak} does not consider the system efficiency then this will have to be considered to provide a given power output at the load end.

vi. System (non module) efficiency presents opportunities for improvement to 75-80 % level through improvement in MPPT tracking, improved inverter efficiency and reduced operational bandwidth; and improvement in operational and maintenance practices such as reduced shading, improved glass surface cleanliness, etc.

REFERENCES

[1] Rephaeli E, Fan S.Absorber and emitter for solar thermo-photovoltaic systems to achieve efficiency exceeding the Shockley-Queisser limit, OpticsExpress, Vol.17(17), Pp; 15145-15159.

[2] Baltus CWA, Eikelboom JA,Zolingen RJC, 1997, Analytical Monitoring of Losses in PV Systems. Paper presented at the 14th European Photovoltaic Solar Energy Conference Barcelona [ftp://ftp.ecn.nl/pub/www/library/report/1997/rx97043.pdf]; 1-5.

[3] Mermoud A, 2012, Modeling Systems Losses in PVsyst. Institute of the Environmental Sciences/Group of Energy/PVsyst. University of Geneva [http://www.docseek.net/mmrtyv/mermoud-pvsyst-thu-840-am.html]; 1-15.

[4] 2010, Doble D.Approaches to Energy Yield Improvement in PV Modules. Fraunhofer Center for Sustainable Energy Systems. Presented at Intersolar North America [http://cse.fraunhofer.org/Portals/55819/docs/energy-yield-improvement-intersolar-2010.pdf]; 1-19.

[5] Firth SK, Lomas KJ, Rees SJ, A simple model of PV system performance and its use in fault detection,Solar Energy,Vol. 84, Pp; 624–635.

[6] Anon, 2012, Grid-Tied Photovoltaic System Sizing, Harmony Farm Solar [http://www.harmonyfarmsupply.com/wp-content/uploads/2010/12/Photovoltaic-Solar-System-Sizing.pdf]; 1-2.

[7] Oozeki T, Izawa T, Otani K,Kurokawa K, An evaluation method of PV systems. Solar Energy Materials & Solar Cells, Vol.75, Pp: 687–695.

[8] Koirala BP, Sahan B,Henze N, 2012, Study on MPP Mismatch Losses in Photovoltaic Applications. Department of Electrical Engineering, Malaviya National Institute of Technology Jaipur, [http://www.docstoc.com/docs/135619823/study-on-mpp-mismatch-losses-in-photovoltaic]; 1-7.

[9] Casanova JZ, Piliougine M, Carretero J, Bernaola P, Carpena P, Lopez LM. Cardona MS, 2011, Analysis of dust losses in photovoltaic modules, World renewable energy congress, Sweden, [http://www.ep.liu.se/ecp/057/vol11/039/ecp57vol11_039.pdf]; 2985-2992.

[10] Sellner S, Sutterluti J, Ransome S, Schreier L, Allet N, 2012, Understanding PV Module Performance: Further Validation of the Novel Loss Factors Model and its Extension to AC Arrays, Steve Ransome Consulting Ltd, [http://www.steveransome.com/PUBS/2012Frankfurt_4EO35_OutdoorPerformance_LFM_Sellner_et_al.,pdf]; 1-6.

[11] Dorado ED, García AS, Carrillo C, Cidras J, 2010, Influence of the PV modules layout in the power losses of a PV array with shadows, University of Vigo, Spain, [http://webs.uvigo.es/carrillo/publicaciones/EPE-PEMC-2010 Influence of the PV modules layout in the power losses of a PV system.pdf]; 1-5.

[12] Mani A, Handbook of solar radiation data for India, New Delhi:Allied Publishers, p 451-462. (1980)