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Energy Metrics Analysis of Roof-Top Photo Voltaic System in North Indian Climate Conditions

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Abstract—*The analysis for energy metrics: energy payback time (EPBT), electricity production factor (EPF) and life cycle conversion efficiency (LCCE) of roof-top Photo Voltaic (PV) system for the climatic condition of north India has been carried out in this paper. The parameters, which have been calculated are embodied energy of the roof-top PV system and the annual electrical energy available from the roof-top PV system. The embodied energy for the roof-top PV system is determined by the manufacturing energy, material production energy, energy use and distribution energy of the system. Analysis shows that the embodied energy (E_{in}) of the PV system under consideration is 8493.16 kWh and EPBT of the rooftop PV system is 8.61 years. The obtained numerical values of EPF and LCCE of the roof-top PV system used in this paper are 0.116 and 0.178 respectively.*

Keywords: *Energy pay- back time, Electricity production factor, Life cycle conversion efficiency, India.*

1. INTRODUCTION

The global trend is moving towards the renewable energy resources as the demand for energy is increasing with the growth in the world population. The demand for energy cannot be satisfied without exploring the new options which are eco-friendly, abundant in nature and cost effective. Nuclear energy, wind energy, biomass, fuel cells and solar energy etc are some of the available options in the field of renewable energy. Solar energy is a renewable and freely available source, especially in Indian context, where most of the regions observe sunny days and clear weather throughout the year. Hence, solar energy is an option, which seems promising and sustainable energy option which ensures is pollution free too [1].

Solar radiations can be converted into either thermal energy or electrical energy or both. New developments in hybrid energy sources are available these days, which ensure the reliability and performance improvement of the overall system. In [2], hybrid renewable solar-wind energy combination has been discussed with simulation and experimental studies. Optimal sizing of Photo Voltaic (PV)/ wind/ fuel cell/ battery hybrid energy system to be used in a small scale industrial application has been explained in [3]. In a hybrid solar energy system, electrical and thermal energies are collectively produced from the associated solar energy system. One of this kind of system is hybrid Photo Voltaic / Thermal (PV/T) system. The hybrid system is more economical than its individual counter parts as it combines the advantages of PV and thermal systems as well. A PV/T system with reflector provides higher electrical and thermal output than its individual counter parts [4].Embodied energy payback is an important parameter to study as it makes no sense of using a technology if its energy production within its life time is lesser as compared to the energy utilized in the manufacturing. In this way, the cost effectiveness of the technology is also analyzed. This study includes the calculation of Energy Pay Back Time (EPBT), Electricity Production Factor (EPF), Life Cycle Conversion Efficiency (LCCE), known as Energy Matrices.

Kalogirou et al. [5] have done the performance analysis of thermal performance, economics and environmental protection using thermos-siphon water heating system for solar applications. Park et al. [6], worked on Building-Integrated PV system which is a very useful PV application technology. The hybrid PV/T collector was introduced as an integration of single-crystalline silicon cells into a solar thermal collector by Jie Ji et al. [7].

Dubey et al [8], have reported that the reduction in the temperature of the PV module by withdrawing the thermal energy associated with the PV module increases the overall electrical efficiency of the PV module. According to Harbi et al. [9], high ambient temperature in summer could lead to 30% drop in PV efficiency, though the thermal efficiency remains good. Bunjongjit et al. found that solar panel with Mono-crystalline and Polycrystalline has power generating capacity close to each other while thin-film can generate less power with the same amount of install area [10].

Pei Gang et al. [11] have observed the thermal and electrical efficiencies of the heat-pipe PV/T system. The authors have introduced a new heat-pipe PV/T system that can supply electrical and thermal energy simultaneously and observed its performance as compared to the conventional systems. Pacca et al. [12], states that the use of PV as breeders may dramatically reduce emissions and save fossil fuel resources. Chauray et al. [13], have done the estimation of CO_2 mitigation potential of solar home system in India by studying the potential for diffusion and the appropriate base line.

Purohit et al. [14], have studied the estimation of CO_2 mitigation potential of solar driven home systems under the clean development mechanism, which results into introducing emission reduction projects in India. Prabhakant et al. [15], analyzed carbon credit earned by each district for supplying electricity for running one fan and one light to each family of energy security in India. Keoleian et al. [16], have done the analysis of a set of model equations for evaluating different parameters under the collaboration between the University of Michigan, the US Environment Protection Agency and the United Solar Systems Corporation.

Alexis de Laboratories [17], proposed that that solar thermal system is an eco-friendly means of providing hot water for domestic use. This study emphasizes the environmental performances of such type of installations with a life-cycle approach. Nayak et al. [18], evaluated the annual solar and thermal energy performance of a PV/T and earth air heat exchanger system, integrated with a greenhouse, located at IIT Delhi, India, for different climatic conditions of Srinagar, Mumbai, Jodhpur, New Delhi and Bangalore. However, Gupta et al. proposed a method using adaptive particle swarm optimization which is efficient and promising for the minimization of real power loss of radial distribution systems [19]. Analysis of hybrid PV modules for the region of New Delhi, India has been done by Tiwari et al., in which they have presented the study of energy metrices [20]. Kim et al. [21] provides an alternative system for a commercial building with a rooftop PV generator and multiple plug-in hybrid electric vehicles (PHEVs).

Tiwari et al. [22], analyzed the EPBT and CO_2 emissions of PV system. The embodied energy for production of PV module based on single crystal silicon, as well as for the manufacturing of other system components have been computed at macro and micro-level assuming irradiation of 800–1200 W/m^2 in different climatic zones in India for inclined surface. The energy requirements for the production of PV panel and balance of system components was analyzed by Fukurozakia et al. [23], to evaluate the EPBT and CO_2 emissions from a 1.2kW roof top PV system in Brazil. Kaldellis et al. [24] has explained the method of utilizing solar energy for PV systems by which the growing worldwide demand of energy can be satisfied with an eco-friendly option even at remote locations too. Learning of financial learning curve concept was explained by Marzella Gorig et al., which is best suited for the study of PV modules and related systems [25].

The literature suggests some inferences, which have been included in this paper. The PV power generation system is best suited for eco-friendly power generation. According to [26], one of the important consideration in applying neural networks to power system security evaluation is the proper selection of training features among a large number of features that may characterize a given power system. Combination of PV array and battery provides a very good concept for minimizing the loss that can be used for various applications and gives more specific power generation options. It also ensures a good availability and reliability of the overall system with optimum matching. Energy metrics – EPBT, EPF and LCCE of the system are important parameters in determining cost effectiveness of a solar PV system. Energy performance based upon various energy matrices has been done to analyze the PV system. Numerical values of EPF and LCCE of this hybrid system proves to be higher than its individual counterparts. Longer sunshine hours, higher insolation, and more number of clear sunny days in a year are the factors which can reduce the numerical value of EPBT.

2. EXPERIMENTAL SET UP FOR ROOF TOP PV SYSTEM

In a simple PV system, the PV module and the load are connected with the water pump motor by direct powering, and are more complex, as in a system to power a house. Generally three types of PV systems, based upon the configuration, have been considered in literature: stand alone, grid connected and hybrid. PV modules with one another means of power generation e. g. wind, biogas, diesel etc make a system hybrid [4].

Arrangement of a number of PV modules or panels is known as PV array, which is used to power generation for different applications. Maximum dc power output (watts) is a parameter to measure the performance of PV modules under standard test conditions. In this paper, we have used a roof top PV module, which has been used for outdoor conditions as shown in Fig 1. The capacity of this module is 1.5kW which is used to supply the electricity to the rest of the circuit. The parameters under consideration are: variation of solar radiation on the module temperature, efficiency of the overall system and power generation.

The experimental set up consists of a PV array of size 7.32 m^2, which uses light energy to generate electrical energy (see Fig 1). A charge controller, which is driven by PV array, is used for regulating the power coming from PV array to the rest of the circuit via switching circuit. It keeps the battery charged and prevents the circuit from over charging. After the switching circuit, an inverter is used to convert DC into AC. Finally the load of the circuit gets the power from this DC output which can be used to perform the application.

During cloudy weather conditions and faulty situations, which lead to the non-functioning of the PV module, grid supply (220V, 50Hz, single phase) can be used. Kerosene power supply is used in case both the systems PV module and grid supply fail. In this way, this hybrid system ensures the overall availability of the power generation for different applications.

The performance parameters under consideration are: EPBT, EPF and LCCE. The period during which embodied energy is recovered, is called EPBT. The energy densities of different materials are required to evaluate embodied energy of various components of system. It is the total time period required to recover the total energy spent to prepare the materials (embodied energy) used for fabrication of the hybrid PV/T systems. It is the ratio of embodied energy and the annual energy output from the system. EPF is defined as the ratio of the output energy and the input energy and is a measure to predict the overall performance of the system. It is basically the inverse of EPBT. LCCE is the net energy productivity of the system with respect to the solar radiation over the life time of the system.

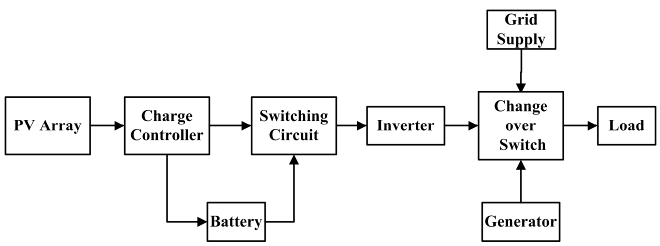

Figure 1: Block diagram of roof top PV system.

The work has been executed by taking following steps sequentially:

At first the study of 1.5 kW domestic rooftop PV systems has been done. After that we have done the data collection of Insolation, temperature, Short circuit current or Isc (Ampere), open circuit voltage or Voc (Volt) etc. (hourly/ daily /monthly) for various atmospheric conditions for determination of energy metrics (EPBT, EPF, LCCE) for Stand –alone PV system. CO_2 emission analysis of coal based plant. In the next step, we have performed the simulation of PV system in MATLAB/ Simulink (with and without maximum power point tracking (MPPT)) and analysis of energy metrics.

Typical north Indian climatic conditions of the states of Bihar, Uttar Pradesh, Punjab, Haryana, Gujarat, Rajasthan etc have been observed through this experiment The life cycle energy analysis has been carried out to quantify the energy in use and generation of energy through PV modules. The analysis has been divided into two divisions namely embodied energy and energy metrics.

The electrical energy was obtained by experimental observations in outdoor conditions for roof top PV system. The experiment has been carried out throughout the year. Hourly electrical energy has been found out by measuring open circuit voltage and short circuit current. The number of clear days in each month has also been recorded to find out the monthly average gain. The monthly electrical energy has been calculated by multiplying the total energy obtained within a day to the number of clear days in a year.

3. EXPERIMENTAL OBSERVATIONS

For analyzing different parameters in this experimental set up, variation in solar intensity, short circuit current and open circuit voltage has been observed throughout the months of January to August for all days and an average has been reported for each hour, during the sunny hours (from 8 am to 4 or 5 pm) of the day.

Solar intensity variation have been recorded and listed in Table 1, which varies from 120 to 600 w / m^2 over the day and observes its peak by noon. It ranges from 140 to 930 W/m^2 and gets its peak at about 1 pm in the month of February. Solar intensity variation ranges from 220 to 930 W/m^2 and during the months of March and April and achieves its peak at about 1 pm. In the months of May and June solar intensity is comparatively higher than any other season because of the summer season and varies from 250 to 935 W/m^2 and peak radiation is recorded at about 1 pm, and lowest radiation can be seen at 5 pm in evening. During the rainy season of July and August, the sun hours reduces from 11 am to 5 pm and solar intensity varies from 70 to 326 W/m^2; showing the highest value around 1 pm in afternoon.

The variation in short circuit current ranging from 5.7 to 30.8 Amp over the period of a day and gets its peak by noon as shown in Table 1. Variation from 8.2 to 48.6 Amp has been observed in the month of February and peak current is recorded at 1pm. In the months of March and April, it ranges from 12 to 49.8 Amp which also gains its peak at 1 pm. Short circuit current becomes higher in the months of May and June, mainly due to summer season and ranges from 13.5 to 50 Amp and again the peak is observed around 1 pm, reduces to about 10 Amp during evening hours around 5 pm. During the months of July and August, the sun hours reduce from 11 am to 5 pm and short circuit current varies from about 5 to 18 Ampere, mainly due to rainy season and observes its peak around 1 pm.

Table 1: Average hourly variation of solar intensity (W/m^2) and short circuit current Isc (Amp.)

Time	Average hourly variation of solar intensity(W/m^2)						Average hourly variation of short circuit current Isc(Amp.)					
	Jan 2016	Feb 2016	Mar 2016	Apr 2016	May–Jun 2016	Jul-Aug 2016	Jan 2016	Feb 2016	Mar 2016	Apr 2016	May–Jun 2016	Jul-Aug 2016
8 am	120	140	220	240	250	-	5.7	8.2	12.0	13.2	13.5	-
9 am	260	380	440	460	480	-	13.7	21.6	23.6	25.1	25.5	-
10 am	360	630	660	660	690	-	18.5	35.2	35.3	36.2	36.3	-
11am	530	800	830	850	890	70	27.00	43.8	44.4	46.1	46.5	4.9
12 noon	600	860	910	920	930	194	30.8	46.0	48.6	49.4	49.7	11.2
1 pm	580	930	920	930	935	326	30.3	48.6	48.8	49.6	49.8	17.8
2 pm	530	910	850	840	850	298	27.7	46.7	45.1	44.8	44.9	16.2
3 pm	330	740	760	750	770	200	17.5	39.3	41.1	40.7	41.0	12.1
4 pm	160	440	470	420	440	150	8.3	24.2	26.2	22.8	22.9	9.8
5 pm	-	-	140	170	180	111	-	-	8.2	9.4	10.0	5.5

Table 2: Average hourly variation of Open Circuit Voltage, Voc (Volt) and Power Generation (Watt).

Time	Average hourly variation of Open Circuit Voltage or Voc(Volt)						Average hourly variation of Power Generated (Watt)					
	Jan 2016	**Feb 2016**	**Mar 2016**	**Apr 2016**	**May–Jun 2016**	**Jul-Aug 2016**	**Jan 2016**	**Feb 2016**	**Mar 2016**	**Apr 2016**	**May–Jun 2016**	**Jul-Aug 2016**
8 am	20.40	20.10	20.50	20.40	20.50	-	81.39	115.37	172.20	188.49	193.72	-
9 am	20.20	20.20	20.60	20.20	20.60	-	193.72	305.42	340.31	354.91	367.71	-
10am	20.00	20.10	20.40	20.00	20.20	-	259.00	495.26	504.08	506.80	513.28	-
11am	19.70	20.00	20.20	19.80	19.90	19.20	372.33	613.20	627.81	638.95	647.74	65.86
12 noon	19.50	19.90	20.00	19.60	19.70	19.10	420.42	640.78	680.40	677.77	685.36	149.74
1 pm	19.60	19.80	19.90	19.40	19.70	19.20	415.72	673.59	679.78	673.57	686.74	229.82
2 pm	19.70	19.90	19.70	19.50	19.60	19.20	381.98	647.75	621.92	611.52	616.03	217.73
3 pm	19.90	20.00	19.90	19.60	19.70	19.20	243.78	550.20	572.52	558.40	565.39	162.62
4 pm	20.10	20.10	20.00	19.70	19.90	19.10	116.78	340.49	366.00	314.41	318.99	131.03
5 pm	-	-	19.50	19.50	19.70	19.00	-	-	111.93	128.31	137.90	73.15

Table 2 shows that open circuit voltage varies from 19.5 to 20.40 Volts over the day and peaks by early morning and late evening. During the month of February, it varies from 19.8 to 20.10Volts and peaks at about 9 am. During March and April it varies from 19.4 to 20.60Volts and peaks at about 9 am. During key summer months of May and June open circuit voltage is high and varies from 19.6 to about 20.6Volts and peaks at about 9 am in morning. However during the rainy months of July and August, the sun hours reduces from 11 am to 5 pm and open circuit voltage varies from about 19 to 19.2 Volts; with comparatively lower variation throughout the day.

Variation in power generation has been tabulated in Table 2, which shows that it ranges from 81 to 420Watts over the day and peaks by 12 noon. It varies from 115 to 673Watts and achieves its peak at about 1 pm in the month of February. Power generated varies from 175 to 680Watts and peaks at about 1 pm during the months of March and April. During summer months of May and June power generated is high and varies from 193 to about 685Watts and peaks at about 1 pm in afternoon. However during the rainy months of July and August, the sun hours reduces from 11 am to 5 pm and power generated varies from about 65 to 230Watts; with comparatively lower variation throughout the day.

The electrical energy provided by this hybrid system to the load has been estimated for one year based upon observations from Table 1 to Table 2. These have been estimated by average of the daily variation which has been considered over the year-

Average Energy generated by the PV array in winter days (over all winter months):

$E_{per\ day}$ (winter) = 3481.365 (Wh) = 3.48 KWh (per day)

Average Energy generated by the PV array in summer days:

$E_{per\ day}$ (summer) = 4687.913 = 4.68 KWh (per day)

Average Energy generated by the PV array in rainy days:

$E_{per\ day}$ (rainy day)= 1.03 KWh (per day)

The total number of days in which clear weather conditions can be observed in north India is about 280 days [6]. Hence, Total electrical energy provided to the load for one year is given as

$E_{per\ year}$ = [$E_{per\ day}$ (winter) × No. of clear days] + [$E_{per\ day}$ (summer) × No. of clear days] + [$E_{per\ day}$ (rainy day) × No. of clear days]

$E_{per\ year}$ = (3.48 × 85) + (4.68×150) + (1.03×45)= 1038.30 kWh

4. EMBODIED ENERGY CONSUMPTION OF ROOFTOP PV SYSTEM

Table 3 shows the total requirement of the energy for individual components of the system and the manufacturing energy[16]. The purpose of analysis of embodied energy regarding the given roof top PV system can be fulfilled by using these calculations.

Table 3: Individual components and their manufacturing energy [16]

Material production Energy (E_{mpe})			
Material	**Embodied Energy (kwh/m^2)**	**Total Area (m^2)**	**Total Embodied Energy (kwh)**
Silicon Purification and Processing: Metallurgical grade silicon production, Electronic grade silicon production, Silicon crystal growth	670.00	7.32	4904.40
Solar Cell Production	120.00	7.32	878.40
PV Module Lamination and Assembly: Steel infrastructure, Ethyle vinyl acetate, Tedler production, Glass Sheet production, Aluminum frame production, Other materials	190.00	7.32	1390.80
Total			7173.6
Total material production energy (E_{mpe}) = 7173.60 kWh.			
PV system installation energy ($E_{inst.}$).			
Support Structure: Iron stand Screw	7.70 (kWh/kg) 8.63 (kWh/kg)	40 kg. 1.00 kg.	308.00 8.63
Charge Controller	210.00 (kWh/kW)	0.36 kW.	75.60
Battery	46.00 (kWh/m^2)	7.32 m^2.	336.72
Inverter	210.00 (kWh/kW)	0.50 kW.	105.00
Wires	3.00 (kWh/m^2)	7.32 m^2.	21.96
			855.91
Total material production energy (E_{inst}) = 855.91 kWh.			
Energy used in maintenance (E_{main})			
Human labor	9.84	7.32	72.03
Energy used in administration (E_{admin})			
Transportation	53.50	7.32	391.62

The total energy associated with material production, transportation, cell/module fabrication, human, installation, maintenance and finally disposal/salvage has been considered for the calculation of life cycle and energy metrics.

Total manufacturing energy (E_{mfg}) = E_{mpe}+E_{main} = 7173.60 + 72.03= 7245.63 kWh. (1)

Total PV System Installation Energy (E_{inst}) =855.91 kWh. (2)

Total energy used in administration (E_{admin}) =391.62 kWh. (3)

Embodied energy (E_{in}) = E_{mfg}+E_{inst}+E_{admin}= 7245.63 + 855.91 + 391.62= 8493.16 kWh. (4)

5. RESULTS

Embodied Energy as calculated in the previous section is 8493.16 kWh. This value is used in the calculation of the EPBT, EPF and LCCE for life cycle span T_{LS} = 20 years).

$$EPBT, T_{ebp} = \frac{E_{in}}{E_{per\ year}} = 8.18\ years \quad (5)$$

$$EPF, \chi = \frac{E_{per\ year}}{E_{in}} = 0.122\ per\ year \quad (6)$$

$$LCCE, \varphi = \frac{(E_{aout} \times T_{LS} - E_{in})}{E_{sol} \times T_{LS}} = \frac{(985.84 \times 20 - 8493.16)}{428.5 \times 7.32 \times 20} = 0.178 \quad (7)$$

Where E_{aout} is the annual output (kW h/m^2/year) and E_{sol} is annual solar radiation input (kW h/m^2/year) [16].

Comparative analysis of CO_2 emission in roof top PV system with coal based plant PV System is given below:

5.1 PV system

An average CO_2 equivalent for electricity generation from coal is approximately 0.98 kg of CO_2 / kWh source [18].

If PV System has life time of 20 years, the CO_2 emission per year by each component can be calculated as [19]:

$$CO_2\ emission\ per\ year = \frac{(E_{in} \times 0.98)}{Life\ time} = 46.16\ kg/year \quad (8)$$

5.2 Coal based plant

In a coal based plant, an average CO_2 equivalent intensity for electricity generation from coal is approximately 0.98 kg. of CO_2 / kWh source[18].

Taking transmission and distribution losses to be equal to 40%, the total CO_2 equivalent intensity for electricity generation from coal will be 1.63 kg. CO_2 /kWh at source.

So, CO_2 emission per year = 1.63 × 1038.30 = 1695.89 kg / year.

Reduction in CO_2 emission (when using PV System over coal based plant for the generation of electricity) =1695.89 – 416.16 = 1279.73 kg / year = 1.28 t CO_2 equivalent

5.3 Trading

Assuming that the CO_2 emission reduction is being traded @ 21/t CO_2 e [21]

Then for the carbon emission reduction by PV system it becomes, 1.28 ×21×73.53

= ₹1976.4864 (per annum).

(Where €1=₹ 73.53 [22])

For life time of 20 years it becomes, ₹1976.4864 × 20 = ₹ 39529.728

6. CONCLUSION

Total embodied energy of the installed PV system under consideration is 8493.16 kWh. EPBT of the rooftop PV system is 8.61 years, which can be reduced for higher isolation, longer sunshine hour and number of clear days in a year. It is also observed that the EPBT is about doubled with change of condition from standard test condition to the varying outdoor condition**.** These results have larger inferences and impacts due to changing political scenario of Energy security, emissions issues, etc.

The cost-benefit analysis as compared to coal based power shows that the numerical values of EPF and LCCE of installed roof top PV system is 0.116 and 0.178 respectively. EPF is less as compared to PV system where MPPT is additionally employed. EPF as compared to coal based plants is still less, has intermittent supply yet its cleaner source, hence solar energy promotion requires national policy, incentives, awareness building and strong campaign to reach national targets.

Reduction in CO_2 emission (when using roof top PV system over coal based plant for the generation of electricity) has been found out as 1.28 t CO_2 e. (75% savings in emissions and enhanced quality of life; environmental gains as precious non-renewable sources can be saved and renewable energy sources are used).

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