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ANALYZING THE ENERGY METRICS OF PHOTOVOLTAIC (PV) SYSTEM IN NORTH INDIAN CLIMATIC CONDITIONS

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Abstract - The solar energy conversion into electricity is a very promising technique, knowing that the source is free, clean and abundant in several countries. With a strong commitment to increase the renewable sources based energy capacity to 175 GW by 2022, India has a target to install 100 GW of solar energy capacity. Of this 40 GW would be the share of grid connected solar PV rooftop. In this paper the performance of a Typical Domestic Rooftop Photovoltaic (RTPV) System through an experimental setup of 1.5kW RTPV installation in the subtropical climate of North India has been shown. Experimental setup was on the hourly electrical readings taken over the different months of year 2021, it has been exhibited that the use of MPPT Technique along with a domestic PV installation, not only reduces the Energy Pay Back Time (EPBT) of the system, but it also increases the Electrical Production Factor (EPF) and Life Cycle Conversion Efficiency (LCCE) significantly.

A SIMULINK model of 780W RTPV system is also being designed and simulated to show the significance of MPPT Technique implemented by Perturb & Observe (P&O) algorithm; in terms of consistent power generation over a long operational time, which in turn reduces EPBT as well. This paper is written with an attempt to blow off economical barriers for the potential customers in North Indian market by integrating MPPT technique with a Conventional, Clean & Renewable Energy Generating system which lowers the EPBT period, allowing access to free and clean energy source in remote or/and rural areas of India in the smallest possible time after the installation.

Keywords: Energy pay- back time (EPBT), Electricity production factor (EPF), India, Life cycle conversion efficiency (LCCE), Maximum Power Point Tracker (MPPT).

1. INTRODUCTION

The increasing political and environmental problems related to fossil fuel are the main drawbacks of traditional energy sources exploitation. A way to overcome these difficulties and to satisfy the growing electricity demand around the world is the use of photovoltaic systems which allow converting solar energy into electricity from sunlight. This clean technology inspired many researchers who studied the performance of different systems aiming to maximize the PV production with the least cost modifications. However, India crossed a significant milestone by providing electric access to all villages in April 2018. Since the transmission and distribution losses and costs are high in remote areas, the national electricity network is best complemented by small module renewable energy generation [IEA, 2014]. In rural and semi-urban areas of India, where 60% of the national population lives – 75 % of

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families connected to grid power in rural areas– regularly get less than six hours of uninterrupted power a day [5]. Hence, experts suggest that medium sized off-grid systems should be used for appliances and machinery in local rural industries, with more potential for livelihood creation. Rooftop PV based solar energy is an important component of the country's ambitious plans to thwart emissions from coal plants, build energy security and compensate for the electricity deficit.

1.1 The Indian RTPV scenario:

The Indian Government has set a target for achieving cumulative capacity of 40,000 MW from Rooftop Solar (RTS) Projects by the year 2022.Total realizable market for the rooftop solar PV is estimated at around 124 GW of the 350 GW gross potential. Indian policy targets capacity expansion programme of 100 GW installed by 2022, which includes 40 GW through decentralized rooftop solar projects. India has higher solar irradiance compared to many other countries and solar electricity potential is between 4 and 7 kWh per sq. m per day in most parts. The Government of India has revised the Solar Mission in 2014 with a target of 100 GW installed capacity of solar electricity by 2022. Out of which 40 GW is now projected to come through grid connected rooftop solar systems. Centralized grid connected and standalone solar energy strategy development is aiming towards energy security of the nation for achieving ‘24 × 7 power to all’ [20]. States and Union Territories in the country have identified their solar energy potential (Fig. 1)

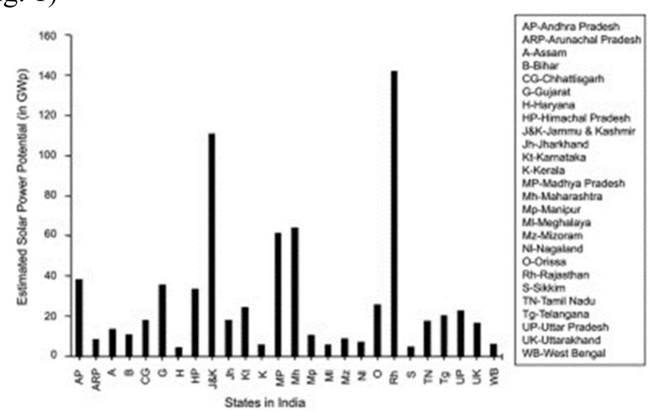

Fig 1 Solar energy potential of different States in India (Source e Ministry of New and Renewable Energy vide notification dated 24.11.14

It has been frequently observed that the-grid RTPV systems which are not integrated to grid cannot be utilized since the cost of installation and generation is high Despite variations in market based commercial arrangements, RTPV systems have offered several advantages such as –

• The overall development and installation time before operations is much less

• The units are installed on rooftops and hence save land hassles.

• The system offers to take off the peak hour afternoon loads thus reducing system congestion
• Comparatively lesser losses in transmission and distribution (T&D) [25]

However there are several factors affecting the productivity of rooftop solar PVsystemThe major factors affecting the energy output of a solar power plant as follows:
A. Location: Solar insolation varies with the location. In India, generally 4-7 kWh/m2/day solar insolation is received. B. Orientation: For obtaining maximum output from rooftop PV system, the orientation of PV array is very important. In the northern hemisphere, south-facing orientation of PV panel is preferred. C. Module type and their efficiency: Depending on the type of material used for fabrication of solar cell, efficiency of module varies. This is shown in Table II. The rated power capacity of module and its efficiency affects the size of PV array and number of modules required. This ultimately affects the roof area required for RTPV system [15]
D. Ambient temperature: In hot weather conditions, ambient temperature is a critical parameter that affects the output, because photovoltaic cell voltage decreases with rise in operating temperature of the module. E. Effect of shadowing: Shadow on photovoltaic modules has serious consequences. It leads to creation of hot spot. Partial shadow on module for long time may damage the module and also decrease the energy yield. F. Tilt angle: The tilt angle of PV modules also affects their productivity. Same PV module with different tilt angles will give different electrical output. Usually latitude angle of a location is taken as the tilt angle of the PV module. [21]

1.2 Literature Review

Various researchers have conducted studies related to outlook, challenges, development potential, and techno-economic feasibility of installing RTPV systems in various parts of the world [2]–[8]. India's energy needs are continually increasing. India, a developing nation, added a total installed electricity capacity from various sources from 1.362 GW in 1947 to 403.7 GW as of 30 June 2022 [1, 2]. The Indian government has set an ambitious goal of generating 175 GW of polluting free power by 2022.

Energy performance based upon various energy matrices has been done to analyze the PV system. [22] states that the use of PV will reduce CO2 emissions and in turn save fossil fuel resources, further reducing the EBP. [2] and [22], estimated CO2 reduction potential for typical solar based systems at homes in India.

[13] and [14] focuses on adoption affinity in developing countries and various barriers to it. Financial learning curve concept was explained by MarzellaGorig et al. [2016], which is aptly suited for the markets of PV modules and related systems. Their study emphasizes the environmental performances of such types of RTPV installations with a life-cycle approach.

According to [15], the 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.
In [16[, we can observe that MPPT - a power electronic interface using boost converter and a line commutated inverter further improves performance.

In [17], we can observe simulated and compared characteristics of the established solar module model under different temperature and irradiance conditions. After that, a model of a PV system with Maximum Power Point Tracker (MPPT), was developed using a DC-DC buck-boost converter with the Perturbation and Observation Method.
In order to understand which MPPT technique has the best performance, TarakSalmi et al., [18], [19], Roberto Faranda et al., KinalKachhiya et al. and Samer Said et al., researched PV array models using MATLAB/Simulink with the assistance of SimPower System toolbox.
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The literature suggests the following inferences:

- The Photovoltaic power generation system is more beneficial for pollution free power generation.
- The optimum matching and combination of PV array and battery capacity leads to more robust power generation with fewer losses for various applications.
- Research to minimize the input cost value of photovoltaic system installation and also to reduce its energy payback time.
- Energy metrics can be a measure to determine cost effectiveness of a solar PV system.
- The annual energy performance is preferred for determining energy metrics.
- MPPT increases the efficiency of the PV cell.

1. EXPERIMENTAL SETUP

Main components of grid connected RTPV system are solar photovoltaic modules, module mounting structure, inverter, interconnection cables & switches, and net energy meter. Grid tied systems usually do not have battery storage system. [12]
a) Solar PV modules should be made in India type. PV modules must be certified by IEC 61215/IS 14286 standards, which tests the quality and type of module and IEC 61730 standard examines the module safety against electrical shock hazard, fire hazard, mechanical, and structural safety. PV modules should be protected against surges and low voltage drop, and bypass diodes should be provided. The total module capacity should not be allowed below 250 W and the module frame should be made from corrosion resistant materials, like anodized aluminium. The variation of peak-power point voltage and current should not be more than 2% from the respective arithmetic-means for all PV modules or strings.
b) Array structure: For mounting the module or string, hot dip galvanized mild steel mounting structures should be used and structure inclination angle should be taken as per site conditions

for obtaining maximum insolation. The structure should be designed perfectly to withstand the speed of wind at the location. The structure design should be certified by a recognized lab or institution. IS 2062 and IS 4759 are the Indian standard specification codes that provide the specification for steel structure and specification for galvanization of the mounting structures respectively. The structure should be designed to allow simple and easy replacement of PV module and also occupy less space without any loss of productivity of PV module. The total weight of the structure including PV modules on the roof should be less than 60 kg/m2. The structure should have a minimum clearance of 0.30 m from the roof level [10].

c) Junction boxes: The junction box may be made of fiber reinforced plastic or powder coated aluminium or cast aluminium alloy. It should be provided with water and dust proof arrangement in the PV array. Junction box should consist of copper bus bars and should confirm to IP 65 standard (International Protection ratings consists of 2 digits, first stand for level of protection against solid bodies and second digit stands for degree of protection against liquid bodies [11]. Each junction box should have Metal Oxide Varistor's (MOVs) of high quality, suitable capacity, and suitable reverse blocking diodes.

d) Inverter The generated DC power is converted into AC power through inverter and control & protection devices. These components are together termed as power conditioning unit. The total capacity of all inverters should not be less than roof top solar power plant rated capacity under standard test conditions. The inverter output should be compatible with the grid frequency. Inverter's no-load losses should be less than 1% of rated power.

e) Metering arrangement and interconnection agreement Net meter is a bi-directional meter. It has the facility to record the net energy values between importing energy and exporting energy from distribution licensee. Distribution licensee means a company granted a license as per electricity act or authorized to operate and maintain a distribution system and supply electricity to his area's consumers. At the end of billing period, if the exported energy value is more than imported energy than distribution licensee will pay the consumer as per agreement. These prices are different for different states in India. Net meter is connected at the interconnection point of consumer and distribution licensee. Jaipur Vidyut Vitran Nigam Ltd (JVVNL) is the distribution licensee company at Kota, Rajasthan. JVVNL provides the guidelines and procedures for net metering and grid connectivity of RTPV power systems.

In this study, we have used a Roof Top PV module, which has been put in outdoor conditions. The capacity of this module is 1.5 kW 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. Block diagram of rooftop PV systems is given in Fig.2

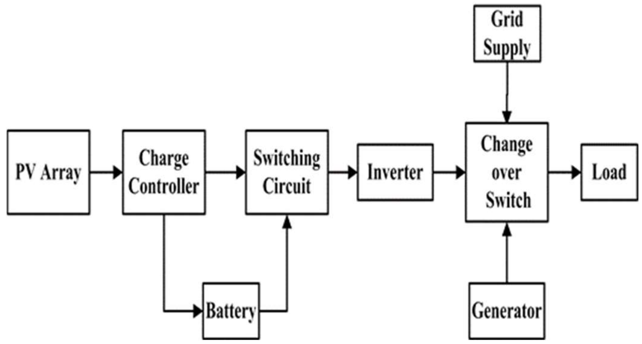


Fig. 2 Block diagram of roof top PV system.

The experimental set up consists of a PV array of size 7.32 m2, which uses light energy to generate electrical energy (see Fig. 1(b). 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) has been used. Kerosene power supply is used in case both the systems PV module and grid supply fail.

The maximum power has been tracked with the help of MPPT. The output of the MPPT has been given to the IGBT gate in order to trigger the IGBT. This will allow the PV array to adjust itself based on the inputs at the maximum power point. The output of PV array, through a current controlled source is fed to a universal bridge which is acting as an inverter in this model. The inverted supply has been fed to the load or to the grid if in excess. 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 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 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, LCCE, EPF) for stand – alone PV system.

Typical north Indian climatic conditions of the states of Bihar, Uttar Pradesh, Punjab, Haryana, Gujarat, Rajasthan etc have been observed through this experiment in Delhi. The life cycle energy analysis is important to quantify the energy used in making of the components and subsequently the generation of energy through PV modules. The electrical energy generation was obtained through experiments and their observations in outdoor conditions for roof top PV system.

The experiment has been carried out in the year of 2017 (from Jan to Dec months). The hourly electrical energy has been estimated through the measurement of an open circuit voltage and short circuit current in the system. The number of sunny days in each of the experiment month have been recorded to compare with the workings of the experiment results to have insights in the monthly average gain during the process. The yearly electrical energy can also be calculated using the sunny hours available throughout the day over months.

2. FINDINGS

2.1 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 December 2021 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, which varies from 120 to 600 w / m2 over the day and observes its peak by noon. It ranges from 140 to 930 W/m2 and gets its peak at about 1 pm in the month of February. Solar intensity variation ranges from 220 to 930 W/m2 and during the months of March -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/m2 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/m2; 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. 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 - 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- 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. the average hourly data is reported in Table-I.

Table-I

Average hourly variation of Open Circuit Voltage, Voc (Volt)

Time	Average hourly variation of Open Circuit Voltage or Voc(Volt)					
	Jan-Feb 2021	Mar-Apr 2021	May–Jun 2021	Jul-Aug 2021	Sept -Oct 2021	Nov-Dec 2021
8:00 AM	20.1	20.4	20.5	18.5	20.5	20.4
9:00 AM	20.2	20.2	20.6	18.8	20.6	20.2
10am	20.1	20	20.2	18.9	20.4	20
11am	20	19.8	19.9	19.2	20.2	19.7
12 noon	19.9	19.6	19.7	19.1	20	19.5
1:00 PM	19.8	19.4	19.7	19.2	19.9	19.6
2:00 PM	19.9	19.5	19.6	19.2	19.7	19.7
3:00 PM	20	19.6	19.7	19.2	19.9	19.9
4:00 PM	20.1	19.7	19.9	19.1	20	20.1
5:00 PM	18.5	18.8	19.5	19.5	19.7	19

Energy metrics – EPBT, EPF and LCCE of the system are important parameters in determining cost effectiveness of a solar PV system. Literature based numerical values of EPF and LCCE of the 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.

The electrical energy provided by this hybrid system to the load has been estimated for one year based upon observations from Table 1 and Fig. 3(a)-(c). 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):
Eper day (winter) = 3481.365 (Wh) = 3.48 KWh (per day)

Average Energy generated by the PV array in summer days:
Eper day (summer) = 4687.913 = 4.68 KWh (per day)

Average Energy generated by the PV array in rainy days:
Eper 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

Electrical Energy Generated for the same 280 days with using MPPT Technique is given by:

Electrical Energy Generated (Yearly) = 1072.37kWh

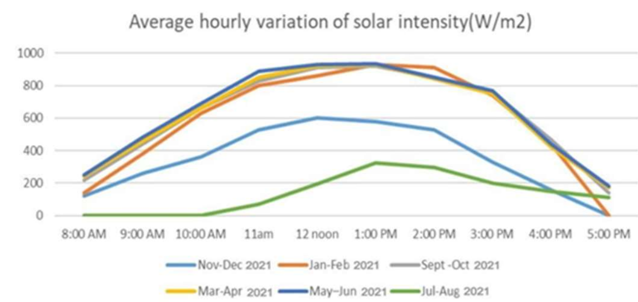


Fig.3 (a) Average hourly variation of solar intensity (W/m2)

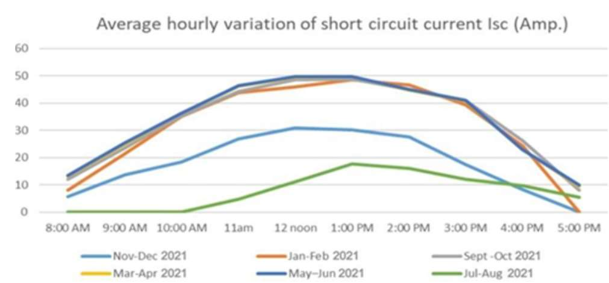


Fig. 3 (b) Average hourly variation of short circuit current Isc (Amp.)

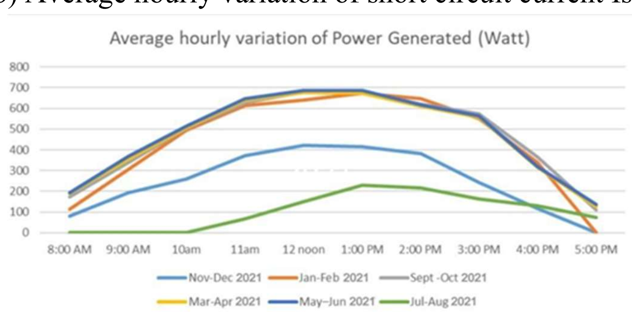


Fig. 3(c) Average hourly variation of Power Generated (Watt)

2.2 Embodied energy conversion in roof top PV

The purpose of analysis of embodied energy regarding the given roof top PV system can be fulfilled by using these calculations. The total energy associated with any kind of material or component production, its logistics and transportation to assembly sites, its basic cell or module fabrication, along with manpower requirements, efforts for its installation, regular maintenance practices. Ideally it shall include the efforts in its disposal should be considered for the accurate estimation of its life cycle and energy metrics [3].

Total manufacturing energy (Emfg) =
Empe+Emain = 7173.60 + 72.03= 7245.63 kWh. (1)

Total PV Installation Energy (Einst) =855.91kWh (2)

Total energy used in administration (Eadmin) =391.62 kWh. (3)

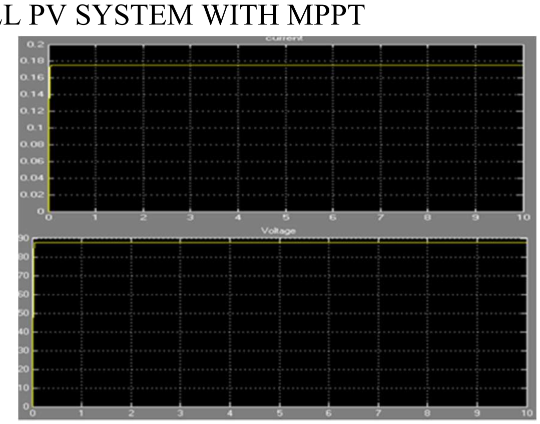
Embodied energy (Ein) = Emfg+Einst+Eadmin
= 7245.63 + 855.91 + 391.62= 8493.16 kWh. (4)

3. PV SYSTEM SIMULATION WITH & WITHOUT MPPT

To verify the function of MPPT discussed above, a Standalone 780W RTPV system is simulated with and without MPPT based on P&O Algorithm. The boost converter employed is then connected with an inverter and load to help simulate the system under study. The overall developed system with MPPT has been shown in Fig. 4(a).

The waveform for voltage and current for without MPPT are shown in Fig. 4b). Perturb and observe is the most popular method has been used in this work for implementing maximum power point tracking. The waveform for voltage and power is shown in Fig. 4(c).
The nature of waveform is in compliance with the actual behavior of the system. The distortion present in the waveform are due to the presence of ripples/harmonic while conversion from DC to AC.

- FIG.4 (A) OVERALL PV SYSTEM WITH MPPT



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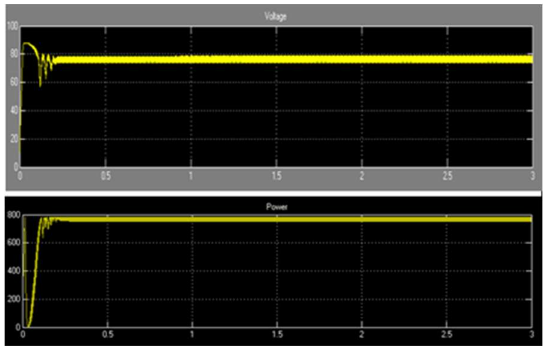
- FIG 4(B) PV OUTPUT VOLTAGE & CURRENT WITHOUTMPPT



o FIG 4(C) PV OUTPUT VOLTAGE & POWER WITH MPPT

5. ENERGY METRICS COMPARISONS

5.1 The EPBT without MPPT

Embodied Energy as calculated in previous section 8493.16 kWh. This further helps in calculating the key components of the Energy Matrices i.e. Payback time period (EPBT), Electricity Production Factor (EPF) and Life Cycle Conversion Efficiency (LCCE):

$$\text{Energy Pay Back Time (EPBT)} = \frac{\text{Embodied Energy}}{\text{Electrical Energy Generated (Yearly)}}$$

$$T_{epb} = \frac{8493.16}{1038.30}$$

$$T_{epb} = \mathbf{8.18\ Years}$$

$$\text{Electricity Production Factor (EPF)} = \frac{\text{Electrical Energy Generated (Yearly)}}{\text{Embodied Energy}}$$

$$\chi = \frac{1038.30}{8493.16}$$

$$\chi = \mathbf{0.122\ per\ year}$$

$$\text{Life Cycle Conversion Efficiency (LCCE)} = \frac{\text{Eaout} \times \text{TLS} - \text{Ein}}{\text{Esol} \times \text{TLS}}$$

$$\Phi = \frac{(1038.30 \times 20) - (8493.16)}{(428.5 \times 7.32) \times (20)}$$

$$\Phi = \mathbf{0.174}$$

5.2 The EPBT with MPPT

Following on the same footsteps but with Egenerated = 1072.37kWh

$$T_{epb} = \frac{8493.16}{1072.37}$$

$$T_{epb} = \mathbf{7.92\ Years}$$

$$\chi = \frac{1072.37}{8493.16}$$

χ =**0.126 per year**

$$\Phi = \frac{(1072.37\times20)-(8493.16)}{(506.8\times7.32)\times(20)}$$

Φ = **0.1746**

The data comparison is given in Table-II. Two observations can be made:

- the EPBT becomes 7.92 years. The EPBT with MPPT is reduced by 0.70 years due to increased value of the yearly generated electrical energy.

- Electricity Production Factor (EPF) with MPPT is enhanced to 0.126 per year. Hence it is enhanced by 0.004 per year.

Table-II

S No.	Key indicator of energy Matrices	Energy Metrics without MPPT	Energy Metrics with MPPT	Impact made
1	Energy Pay Back Time (EPBT)	8.18 Years	7.92 years	Reduced by 0.70 years
2	Electricity Production Factor (EPF)	0.122 per year (χ)	0.126 per year	Enhanced by 0.004 per year
3	Life Cycle Conversion Efficiency (LCCE)	0.178 (Φ)	0.1746	Improvement by approx. 3%

4. CONCLUSIONS

Total embodied energy estimated in the experiment of the installed PV system in Delhi is 8493.16 kWh. EPBT of the rooftop PV system in the study is estimated to be 8.61 years. This can be reduced by 5% to 8% with the intervention of Maximum Power Point Tracker (MPPT) which is nowadays commonly available. It is also observed that the EPBT is slightly improved with use of MPPT as compared to standard test condition to the varying outdoor condition. Additionally EPBT can be higher with higher insolation for the better locations nearing equator (in south Indian conditions), longer sunshine hours available due to local climatic conditions and number of clear and sunny days in a year.

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.

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