Solar Energy 159 (2018) 415–422

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Life cycle assessment of the 3.2 kW cadmium telluride (CdTe) photovoltaic system in composite climate of India

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A R T I C L E I N F O

Keywords:
Performance assessment
Photovoltaic systems
Life cycle assessment
CdTe
Carbon credit
Energy payback time

A B S T R A C T

Life cycle assessment for new emerging photovoltaic (PV) technology is an important tool to establish a PV system in field condition. In this paper, life cycle assessment of the 3.2 kW cadmium telluride (CdTe) PV system has been carried out on the basis of actual field performance data in a composite climate of India. Further, analysis has been performed on the basis of the energy metrics, life cycle assessment, per unit cost of electricity and carbon credit earned. The analysis of the PV system has been performed under the same environmental conditions likely solar irradiation, ambient temperature and wind speed, etc. Energy payback time (EPBT), energy production factor (EPF) and life cycle conversion efficiency (LCCE) of the PV system has been found to be 3.60 years, 0.27 and 0.0018 respectively. The unit cost of electricity of the PV system has been calculated as 9.85 INR/kW h for 5% interest rate and 30 years life span.

1. Introduction

Cadmium telluride is an emerging technology to use in the terrestrial applications. The advantages of CdTe material are its suitable band gap, and its high optical absorption coefficient nearly about 100% due to the fact of thickness being approximately 2 μm (Ferekides et al., 2004). Large area CdTe PV module has also demonstrated high performance and the ability to attract production scale capital investment (Wu, 2004). It's composed two types of layers p type as light absorbing layer and n type as the front surface layer as shown in Fig. 1 (Li and Liu, 2015). However, the conversion efficiency of the thin film PV module is slightly lower than crystalline silicon (c-Si) PV module. So, the production of CdTe PV module is marginally lower than the other c-Si PV module. However, the global production of the different PV technologies has been increased up to 303 GW at the end of 2016 in which the contribution of CdTe PV technology is around 2.5 GW (REN21, 2017). Nevertheless, the PV market dominated by the c-Si PV technologies, but thin film PV technologies account for 12% of the total production in 2010 (Mints, 2011). One of the major issue at this time is the reduction of the CO_2 emission from the environment and promote the renewable energy technologies to generate the electricity (Vellini et al., 2017). At the same time doubt identified by PV system is energy payback time (EPBT), because EPBT is best indicator of the net potential for CO_2 mitigation (Alsema, 2000; Candelise and Winskel, 2012). At first, Slesser and Hounam (1976) reported EPBT of PV module is 40 years. Yamada et al. (1995) concluded that the CO_2 emission from a rooftop PV system is higher (50–60 g/kW h) in comparison to ground mounted system (20 g/kW h) respectively. The EPBT of rooftop PV system and ground mounted PV system is 2.5–3 years and 3–4 years respectively. Mason et al. (2006) carried out performance analysis of 3.5 MW mc-Si PV system installed at Tuscon. The amount of greenhouse gas emission from system is 29 kg CO_2-eq./m^2 and EPBT is 0.21 years. Nugenta and Sovacool (2014) reveal a range of CO_2 emission intensities from 1 g CO2-eq/kW h to 218 g CO2-eq/kW h for PV module. Rochhetti and Beolchini (2015) studies the recycle of the CdTe and Copper indium gallium selenide (CIGS) material at the end of the life of the PV module. They have been reported that the recycling of the CIGS PV module shows large emission of CO_2 in comparison with CdTe PV module. The economic analysis of PV power plants range from 3 kW to 1.14 MW has been studied by the (Liu et al., 2015). The results of PV system show

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https://doi.org/10.1016/j.solener.2017.10.087
Received 20 July 2017; Received in revised form 22 September 2017; Accepted 30 October 2017
Available online 11 November 2017

Nomenclature

E_{in}	embodied energy (kW h/yr)
E_{out}	total energy output (kW h/yr)
$F_{CR,i,n}$	capital recovery factor (%)
$F_{SR,i,n}$	sinking fund factor (%)
I	rate of interest (%)
I	current (A)
n_{sys}	life of system (year)
P_{mr}	maintenance and repair cost (INR)
P_s	salvage value (INR)
M_s	maintenance cost (INR)
n	number of years (INR)
P	power (W)
Ps	net present cost (INR)
V	voltage (V)
AM (Amb)	average monthly ambient temperature (°C)
AM (Mt)	average monthly module temperature (°C)
AM (Irr)	average monthly irradiation (kW h/m^2)

Abbreviation

a-Si	amorphous silicon
BOS	balance of system
CO_2	Caron dioxide
c-Si	crystalline silicon
EPBT	energy payback time
EPF	energy production factor
CdTe	cadmium telluride
CO_2	carbon dioxide
JNNSM	Jawaharlal Nehru National Solar Mission
LCCE	life cycle conversion efficiency
mc-Si	multi crystalline silicon
MNRE	Ministry of New and Renewable Energy
NISE	National Institute of Solar Energy
PV	photovoltaic module
PV/T	photovoltaic thermal
sc-Si	mono crystalline silicon
UAC	uniform cost analysis

Subscript

Max	power point at reference value
Oc	open circuit
Sc	short circuit

that the 35–58 g CO2-e/kW h greenhouse gas emitted during 25 years of lifespan and the cost payback period is range from 14.4 to 26.7 years for a 50 kW PV system. RaviKumar et al. (2016) reported that the 24% CO_2 emission will be reduced due to recycling of CdTe PV system and without BOS it can save about 13.2 kg of glass, 0.007 kg of Cd, and 0.008 kg of Te per m^2. Raugeia et al. (2017) studied EPBT for PV system in comparison with nuclear system. They have found that the PV system is more suitable source for electricity in commercial level in comparison with nuclear electricity. The comparative study of performance analysis and EPBT for different PV technologies likely sc-Si, mc-Si, a-Si, CIGS and CdTe has been reported by (Saini et al., 2017). They have found that the CdTe technology is best in terms of performance evaluation while the CIGS is better in case of EPBT. In this way standalone PV systems are also helpful to reduce the 6.8 tCO_2 emission annually. The maximum value The average electricity generation cost in the range (5.4–7.02 €/kW h to 1.2–1.7 €/kW h) has been reported in Alberta. The life cycle cost of pellet combustion is 0.94 €/kW h, which is lower than the electricity generation in Alberta (Weldu and Assefa, 2017). Kim et al. (2014) reported the life cycle assessment of 100 kW CdTe PV system. The embodied energy and total CO_2 emission could pay back after 342 and 277 days. Many researchers (Tyagi et al., 2008; Fu et al., 2012; Singh and Kumar, 2013; Rajput et al., 2017) have done the economic analysis of different renewable energy technologies likely, PV, Solar thermal and Biomass etc. However, the present study is different from the past studies. In the present study performance evaluation and economic analysis of CdTe PV system has been reported using the actual measured performance data in outdoor condition. The present study will helpful to establish the new emerging technology to compare the performance and economic aspects of the other PV technologies. It is also helpful for manufacturers to improve the quality and performance of the PV material.. However, the CdTe technology is a new emerging technology, which has not completed the lifespan span of 20–25 years in the field conditions. So, it is a helpful analysis for CdTe technology to make it more reliable and cost effective in comparison to c-Si technologies. However, research is going on to predict the reliability and economic aspect of the CdTe PV module in world wide. In context, the present study is also helpful to change the old qualification standards (IEC61215 for c-Si and IEC 61646 for thin film technology) on the basis of the technology and environmental conditions.

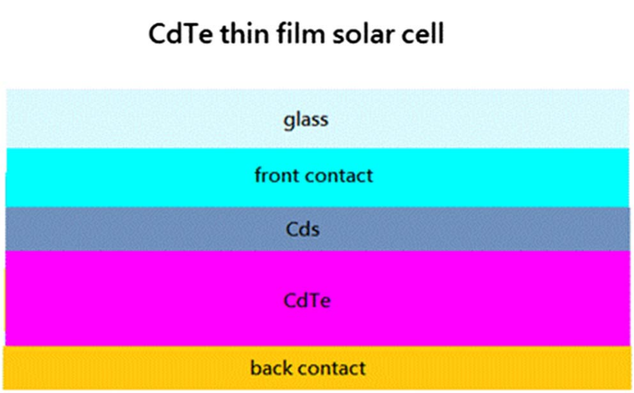

Fig. 1. Composition of CdTe solar cell.

A comparative study of life cycle assessment of thin film PV technologies has been shown in Table 1. Keeping view of the past study, the present study has been performed under the composite climate of India. In the present study, energy metrics analysis likely energy payback time (EPBT), energy production factor (EPF) and life cycle conversion efficiency (LCCE) for standing PV system (at the National Institute of Solar Energy, Gurgaon, India) have been carried out. Life cycle assessment on the basis of cost per unit energy and carbon credit earned has been carried out. To calculate the more realistic assessment, actual performance data of the PV system have been used with respect to the same environmental conditions.

The paper has been organized in the following sections: Energy metrics and enviroeconomic analysis have been given in Sections 2–4. Methodology has been presented in Section 5. Section 6 gives information about the experiment set up installed in outdoor condition. Section 7 represents the results and Discussion. A conclusion has been cried out in Section 8.

2. Embodied energy consumption

In order to make the economic analysis of the PV system, understanding about the embodied energy (E_{in}) is almost important. So, embodied energy is to be discussed first. Embodied energy is a sign of the level of energy intake. The quantity of energy required to make a component and product during the manufacturing process i.e. direct

Table 1
Comparative study of different technology PV systems.

S. no.	Location	Type of technology	Total capacity of installed PV module	Energy payback time (years)	CO_2 mitigation	References
1	Malaysia	CdTe	100 kW	0.94	0.76 g of CO_2/kW h	Kim et al. (2014)
2	Italy	CdTe	1 m^2	1.30	–	Vellini et al. (2017)
3	USA	a-Si	33 kW	3.2	34.3 g of CO_2/kW h	Pacca et al. (2007)
4	Germany	CdTe	1 m^2	1.1	30 g of CO_2/kW h	Held and Ilg (2011)
5	China	a-Si	100 MW	2.2	15.6 g of CO_2/kW h	Ito et al. (2008)
6	India	CdTe	3.2 KW	3.60	89.98 tCO2e	Present study

energy plus indirect energy is termed as embodied energy (Treloar, 1994). For the embodied energy analysis of 3.2 kW PV system, the total energy needed for separate components with their manufacturing energy needs to be evaluated. In the present study, life cycle energy analysis of the 3.2 kW PV system, has been performed at the National Institute of solar energy, Gurgaon, India. The breakup of embodied energy of each component of the existing PV system is presented in Table 2.

2.1. Mathematical formulation of energy metrics

Energy metrics are also referred as return estimation cost analysis. The return estimation of the PV system is analyzed on the basis of energy metrics. These are the energy payback time (EPBT), electricity production factor (EPF) and life cycle conversion efficiency (LCCE).

2.2. Energy payback time (EPBT)

The time required to recover the energy devoted during the manufacture of material and product for a PV system is known as the EPBT (Singh and Kumar, 2013).

$$\text{EPBT} = \frac{E_{in}}{E_{out}} \tag{1}$$

An E_{in} is the embodied energy of PV system (kW h) and E_{out} is the annual energy output (kW h/yr) of a PV system. For the sustainable energy character, EPBT should be less than the entire installation service period.

$$\text{EPBT} \leqslant n_{sys}$$

The EPBT is an indicator of performance of the PV system during his service lifetime. A drawback of EPBT is that it does not account for the energy gain during the rest of the economic lifetime.

2.3. Energy production factor (EPF)

EPF is the ratio of energy produced by the PV system during operation time and energy input as embodied energy required to prepare the completed PV system (Kittner et al., 2013).

$$\text{EPF} = \frac{E_{out}}{E_{in}} = \frac{E_{out} \times n_{sys}}{E_{in}} = \frac{n_{sys}}{EPBT} \tag{2}$$

E_{out} is the total energy output in (kW h/yr) and n_{sys} is the life time of the system (year). Thus, the electricity production factor (EPF) is inversely proportional to the EPBT.

2.4. Life cycle conversion efficiency (LCCE)

It is the ratio of total energy produced by the PV system with respect to the solar radiation as the input over the service lifetime (n_{sys} years) and can be calculated by (Tiwari et al., 2009).

$$\text{LCCE} = \frac{E_{out} - E_{in}}{E_{sol} \times n_{sys}} = \frac{E_{out}}{E_{sol}}\left(1 - \frac{E_{in}}{E_{out} \times n_{sys}}\right) \tag{3}$$

E_{out} is the annual output in kW h/yr, n_{sys} (life of a PV system) = 25 years, have been considered for present study and E_{sol} (kW h) is annual solar energy input.

3. Life cycle cost assessment

In the present analysis, present and future cost of the different components of PV system has been sum during the life span.

3.1. Capital cost (P)

It is the sum of the cost of all different components of a PV system. Table 3 gives the breakup of initial capital cost (P) of existing PV system.

3.2. Maintenance and repair cost (P_{mr})

Maintenance and repair cost of the PV system is acquired at the time of the operation condition of the system. In the present study, R is considered as the annual maintenance and repair cost of the PV system. It is represented in terms of present value is given by:

$$P_{mr} = R \times \left(\frac{(i+1)^n - 1}{i(i+1)^n}\right) \tag{4}$$

3.3. Replacement costs (P_r)

A PV system consists of different components likely PV module, battery, inverter, mounting structure and cables, etc. Out of these components, battery may be replaced at the service life of the system. The number of replacements of the components of the PV system depends on the life of the components and system. If R_5, $R1_0$, R_{15}…, R_n is the replacement cost acquired in batteries and other components made in every five years then the net replacement costs in terms of present values is (Nawaz and Tiwari, 2006)

Table 2
Breakup of embodied energy of different components of existing PV system (Tiwari et al., 2009; Alsema, 2000; Sharma and Tiwari, 2013).

Components	Embodied Energy (kW h)
PV module (Glass to glass) Energy density: (333.33 kW h/m^2) Existing PV area: 28.8 m^2	9599.90
M. S. Support Structure (1) Steel angle 200 kg; (2) Screw 3 kg (3) Nut and bolt 2 kg Energy density (8.89 kW h/kg of each)	1822.45
Inverter Energy for production: (331 kW h)	284.00
Charge regulator Energy for production: (331 kW h)	182.00
Overall operation and maintenance, electronic components, cables and miscellaneous etc. taken into account 10% extra	1188.35
Total embodied energy (kW h)	13076.70

Table 3
Capital cost break-up of PV system.

Component	No. of units	Cost of each unit (INR)	Total cost (INR)
PV modules, 80 Wp each	40	3600	144,000
3.3 kVA AC/DC inverter	1	99,000	99,000
Mounting Structure	1	64,000	64,000
Wiring cost		38,400	38,400
Labor cost		48,000	48,000
Capital cost (INR)			393,400

$$\mathrm{Pr} = \mathrm{R}_5 \times \left[\frac{1}{(i+1)^5}\right] + \mathrm{R}_{10} \times \left[\frac{1}{(i+1)^{10}}\right] + \mathrm{R}_{15} \times \left[\frac{1}{(i+1)^{15}}\right] + \ldots + \mathrm{R}_n \times \left[\frac{1}{(i+1)^n}\right] \quad (5)$$

3.4. Salvage value (P_s)

The cost of the PV system after complete the service life during dumping of the PV system is called the salvage value. If S is the salvage value at the end of the system, then the net salvage value in terms of present value is

$$\mathrm{P_s} = \mathrm{S}\times \left[\frac{1}{(i+1)^n}\right] \quad (6)$$

Thus, net present value of the PV system in terms of present value is given by

$$\text{Net present value } (\mathrm{P_{NET}}) = \mathrm{P} + \mathrm{P_{mr}} + \mathrm{P_r} - \mathrm{P_s}$$

$$\mathrm{P_{NET}} = \mathrm{P} + \mathrm{R}\times \left[\frac{(i+1)^n - 1}{i(i+1)^n}\right] \times \mathrm{R}_5 \times \left[\frac{1}{(i+1)^5}\right] + \mathrm{R}_{10} \times \left[\frac{1}{(i+1)^{10}}\right] + \mathrm{R}_{15} \times \left[\frac{1}{(i+1)^{15}}\right] + \ldots + \mathrm{R}_n \times \left[\frac{1}{(i+1)^n}\right] - \mathrm{S}\times \left[\frac{1}{(i+1)^n}\right] \quad (7)$$

3.5. Annualized uniform cost (uncost)

The annualized uniform cost (uncost) of the PV system is a product of the present value of the PV system and capital recovery factor (CRF)

$$\text{Uncost } (\mathrm{P_A}) = \text{Net present value } (\mathrm{P_{NET}}) \times \text{Capital recovery factor (CRF)} \quad (8)$$

The capital recovery factor (CRF) over the lifetime is stated by

$$\mathrm{CRF} = \frac{i(i+1)^n}{(i+1)^n - 1} \quad (9)$$

3.6. Cost per unit electricity

It is the ratio of annualized uniform cost and annual electricity generated by the PV system. Generally, cost per unit of electricity denoted by INR.

$$\text{Cost per unit electricity} = \text{Annualized uniform cost/Annual energy output} \quad (10)$$

4. CO_2 emission, mitigation and carbon credit

CO_2 mitigation is an important issue to make the clean environment and overcome the greenhouse gases from the environment.

4.1. CO_2 emission

The PV system is an environment friendly and generate the power without emission of the harmful gases. The average carbon dioxide concentration of release for electricity generation from coal based thermal power plant is approximately 0.98 kg of CO_2 per kW h at the source (Watt et al., 1998). If the transmission and distribution losses for Indian condition are taken as 40% and poor inefficient electric equipment losses are around 20%, then figure 0.98 can be taken as 1.58 (Alsema, 2000).

$$\text{Annual } CO_2 \text{ emission} = \frac{E_{in} \times 1.58}{n_{sys}} \quad (11)$$

where E_{in} and n_{sys} is the embodied energy and life time of PV system respectively.

$$\text{Hence, } CO_2 \text{ emission over the life time} = E_{in} \times 1.58 \quad (12)$$

4.2. CO_2 mitigation

$$\text{The } CO_2 \text{ mitigation (kg of } CO_2\text{) per year} = \mathrm{E_{out}} \times 1.58 \quad (13)$$

where E_{out} is annual energy available from the PV system Therefore,

$$CO_2 \text{mitigation kg of} CO_2 \text{over life time} = \mathrm{E_{out}} \times \mathrm{n_{sys}} \times 1.58 \quad (14)$$

$$\text{Net } CO_2 \text{ mitigation of } CO_2 \text{ over life time} = (\mathrm{E_{out}} \times \mathrm{n_{sys}} - \mathrm{E_{in}}) \times 1.58 \times 10^{-3} \quad (15)$$

4.3. Carbon credit earned

Carbon credit earned by the PV system in terms of Indian currency (INR) by considering that carbon dioxide has been traded @ € 21/tCO_2e (European Climate Exchange) can be expressed as carbon credit earned (Sharma and Tiwari, 2013).

$$\text{Carbon credit earned (INR)} = (\mathrm{E_{out}} \times \mathrm{n_{sys}} - \mathrm{E_{in}}) \times 1.58 \times 10^{-3} \times 21 \times 68 \quad (16)$$

where € 1 = INR 64.46; June, 2017; 1 ton = 10^3 kg; 1 Credit = 1 tCO_2e.

5. Methodology

Life cycle assessment of 3.2 KW photovoltaic system has been analyzed into three parts specifically energy metrics estimation, life cycle cost analysis, carbon credit calculation. The embodied energy of different components of PV system has been evaluated as described in Sections 2–4. The detail list of the experimental set-up used in the present study has been represented in Section 6. The experiments carried out throughout the year 2016–17 in real outdoor condition has been explained in Section 6. Hourly subsequently daily, monthly and finally annual electrical energy output of PV system has been evaluated. In the present study of economic evaluation of 3.2 KW PV system following assessment have been carried out:

- The energy output of the existing PV system has been evaluated using the actual performance during real operation condition. Cost of electricity for the standing PV system has been assessed using actual experimentally measured energy output. Additional the cost of energy output has also been accessible by considering the existing PV array system with same existing experimental environmental conditions.
- To evaluate overall energy performance, energy metrics likely EPBT, EPF, and LCCE have been evaluated with actual electrical energy output and embodied energy. Further, energy metrics using Eqs. (1)–(3) have also been evaluated.

- For present PV system per unit electricity cost, CO_2 emission and carbon credit earned have been evaluated using actual on-field performance assessment and embodied energy with the help of Eqs. (10)–(16).

A flow chart diagram of the methodology has been given in Fig. 2

6. Experimental setup

The 3.2 KW CdTe PV system has been installed at outdoor condition of the National Institute of Solar Energy, Gwalpahari, Gurgaon, Haryana, India during 2012 as shown in Fig. 3. The system comprises the total 40 PV modules. In which 10 PV modules connected in series and such PV modules has been connected in 4 parallel connections as shown in Fig. 4. A weather station has been installed to store the data of environmental parameters likely ambient temperature, solar irradiance, wind speed and relative humidity etc. along with the PV system. The system has been installed at the fix mounted structure of aluminum facing towards the south. The specification of the represented PV module has been given in Table 4. The reference PV modules also used to clarify the weather data and performance of the 3.2 kW PV system. The output of the reference PV modules and the 3.2 KW PV system has been stored in the data logger Campbell Scientific CR-3000 data around every 10 s interval. The output of the 3.2 KW PV system has been connected to the inverter (SMA Sunny Boy 3000HF-30) with inbuilt MPPT to track the maximum power output at the given environmental condition.

7. Results and discussion

7.1. PV system electrical energy generation

The actual output performance of 3.2 kW PV system has been analyzed during 2016–2017 from January to December. The monthly variation of average ambient temperature, average module temperature and average irradiance has been shown in Fig. 5. The actual output of the PV system has been considered to 2662.01 kW h in field condition under same solar intensity and PV operating temperature as shown in Table 5. The actual output of the PV system in field condition at the load terminal decreases from the PV array due to efficiency coefficients of various other components of PV system such inverter, battery, wiring and cabling etc. With the system age or long term exposure of PV modules, energy output obtained from the PV system decreases continuously with life time due to PV degradation caused by various factors.

Fig. 3. 3.2 KW PV system with reference PV module and Pyranometer.

7.2. Energy metrics analysis

The EPBT of the existing PV system has been calculated with the help of Eq. (1) for actual field performance data. The existing PV system has ground mounted, its embodied energy has been given in Table 2. The average on field annual electrical output of the PV system is estimated at 2662.01 kW h and total embodied energy for PV systems is 13076.70 kW h. The EPBT with the help of ground mounted PV system has been calculated as 3.60 years using Eq. (1). Table 6 shows the

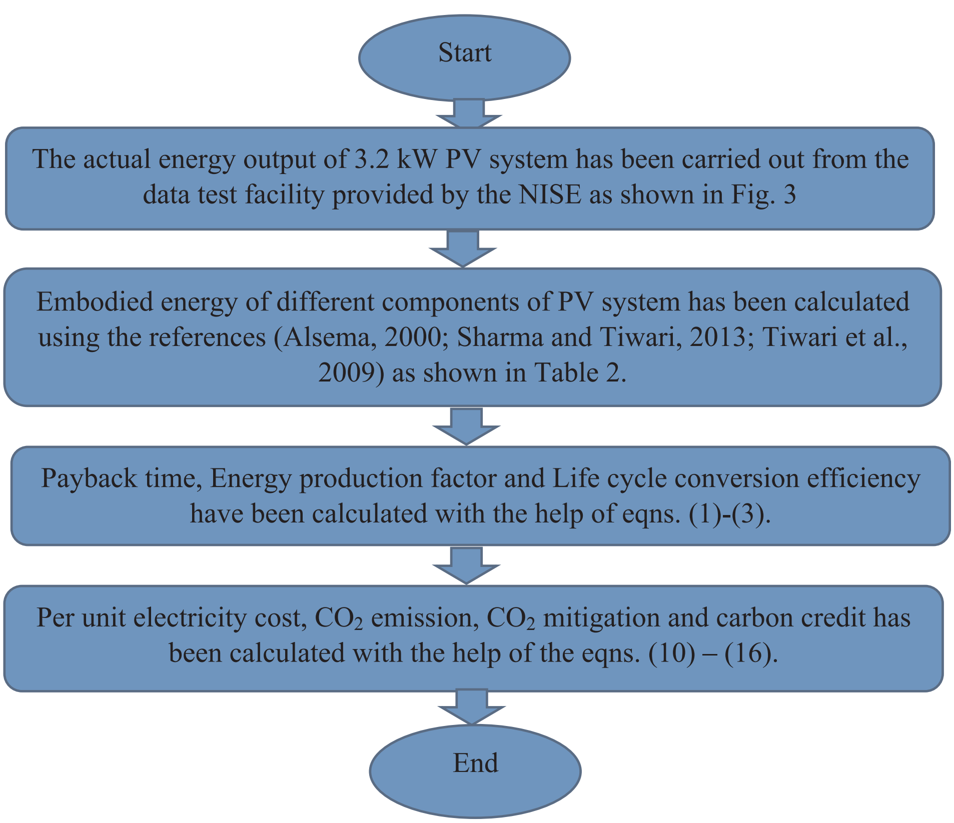

Fig. 2. Methodology of life cycle assessment of PV system.

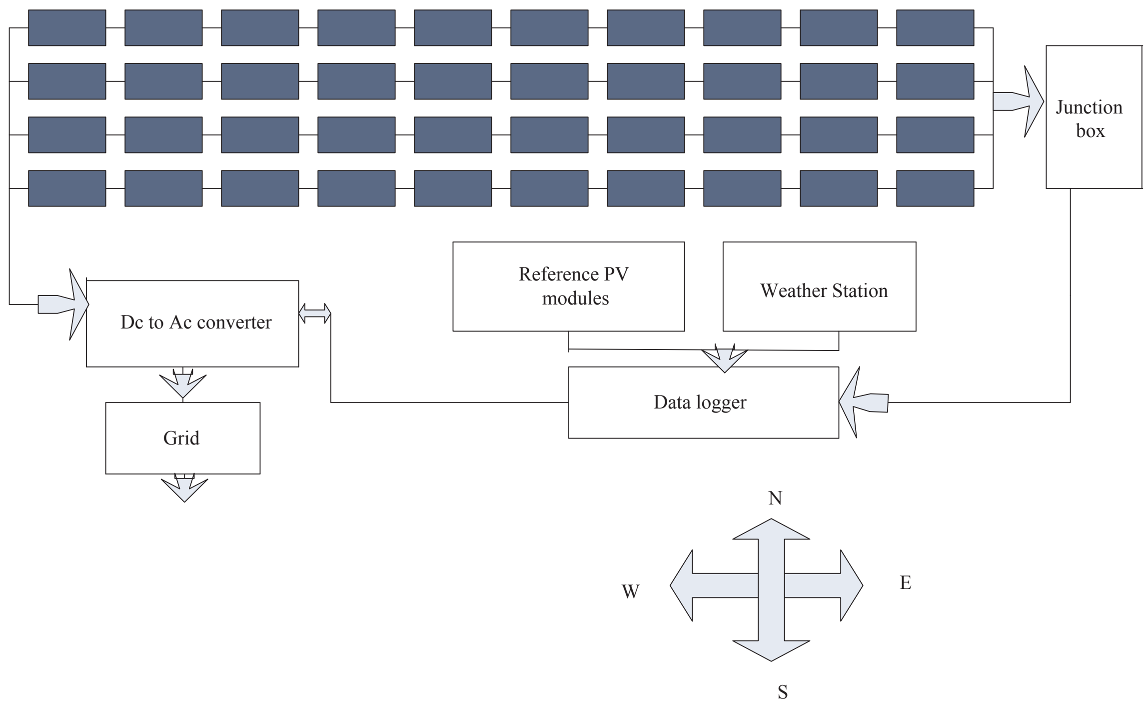

Fig. 4. Systematic diagram of 3.2 KW CdTe PV system.

Table 4
Specification of representative PV module.

Parameter	Specification
Type of material	Cadmium telluride
Area of PV module	0.72 m^2
Maximum power (P_{max})	80 W
Maximum power voltage (V_{max})	48.5 V
Maximum power current (I_{max})	1.65A
Open circuit voltage (V_{oc})	60.8 V
Short circuit current (I_{sc})	1.88A
Efficiency (η)	11%

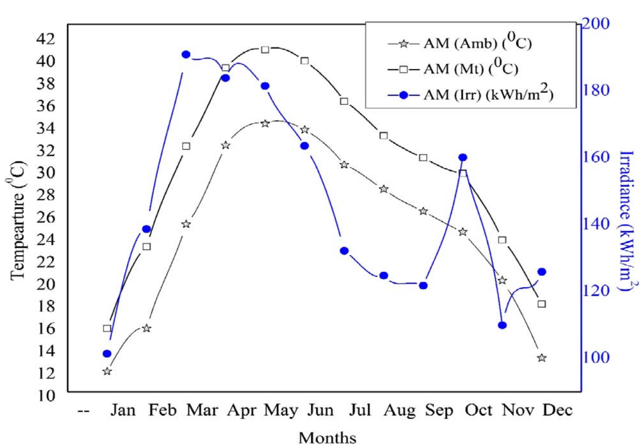

Fig. 5. Variation of average ambient temperature, average module temperature and average irradiance thought the year.

performance of the current PV system in terms of Energy payback time (EPBT) for different mentioned conditions. Eq. (2) has been used to obtain the EPF for different environmental conditions on lifetime basis and results have been given in Table 6. It is eminent that EPF for standing ground-mounted system is calculated as 0.27 based on actual on-field electrical energy output. The LCCE of the standing PV system has been calculated by using Eq. (3) and the results have been reported in Table 6 for different condition. It has been seen that for standing PV system, with an average on-field annual electrical energy output LCCE obtained, is low i.e. 0.0018. It is also perceived that LCCE rises by considering the same ground mounted PV system due to some decrease in embodied energy.

7.3. Unit cost analysis

With the consideration of useful life of 20–30 years for PV array, the life cycle cost analysis has been carried out for (PV) system for different interest rates. The aim of life cycle cost analysis is to estimate the cost per unit electricity generated by PV system in terms of INR. The cost break-up of installed PV system is given INR 393400 without considering the land cost for existing PV system (Table 3). Installation/cartridge charges were considered 5% of the total system cost. For the life cycle cost analysis, the annual maintenance and repair cost has been assumed 10% of the total capital cost (P). Salvage value at the end of 30 years is considered 10% of the capital cost (P). Maintenance and repair cost, replacement cost and salvage value all in terms of present value have been obtained by using Eqs. (4)–(10) respectively. The PV capital cost, maintenance and repair cost, inverter cost, and the salvage value given in Table 3. Annualized uniform cost (uncost) is obtained from Eq. (10). Dividing the annualized uniform cost with annual actual on-field electrical energy output gives the present cost per unit energy generation. For existing PV system cost per unit electricity has been calculated INR 9.85 per kW h for 5% interest rate and 30 year's service life. The actual on field annual electrical energy output from the existing PV system of 3.2 kW is calculated 2662.01 kW h during 2016–17 with same experimental environmental conditions.

The annual interest rate usually offered by government sectors in India to promote the use of renewable energy applications is 5%. Let us consider system life span, n_{sys} = 30 years and i = 5%, then Table 6 presents cost breakup for various heads to determine annualized cost and finally the present cost of unit power generation for the existing PV system. For existing ground mounted system (without considering the land cost) present cost of electricity for an existing PV system using actual experimentally measured performance has been evaluated INR

Table 5
Experimentally calculated average monthly electrical energy output (in kW h) of existing outdoor PV arrays in each month during a year 2016–17.

Months	No. of clear days	Entire PV array total electrical energy output (kW h)
Jan	22	181.87
Feb	25	198.24
Mar	29	242.56
Apr	28	240.17
May	30	238.45
Jun	25	203.77
Jul	16	247.54
Aug	17	240.17
Sep	23	224.96
Oct	25	251.45
Nov	22	204.21
Dec	20	188.62

Table 6
Energy payback time (EPBT), energy production factor (EPF) and life cycle conversion efficiency (LCCE) of 3.2 kW PV system on annual electrical energy basis.

Type of PV module	Energy payback time (EPBT) (year)	Energy production factor (EPF) annually	Energy production factor on lifetime basis	Life cycle conversion efficiency
CdTe	3.60	0.27	6.75	0.0018

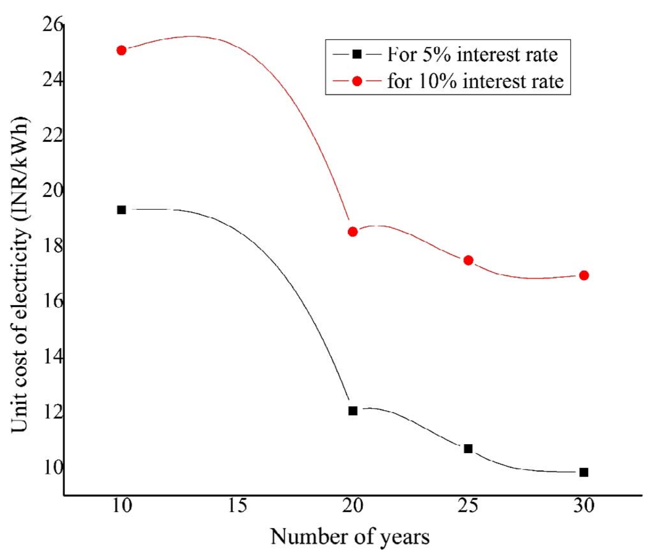

Fig. 6. Variation of unit cost of electricity with number of years for different interest rate.

Table 7
Uniform annualized cost (UAC) and cost/kW h of system for different life time and interest rates.

n	*i* (%)	S_S (INR)	M @ 10 (%)	$F_{CR,i,n}$ (%)	$F_{SR,i,n}$ (%)	UAC (INR)	Unit Cost (INR/kW h)
10	5	58232.81	39340	0.1295	0.0795	51412.03	19.31
20	5	86198.78	39340	0.0802	0.0302	32117.30	12.06
25	5	104874.00	39340	0.0709	0.0209	28506.59	10.70
30	5	127595.25	39340	0.0650	0.0150	26229.86	9.85
10	10	58232.81	39340	0.1627	0.0627	66772.60	25.08
20	10	86198.78	39340	0.1174	0.0174	49324.47	18.52
25	10	104874.00	39340	0.1101	0.0101	46607.76	17.50
30	10	127595.25	39340	0.1060	0.0060	45129.05	16.95

9.85 and INR 16.95 for different interest rates of i = 5% and i = 10% respectively as shown in Fig. 6 and Table 7. For ground mounting with land cost consideration, total capital cost of PV system is obtained INR 393400 by adding capital cost (P) given in Table 3 with a land cost of which PV system is mounted.

7.4. CO_2 emission, mitigation and carbon credit

In comparison to other sources of electrical energy, PV power system is found environment friendly. The average carbon dioxide intensity of emission for electricity generation from coal based thermal power plant is approximately 0.98 kg of CO2 per kW h at the source (Nawaz and Tiwari, 2006; Watt et al., 1998). If the transmission and distribution losses for Indian condition are taken as 40% and poor inefficient electric equipment losses are included.

CO_2 emission over the lifetime of the existing PV system has been evaluated by using Eq. (12). It depends on the embodied energy of the system. For actual existing ground mounted system, CO_2 emission over the lifetime has been evaluated 20660.08 tCO_2e (here tCO_2e means tons of CO_2 equivalent; 1t = 10^3 kg). Eq. (15) has been used for evaluating net CO_2 mitigation for the existing PV system and the results have been given in Table 8 for different conditions. It is noted that net CO_2 mitigation for existing ground mounted system is calculated 25.80 tCO_2e using calculated average on-field annual electrical energy output of 2662.01 kW h/yr. Potential performance of PV system in terms of net CO_2 mitigation in ideal condition of newly installed system with maximum electrical energy output under same on-field experimental environmental conditions is estimated 89.98 tCO2e. Presented actual on-field performance of the PV system is obtained comparatively lower than the potential performance due to an existing system ageing. CO_2 emission over the lifetime of the existing PV system has been evaluated by using Eq. (12). It depends on the embodied energy of the system. CO_2 emission over a useful life span has also been evaluated 20660.08 tCO2e by considering same PV system.

8. Conclusions

The life cycle assessment of the 3.2 kW CdTe PV system has been done on the basis of energy metrics analysis for the same climatic condition. On the basis of the study, the following conclusions have been drawn.

- The EPBT of 3.2 kW CdTe PV system has been calculated as 3.60 years on the basis of actual energy output.
- The unit cost of electricity has been found to be 9.85 INR/kW h for 5% interest rate and 30 years of life span.
- The Net CO_2 mitigation of the PV system has been found to be 89.98 ton on the basis of actual energy output and embodied energy of the PV system.
- The carbon credit earned by PV system has been calculated as INR 114368.54.

The performance of the PV technologies depends on the type of the material and operating environment condition. The CdTe PV technology has a lower value of the embodied energy in comparison to the other c-Si PV technologies (Alsema, 2000). So, EPBT of CdTe PV technology is lesser than the c-Si PV technologies. The results of the CdTe PV system has been proved that it is environmental friendly technology. Therefore, it has potential to mitigate the CO_2 from the environment.

Acknowledgement

One of author, Mr. Pramod Rajput is thankful to Ministry of New and Renewable Energy (Government of India), for partial financial support for the present study.

Table 8
Carbon dioxide reduction per annum and environmental reduction cost per annum for 3.2 kW PV system.

Type of PV module	Annual CO_2 emission in (Kg)	CO_2 emission over the lifetime (Kg)	Net CO_2 mitigation (in t)	Carbon credit earned (in INR)
CdTe	826.40	20660.08	89.98	114368.54

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