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

Pramod Rajput[a,*], Yogesh Kumar Singh[b,e], G.N. Tiwari[a,c], O.S. Sastry[d], Santosh Dubey[e], Kailash Pandey[e]

[a] Center for Energy Studies, Indian Institute of Technology Delhi, Hauz khas, New Delhi 110016, India
[b] National Institute of Solar Energy, Ministry of New and Renewable Energy, New Delhi 110003, India
[c] Bag Energy Research Society (BERS) SODHA BERS COMPLEX, Plot No. 51, Mahamana Nagar, Karaudi, Varanasi, UP, India
[d] Interim Secretariat ISA, Surya Bhawan 3rd Floor, Gwalpahari, Gurugram, Haryana, Ministry of New and Renewable Energy, New Delhi 110003, India
[e] University of Petroleum and Energy Studies, Dehradun, Uttarakhand 248007, India

ARTICLE INFO

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

ABSTRACT

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

* Corresponding author.
E-mail addresses: pramodraj.rajput3@gmail.com (P. Rajput), yogeshkumarsingh7@gmail.com (Y.K. Singh), gntiwari@ces.iitd.ac.in (G.N. Tiwari), sastry284@gmail.com (O.S. Sastry), santosh.dubey@ddn.upes.ac.in (S. Dubey), kpandey@ddn.upes.ac.in (K. Pandey).

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
0038-092X/

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.

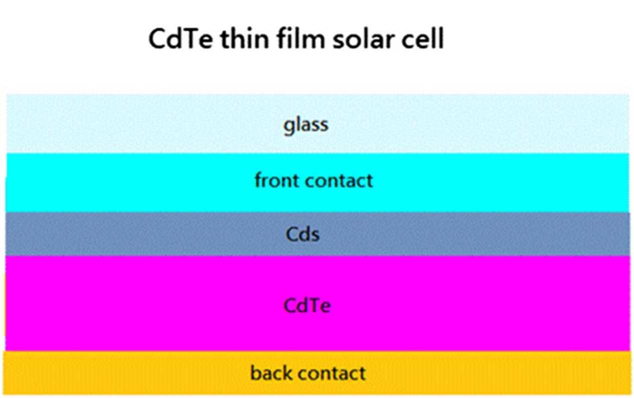

Fig. 1. Composition of CdTe solar cell.

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