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Life Cycle Cost Assessment and Enviroeconomic Analysis of Thin Film Amorphous Silicon Photovoltaic System

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Abstract

In this paper, an analysis has been carried out to evaluate the life cycle cost and environmental cost of thin film amorphous silicon photovoltaic system. The annual energy from 1000 WP photovoltaic system has been calculated for composite climatic conditions of New Delhi. The cost of electricity generation per unit from thin film amorphous silicon with and without carbon credit has been determined as 0.17 and 0.20 US$/kWh respectively. The energy payback period for the system has been calculated approximately 12 years. The cost per kWh for thin film amorphous silicon is more economical in comparison with crystalline silicon photovoltaic system.

Keywords: Enviroeconomic; Life cycle cost; Carbon credit; Energy payback period

Introduction

On the basis of present world energy scenario, there is possibility that renewable (non-conventional) sources of energy may partially supplement fossil fuel (conventional sources) energy. In recent decades, life cycle cost analysis of Standalone Photovoltaic (SAPV) systems have been carried out by many scholars [1-4]. Agarwal and Tiwari [5] have carried out review of the life cycle cost analysis of standalone and building integrated photovoltaic thermal systems. Recently, Rajoria et al. [6] has carried out the enviroeconomic and exergetic analysis of novel hybrid photovoltaic thermal array of two different designs and flow configuration.

Gaur and Tiwari [7] have carried out the exergoeconomic and enviroeconomic analysis of different semitransparent and opaque photovoltaic modules. They have calculated annual electricity, net present value, CO2emissions reduction per annum, environmental cost reduction per annum, and net energy and exergy loss rates for these PV modules. They concluded that among all PV technologies, amorphous silicon PV module has highest environmental cost reduction per annum. Although they have calculated net present value for various components of PV system but they have not specified the capacity of individual component. Since the size or capacity of each component should be according to size of PV module and the electrical ac load connected to the system.

In this paper, we have focused our study on standalone system as shown in Figure 1 by using thin film amorphous silicon PV module. We have determined the size and cost of each component of PV system. The unit cost of electricity is calculated with and without carbon credit potential for different rate of interest. The energy matrices for the system have also been calculated. The specifications of photovoltaic module have been given in Table 1.

Methodology

In this study photovoltaic module PVL-68 from Kalzip Solarclad has been used. The data for climatic parameters like ambient temperature, total number of clear days in each month for four different weather conditions and solar intensity including beam, diffuse and global intensity on horizontal surface has been obtained from Indian Metrological Department, IMD (Pune). The operating parameters and design parameters for photovoltaic system have been given in Tables 1 and 2 respectively. The steps for evaluating electrical efficiency of module, electricity and per unit electricity generation cost are given as:

Step-1: The hourly solar intensity on 30° inclined photovoltaic module surfaces has been calculated using MATALB-13.0 software and Liu and Jordan formula [8].

Step-2: For given climatic, design and operating parameters, the electrical efficiency of module has been calculated using following equation [7]:

$$\eta_m = \frac{\eta_0\left[1-\beta_0\left[\frac{\alpha_c(1-R_E)I(t)}{U_L}+(T_a-T_0)\right]\right]}{1-\frac{\eta_0\beta_0}{U_L}I(t)} \quad (1)$$

Step-3: The hourly electricity of module (W) has been calculated

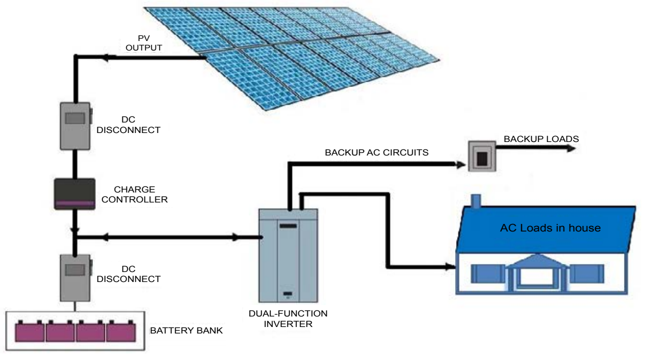

Figure 1: Schematic circuit diagram of standalone photovoltaic system.

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Photovoltaic module PVL-68			
Short circuit current, I_{SC} (A)	5.1	Maximum voltage, V_{max} (V)	16.5
Open circuit voltage, V_{OC} (V)	23.1	Rated power, W_P (W)	68
Maximum current, I_{max} (A)	4.13	Fill factor	0.58

Table 1: Photovoltaic module specifications.

A_m	18.5 m²	K_A	0.033 W/m-K
h_0	7.6 W/m²-K	U_L	10.83 W/m²-K
h_i	3.4 W/m²-K	U_b	3.23 W/m²-K
v_t	0.5 m/s	L_A	0.0005 m
v_b	0.2 m/s	R_A	0.15
β_0	0.001 / °C	α	0.85
η_0	0.064		

Table 2: Values of Various Parameters of PV module.

by [9]

$$E_{el,hourly} = \eta_{m,\,hourly} \times A_m \times I(t)_{hourly} \quad (2)$$

Step-4: The daily electricity of photovoltaic module has been calculated by summing the hourly electricity and then monthly electricity has been calculated by multiplying daily electricity and number of clear days in that month.

The daily electricity in kW h is [9]

$$E_{el,daily} = \sum_{i=1}^{N} \frac{E_{el,hourly,i}}{1000} \quad (3)$$

The monthly electricity (kW h) is given by [9]

$$E_{el,\,monthly} = E_{el,\,Daily} \times \eta_0 \quad (4)$$

Step-5: The annual electricity in kWh can be calculated by summing monthly electricity for 12 months which is given by [9]

$$E_{el,annual} = \sum_{k=1}^{12} E_{el,monthly,k} \quad (5)$$

Step-6: For 1000 WP module, the number of photovoltaic modules required, capacity of battery bank and charge controller cum inverter have been calculated.

Step-6: The cost for all components of photovoltaic system has been given in Table 3.

Step-7: The uniform annual life cycle cost and per unit electricity generation cost has been determined using Eq. (11) and Eq. (12) respectively.

Step-8: The carbon credit potential of the photovoltaic system has been calculated using Eq. (14) The carbon credit cost has been subtracted from net present cost of the system to find the resultant net present cost of the photovoltaic system and then unit cost of electricity generation has been calculated which is less than that of earlier calculated. The life cycle cost analysis has been carried out for three different interest rates of 4%, 8% and 12%.

Step-9: The embodied energy for the present system has been calculated and then energy payback period, energy production factor and life cycle conversion efficiency have been calculated which are given in Tables 4 and 5.

Life Cycle Cost Assessment

The cost of overall stand alone photovoltaic system (SAPV) can be determined based on different components specifications. The life of photovoltaic module battery bank system has been assumed to be 20 years and 5 years respectively. In this study, 4 batteries of each 100 Ah have been used. The battery and hybrid inverterare made of Luminous. The battery bank system replacement cost has been determined by considering 5% rebate. The battery bank system replacement cost has been assumed to be constant throughout the photovoltaic system life. The cost of balance of system includes the cost of procurring the land for SAPV system and stand cost and it is considered as 20 % of the total photovoltaic system components cost.

Present cost of battery bank system, PBB =

$$\left[\frac{C_{BB,R}}{(1+i)^5}\right] + \left[\frac{C_{BB,R}}{(1+i)^{10}}\right] + \left[\frac{C_{BB,R}}{(1+i)^{15}}\right] \quad (6)$$

With these assumptions, the capital cost of SAPV system is calculated as follows:

Capital cost of SAPV system, PSAPV (US\$) =1.2 ×(Photovoltaic array cost + battery bank cost + SPCU cost) (7)

The operational and maintenance cost (OM) and salvage value (S) of SAPV system after 20 years has been assumed to be 5 and 10% of present cost of SAPV system. The present OM and S value of SAPV system can be determined by knowing unicast present value factor and present value factor using Eq. (6) and Eq. (7) respectively. The present life cycle cost can be obtained from Eq. (10) by knowing present value of capital cost of SAPV system, battery bank systems Cost, OM cost and salvage value using equations (6), (7), (8), (9).

The uniform annualized life cycle cost can be obtained from Eq. (11) by knowing present life cycle cost.

After calculating uniform annualized life cycle cost, per unit electricity generation cost can be obtained from Eq. (12) for different interest rates. The values for these different costs have been given in Table 3. The cash flow diagram for SAPV system is given in Figure 2.

Present OM value, $P_{OM} = OM \times \frac{\left((1+i)^{20}-1\right)}{i \times (1+i)^{20}}$ (8)

Present salvage value, $P_S = \left[\frac{S}{(1+i)^{20}}\right]$ (9)

Net present life cycle cost, PNet = PSAPV + PBB -POM -Ps (10)

Uniform annualized life cycle cost, $P_A = P_{Net} \times \left[\frac{\left(i \times (1+i)^{20}\right)}{(1+i)^{20}-1}\right]$ (11)

$$C(US\$/kWh) = \left[\frac{P_A}{E}\right] \quad (12)$$

Enviroeconomic analysis

The CO2 emissions mitigation per year from the photovoltaic module is given by [6]:

$$\varphi_{CO_2} = \frac{\psi_{CO_2} \times E}{1000} \quad (13)$$

The carbon credit potential of photovoltaic module is given by [6]

$$Z_{CO_2} = z_{CO_2} \times \varphi_{CO_2} \quad (14)$$

The international carbon price has average value of 14.5 \$/tCO2 [11]. This factor represents monetary value of one carbon credit for 1 ton of CO2 emissions mitigation.

Component	Capacity (W)	Cost per unit US$/W	Cost for 4 % Interest Rate (US$)	Cost for 8 % Interest Rate(US$)	Cost for 12 % Interest Rate(US$)
PV array	1000	0.50	502.49	502.49	502.49
Battery bank	400	1.25	498	498	498
Inverter cum Charge controller	1200	0.17	199.2	199.2	199.2
Cost of balance of system	-	-	239.94	239.94	239.94
SAPV system cost	-	-	1439.59	1439.59	1439.59
Cost of battery replacement	-	-	473.1	473.1	473.1
Present battery bank replacement cost	-	-	969.86	690.73	506.22
Operational and maintenance cost	-	-	143.96	143.96	143.96
Present operational and maintenance cost	-	-	1956.42	1413.69	1075.38
Salvage value	-	-	71.98	71.98	71.98
Present salvage value	-	-	32.85	15.44	7.46
Net present cost for SAPV system	-	-	4333.02	3528.57	3013.73
Uniform annualized life cycle cost	-	-	303.31	359.91	403.84

In July'2013, price of thin film amorphous silicon was 0.502493 US$/Wp [12].

Table 3: Capacity of active components and cost of each component of standalone photovoltaic system for different interest rate.

Interest rate (%)	Cost of electricity without carbon credit (US$/kWh)	Cost of electricity with carbon credit (US$/kWh)
4	0.20	0.17
8	0.23	0.21
12	0.26	0.24

Table 4: Unit cost of electricity.

PV technology	Expected life(Years)	Embodied energy (kWh)	EPBP (Years)	EPF (per year)		LCCE
				X_a	X_{LT}	
Thin film a-Si	20	17472.2	11.38	0.088	1.76	0.03

Table 5: Energy matrices parameters for amorphous silicon PV technology

Embodied energy: In the present study, embodied energy of system involves embodied energy of amorphous silicon photovoltaic array, battery bank system, inverter cum charge controller, photovoltaic frame, operational and maintenance, wires. The embodied energy for thin film amorphous silicon photovoltaic technology including other system components is 944.44 kWh/ m2 [11].

Energy matrices: The evaluation of performance of standalone photovoltaic system can be defined by three parameters which are called energy matrices. These parameters include energy payback period (EPBP), energy production factor (EPF) and life cycle conversion efficiency LCCE.

$$EPBP = \frac{Embodied\ Energy\left(E_{in}\right)}{Annual\ energy\ output\left(E_{aout}\right)} \tag{15}$$

EPF, $$\chi_a = \frac{E_{aout}}{E_{in}} \tag{16}$$

$$\phi = \eta\left(1 - \frac{EPBP}{n}\right) \tag{17}$$

Results and Discussions

The average hourly variation of solar radiations at 300 inclinations for all months has been plotted from 8 am to 5 pm in Figure 3 which depicts that solar radiations for all months are at their peak values between 12 pm to 1 pm. Also it shows that maximum solar intensity in January is more than that of in June due to smaller angle of incidence in January than that of in June because south facing surfaces receive higher radiations in winter compared to summer for given inclination.

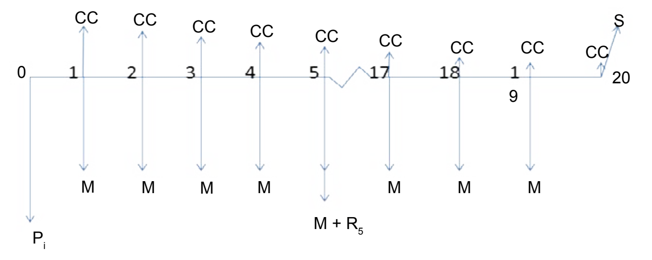

Figure 2: Cash flow diagram for the photovoltaic system.

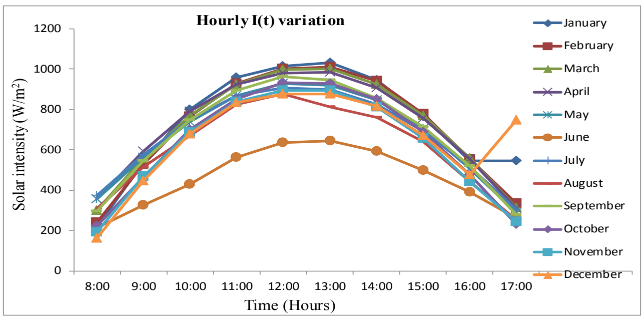

Figure 3: Hourly variation of solar intensity for 12 months for composite climatic conditions of New Delhi.

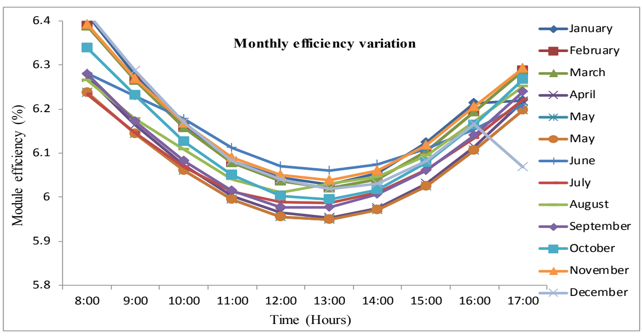

Figure 4: Hourly variation of module efficiency for 12 months for composite climatic conditions of New Delhi.

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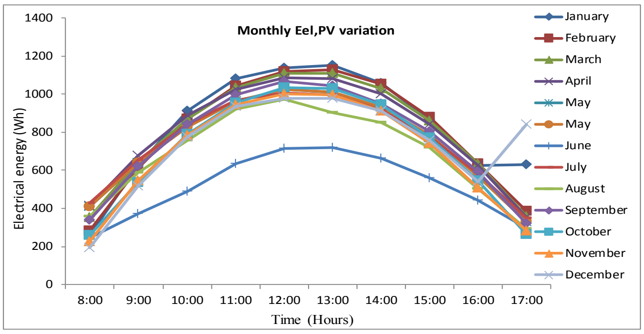

Figure 5: Hourly variation of electricity for 12 months for composite climatic conditions of New Delhi.

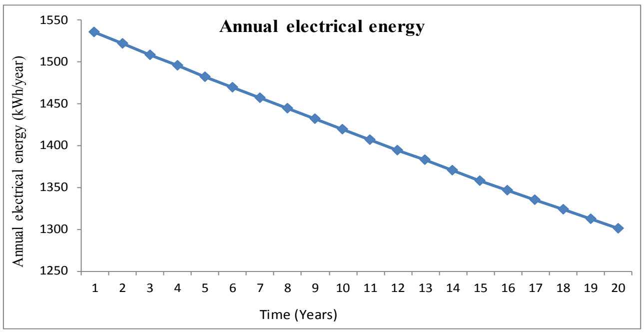

Figure 6: Degradation of electricity for 20 years for composite climatic conditions of New Delhi.

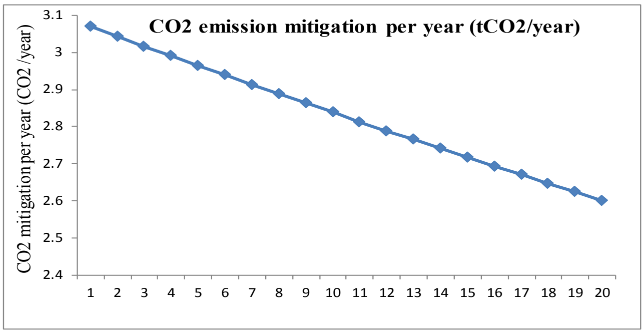

Figure 7: Reduction in CO_2 emissions mitigation for 20 years for composite climatic conditions of New Delhi.

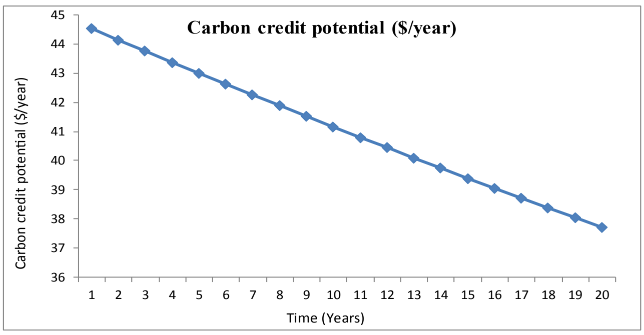

Figure 8: Reduction in carbon credit potential for 20 years for composite climatic conditions of New Delhi.

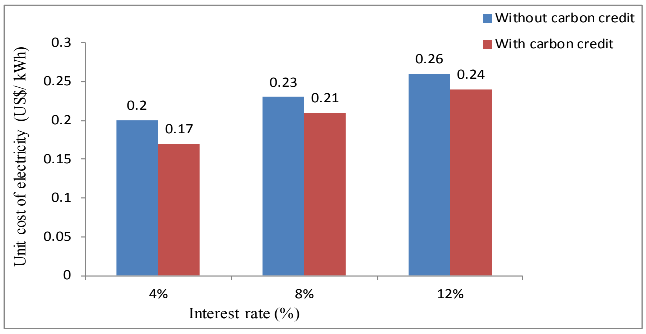

Figure 9: Unit cost of electricity for different interest rates.

As solar radiations on a particular surface depends on different sun-earth angles like angle of declination and solar altitude etc. The smaller angle of inclination results in lesser solar radiations since the radiations have to travel longer path. For given inclination, solar altitude is more in summer than that of in winter. The hourly variation of module efficiency for all months has been shown in Figure 4. It is clear from the figure that module efficiency is higher in June compared to January. Also for a typical month, module efficiency is maximum at 8 am and 5 pm and minimum between 12 pm to 1 pm because the module used in this study is thin film opaque PV module of very small thickness, so the solar radiations falling on the module can't transmit through back side of module and they are absorbed by Aluminum sheet. This absorption results in increase of module temperature and thus module efficiency decreases. Since module temperature initially increases and attains maximum value between 1 pm and 2 pm which corresponds to maximum solar intensity. So at maximum module temperature, collisions among the charge carriers will also increase which results in more recombination of charge carriers and thus module efficiency will be minimum at maximum module temperature. The hourly variation of electricity is shown in Figure 5 for 12 months which depicts that electricity is minimum in June and maximum in January since it depends on solar intensity which is maximum in January and minimum in June for 30° inclined surfaces. Also for a particular month, electricity is maximum between 12 pm and 2 pm and it is minimum at 8 am and 5 pm. Since electricity directly depends on solar intensity which is maximum between 12 pm and 2 pm and minimum at 8 am and 5 pm. The degradation rate of thin film amorphous silicon photovoltaic module is considered as 0.87 % per year [9]. The degradation of electricity from PV module for 20 years life has been shown in Figure 6. This degradation is linear since amorphous silicon degradation rate is considered to be linear. Thin film amorphous silicon degrades more rapidly than crystalline silicon PV technology due to disordered nature of amorphous silicon which results in Staebler-Wronski effect. The reduction in CO2 emissions mitigation due to degradation in PV module with time during the life of system has been plotted in Figure 7. Due to this, the carbon credit potential earned by the system during its life will also decrease with time which is shown in Figure 8. The total carbon credit potential has been calculated by taking each year carbon credit potential back to present value and then summing all these values. The unit cost of electricity generation from the system for different interest rate with and without carbon credit potential has been shown in Figure 9. It shows that unit cost of electricity is less when carbon credit potential is considered. Also unit cost of electricity is minimum for subsidized 4 % interest rate which is offered by government to promote renewable energy.

Conclusions

In this study, the life cycle cost assessment has been done for 1000 W photovoltaic system to determine unit cost of electricity generation. The carbon credit potential further reduces the unit cost of electricity generation from photovoltaic system and thus this can be used as a policy tool to promote renewable photovoltaic systems in remote and rural areas where climatic conditions are suitable for power generation from photovoltaic systems. Since crystalline silicon photovoltaic technology is more costly than thin film silicon photovoltaic technology so the unit cost of electricity generation from the earlier is more as compared to the later one. So thin film silicon photovoltaic technology is better option from economic point of view for remote rural areas. Therefore thin film photovoltaic systems can be installed in remote and rural areas to fulfill the basic electricity requirements in homes, hospitals and in farms for irrigation. The cost of electricity generation from thin film amorphous silicon photovoltaic technology is approximately equal to electricity generation from thermal power plants. In India, central and state government provides large subsidy to promote the use of renewable solar thermal and photovoltaic systems.

Future Scope

In the present study, the life cycle cost and enviroeconomic analysis has been carried out for standalone photovoltaic system. If this photovoltaic system is integrated to roof of a building then it further reduces the unit cost of electricity generation. In the present system only electricity has been used but by installing a duct below the module, the thermal energy of module can also be utilized and thus overall efficiency, overall energy and exergy of the system increases. Thus unit cost of electricity generation from photovoltaic system will further decrease.

Nomenclature

A_m:	Photovoltaic module Area (m^2)
h_0:	Heat transfer coefficient from the top to ambient (W/m^2-K)
h_i:	Heat transfer coefficient from the bottom to ambient (W/m^2-K)
I(t):	Incident solar intensity (W/m^2)
K_A:	Thermal conductivity of Aluminium sheet (W/m-K)
T_a :	Ambient temperature (ºC)
U_L:	Overall heat transfer coefficient from solar cell to ambient (W/m^2- K)
U_b:	Overall bottom loss heat transfer coefficient from solar cell to ambient (W/m^2- K)
L_A:	Length of Aluminiumsheet (m)
R_E:	Reflectivity of EVA
i:	Interest rate (%)
E_{el}:	Electricity (W)
n_0:	Number of clear days in a month
N:	Number of sun shine hours in a day
$C_{BB,R}$:	Battery bank system replacement cost(US$)
C:	Per unit electricity generation cost(US$)
ψ_{O_2} :	Average CO_2 equivalent intensity from coalthermal power plant (2.0 $kgCO_2/kWh$) [12]
ϕ_{O_2} :	CO_2 emissions mitigation per annum (tCO_2/year)
z_{O_2} :	Carbon price per tCO_2 (14.5 $/$tCO_2$)
Z_{O_2} :	Eviroeconomicparameter ($/year)
n:	Life of photovoltaic system
STC:	Standard test conditions
SPCU:	Solar power conditioning unit

$$U_b = \left[\frac{L_A}{K_A} + \frac{1}{h_i}\right]^{-1}$$

$$U_L = h_0 + U_b$$

Greek Letters

α:	Absorption factor
β0:	Temperature coefficient of the silicon (K-1)
ηm:	Efficiency of photovoltaic module
η0:	PV module efficiency at STC(I(t) = 1000 W/m2 , Ta = 25 0C)
χa:	Energy production factor
φ:	Life cycle conversion efficiency

Subscripts

α:	Ambient
m:	Photovoltaic module
A:	Aluminium
E:	EVA

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