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Analysis of hybrid PV/T air collector on the basis of carbon credit earned & energy matrices

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Abstract-In this paper study has been carried out to evaluate overall thermal energy gain and exergy gain for the different Indian climatic condition of Jodhpur, Srinagar, Bangalore & New Delhi. This study involves the electrical and thermal output of opaque PV module having duct above the module. Further carbon credit & energy matrices analysis mainly in terms of energy payback period (EPBT), energy production factor (EPF) & life cycle conversion efficiency (LCCE) have been carried out which is based on overall thermal & exergy gain. The effect of different rate of interest of 8%, 10% & 12% on annualized uniform cost (AUC), EPF & LCCE has also been analyzed. It was found from envireoeconomic analysis that in terms of overall thermal & exergy gain, environmental cost is Rs 3261.97 /annum & Rs 699.99 /annum. It has been observed that annualized uniform cost (AUC) is higher for all cities in case of overall exergy gain as compare to overall thermal gain.

Key words: hybrid air collector, energy payback period, energy production factor, carbon credit earned, Solar cell, PV module, Life cycle conversion efficiency

1. INTRODUCTION

A lot of research work has been carried out in terms of the energy matrices of hybrid PVT air collector. Firstly energy payback period of about 40 years was reported by Slesser & Houman [15] but by doing the similar study energy payback period of about 12 years was reported by Hunt [8] which is in also support of the work done by kato et al.[11] for crystalline Si solar cell module. Furthermore an analysis has been done on the forecasting of EPBT for monocrystalline solar cell for the year 2020 by considering the various improved solar cell technology & efficiencies. Finally by doing forecasting Alsema & Nieuwlar [3] have reported that present EPBT of 5-6 years get reduced to 1.5-2 years. Taking into consideration annual cell production rate of .01 GW/y & cost in a range of 30,000-200,000 yen/t-c for reducing CO_2 emission, Yamada et al. [19] evaluated the EPBT to be around 6 years. Based on the survey, Gaiiddon and Jedliczaka [6] has done the comparative assessment and found that for a roof-mounted system EPBT of a complete PV system in the range of 1.6-3.3 years and for a PV façade it is 2.7 to 4.7 years. The value of energy relation factor by considering 30 year life period is found to be between 8 &18 for roof mounted system and between 5.4 & 10 for PV façade. They also give very useful result keeping in mind the environmental parameters which conclude that 40 ton of carbon dioxide is reduced by one single kWp of PV panel during its life cycle while carbon reduction of 23.5 ton is achieved per kWp for PV facades. Kalogirou [9] uses thermosiphon solar water heating system to study thermal performance, economics and environmental protection. His comparison shows the system to be financial with payback period of 4.5 years and with electricity back up found the life cycle saving of ϵ2240 while with diesel back up he found payback period of 4.5 years and life cycle saving of ϵ1056. When a system is in thermodynamic equilibrium with the environment, it is said to be in the dead state .At this state system possess no kinetic & potential energy and it has the temperature and pressure of its environment state. Considering the nine different dead state temperatures, Hakan et al. [7] analyzed the maisotsenko cycle based novel air collector on the basis of energy ,exergy, exergeoeconomic & enviroeconomic and found 58.85$/year to be the electrical energy consumption while from envireoeconomic point of view CO_2 emission cost was found to be 6.96$/year. In India about 60% of the electricity production is by means of coal which is the main cause behind CO_2 emission & that of acid rain. In present scenario whats so ever oil, gas and coal we have reserved, it will exhaust in about 22 years, 30 years and 80 years respectively. If India continues to grow at 8% Kalshion [10] the coal reserves will last in about less than 40 years. Raman & Tiwari [14] has done the analysis of hybrid PVT air collector, single & double pass for different Indian climatic condition of Jodhpur, New Delhi, Bangalore & Srinagar and found Jodhpur is most economical in terms of cost/kWh. After calculating carbon credit earned by PVT system at IIT, Delhi, Prabhakant & Tiwari [12] suggested that in order to reduce the emission of carbon dioxide & earned carbon credit, there should be more development of solar energy park.

By studying the potential of solar home system for diffusion and appropriate baseline, Chaurey & Kandpal [5] has made an attempt to estimate the CO_2 mitigation potential & concluded that if the carbon prices are taken as \$10/tCO_2 without transaction cost, carbon finance could reduce the effective burden of SHS to the user by 19%. An attempt was also made by Purohit [13] to estimate the CO_2 mitigation potential of solar home system under CDM in India. Overall performance of Opaque PV module having duct above the module has been analyzed by Deepika et al.[4] for Indian climatic condition of Jodhpur, New Delhi, Bangalore & Srinagar and concluded that the Bangalore city is having highest performance in terms of thermal energy, electrical energy, overall thermal energy, overall exergy gain, exergy efficiency.

2. PROPOSED MODULE DESCRIPTION

Proposed hypothetical module of hybrid PVT air collector with given dimension, design parameter, variation of climatic parameter have been used as in Deepika et al [4] as shown in figure 1(a) and its cross section view is shown in figure 1 (b).

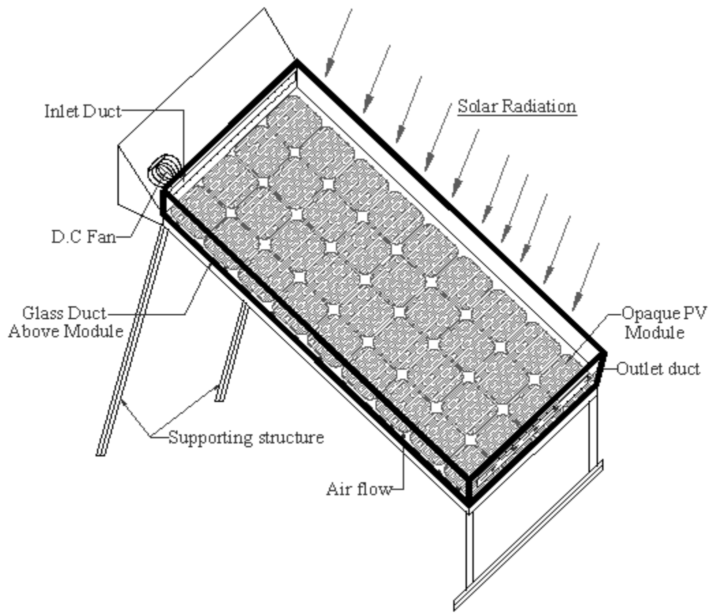

Figure 1 (a) Schematic diagram of opaque PV module having air duct on top of module

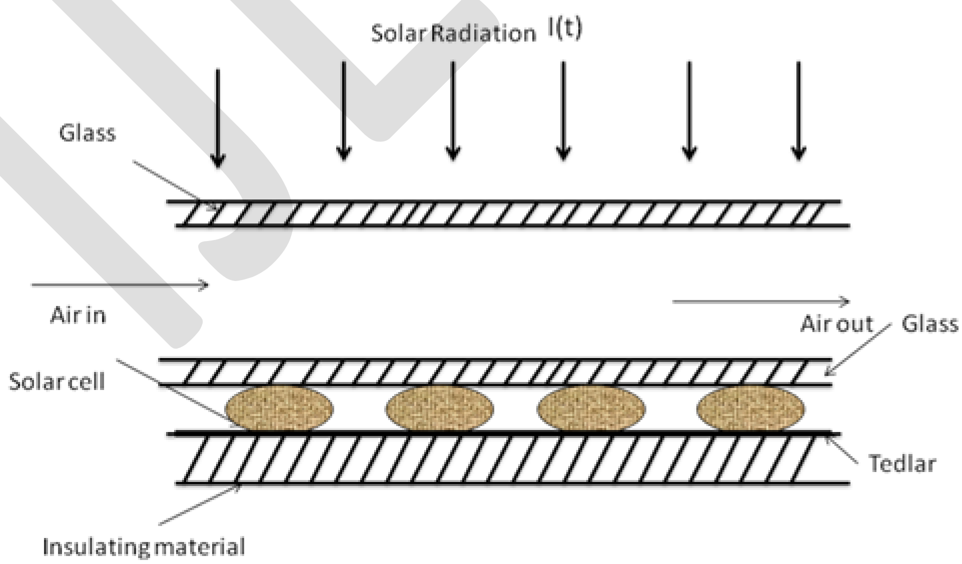

Figure 2(b): Cross-section view of opaque PV module having air duct on top of module

The value of overall thermal energy and exergy gain obtained from this has been used in this analysis. The hourly variation of monthly solar radiation, number of days falls under different climatic condition & hourly variation of ambient temperature are used as in Agarwal & Tiwari [1].

3. MATHEMATICAL FORMULATION OF VARIOUS FORMS OF ENERGY

The analysis which involved in life cycle cost analysis mainly covers the two forms of energy analysis. The first one is the embodied energy and other is energy matrices. Early researchers have carried out the study of life cycle conversion analysis (LCCA) without considering the effect of EPBT due to which actual life cycle cost was not obtained. In the present study an attempt has been made for investigation of life cycle cost of the PVT system by taking into account the effect of EPBT. The system has been analyzed based upon the overall exergy gain & thermal energy gain for climatic condition of New Delhi, Jodhpur, Srinagar and Bangalore, India. To calculate the quantity of energy use in generation of energy through PVT system LCCE analysis is to be done. This analysis mainly covers the field of embodied energy and energy matrices.

3.1 ANALYSIS OF EMBODIED ENERGY

Embodied energy can be defined by Treolar [18] as "the quantity of energy required by all of the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making equipments and in other supporting functions i.e direct energy plus indirect energy" .Thus embodied energy analysis is used to calculate the amount of required energy for manufacturing a material. After this analysis, there is also a need to know about the energy of different component. The breakup of embodied energy of each component of fabrication of PVT air collector is shown in Table 1.

Table 1. Breakup of embodied energy of different component of opaque PV module

Sr. No.	Component	Total embodied energy (kWh)
1	MS support structure	105.16
2	PV module (glass-Tedlar type) with duct above module	667.15
3	DC fan	26.82
Total		799.13

Table 2. Capital cost (Pc), Salvage value (Sv) & Maintenance cost (Mc) of hybrid PVT module air collector

Component	Quantity	PVT air collector	Salvage value (Sv) at the inflation rate of 4% (Present value of scrap for Iron @ Rs (15 kg)		
			After 20 year Iron scrap @Rs 33(kg)	After 30 year Iron scrap @Rs 49(kg	After 40 year Iron scrap @Rs 72(kg
Mild steel support structure @ Rs 50(kg)	10.7	535	353	524	770
PV module @ Rs 5000/ 75Wp	1no.	5000	100	100	100
DC fan(12 v &1.8 A)	1 no.	350	15	15	15
Paint @ Rs 80(kg)	0.4 kg	32	NA	NA	NA

Fabrication charges		500	NA	NA	NA
Capital cost		Rs 6417	Rs 468	Rs 639	Rs 885

Operational & maintenance cost=Rs 500/per year

Fan replacement cost & paint=Rs 600/-in every 10 year.

NA-no salvage value.

3.2 ENERGY MATRICES

Basically there are three energy matrices which are used to evaluated the performance of PVT system i.e energy payback period (EPBT), energy production factor (EPF) & LCCE (life cycle conversion efficiency).

3.2.1 ENERGY PAYBACK PERIOD (EPBT)

EPBT is defined as the ratio of total energy consumed in the production & installation of the system (Eenergyin) to the total energy available at the output.

$$EPBT = \frac{E_{energyin}(Kwh)}{E_{energyout}(kwh/year)} \quad (1)$$

3.2.2 ENERGY PRODUCTION FACTOR (EPF)

Overall performance of the PVT system can be evaluated by comparing the total energy supplied to the system and the total output energy available. The ratio of total energy output to the total energy input is defined as the energy production factor (EPF). The evaluation of EPF can be done on annual and life time basis as follows–:

i) On annual basis

$$\chi_{ann} = \frac{E_{energyout}}{E_{energyin}}$$

$$\text{or} \quad \chi_{ann} = \frac{1}{EPBT} \quad (2)$$

If $\chi_{ann} \longrightarrow$ 1 for EPBT=1, the system is worthwhile from energy point of view otherwise it is not.

ii) On Life time basis

$$\chi_{Life} = \frac{E_{energyout} \times T}{E_{energyin}} \quad (3)$$

Where T=Life time

$E_{energyout}$ = Total energy output

$E_{energyin}$ = Total energy input

3.2.3 LIFE CYCLE CONVERSION EFFICIENCY (LCCE)

This is defined as the net energy productivity of the system over the life time (T) years w.r.t input solar radiation

$$\phi_{Life}(t) = \frac{(E_{energyout} \times T) - E_{energyin}}{E_{solar} \times T} \quad (4)$$

4. ANNUALIZED UNIFORM COST

Present and future costs are also involved in order to calculate the life cycle cost analysis. There are various cost parameters that are to involved in the analysis like initial cost, operation & maintenance cost, replacement cost and salvage value. Let P is the initial cost which include support structure cost, DC fan cost, module cost etc,R_1,R_2-----Rn is the operation & maintenance cost which charged annually , $R_{10,1}$,$R_{10,2}$-----is the replacement cost of the fan & paint made in every ten year. By Raman & Tiwari [14] , the capital recovery factor over the life time can be expressed as-

$$CPRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (5)$$

Where i = rate of interest per year

n = number of years

Then the net present value can be calculated based on different criterion-

i) Without considering the effect of EPBT

The computation of life cycle cost of the PVT system can be obtained by conventional cash flow diagram as shown in Figure (2)

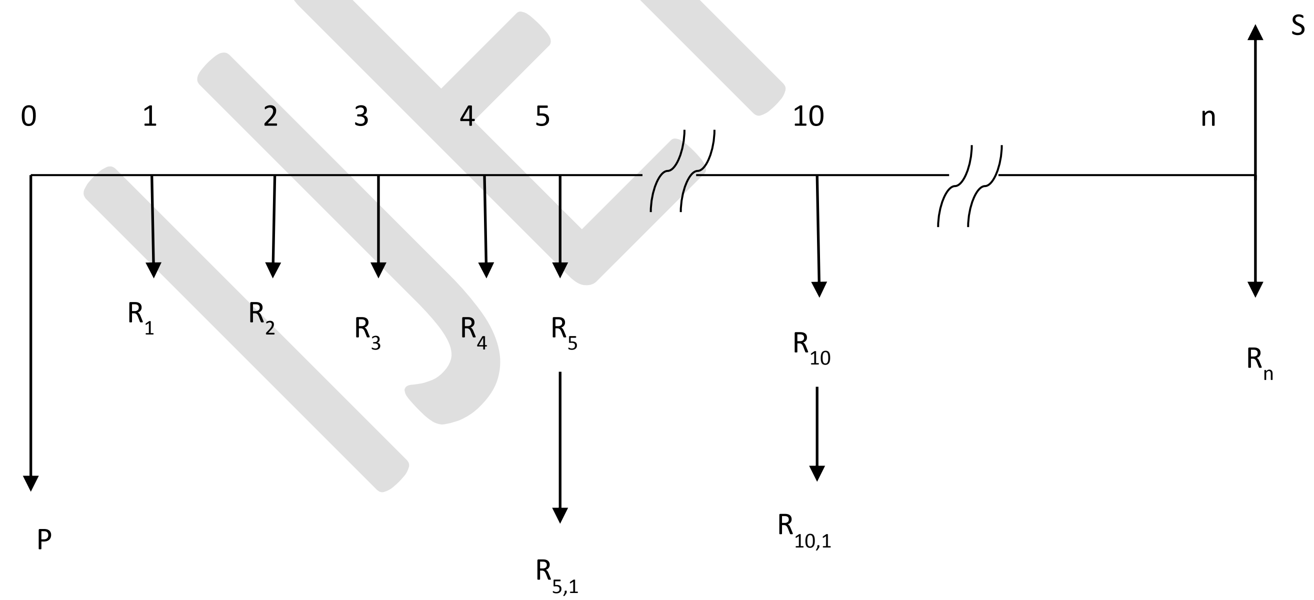

Figure. 2. Conventional cash flow diagram for life cycle cost of PVT system without considering effect of EPBT

Here NPVL can be calculated by the given formula-

$$NPVL = P_c + R_1 \times \left[\frac{(1+i)^n - 1}{i(1+i)^n}\right]_{i,n} + R_{10,2} \times \left[\frac{1}{(1+i)^n}\right]_{i,10} + ------ + R_{10,1} \times \left[\frac{1}{(1+i)^n}\right]_{i,10}$$
$$+ --------- S_v \times \left[\frac{1}{(1+i)^n}\right]_{i,n} \qquad (6)$$

Where NPVL = Net Present Value of the PVT system

ii) Considering the effect of EPBT

Here the conventional cash flow diagram can be obtained as shown in figure (3)

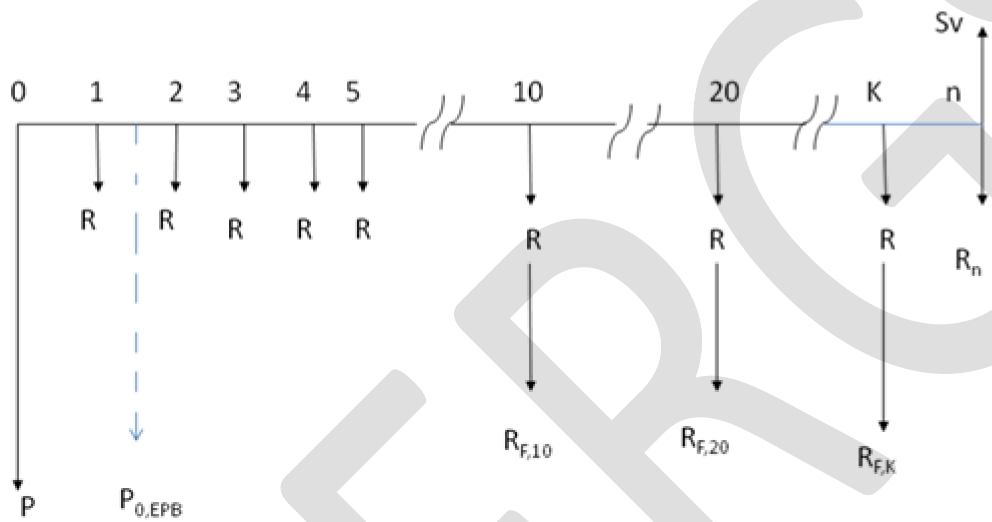

Figure. 3. Conventional cash flow diagram for life cycle cost of PVT system with considering effect of EPBT

$$NPVL = P_{EPBT} = P_c(1+i)^{EPBT} + R \times (1+i)^{EPBT-1} + R + R \times \left[\frac{(1+i)^{n-EPBT} - 1}{i(1+i)^{n-EPP}}\right] + R_{F,10} \times \left[\frac{1}{(1+i)^{10-EPBT}}\right] + R_{F,20} \times \left[\frac{1}{(1+i)^{20-EPBT}}\right] \qquad (7)$$
$$+ ------- + R_{F,K} \times \left[\frac{1}{(1+i)^{K-EPBT}}\right] + -------- S_v \times \left[\frac{1}{(1+i)^{n-EPBT}}\right]$$

Therefore Annualized uniform cost (AUC) by Tiwari [17] is defined as the multiplication of the net present value of the PVT system and capital recovery factor is given by

$$AUC = NPVL \times CPRF \qquad (8)$$

The cost of per unit of electricity generated by the PVT system is defined as the ratio of annualized uniform cost and overall thermal energy or exergy produced by the PVT system.

5. CARBON CREDIT EARNED

The production of electricity from fossil fuel which result emission of CO_2 in the environment causes great hazard to human being. In order to avoid the CO_2 emission envireoeconomic analysis is very important mechanism to promote the development of renewable energy technology which does not emit any carbon to the atmosphere. Total carbon credit earned on life time basis has been obtained on the basis of overall thermal energy gain & exergy gain.

5.1 Overall Thermal Energy Gain Basis

Overall thermal energy produced per annum for Bangalore is 1029.33 kWh

5.5 is taken as the unit cost of energy per annum then cost of energy produced per annum=1029.33x5.5=Rs 5661.31

The amount of CO2 emission for unit power consumption will be 2.08x0.982 = 2.04 kg/kWh

The carbon dioxide reduction per annum = 2.04x1029.33 = 2099.83kg

In ton = 2.099 t CO_2e

If carbon dioxide emission at present is being traded @ϵ23/t CO_2e, then cost of carbon emission reduction per annum = 23x2.099 = ϵ 48.296

This can be converted in rupees by multiplying current euro rupee conversion factor = 48.296x67.54 = Rs 3261.92

5.2 Overall Exergy Gain Basis

Overall exergy gain produced per annum for Bangalore is 220.89 kWh

5.5 is taken as the unit cost of energy per annum then cost of energy produced per annum=220.89 x5.5=Rs 1214.89

The amount of CO_2 emission for unit power consumption will be 2.08x0.982 = 2.04 kg/kWh

The carbon dioxide reduction per annum = 2.04x220.89 = 450.61 kg

In ton = 0.450 tCO_2e

If carbon dioxide emission at present is being traded @ϵ23/t CO_2e, then cost of carbon emission reduction per annum=23x0.450= ϵ 10.364

This can be converted in rupees by multiplying current euro rupee conversion factor = 10.364x67.54 = Rs 699.99

Similarly carbon credit analyzed can be done for New Delhi, Jodhpur, Srinagar and earned carbon credit as shown in Table 3.

Table 3.Total carbon credit earned by different cities for given PV module

City	CO_2 mitigation per annum (tCO_2/annum)		Envireoeconomic (environmental cost) parameter Rs/annum	
	In terms of overall thermal energy gain	In terms of overall exergy gain	In terms of overall thermal energy gain	In terms of overall exergy gain
Bangalore	2.09	0.450	3261.97	699.99
New Delhi	1.90	0.406	2959.88	631.95
Jodhpur	2.05	0.446	3196.57	693.05
Srinagar	1.86	0.396	2889.37	615.97

6. RESULTS & DISCUSSION

THE OVERALL THERMAL ENERGY & EXERGY GAIN FOR THE OPAQUE PV MODULE HAVING DUCT ABOVE THE MODULE IS TAKEN AS IN DEEPIKA ET AL. [4] FOR DIFFERENT INDIAN CLIMATIC CONDITION. THE BREAKUP OF THE EMBODIED ENERGY OF DIFFERENT COMPONENT USED IN FABRICATION AND THE CAPITAL COST (PC) & SALVAGE VALUE (SV) OF THE GIVEN MODULE HAS BEEN SHOWN IN TABLE 1 & 2 RESPECTIVELY

TABLE 4.ENERGY PAYBACK PERIOD AND ENERGY PRODUCTION FACTOR ANNUALLY ON THE BASIS OF OVERALL THERMAL ENERGY & OVERALL EXERGY FOR
DIFFERENT CITIES

Basis	Energy Payback Period (EPBT)				Energy Production factor(EPF)			
	Bangalore	New Delhi	Jodhpur	Srinagar	Bangalore	New Delhi	Jodhpur	Srinagar
Overall Thermal Energy	0.77	0.85	0.79	0.87	1.29	1.17	1.26	1.14
Overall Exergy	3.61	4	3.65	4.11	0.27	0.25	0.27	0.24

TABLE 5 EPF & LCCE ON THE BASIS OF OVERALL THERMAL ENERGY & EXERGY FOR DIFFERENT VALUES OF LIFE TIME PERIOD (N=20, 30, 40 YEARS)

Life Time (Years)	City	EPF		LCCE	
		Energy basis	Exergy basis	Energy basis	Exergy basis
20	Bangalore	25.8	5.4	1.24	0.221
	New Delhi	23.4	5	1.12	0.2
	Jodhpur	25.2	5.4	1.21	0.220
	Srinagar	22.8	4.8	1.09	0.190
30	Bangalore	38.7	8.1	0.327	0.237
	New Delhi	35.1	7.5	0.297	0.216
	Jodhpur	37.8	8.1	0.318	0.237
	Srinagar	34.2	7.2	0.286	0.207
40	Bangalore	51.6	10.8	1.26	.2456
	New Delhi	46.8	10	1.14	0.225
	Jodhpur	50.4	10.8	1.235	.2453
	Srinagar	45.6	9.6	1.11	0.215

TABLE 6 VARIATION OF ANNUALIZED UNIFORM COST FOR DIFFERENT CITIES AT DIFFERENT RATE OF INTEREST & EXPECTED LIFE TIME PERIOD OF THE SYSTEM WITHOUT CONSIDERING THE EFFECT OF EPBT

Life Time (Years)	City	Annualized Uniform cost(AUC)					
		i=0.08		i=0.1		i=0.12	
		Energy basis	Exergy basis	Energy basis	Exergy basis	Energy basis	Exergy basis
20	Bangalore	1.15	5.39	1.25	5.84	1.34	6.25
	New Delhi	1.27	5.97	1.38	6.47	1.480	6.93
	Jodhpur	1.18	5.45	1.27	5.90	1.370	6.32
	Srinagar	1.30	6.13	1.41	6.64	1.51	7.11
30	Bangalore	1.07	4.98	1.18	5.51	1.291	6.01
	New Delhi	1.17	5.52	1.30	6.10	1.423	6.66
	Jodhpur	1.09	5.03	1.20	5.56	1.318	6.07
	Srinagar	1.20	5.66	1.33	6.26	1.45	6.84
40	Bangalore	1.06	4.94	1.18	5.50	1.295	6.03
	New Delhi	1.16	5.47	1.30	6.09	1.427	6.68
	Jodhpur	1.08	4.99	1.20	5.55	1.321	6.09
	Srinagar	1.19	5.62	1.33	6.25	1.46	6.86

Table 7 Variation of annualized Uniform Cost for different cities at different rate of interest & expected life time period of the system with considering the effect of EPBT

Life Time (Years)	City	Annualized Uniform cost(AUC)					
		i=0.08		i=0.1		i=0.12	
		Energy basis	Exergy basis	Energy basis	Exergy basis	Energy basis	Exergy basis
20	Bangalore	1.26	6.59	1.40	7.65	1.53	8.77
	New Delhi	1.40	7.42	1.55	8.67	1.69	10.01
	Jodhpur	1.29	6.67	1.43	7.74	1.56	8.88
	Srinagar	1.43	7.65	1.59	8.96	1.73	10.36
30	Bangalore	1.17	6.16	1.32	7.28	1.47	8.50

	New Delhi	1.30	6.94	1.46	8.26	1.63	9.71
	Jodhpur	1.20	6.23	1.35	7.38	1.50	8.61
	Srinagar	1.33	7.15	1.50	8.54	1.67	10.05
40	Bangalore	1.14	6.01	1.30	7.16	1.45	8.39
	New Delhi	1.26	6.78	1.44	8.12	1.61	9.59
	Jodhpur	1.16	6.08	1.32	7.25	1.48	8.50
	Srinagar	1.29	6.99	1.47	8.39	1.65	9.93

The energy payback period & energy production factor on the basis of overall thermal energy gain and exergy gain can be calculated from equation (1) & (2) respectively. The value of EPBT & EPF of given hybrid PV module have been shown in Table 4.It has been observed that the value of EPBT & EPF is more when analysis has been done on the basis of overall thermal energy gain basis and overall exergy gain respectively. The minimum value of EPBT for Jodhpur on the basis of overall thermal energy gain & exergy gain is 0.77 & 3.61 respectively while it is maximum for Srinagar is 0.87 & 4.11 respectively. The maximum value of EPF on the basis of overall thermal energy gain & exergy gain are 1.29 & 0.27 respectively. Life cycle conversion efficiency & annualized uniform cost for different life time period have been evaluated by equation (4) & (8) respectively while the net present value for different criterion has been evaluated by equation (6) & (7). It has been observed that value of EPF & LCCE increases from Srinagar to Bangalore and the same increasing trend follow while increasing the life time period of the system both on energy & exergy gain basis. The result of EPF & LCCE for the given PV module for the different Indian climatic condition have been shown in Table (5).

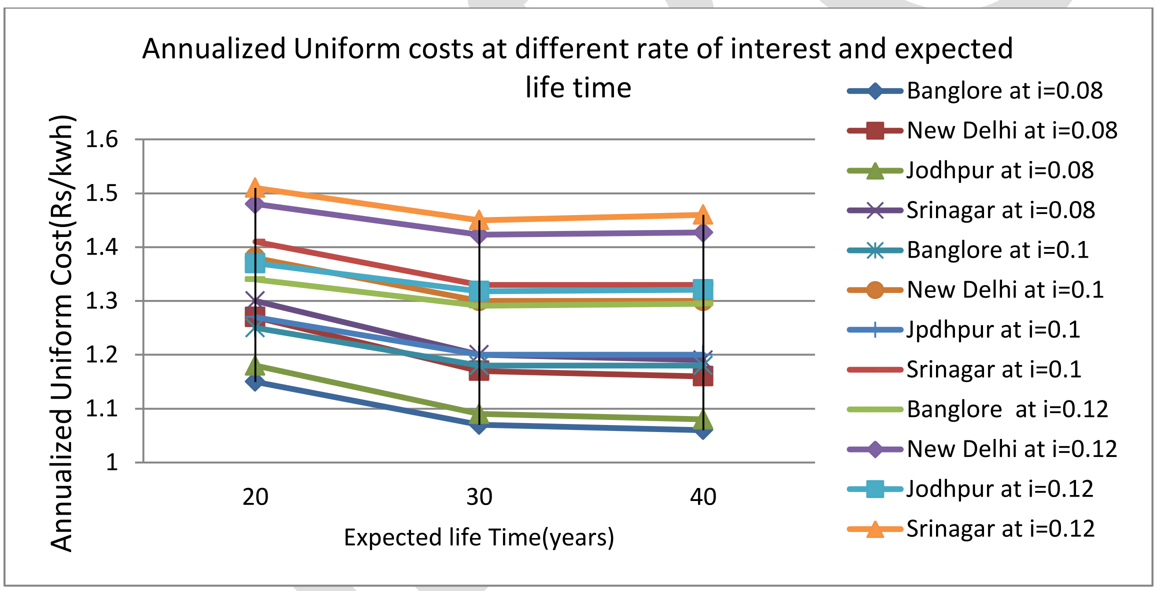

Figure 4 variation of annualized uniform cost at different rate of interest & expected life time period without considering the effect of EPBT

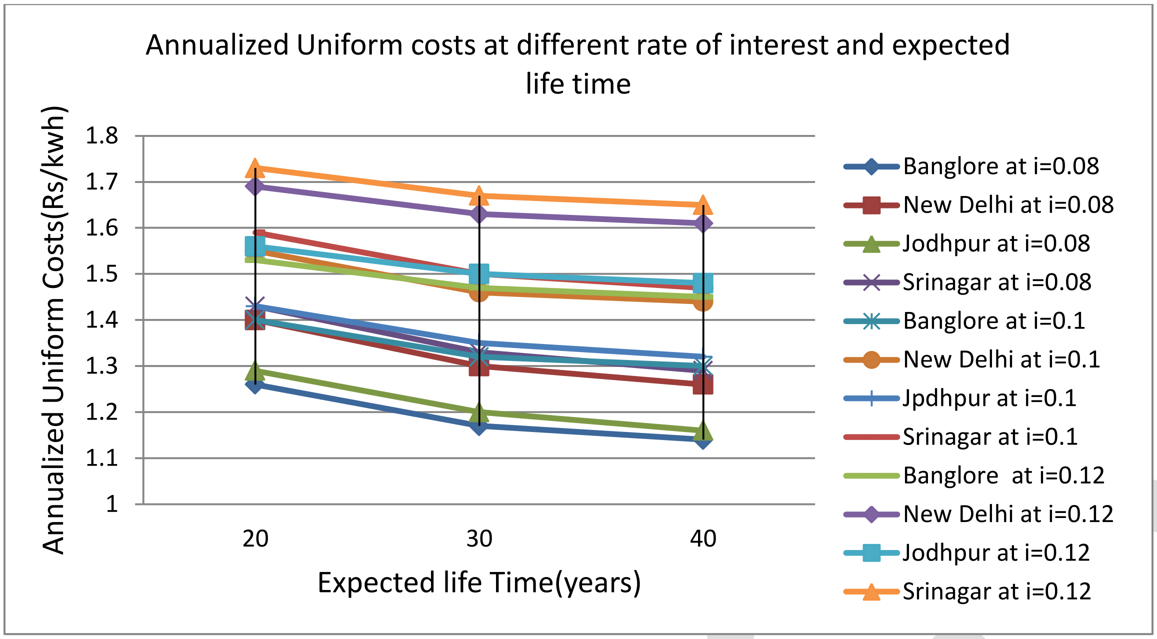

Figure 5 variation of annualized uniform cost at different rate of interest & expected life time period with considering the effect of EPBT

The effect of annualized uniform cost with different rate of interest & for different life time period without & with considering the effect of EPBT has been shown in Table (6) & (7) respectively. It has been found that with the increase in life time period of the system, the value of annualized uniform cost deceases while value of EPF & LCCE increases this result also proves the work done by Solanki et al.[16]. From Table 6 & 7, it has been observed that annualized uniform cost (Rs/kWh) is higher on the basis of overall exergy gain in comparison to overall thermal energy gain this is in accordance with result obtained by Agrawal & Tiwari [2].Here annualized uniform cost is an indication of energy incurred in the system and hence it can be concluded that system which is having lower value is a better system. It has also been that with considering the effect of EPBT annualized uniform cost has been increased by 7.5% for the minimum value & 45.7% for the maximum value. The plot of annualized uniform cost against various life time period & at different rate of interest with 8%,10% &12% is shown in the Figure (4) & (5) without & with considering the effect of EPBT. By comparing the figures (4) & (5), it has been found that Srinagar has got highest annualized uniform cost while Bangalore has got lowest one in both the cases.

6. CONCLUSION

From the present study various points have been concluded-

Highest payback period is 0.87 & 4.11 on the basis of overall thermal energy & exergy gain respectively.

Highest & lowest value of EPF & LCCE on the basis of overall thermal energy gain & exergy gain is for Bangalore & Srinagar respectively.

Bangalore has got the highest value of carbon credit earned on the basis of energy & exergy gain .

The value of annualized uniform cost without & with considering the effect of EPBT is highest for Srinagar for high rate of interest while Bangalore has got lower value at lower rate of interest.

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