Applied Energy 86 (2009) 1995–2004

Contents lists available at ScienceDirect

Applied Energy

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

Life cycle cost analysis of single slope hybrid (PV/T) active solar still

Shiv Kumar *, G.N. Tiwari

Centre for Energy Studies, Indian Institute of Technology, Hauz Khas, New Delhi 110 016, India

ARTICLE INFO

Article history:
Received 2 September 2008
Received in revised form 2 March 2009
Accepted 3 March 2009
Available online 2 April 2009

Keywords:
Passive and hybrid (PV/T) active solar still
Life cycle cost analysis
Energy payback period

ABSTRACT

This paper presents the life cycle cost analysis of the single slope passive and hybrid photovoltaic (PV/T) active solar stills, based on the annual performance at 0.05 m water depth. Effects of various parameters, namely interest rate, life of the system and the maintenance cost have been taken into account. The comparative cost of distilled water produced from passive solar still (Rs. 0.70/kg) is found to be less than hybrid (PV/T) active solar still (Rs. 1.93/kg) for 30 years life time of the systems. The payback periods of the passive and hybrid (PV/T) active solar still are estimated to be in the range of 1.1–6.2 years and 3.3–23.9 years, respectively, based on selling price of distilled water in the range of Rs. 10/kg to Rs. 2/kg. The energy payback time (EPBT) has been estimated as 2.9 and 4.7 years, respectively.

1. Introduction

Many developed and developing countries of the world are making sustained efforts to harness the renewable energy resources due to the free availability and faster depletion of conventional energy resources. Also, use of fossil fuels leads to long term environmental problems, such as acid rains and greenhouse effects. Similarly, the heavier problems are encountered with nuclear energy, mainly due to the serious risks it implies to harmful radiations. Under these conditions, there is growing interest for renewable and eco-friendly energy sources such as solar energy. Solar energy is a one of the renewable energy resources and avoids most of the negative impact due to the use of fossil fuels. It has many applications; one of which is solar distillation. Water is one of the most abundant resources on earth, covering about 75% of the earth surface. However, about 97% of it is salt water in the oceans, and about 3% is fresh water. Out of the available fresh water, less than 1% is available for human and animal needs. The total water requirements have been increased over the last years for various reasons and most important one is fast economic development, which has lead to a higher standard of living. Solar distillation is an oldest method to produce potable water from brackish or saline water by utilizing the solar energy as reported by various researchers. It is more economical in the areas receives more solar radiation and better solution to the problem of energy security and climatic change with zero running cost. Conventional solar still uses the greenhouse effect to evaporate the pure form of water from the brackish/salty water. The still acts as a heat trap because of transparent roof to incoming sunlight but opaque to the infrared radiation emitted by the hot water. The passive solar still is one of a conventional design in use since 1842 (built in Chile of 4000 m^2 area). The low distillate yield from passive solar still (2–4 l/m^2 day) is a major barrier in its commercialization. In order to meet the requirement of fresh water rigorous research have been carried out by various scientists on design, fabrication and development of the solar stills for distillation to increase its absorptivity to solar radiation. The various solar stills, such as double-roof stills, diffusion stills, wetted wick stills and coupling of solar stills to the external assisting systems (flat-plate collectors, concentrators, heat pipes and waste-heat sources) have been investigated to improve the performance. Malik et al. [1] have reported that the maximum thermal efficiency of a conventional solar still can be 30%, which further depends on the solar intensity, location, time and weather conditions. Al-Hinai et al. [2] have reported the effect of water depth (0.02–0.30 m) on daily distillate yield and recommended the brine water depth in the range of 0.02–0.06 m for better yield from the passive solar still. El-Sebaii [3] has carried out the parametric study of vertical solar still by computer simulation and found that the daily yield decreases with increase in an air space between absorber and glass cover, possibly due to long path of water vapour to travel.

Monthly performances of the passive and active solar stills have been evaluated by Singh and Tiwari [4] for different Indian climatic conditions. They inferred that an annual yield depends on water depth, condensing cover inclination and collector area. They have reported the maximum annual yield at 28.35° inclination of condensing cover, which is latitude of New Delhi (India).

Photovoltaic–thermal (PV/T) technology refers to the integration of a PV module and conventional solar thermal collector in a single piece of equipment. The rationale behind the hybrid concept

* Corresponding author. Tel.: +91 9868878227.
E-mail addresses: skdubey_1966@rediffmail.com, skdubey1995@yahoo.com (S. Kumar).

0306-2619/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.apenergy.2009.03.005

Nomenclature

CPK	cost of distilled water per kg (Rs./kg)
CF	annual cash flow (Rs.)
$F_{CR,i,n}$	capital recovery factor
$F_{SR,i,n}$	sinking fund factor
$HA_{,Com}$	proposed hybrid active solar still
$HA_{,Exp}$	present (experimental) hybrid active solar still
i	rate of interest, fraction (%)
L	latent heat of vaporization, J/kg
M_s	annual maintenance cost of solar still (%)
M	total maintenance cost (Rs.)
M_{yield}	annual yield (kg)
n	expected life of solar still (year)
n_p	payback period (year)
N	no. of clear day in a month
P	present capital cost of the system (Rs.)
$P_{,Com}$	proposed passive solar still
$P_{,Exp}$	present (experimental) passive solar still
P_p	cost of DC water pump (Rs.)
P_m	annual power generated from PV module (kW h)
P_u	annual power utilized from PV module (kW h)
P_s	net present cost of the solar still (Rs.)
S_s	salvage value of solar still as a fraction of capital cost P_s (Rs.)
$S_{p,elect}$	electricity rate per unit (Rs./kW h)
UA	the uniform end of year annual cost (Rs.)
UA_{net}	net uniform end of year annual cost (Rs.)

Subscripts

Exp	experimental solar still
Com	proposed design solar still

Conversion unit

1$	Rs. 39 in 2006

is that a solar cell converts solar radiation to electrical energy with peak efficiency in the range of 9–12%, depending on specific solar-cell type and thermal energy dissipated for water heating. More than 80% of the solar radiation falling on photovoltaic (PV) cells is not converted to electricity, but either reflected or converted to thermal energy. In view of this, hybrid photovoltaic and thermal (PV/T) collectors are introduced to simultaneously generate electricity and thermal power [5]. Chow [6] has analyzed the PV/T water collector with single glazing in transient conditions, consisting of tubes, in contact with the flat plate, reported an increase of electric efficiency by 2%, and obtained the thermal efficiency of 60% at 0.01 kg/s flow rate of water. Further, Zakharchenko et al. [7] have studied the unglazed hybrid (PV/T) system with suitable thermal contact between the PV module and the collector and reported that the area of module and collector in the PV/T system need not to be equal for higher overall efficiency. To operate the PV module at low temperature, the PV module should be fixed at lower temperature part of the collector (i.e. at the inlet of feed water). The parametric study of different configuration of hybrid (PV/T) air collector has also carried out by Tiwari and Sodha [8]. Kumar and Tiwari [9] have reported that daily yield obtained from hybrid (PV/T) active solar still is 3.5 times of the passive solar still. Tiwari et al. [10] have validated the theoretical and experimental results for photovoltaic (PV) module integrated with air duct for composite climate of India and concluded that an overall thermal efficiency of PV/T system is significantly increased due to utilization of thermal energy from PV module. Recently, Dubey et al. [11] have reported the higher annual average efficiency of glass to glass type PV module with and without air duct as 10.41% and 9.75%, respectively.

The economics of any energy system is essential to understand the cost of production and economic payback period on the investment to reduce the risk of project failure. The life cycle cost analysis of solar still depends on several key variables such as

- initial investment
- rate of interest
- annual distillate yield
- maintenance cost
- life time of solar stills
- production cost of distilled water
- selling price of distilled water
- salvage value of the system, etc.

Tleimat and Howe [12] have reported that the solar distillation plants of capacity less than 200 l/day are more economical than the other type of plants. Mukherjee and Tiwari [13] have carried out the economic analysis of three different types of the solar stills, namely a single slope fiber-reinforced plastic (FRP) still, a double slope FRP solar still and a double slope concrete solar still for Indian climatic conditions. They have concluded the minimum cost of distilled water produced from conventional solar stills. Sinha et al. [14] have carried out the techno-economic analysis on active solar distillation system and solar water heater considering 14 years life of the systems.

It has also inferred from the literatures that the maintenance cost of the solar stills is less and required only to clean the systems as well as filling and collection of yield. Therefore, the cost of distilled water mainly depends on initial investment and interest rate. The various scientists have also studied the life cycle cost analysis of the passive solar still under different climatic conditions. Various researchers have done the economic analysis of the solar still plant in different places and the cost of distilled water obtained is presented in Table 1.

Fath et al. [17] have recommended the acceptable cost of the distilled water for potable use in remote areas, if produce from solar stills at $0.03/L (i.e. Rs. 1.20/kg). Kalogirou [18] has estimated that the 25% of the price of distilled water attributes to the energy cost, if produced using conventional fossil fuel in Cyprus. However, the cost analysis carried out by different researchers as mentioned above concludes that the solar stills can be used to provide fresh water at reasonable cost.

In this paper, annual performance and cost of distilled water produced from newly designed hybrid (PV/T) active and passive

Table 1
Cost of distilled water reported by various investigators.

Cost	Year	Investigators	Size of the plant
$20 m^{-3}	1994	Ghoneyem and Ileri [15]	For large size plant
$2.4 m^{-3}	1995	Madani and Zaki [16]	For 50 m^3/day production capacity using porous basin solar stills
$16.3 m^{-3}	2002	Al-Hinai et al. [2]	Based on distillate yield of 52 weeks using a cluster of 250 simple solar stills.
$30 m^{-3}	2003	Fath et al. [17]	Pyramid shaped solar still

solar stills has been carried out in order to estimate the viability of both the systems. The cost payback period and energy payback time (EPBT) considering the initial investment, salvage value, maintenance cost, interest rate and life of the systems into account have also been incorporated. The economics of hybrid (PV/T) active solar still has not been presented by any researchers before.

2. Experimental solar stills

The experimental setup of passive and hybrid (PV/T) active solar stills fabricated, installed and tested at solar energy park at IIT New Delhi are described below.

2.1. Single slope passive solar still

The single slope passive solar still of an effective basin area of 1 m × 1 m was fabricated by using glass reinforced plastic (GRP) material. The photograph is shown in Fig. 1a. A glass cover with an inclination of 30° is fixed at the top of the vertical walls of the solar still by using a rubber gasket and clamps. The glass cover is further sealed with window-putty to avoid the leakage of vapour to outside. The distillate output is collected in a channel (trough) fixed at the end of the lower vertical side wall of the basin and taken to outside through a plastic pipe, connected to this channel. The inner surface of the basin is painted black to increase the absorptivity to solar radiation. A plastic hose-pipe is fixed through a hole drilled at the bottom of the basin to drain out the water during cleaning of the basin. Holes are also drilled in the body of the

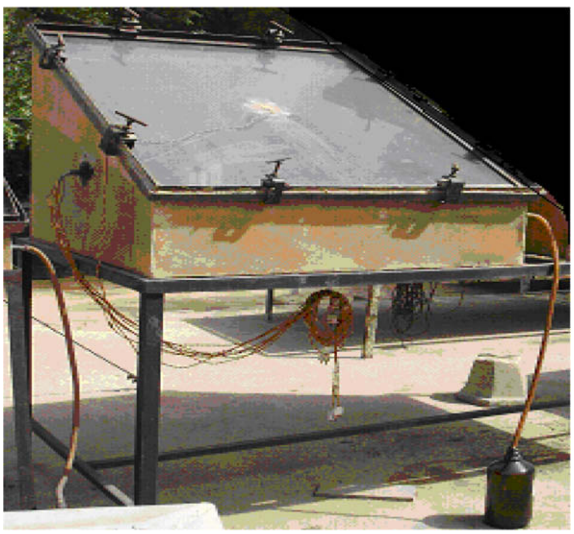

Fig. 1a. Photograph of a passive solar still.

Fig. 1b. Photograph of hybrid (PV/T) active solar still.

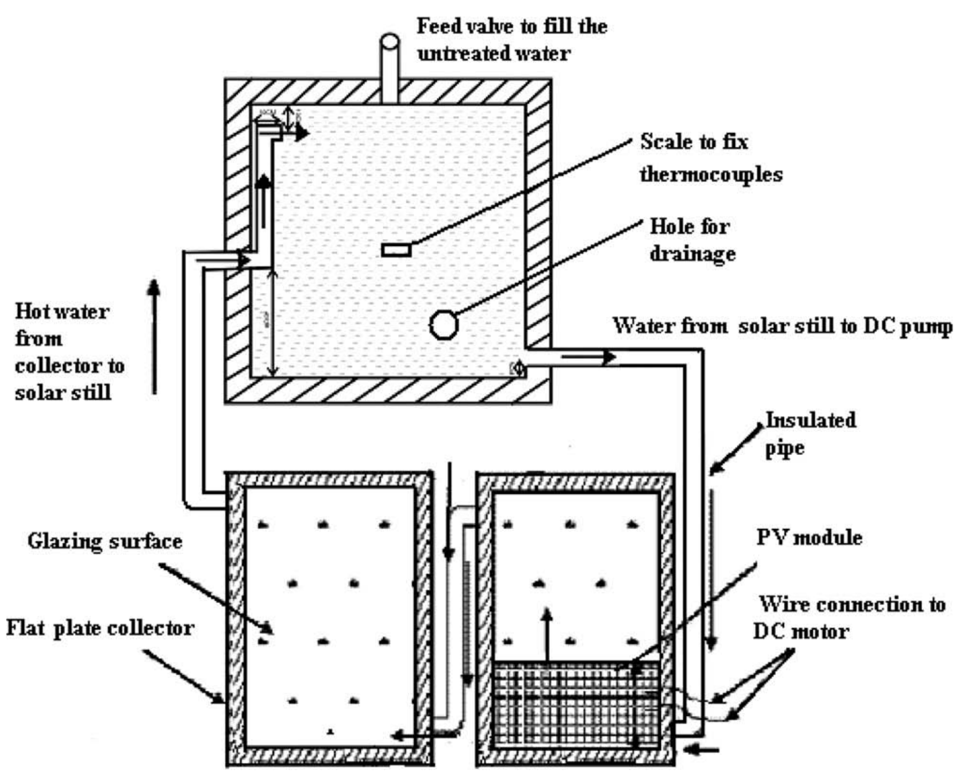

Fig. 1c. Schematic top view of a hybrid (PV/T) active solar still.

still to fix the thermocouples to measure the temperatures of water in the basin and the inner glass cover. The whole unit is mounted on an angle iron stand. The solar still is oriented due south in order to receive maximum solar radiation throughout the year.

2.2. Single slope hybrid photovoltaic (PV/T) active solar still

The feeding of hot water available from a flat plate collector panel to the basin of solar still has been considered as one of the most effective active methods to increase the water temperature. The temperature difference between the evaporating (water) and condensing surface (glass) can be increased by feeding the additional thermal energy from the flat plate collector in the basin of the solar still. The photograph and schematic of the fabricated hybrid (PV/T) active solar still are shown in Figs. 1b and c, respectively. The operating principle of hybrid (PV/T) active solar still involves implementation of following components:

- PV integrated flat plate collectors
- DC motor pump
- Solar still

Two flat plate collectors are connected in series and integrated to the basin of solar still by means of insulated pipes. The connecting pipes are insulated to avoid thermal losses from the hot water flowing in the pipe to the ambient. Each collector has an effective area of 2 m^2. A glass to glass photovoltaic (PV) module with an effective area of 0.66 m^2 (consists of 36 solar cells and peak power capacity of 75 Wp) is integrated at the bottom of one of the collector at entry side of lower temperature water. Therefore, space and cost of installation of PV module separately from the system has been avoided. In this case, solar radiation is transmitted through non-packing area of PV module and finally absorbed by the blackened absorber. Further, the thermal energy associated with PV module is dissipated to the absorber by convection for further heating. Water below absorber gets heated and moves in the upward direction. The outlet of water at the end of absorber, which is covered with PV module, becomes inlet to the remaining portion of first flat plate collector. Such collector is referred a photovoltaic/thermal (PV/T) water collector. The outlet of photovoltaic/thermal (PV/T) water collector is further connected to the inlet of second flat plate collector for higher operation temperature. Both collectors are connected to the solar still mounted on an iron stand.

There is a provision of a DC water pump (18 V, 60 W, 2800 rpm) connected to PV module to circulate the water between collectors and solar still in a forced mode. The some part of DC power generated (P_m) by PV module is utilized (P_u) to operate the water pump. The excess power (P_{net}) generated can be utilized for other purposes. The DC pump operates only during sun-shine hours to avoid reverse heat flow during off sun-shine hours. In a hybrid (PV/T) active solar still, the water in the basin is heated directly as well as indirectly through flat plate collectors.

The quantity of material used in fabrication and the cost break up of solar stills are given in Table 2. The initial capital investment for procuring the solar stills varies with design, size and material of construction. The scrap value in the developed countries is almost negligible, whereas the scrap value, inflation rates etc. in developing countries are higher than the developed countries. The scrap value of iron, copper and aluminium will also increase with time due to inflation. The expected rates of these materials have also

Table 2
Capital cost (P_s), Salvage value (S_s) and maintenance cost (M_s) of single slope passive and hybrid (PV/T) active solar still (1$ = Rs. 39 in 2006). * Not relevant for that component.

Components	Qty in kg	Passive solar still (Rs.)	Hybrid active solar still (Rs.)	Salvage value of different components (S_s) at the inflation rate of 4% (present values of scrap for, Iron @ Rs. 15/kg, Aluminum @ Rs. 80/kg and Copper @ Rs. 250/kg) Scrap value after 15 year	After 30 year
				Iron @ Rs. 27/kg Aluminum @ Rs. 144/kg Copper @ Rs. 450/kg	Iron @ Rs. 49/kg Aluminum @ Rs. 259/kg Copper @ Rs. 811/kg
Maintenance/operational cost (M_S) is 10% annually					
GRP body @ Rs. 320/kg	21.17	6774	6774	200	200
Glass cover	1.16 m^2	330	330	*	*
Iron stand passive still	14	700	*	378	686
Iron stand active still	20	*	1000	540	980
Inlet/outlet nozzle	0.10	50	50	3	5
Iron clamp	2	100	100	54	98
Iron clamping frame	5	250	250	135	245
Gaskets	8.9 m	130	130	*	*
Putty	1	30	30	*	*
Total cost of still(P/HA)		**8364**	**8664**	**770/932**	**1234/1528**
Flat plate collectors (2)					
Copper riser @ Rs. 380/kg	8.2	*	3116	3690	6650
Cu Header @ Rs. 380/kg	3.8	*	1440	1710	3081
Al sheet @ Rs. 165/kg	12	*	2160	1728	3108
Al angle1 in. × 12 m	2.5		450	360	647
Cu sheet @ Rs. 360/kg	11	*	4070	4950	8921
Toughened glass 4 mm	3.75 m^2	*	4340	*	*
Glass wool @ Rs. 60/m^2	0.165 m^3	*	2100	*	*
GI pipes ½ in.	9.3	*	500	251	456
Mild steel stand	40	*	2000	1188	1960
GI elbow/union	1.5	*	300	40	75
Total cost of FPC		*	**20,296**	**13,917**	**24,823**
PV module	*	*	13,500	500	500
DC Water pump	*	*	1000	The salvage value of pump deducted during purchase of new pump after each 10 year	
Paint 1lts(black)	1L	75	130	*	*
Fabrication/cartridge charges	*	200	2000	*	*
Capital cost passive(Rs.)		**8639**		**770**	**1234**
Capital cost active(Rs.)			**45,760**	**15,349**	**26,851**

Table 3
Dimension and capital cost of proposed solar still for 30° Cover inclination (1$ = Rs. 39 in 2006).

Sl. no.	Dimension	Experimental solar still @ 320/kg	Proposed solar still @ 320/kg	Proposed solar still if produced commercially @ Rs. 160/kg
1	Length	1 m	1 m	1 m
2	Width	1 m	1 m	1 m
3	Lower height (front side)	0.30 m	0.08 m	0.08 m
4	Higher height (back side)	0.88 m	0.66 m	0.66 m
5	Total area	3.36 m^2	2.48 m^2	2.48 m^2
6	Weight	21.17 kg	15.6 kg	15.6 kg
7	Cost	Rs. 6774	Rs. 4999	Rs. 2499
8	Embodied energy (kW h)	542.8	459	459
9	Proposed passive solar still system produced on commercial scale		Total cost of the system = Rs. 4089 Embodied energy = 659.2 kW h	
10	Proposed hybrid active system attached with 40 Wp PV module (½ of the present size) produced on commercial scale		Cost of PV module = Rs. 7000 Total cost of system = Rs. 35,005 Embodied energy = 3689 kW h	

been shown in the same table for different life span of the solar stills at 4% inflation rate in India. It has been experimentally observed that the water depth of 0.05 m produced highest annual yield. Therefore, the design of the solar stills with different dimensions (proposed) has been given in Table 3. The vertical wall heights of both the solar stills have been kept at 0.08 m (front side wall height) and 0.66 m (back side wall height), which is adequate to accommodate water to a depth of 0.05 m in the basin of solar still. Thus the initial cost of the solar still has been reduced by reducing the size.

3. Economic analysis

The utilization of the hybrid (PV/T) active solar stills as a source of distilled water for commercial purposes should be determined by its economics. The better economic return on the investment depends on the production cost of the distilled water and its applicability. The annual costs of the passive and hybrid active solar distillation systems have been calculated using annualized (UA) life cycle costing [19]. Annualized uniform cost is defined as a product of present value of the system and capital recovery factor (CRF) and expressed as

$$UA = [P_s + (P_s \times M_s)] \times F_{CR,i,n} - S_s \times F_{SR,i,n} \tag{1}$$

where $F_{CR,i,n}$ is a capital recovery factor and $F_{SR,i,n}$ is known as sinking fund factor. These are expressed as

$$F_{CR,i,n} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

and

$$F_{SR,i,n} = \frac{i}{(1+i)^n - 1} \tag{3}$$

here, n = no. of years and i = interest rate per year.

The life cycle cost analysis for both the solar stills has been carried out by considering the expected useful life of 15 years and 30 years for FPC and PV module, respectively. The GRP made solar stills are expected to offer more than two times better durability than FPC material. Therefore, the life of the present solar still has been considered as 30 years, while for the DC water pump as 10 years. It has also been assumed that the cost of pump (P_p) remains same on each purchase after adjusting its salvage value in future.

The net present cost (P_s) for 30 years life span of hybrid (PV/T) active solar still can be expressed as

$$P_s = P + \left[\frac{P_p}{(1+i)^{10}}\right] + \left[\frac{P_p}{(1+i)^{20}}\right] + \left[\frac{P_{FPC(net)}}{(1+i)^{15}}\right] \tag{4}$$

where P is the present capital cost of the system and can be expressed as

$$\begin{aligned} P = {} & \text{Cost of solar still} + \text{Cost of FPC} + \text{Cost of PV module} \\ & + \text{Cost of DC pump} + \text{Cost of piping} + \text{Labor} \end{aligned}$$

and

$$\begin{aligned} P_{FPC(net)} = {} & \text{Cost of FPC after 15 years @ 4\%inflation} \\ & - \text{Salvage value of FPC at the end of15 years} \end{aligned}$$

The net effective annualized cost of hybrid active solar still can be written as

$$UA_{net} = UA + S_{p,elect} \times (P_m - P_u) \tag{5}$$

for passive solar still $P_s = P$ and $UA_{net} = UA$.

In India the different agencies have proposed the following interest rate for borrowing the fund for promoting the renewable energy system:

- for house uses, government sector offers subsidized interest rate at 2%,
- for institutional uses, government sector offers subsidized interest rate at 3%,
- for commercial uses, government sector offers subsidized interest rate at 4%,
- nationalized banks offers the interest rate at 7–8%,
- private Banks offers the interest rate at 11–12%.

Therefore, three interest rates i.e. 4%, 8% and 12% have been considered in the analysis.

The maintenance/operational cost of the solar still is required for regular filling of brackish water, collecting the distilled water, cleaning of the glass cover, removal of salt deposited (scaling) and maintenance of the DC pump. Higher the depth of water, less frequent will be the filling of water in the basin. As the system life passes on, the maintenance on it also increases. Therefore, 10% of net present cost has been considered as maintenance cost. The cost of distilled water per kg (CPK) can be calculated by dividing the net annualized cost of the system by annual yield of solar still and expressed as

$$CPK = \frac{UA_{net}}{M_{yield}} \tag{6}$$

3.1. Cost payback period, n_p

The payback period is the time required to bring the investment cost to zero. In other words the number of years after which the initial investment becomes equal to the sum of cash flow is known as payback period. Considering the interest rate over cash flow, the net present cost can be expressed as

$$P_s = \sum_{1}^{n_p}[CF_t \times (1+i)^{-n_p}] \tag{7}$$

If the net cash flow (CF_t) at the end of each year is assumed same then,

$$P_s = CF \times F_{RP,i,n} \tag{8}$$

where $F_{RP,i,n} = \frac{[1+i]^{n_p}-1}{[1+i]^{n_p}\times i}$

On simplifying Eq. (8) one get,

$$n_p = \frac{\ln\left[\frac{CF}{CF-P_s\times i}\right]}{\ln[1+i]} \tag{9}$$

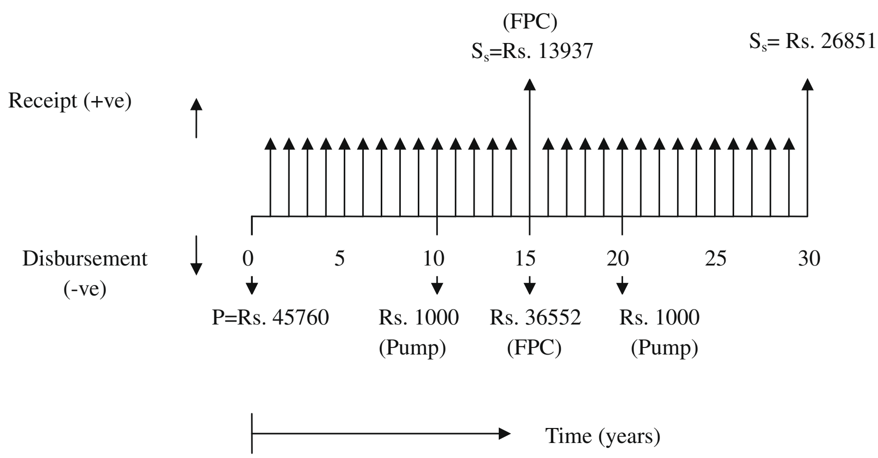

Fig. 2. Cash flow chart of hybrid (PV/T) active solar still for 30 years (annual maintenance cost @ 10% of initial investment is also taken as disbursement, which is not shown in figure). The small arrows pointing upward show the annual receipt (CF) after selling the distillate.

Table 4
Break up of embodied energy of different components of fabrication of single slope passive and hybrid (PV/T) active solar still * Insignificant value.

Component	Items	Quantity	Total weight (kg)	Embodied energy (MJ/kg)	Total Embodied energy	
					MJ	kW h
Solar still	GRP body	1	21.17	92.3	1954.0	542.8
	Glass cover 4 mm	1	1.16	40,060 MJ/m^3	185.9	51.6
	M S clamping frame	1	5	34.2	171.1	47.5
	M S clamp	8	2	34.2	68.4	19.0
	Mild steel stand	1	14/20	34.2	478/684	133/190
	Inlet/outlet nozzle	2	0.100	44.1	4.4	1.2
	Gaskets 8.9 m	1	2.1	11.83	24.8	6.9
Sub total						**802/859**
Flat plate collector quantity 2	Copper riser ½ in.	20 × 1.8 = 36 m	8.2	81.0	664.2	184.5
	Header 1 in.	4 × 1.15 = 4.6 m	3.8	81.0	307.8	85.5
	Al box	2	10	199.0	1990.0	552.0
	Cu sheet	2	11	132.7	1460	405.6
	Glass cover toughened 4 mm	2(3.75 m^2)	0.01464 m^3	66,020 MJ/m^3	966.5	268.3
	Glass wool	36 m^2	0.164 m^3	139 MJ/m^3	22.8	6.3
	Nuts/bolts/screws		1	31.06	31.06	8.6
	Union/elbo		1.5	46.8	70.2	19.5
	Mild steel stand		40	34.2	1368	380
	paint	1L	1L	90.4	90.4	25.1
	Rubber gasket	18 m	4.2	11.83	49.7	13.8
	GI pipes ½ in.		9.5	44.1	418.9	116.4
	Al frame 1 in.	12 m	2.5	170	425	118
	Al sheet 24 gauge		2.5	170	425	118.0
PV module	Glass to glass	1	0.66 m^2	3528 m^{-2}	2328.48	646.8
	BOS			720.0	720.0	200.0
Water pump	Copper wire		0.150	110.19	16.5	4.6
	Copper commuter	2	0.04	70.6	2.8	0.78
	Si-steel armature	1	0.05	*	*	*
	Wire insulation	2	0.01	*	*	*
	Motor body(SS)	1	0.100	36.1	3.61	1.0
	Casing (brass)	1	0.300	62.0	18.6	5.2
	bearings	2	0.030	*	*	*
	Steel shaft	1	0.050	12.5	0.625	0.17
	Impellers(plastic)	1	*	*	*	*
	Nuts/screws/flange		0.100	31.06	3.1	0.86
Total embodied energy of passive still						**802**
Total embodied energy of hybrid active still						**4012**

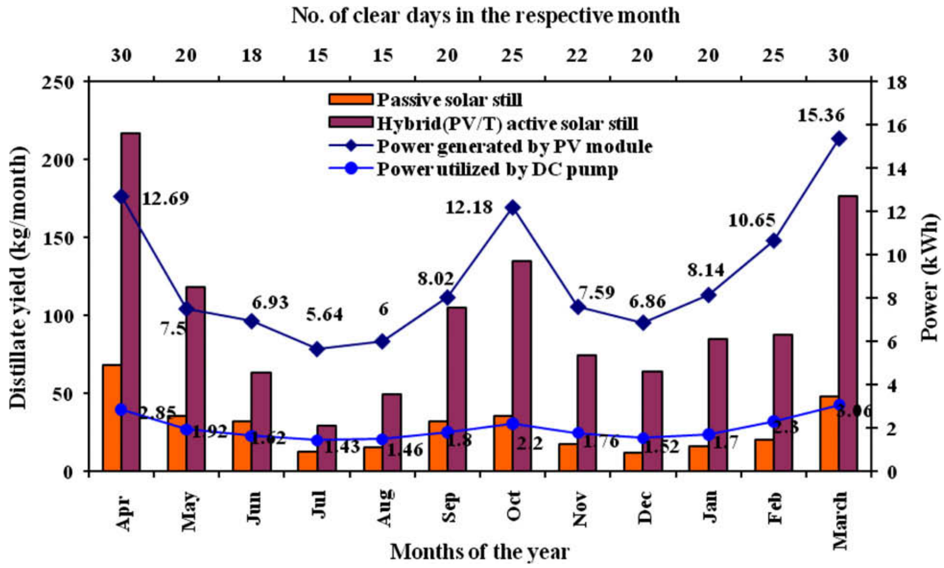

Fig. 3. Observed monthly yield obtained from passive and hybrid (PV/T) active solar still for 0.05 m water depths and power generated by PV module for the year 2006–2007.

There are two cases to get the net cash flow from the system:

Case 1. If the distilled water is sold at the production rate (*CPK*), then the annual cash flow is expressed as

$$CF = UA_{net} \tag{10}$$

Case 2. If the distilled water is sold at rate of selling price (S_p) other than cost of production, then the annual cash flow is expressed as

$$CF = M_{yield} \times S_p \tag{11}$$

The cash flow chart (receipts and disbursements) from hybrid (PV/T) active solar still for 30 years expected life is shown in Fig. 2. The small arrows pointing upward show the annual cash flow (*CF*), which will be received after selling the distillate in the market. The salvage value of the flat plate collectors (FPC) at the end of expected life (15 year) is also shown in the same figure.

3.2. Energy payback time (EPBT)

Embodied energy analysis shows the total energy consumed in manufacturing of the product. In addition to material production energy, energy investment in procuring the equipment and operation during the various manufacturing stages includes; the process fuels, maintenance of manufacturing equipment, the labor, research and development and administrative activity. However, the energy investment in procuring the equipment and operation is very less and has been neglected in the analysis. The embodied energy of single slope passive and hybrid (PV/T) active solar stills have been evaluated by multiplying mass of each component with their energy density and given in Table 4.

Energy payback time (EPBT) is defined as the time required to recover the energy invested in the system. Energy payback time (EPBT) of the solar stills can be evaluated by using the following equation.

$$\text{EPBT} = \frac{\text{Embodied energy}}{\text{Annual output of energy from the system}} \tag{12}$$

Annual output energy from hybrid active solar still (neglecting the energy invested in maintenance and operation) can be obtained as

$$\text{Total energy output} = M_{yield} \times L + (P_m - P_u) \tag{13}$$

4. Experimental observations

The experiments were carried out in the solar energy park of Indian Institute of Technology, New Delhi (India) on the passive and hybrid (PV/T) active solar stills under tropical climatic condition for the period, April–March, 2006–2007. During the course of experimentation, under ground water has been used to distillate for commercial purposes such as in battery, hospital, dispensary etc. Experimentation for the three different water depths (0.05, 0.10 and 0.15 m) has been carried out on different typical days for 24 h. The experimental data of the typical days have been used to evaluate monthly output during clear days by multiplying daily yield with number of clear days in the respective month. The monthly yield, power produced and power utilized during the clear days in different months obtained for 0.05 m water depths in the basin are depicted in Fig. 3. It has been observed that the hybrid (PV/T) active solar still gives higher productivity than the passive solar still. Highest yield was obtained in the month of April, 2006, because of intense solar radiation. The annual yield (for 260 clear days) obtained from hybrid active solar still (1203.46 kg) is around 3.5 times higher than the passive solar still (343.36 kg). The net power saved is around 83.2 kW h, which can be utilized for other applications when such systems are connected in array. However, if no extra energy is required for other applications, the size of PV module can be further reduce (cover only maximum load of pump) to reduce the initial investment. In order to estimate

Table 5
Tested water quality parameters obtained from solar still.

Sl. no.	Parameters	Ground water	Distilled water
1	Appearance	Clear	Clear
2	Odour	None	None
3	pH	7.68	6.32
4	Total dissolved solids	724 ppm	0.32 ppm
5	Total hardness as $CaCO_3$	456 ppm	0.84 ppm
6	Chloride	282 ppm	0.46 ppm
7	Alkalinity	376 ppm	0.06 ppm
8	Nitrate	22 ppm	0.7 ppm
9	Sulphate	66 ppm	0.52 ppm
10	Zinc	5.2 ppm	0.01 ppm
11	Iron	4.8 ppm	0.01 ppm

the improvement in purity of distilled water produced by the solar still, the physical and chemical properties tests were carried out on a sample of water before and after distillation. Comparisons of the results of the tests are given in Table 5. A comparison of the results showed that the total dissolved salts (TDS) value has come down from 724 ppm to 0.32 ppm after distillation. The presence of iron (0.01 ppm) and zinc (0.01 ppm) has also been found to be reduced drastically after distillation.

5. Results and discussion

The costs of distilled water has been obtained using Eq. (6) and shown in Table 6. The cost of distilled water produce from hybrid (PV/T) active solar still (Rs. 2.54/kg) has been obtained around 1.6 times higher than the passive solar still (Rs. 1.54/kg) for a fixed life of 30 years and with 4% interest rate on the finance.

Fig. 4 shows the effect of maintenance cost on the distilled water obtained from experimental and proposed designs of the solar stills for an expected systems life of 15 years and 30 years, respectively. The 10% increase in cost per kg (*CPK*) has been estimated with an increase in maintenance cost from 5% to 15%, irrespective of the systems life. The cost of production of the distilled water decreases in linearity with increase in the system life. This is because of linier decrease in the values of $F_{CR,i,n}$ and $F_{SR,i,n}$ (i.e. annualized cost decreases) with increase in the life of the systems at fixed interest rate. In general at fixed interest rate of 4%, if the life of the passive solar still increases by 100%, the production cost of distillate reduces to 33%, irrespective of the maintenance cost. However, for the hybrid active solar still, the cost found to be reduced by 4% for proposed design. The figure also reveals that the lowest costs obtained for the proposed passive and hybrid active solar stills are Rs. 0.70/kg and Rs. 1.94/kg, respectively.

Fig. 5 shows the variation the cost (*CPK*) of distillate obtained from the passive and hybrid (PV/T) active solar stills with respect to interest rate for a fixed maintenance cost of 10% and for different systems life (15 and 30 years). It has been estimated that the cost per kg (*CPK*) of distillate obtained from passive solar still increases almost 1.7 times with the increase of interest rate from 4% to 12%. However, the cost of distillate obtained from the hybrid (PV/T) active solar still increased by 2.0 times. The increase in the production cost is due to increase in the value of $F_{CR,i,n}$ (i.e. annualized cost increases) with increase in interest rate. It has also been noticed that the cost per kg (*CPK*) of distillate produce from hybrid (PV/T) active solar still remains almost same irrespective of life due to replacement of flat plate collectors after 15 years.

Fig. 6 shows the variation of the payback periods with selling prices of distilled water on proposed designs of passive and hybrid (PV/T) active solar stills for different interest. It is clear that with increase in selling price from Rs. 2.0/kg to Rs. 6.0/kg, the payback period reduces significantly. The Payback period of 6.2 years and 23.9 years has been estimated for the passive and hybrid (PV/T) solar still, respectively, at lowest interest rate of 4% and for market selling price of Rs. 2.0/kg, which is almost a cost of production of distillate from the hybrid active solar still. The Payback period of 1.1 year and 3.3 years has been obtained for passive and hybrid (PV/T) active solar still, respectively, if the distilled water would have sold at the rate of Rs. 10/kg. It is to be noted that with increase in interest rate, the payback period increases for both the stills. It has also been found that with increase in interest rate ($i = 8\%$ and $i = 12\%$), the distilled water produce from the hybrid active solar still should be sold in the market at the minimum rate of Rs. 3/

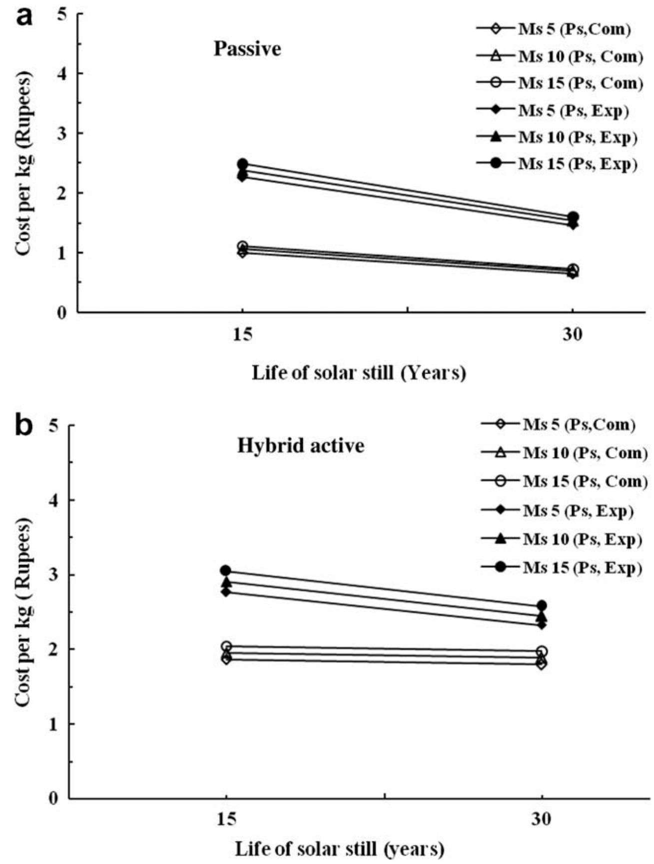

Fig. 4. Variation of cost per kg (*CPK*) of distilled water with respect to their designed life (n), at different maintenance cost (M_s), capital cost ($P_{s,Exp}$, and $P_{s,Com}$) and for fixed interest rate($i = 4\%$), (a) passive and (b) hybrid (PV/T) active solar still.

Table 6
Cost of water from experimental and proposed single slope passive and hybrid (PV/T) solar still on the basis of annual distillate yield (0.05 m water depth).

P_s (Rs.)	M @ 10% (Rs.)	S_s (Rs.)	i	n (year)	$F_{CR,i,n}$	$F_{SR,i,n}$	UA (Rs.)	Elec. Cost (Rs.)	UA_{net} (Rs.)	CPK (Rs./kg)	Proposed solar still CPK (Rs./kg)
(a) Cost per kg from single slope passive solar still (experimental)											
8639	864	770	0.04	15	0.09	0.05	816.8	–	816.8	2.38	1.07
8639	864	1234	0.04	30	0.058	0.018	529	–	529	1.54	0.7
8639	864	770	0.08	15	0.117	0.037	1083.3	–	1083.3	3.15	1.45
8639	864	1234	0.08	30	0.089	0.009	834.7	–	834.7	2.43	1.13
8639	864	770	0.12	15	0.147	0.027	1376.1	–	1376.1	4.01	1.87
8639	864	1234	0.12	30	0.124	0.004	1173.4	–	1173.4	3.42	1.61
(b) Cost per kg from single slope hybrid (PV/T) active solar still (experimental)											
45,760	4576	12,637	0.04	15	0.09	0.05	3750.89	251.7	3499.2	2.91	1.96
45,760	4576	18,402	0.04	30	0.058	0.018	3205.29	251.7	2953.6	2.45	1.93
45,760	4576	26,851	0.08	15	0.117	0.037	5318.39	251.7	5066.7	4.21	2.94
45,760	4576	12,637	0.08	30	0.089	0.009	4929.76	251.7	4678.1	3.92	2.99
45,760	4576	18,402	0.12	15	0.147	0.027	6989.62	251.7	6737.9	5.6	3.97
45,760	4576	26,851	0.12	30	0.124	0.004	6713.63	251.7	6461.9	5.37	4.04

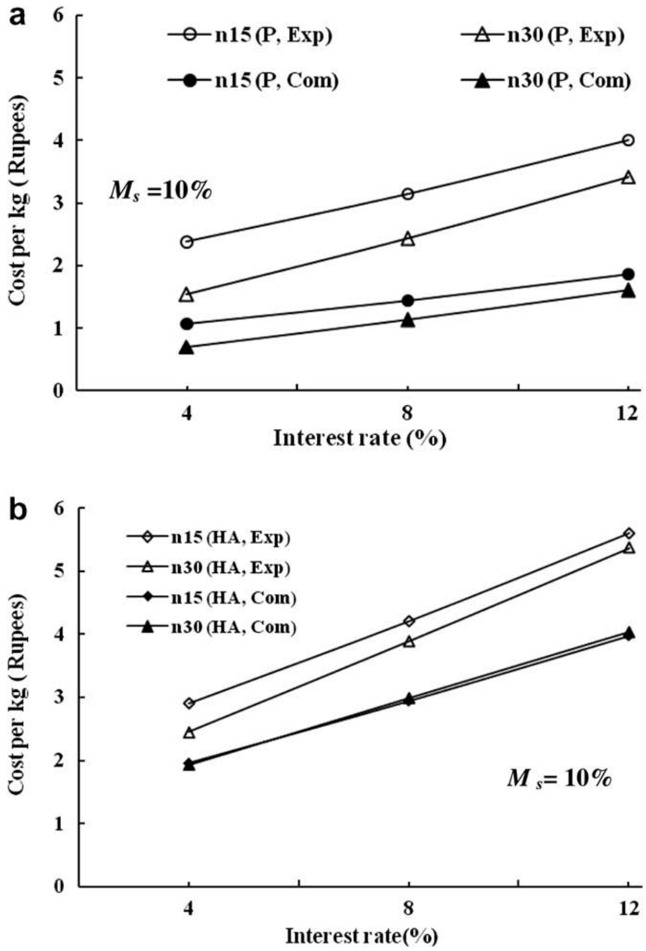

Fig. 5. Variation of cost per kg (*CPK*) of distilled water obtained from (a) passive and (b) hybrid (PV/T) active solar still for different designs (Experimental and Proposed) with respect to rate of interest (*i*) and system life (*n*) at fixed 10% maintenance cost(M_s).

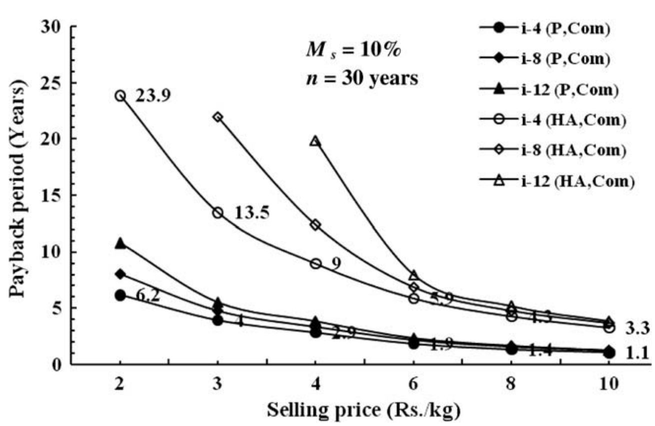

Fig. 6. Variation of payback periods (n_p) with respects to selling price (S_p) for proposed passive ($P_{,Com}$) and hybrid (PV/T) active ($HA_{,Com}$) solar stills, with their designed life 30 years.

kg and Rs. 4/kg, respectively, to make the system feasible with minimum financial risk. It is important to note that the distilled water obtained from the hybrid (PV/T) active solar still may be more bacteria free due to high operating temperature, which gives its wide range of applicability. This will further compensate the cost of distillate water obtained from the hybrid (PV/T) active solar still after selling it at higher cost than the passive solar still. It is important to mention that amount invested for the hybrid (PV/T) active solar still can not be recovered if the distilled water is sold at less than Rs. 2/kg and project is financed at 4% interest rate.

The energy payback time (EPBT) of the systems has been evaluated by using Eqs. (12) and (13). The annual energy utilized in vaporizing the water in the solar still and net energy of PV module is taken into account. The energy payback time for the passive and hybrid (PV/T) active solar stills under study have been evaluated as 3.6 years and 5.2 years, respectively. Further, the energy payback time of passive and hybrid (PV/T) active solar still is reduced to 2.9 years and 4.7 years, respectively, as per suggested modification of the solar stills.

6. Conclusions and recommendations

Life cycle cost analysis and comparison of two solar stills configurations, passive and hybrid (PV/T) active, have been presented. On the basis of present study the following conclusions and recommendations have been drawn;

(i) The annual distillate yield from hybrid active solar still is 3.5 times higher than the passive solar still. The lowest cost per kg of distilled water obtained from the passive and hybrid (PV/T) active solar stills is estimated as Rs. 0.70 and Rs. 1.93, respectively. It is much economic in comparison to the bottled water available, which costs around Rs. 10/kg in Indian market for the consumers.
(ii) The Payback periods of the passive and hybrid (PV/T) active solar stills are obtained in the range of 1.1–6.2 years and 3.3–23.9 years, respectively, for the selling price of distilled water in the range of Rs. 10 to Rs. 2/kg. Therefore, passive solar stills are acceptable for potable use.
(iii) The distilled water cost obtained from the hybrid (PV/T) active solar still is found to be 2.8 times than the passive solar still. For commercial use in remote areas, the cost of distilled water obtained from hybrid (PV/T) solar still could be acceptable when compared to water transportation and selling the water at higher rate to avoid the financial risk.
(iv) The cost of production and pay back periods can further be reduced for higher solar radiation, longer sun-shine hours and number of clear days in a year.
(v) The energy payback times (EPBT) of proposed passive and hybrid (PV/T) active solar stills are estimated as 2.9 years and 4.7 years, respectively.
(vi) The systems operate today on solar energy are expensive, but they are being continuously developed and made more efficient and cheaper to install and operates. The cost of PV modules is presently high, but there is growing demand (expending at the rate of 30% per year) to use PV module in developing countries. It is expected that with the evolvement of current technology the production cost of PV module will be further reduce to \$ 1.0/Wp (i.e. Rs. 40/Wp) as forecasted by Lesourd [20]. Therefore, the cost of production of distilled water obtained from hybrid (PV/T) active solar still as well as the payback period will be further decrease in future.

Acknowledgement

We are thankful to Bag Energy Research Society to encourage, assist, guide and render specialized services from time to time to carry out the experimental study on hybrid (PV/T) active solar still.

References

[1] Malik MAS, Tiwari GN, Kumar A, Sodha MS. Solar distillation: a practical study of a wide range of stills and optimum design, construction and performance. New York: Pergamon Press; 1982.

[2] Al-Hinai H, Al-Nassari MS, Jubran BA. Effect of climatic, design and operational parameters on the yield of a simple solar still. Energy Convers Manage 2002;43:1639–50.

[3] El-Sebaii AA. Parametric study of a vertical solar still. Energy Convers Manage 1998;13:1303–15.

[4] Singh HN, Tiwari GN. Monthly performance of passive and active solar stills for different Indian climatic conditions. Desalination 2004;168:145–50.

[5] Ji J, Lu JP, Chow TT, He W, Pei G. A sensitivity study of a hybrid photovoltaic/thermal water-heating system with natural circulation. Appl Energy 2007;84:222–37.

[6] Chow TT. Performance analysis of photovoltaic–thermal collector by explicit dynamic model. Solar Energy 2003;75:143–52.

[7] Zakharchenko R, Licea-Jime'nez L, Pe'rez-Garci'a SA, Vorobiev P, Dehesa-Carrasco U, Pe'rez-Robels JF, et al. Photovoltaic solar panel for a hybrid PV/Thermal system. Solar Energy Mater Solar Cell 2004;82(1–2):253–61.

[8] Tiwari A, Sodha MS. Performance evaluation of hybrid PV/thermal water/air heating system: A parametric study. Renew Energy 2006;31:2460–74.

[9] Kumar S, Tiwari A. An experimental study of hybrid photovoltaic thermal (PV/T) active solar still. Int J Energy Res 2008;32:847–58.

[10] Tiwari A, Sodha MS, Chandra A, Joshi JC. Performance evaluation of photovoltaic thermal solar air collector for composite climate of India. Solar Energy Mater Solar Cells 2006;90:175–89.

[11] Dubey S, Sandhu GS, Tiwari GN. Analytical expression for electrical efficiency of PV/T hybrid air collector. Appl Energy 2009;86:697–705.

[12] Tleimat BW, Howe ED. Nocturnal production of solar distillers. Solar Energy 1966;10:61–6.

[13] Mukherjee K, Tiwari GN. Economic analysis of various designs of conventional solar stills. Energy Convers Manage 1986;26:155–7.

[14] Sinha S, Kumar S, Tiwari GN. Active solar distillation system – an investment alternative to a solar hot water system. Energy Convers Manage 1994;35:583–8.

[15] Ghoneyem A, Ileri A. Software to analyze stills and an experimental study on the effects of the cover. Desalination 1997;114:37–44.

[16] Madani AA, Zaki GM. Yield of stills with porous basins. Appl Energy 1995;52:273–81.

[17] Fath HES, El-Samanoudy M, Fahmy K, Hassabou A. Thermal-economic analysis and comparison between pyramid shaped and single-slope solar still configurations. Desalination 2003;159:69–79.

[18] Kalogirou SA. Effect of fuel cost on price of desalination water: a case for renewable. Desalination 2001;138:137–44.

[19] Tiwari GN, Ghosal MK. Renewable energy resources: basic principles and applications. New Delhi: Narosa Publishing House; 2005.

[20] Lesourd JB. Solar photovoltaic systems: the economics of a renewable energy resource. Environ Modell Softw 2001;16:147–56.