Embodied Energy, Pay-back Period and Cost Analysis of Triple Slope Solar Still Integrated with Glass-Glass PV Module

Gaurav Kumar[1], Piyush Pal[2*], Pulkit Agarwal[2], Rahul Dev[2], Akhilesh Kumar Chauhan[1]

[1] Mechanical Engineering Department, Kamla Nehru Institute of Technology Sultanpur, Sultanpur–228118, Uttar Pradesh, India
[2] Department of Mechanical Engineering, Motilal Nehru National Institute of Technology Allahabad, Prayagraj–211004, Uttar Pradesh, India

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ABSTRACT

In this paper, the embodied energy, pay-back period and cost analysis of triple slope solar still (TSSS) are studied which is compared with the double slope solar still (DSSS). The embodied energy is an important factor in determining optimum material for solar still whose value depends on local availability of materials and their manufacturing processes. The total embodied energy of TSSS comes out to be 3297.35MJ. Energy pay-back time is 0.251 years and the total cost for constructing TSSS is Rs. 14049. The TSSS embodied energy comes out to be 9.28% less than double slope solar still. EPBT of TSSS comes out to be 153.7 % smaller than of DSSS.

1. Introduction

As long as hundreds of millions of years ago the water we drink today is been around in one form or other. Over time, the amount of freshwater on earth is remained fairly constant by recycling continuously. But at the same time, the human population is growing at an alarming rate i.e. in 2018 at the growth rate of around 1.09% (i.e. 83 million people per year) resulting in a shortage of freshwater.

Today, the world fresh water need is mostly fulfilled by using devices that run on non-renewable resources of energy like coal, oil, gas etc. This way of purification of water is not only high on cost but also requires experienced personnel to deal with the complexity of it. Also, it causes a significant amount of environmental pollution.

To ease the burden on conventional sources of energy, a solar distillation technology is been worked upon. Solar still is a device which is used for purifying saline water with the help of solar radiation. There is an immense diversity of solar stills available, both active and passive. Several forms of solar still are made such as hemispherical solar still, pyramid solar still, spherical solar still, double basin glass solar still, tubular solar still, concentrator coupled single slope solar still, and tubular solar still coupled with pyramid solar still [Arunkumar et al., 2012]. Many types of research have been done to enhance the output yield of solar stills. Some research work suggests that with a rise in ambient temperature and solar intensity results in increased productivity. Also, by lowering the water depth from

3.5 cm to 2 cm there is a rise in productivity [Badran & Abu-Khader, 2007]. The rate of evaporation is also found out to be proportional to the basin temperature. The temperature of the basin is also raised by coupling it with several elements like aluminum fins, a long hollow stainless-steel tube, helical copper coil and an iron plate. The solar still integrated with aluminium fins give the highest yield [Malaiyappan & Elumalai, 2016]. The thermal performance of a finned single basin solar still is studied using different materials for finned basin liner such as glass, stainless steel, mica, aluminium, iron, copper and brass. He concluded that the fin material does not have a significant effect on productivity and efficiency. Rather by adding fins to basin improve productivity by 16.39% [El-Sebaii & El-Naggar, 2017]. The effects of nanoparticle-enhanced phase change material (NPCM) on solar still productivity is studied. Two properties are important for melting and solidification of NPCM namely thermal conductivity and latent heat respectively. High thermal conductivity helps in decreasing the melting time of PCM (paraffin); while increased latent heat helps in releasing more heat during solidification. Improvements of 23.0%, 39.3%, 43.2% and 18% were obtained for SSPCM (Single Slope Phase Change Material), SSNPCM-1 (Single Slope Nanoparticle-enhanced Phase Change Material), SSNPCM-2, and SSNPCM-3, against the productivity of a conventional still [Rufuss et al., 2018]. (NPCM-1, NPCM-2, and NPCM-3 contains TiO_2, CuO and GO nanoparticles, respectively impregnated in paraffin). The productivity of solar still using jute cloth knitted with sand heat

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* Corresponding Author : *piyushpal19@gmail.com, rme1454@mnnit.ac.in*

energy storage is studied. They found out that the yield of fresh water is dependent on the mass of sensible energy material and depth of water present inside the basin. The average rise in temperature of the water was found to be 25% higher in the case of jute cloth knitted to sensible heat storing material as compared to conventional solar still [Kabeel et al., 2018]. Characteristic equation of double slope solar still is developed on the basis of experimental study and it shows that non-linear characteristic curves are more accurate for analyzing the performance of solar still. It is achieved by plotting regression curves for loss efficiencies and instantaneous gain with respect to a non-dimensional representative factor ($\{(T_w-T_a)/I(t)\} / \{(T_w-T_a)/I(t)\}_{max}$) of climatic and operational parameters together [Dev et al., 2011]. Performance of a modified double slope solar still for the climatic condition of Allahabad (Prayagraj) is predicted theoretically by developing a thermal model. By using expressions for water and glass temperature, hourly yield is calculated. For the period of 24-hour, 16 Kg of potable water is obtained from 25 Kg of impure water [Nayak & Dev, 2016]. The productivity of double slope solar still can also be improved by using wicks. Distilled water yield for black cotton wick comes out to be 4.50 l/m²-day where as for the jute wick it is 3.52 l/m²-day at 2 cm water depth. Also, thermal efficiency of black cotton wicks and jute wick is 23.03% and 20.94%, respectively [Pal et al., 2017]. The energy matrices, exergo-economic and enviro-economic analysis of modified multi-wick basin type double slope solar still is also studied. The total cost of setup comes out to be Rs. 14000 and EPBT are 0.69 years. Also, total embodied energy comes out to be 3635.98 MJ [Pal et al., 2018]. Comparative study among various materials such as FRP, concrete, PVC and wood are done that can be used for building solar still. Materials which are having low embodied energy and lower thermal conductivity than FRP such as concrete, PVC, wood can be used against FRP to lower the embodied energy consumption for optimal performance[Singh et al., 2011]. Performance comparison between two types of photovoltaic (PV) module is done i.e. glass-to-glass and glass-to-tedlar. It was found out that glass-to-glass PV/T air collector gives superior results in reference to thermal efficiency as compared to glass-to-tedlar PV/T air collector [Joshi et al., 2009].

As per the literature survey, several designs of solar still are developed. To enhance the productivity of conventional solar stills, various modifications are made by using fin, wicks and nanoparticle phase changing material. All these modifications in solar still results in higher yield of distilled water. Currently no research work has been done on triple slope solar still. It is modified form of double slope solar still with integrated PV module which generate electric power as well as allow solar radiation to pass through in order to heat the water in basin. The objective of the present paper is to discuss about the design of TSSS and find out the embodied energy, energy pay-back period and cost analysis of triple slope solar still integrated with the glass-glass PV module.

2. Materials and Methods

This section covers the materials used for Triple Slope Solar Still including design specification. It also covers the model of setup, working principle and thermal modelling of solar still.
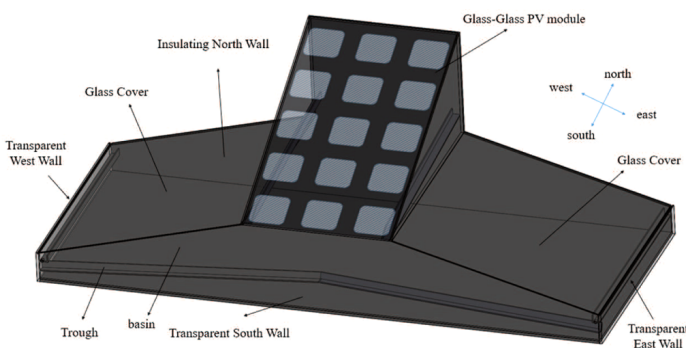
2.1   Solar Distillation System

Figure 1: Model of Triple Slope Solar Still

Fig. 1 shows the isometric view of the proposed design of triple slope solar still, which is modeled using Solid Works 2018 software. Solar still is a box-type structure. It consists of a rectangular base, known as a basin, of dimension 0.825 m × 2 m in which saline water is filled from the holes provided on the north wall. FRP (5 mm thickness) is used as the material

of construction of north and base wall of the solar still.

The setup is East-West oriented to have glass covers on both east and west side which are inclined at an angle of 15°. Transparent acrylic sheet (3 mm thickness) is used as a material of construction for East, West and South walls. Condensed water from the glass cover and walls is collected through three troughs, one trough on each wall i.e. east, west and south. A glass-to-glass photovoltaic panel facing due south is kept at an angle of 25 degrees (latitude of Prayagraj). It has three slopes of 25°, 15° and 15° for south solar panel, east glass and west glass, respectively. Hence it is named as 'Triple Slope Solar Still'. At the end of each trough, the outlet pipe is provided for collecting condensed water. One inlet pipe is used for feeding brackish water into the basin through a hole in the north wall. Walls height at East-West ends is 11 cm and a peak height of the south wall from the base is 31 cm. To generate electric power, glass-to-glass PV module is mounted on the solar still. Table 1 shows the various specification of triple slope solar still.

Glass-to-Glass PV module structure provide several advantages over the conventional Glass-backsheet structure. Some of the advantages are listed below:
1. Transparency in solar module allows for the natural light to pass through glass which is utilized for solar thermal application along with the electricity produced by solar cells.
2. Tensile strength of the PV module is high due to the presence of two glass layers which allows for its use in high wind areas.
3. Have higher reliability and durability.

Table 1: Design Specifications of Triple Slope Solar Still

Parameters	Specification
Orientation	East – West
Location	MNNIT Allahabad, Prayagraj, India
Location Coordinates	25.4358° N, 81.8463° E
Climate	Warm and humid
Body material (Base & north wall)	FRP (Fibre-Reinforced Plastic)
Body material (East, west & South wall)	Acrylic
Basin area	0.825 m × 2 m
Thickness of FRP	5 mm
Thickness of Acrylic	3 mm
Height at ends	0.11 m
Height at center	0.31 m
Glass cover dimension	815.7 mm × 755.57 mm × 4 mm
Number of the glass cover	2
The inclination angle of the glass cover	15°
The color of the inside of north wall	Black
Number of inlets to saline water	1
Number of troughs	5
The inclination of the PV module	25°

2.2   Working Principle

Solar still is filled with brackish water from the hole provided in the north wall. Solar radiation is incident on the still and passes through the glass panel and transparent acrylic sheet in order to be absorbed by the basin and saline water present in it. This results in the rise of water temperature which causes faster evaporation rates. Water vapor gets mixed with air inside the solar still and raises its temperature. It increases the kinetic energy of water and air molecules such that when they collide with walls and glass cover, they release latent heat of vaporization to undergo a process of phase change from vapor to liquid state. During the course of the day more solar radiation is absorbed by water, thus further raising water temperature and enhancing the rate of evaporation. The condensate is collected in the collecting vessel placed outside the solar still at east, west and south walls. The output from the above process gives safe and potable water. The electricity produced by glass-glass PV module can be used for running DC operated devices like water pump (to lift the water and heat it by a north wall which is having a high temperature) or rotating the stirrer (to agitate water in the basin) in order to increase the rate of evaporation.

2.3 Photovoltaic (PV) Module

Solar cell utilizes sunlight to give electricity by the photoelectric effect. The meaning of term PV is photo (light) and voltaic (electricity). The photovoltaic module consists of 36 solar cells. Each solar cell has an effective area of 0.0044 m². Area of one PV module is 0.159 m². Packing factor is 0.7. Each cell has an output of 0.5 V which are connected in series to give total output of 18 V.

2.4 Thermal Modelling

The thermal model of the triple slope solar still is developed and energy balance equation of different components of solar still are studied which are based on the following assumptions

1. Inclination of glass cover is small so that radiation exchange between water mass and glass cover is easily studied by taking them as parallel to one another.
2. The solar still is sealed to make it leak proof.
3. The water level in the basin is always kept at constant level.
4. Film type condensation occur at glass cover.
5. The heat capacity of the glass cover, basin and insulation material are negligible.
6. Zero temperature gradient is considered along the glass cover thickness and within the water.
7. The system is assumed to be in a quasi-static condition.
8. Heat transfer coefficients are temperature independent.

Solving equations of thermal model gives a differential equation of water temperature

$$\frac{dT_w}{dt} + aT_w = f(t) \quad (1)$$

Where

$$a = (h_{vw}A_b + h_{bw}A_b)\frac{1}{MC_w} \quad (2)$$

$$f(t) = (\tau_{arc}\alpha_w I_{sw}A_{sw} + \tau_{arc}\alpha_w I_{ew}A_{1ew} + \tau_g\alpha_w I_{eg}A_{eg} + \tau_{arc}\alpha_w I_{ew}A_{2ew} +$$
$$\tau PV_{g1}PV_{g2}\alpha_w I_{PV}(1-\beta)\,A_{PV} + \tau_{arc}\alpha_w I_{ww}A_{1ww} + \tau_g\alpha_w I_{wg}A_{wg} + \tau_g\alpha_w I_{ww}A_{2ww} +$$
$$h_{bw}A_b T_b + h_{vw}A_b T_v)\,\frac{1}{MC_w} \quad (3)$$

By solving above equation (1), we get water temperature as

$$T_w = \frac{\overline{f(t)}}{a}\left(1 - e^{(-at)}\right) + T_{wo}e^{(-at)}$$

2.5 Embodied Energy

It is defined 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 energy equipment and in other supporting functions i.e. direct energy plus indirect energy" [Tiwari et al., 2016].

2.6 Energy Payback time

Energy Payback Time (EPBT) of the solar still defines the approximate time period required to recover the total energy consumed in the material preparation for constructing the solar still. EPBT depends on the embodied energy of various components used in the solar still and the annual energy output i.e. distillate yield obtained from the triple-slope solar still [Pal et al., 2018]. EPBT can be evaluated as

$$EPBT = \frac{Embodied\ energy\ in}{Annual\ energy\ out} \quad (4)$$

Annual Energy Out ($E_{out,\ ann}$) is given by:

$E_{out,\ ann}$ = Average daily yield x number of clear days in a year x latent heat of vaporization of water. (5)

3. Results and Discussion

This section deals with results obtained from calculation of various parameters such as embodied energy of TSSS, EPBT, and thermal analysis and finally cost analysis of various components is discussed.

3.1 Embodied Energy

The embodied energy of the components used in solar still is shown in Table 2 and 3. In Table 2, components which make up the control volume of the solar still is listed such as FRP, glass and acrylic. FRP have the greatest mass of 21.5 kg and contribute highest in total embodied energy. Acrylic sheet has least mass of 3.75 kg and consumes 375 MJ of embodied energy. Mass and embodied energy of glass lies between that of FRP and acrylic sheet. The embodied energy of solar still comes out to be 2595.22 MJ when minor components are excluded.

In Table 3, all the components that makes up the solar still are listed such as FRP, glass, acrylic sheet, GI iron stand, nozzle, Silicon Gaskets, black paint and glass putty. In this GI iron stand have higher contribution of 449.7 MJ of embodied energy with mass of 9 kg. By considering all

Table 2: Embodied Energy of Triple Slope Solar Still (excluding minorcomponents)

Name of Component	Mass of Component (kg)	Mass Density (kg/m³)	Energy Density (MJ/m³)	Embodied Energy (MJ)
FRP(5 mm thickness)	21.5	1850	92.2	1982.44
Glass(4 mm thickness)	14.95	2600	15.9	237.78
Acrylic (3 mm thickness)	3.75	1200	100	375
Total	**40.2**			**2595.22**

Table 3: Embodied Energy of Triple Slope Solar Still (including all components)

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FRP (5 mm thickness)	21.5	1850	92.2	1982.44
Glass (4mm thickness)	14.95	2600	15.9	237.78
Acrylic (3 mm thickness)	3.75	1200	100	375
GI iron stand	9	7850	49.968	449.712
Nozzle	0.2	946	44.1	88.2
Silicon Gaskets	4	250	11.83	47.32
Black Paint	1	880	90.40	90.40
Glass putty	5	1.22	5.30	26.5
Total	**59.4**			**3297.352**

the components for building TSSS, glass putty required least amount of embodied energy of magnitude 26.5 MJ. The total embodied energy when considering all the components is 3297.35 MJ.

3.2   Energy Payback time

From the theoretical analysis of the above setup average daily yield was estimated to be 11.75 kg/m^2. Also, assuming 300 clear days in a year and latent heat of vaporization to be 0.627 kWh/kg. By using the above data, the EPBT of triple slope solar still (excluding minor components, Table 2) is estimated to be around 0.202 years and when all the parts are considered (Table 3) then it comes out to be 0.251 years. The EBPT of TSSS is smaller than the conventional double slope solar stills.

3.3   Cost Analysis

Cost analysis of triple slope solar still is shown in Table 4. FRP material is available at Rs. 400/kg and similarly Acrylic sheet at Rs. 182.50/kg. Total cost for constructing the triple slope solar still comes out to be Rs. 14,049. This cost is much smaller than the conventional double slope solar still and almost equal to the modified multi–wick double slope solar still.

Table 4: Cost of Various Components Used in Triple Slope Solar Still

Component	Cost (Rs.)
FRP body @ 400/kg	8600
Acrylic body @182.50/kgGlass cover	6841245
Iron stand	600
Inlet/Outlet nozzle	120
Silicon gaskets	550
Black paint and glass putty	250
Labour and other charges	2000
Total Cost of Still	**14049**

3.4 Thermal Analysis

Variation of global solar radiation (W/m^2) with respect to time (h) for typical day in a month of February at Prayagraj, U.P., India is shown in Fig. 2. From the figure it is clearly visible that solar radiation starts increasing from sunrise and rises slowly to reach a maximum value, and then ultimately decreases till the sunset. The maximum value of global solar radiations reached was 490 W/m^2.
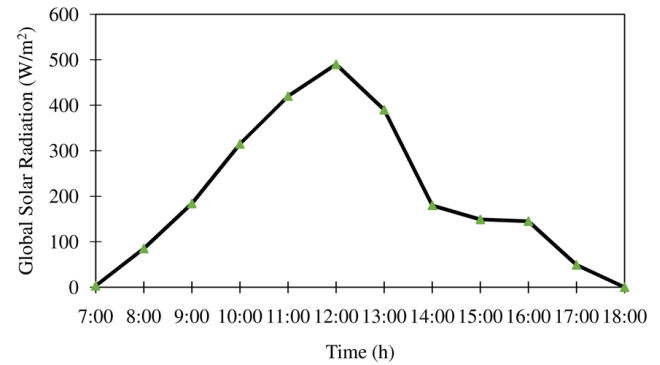

Figure 2: Variation of Global Solar Radiation

Variation of ambient temperature (^{0}C) with respect to time (h) for a typical day in a month of February at Prayagraj, U.P., India is shown in Fig. 3.The maximum value of temperature measured is 24.5^0 C. In this month the weather is generally partially cloudy due to which small increase or decrease in ambient temperature is observed from the general trend such as at 16:00 h. Low ambient temperature and high solar radiation input is desirable as it results in higher temperature difference between the water and glass. But, during day when sun light is present the ambient temperature is higher than the temperature in the night. Also, during night when temperature is lower, but the sunlight is not present. This result in lower yield output during the night.
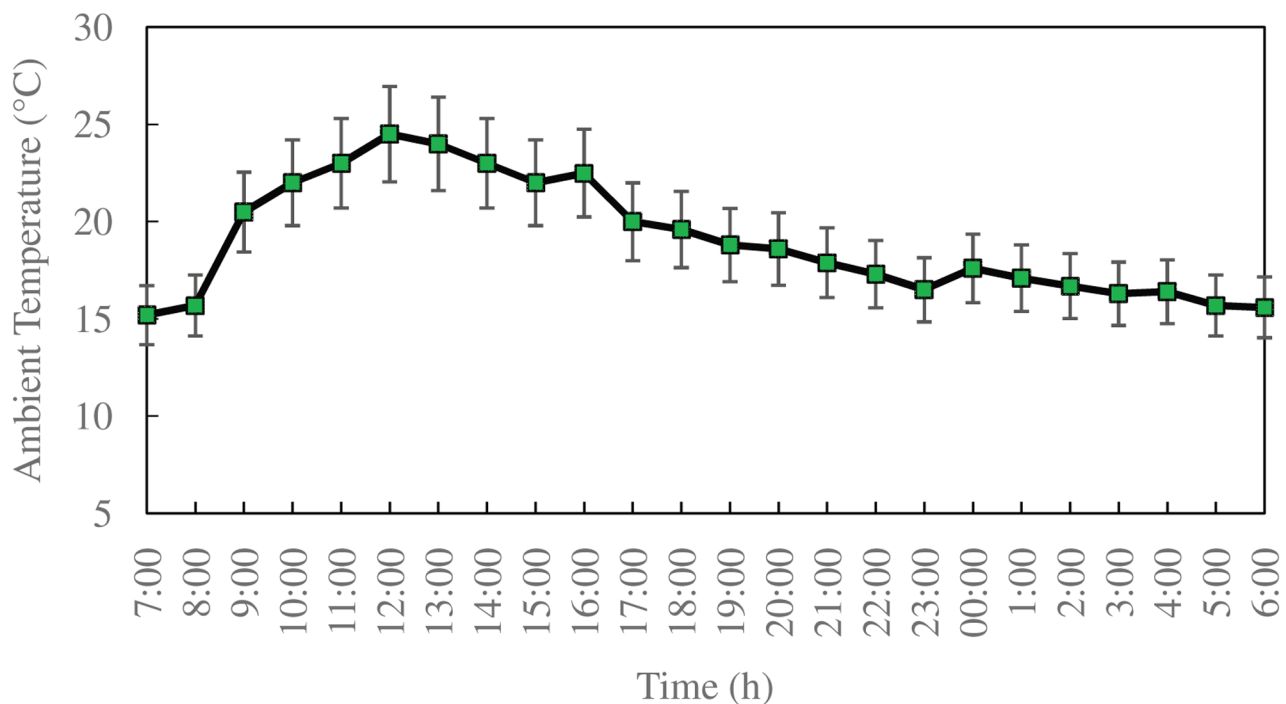

Figure 3: Variation of Ambient Temperature

Hourly variation of theoretical water temperature (°C) with respect to time (h) for a typical day in a month of February is shown in Fig. 4. Higher water temperature leads to larger temperature difference between water and glass, thus resulting in increased hourly yield. Solar radiation coming through the transparent glass and acrylic sheet raises the temperature of the water. Water absorbs part of the solar radiation falling on it and then allows the remaining radiation to be transmitted to the FRP basin. This causes the temperature of the basin to rise to maximum value than the temperature of other components in the solar still. With increase in water temperature the evaporation rate tends to rise and thus also raising the temperature of the water vapour. Higher value of the water temperature results into higher yield output. Highest temperature of 52 °C is estimated at 13:00 h.

By taking suitable assumptions, the thermal analysis is done in MATLAB 2018 to calculate the expected water yield output of the triple slope solar still. Fig. 5 shows the theoretical hourly water yield. Water vapour after evaporating from the basin tends to condense on cooler glass surface by losing its latent heat. During the night, water act as a thermal mass which continues to produce water vapour which then condense to give distilled water though of small quantity. The maximum yield was 1.53 l/h at 14:00 h in February and total yield estimated to be 17 litres.

3.5 Comparison among various solar still designs

Various solar still designs are compared based on embodied energy, EPBT, capital investment and water yield. Table 5 shows that conventional double slope multi-wick solar still have highest embodied energy. Also, conventional double slope passive solar still give higher EPBT and subjected to high capital investment. It is clearly shown that TSSS gives least embodied energy and EPBT. The capital investment on TSSS is also comparable to modified multi–wick double slope solar still with jute wick at 1 cm water depth [Pal et al., 2018]. Table 6 shows comparison among various solar stills based on total yield per square metre. The total water yield in 24 hrs per m² obtained from the triple slope solar still is more than twice the yield of modified multi-wick double slope solar still.
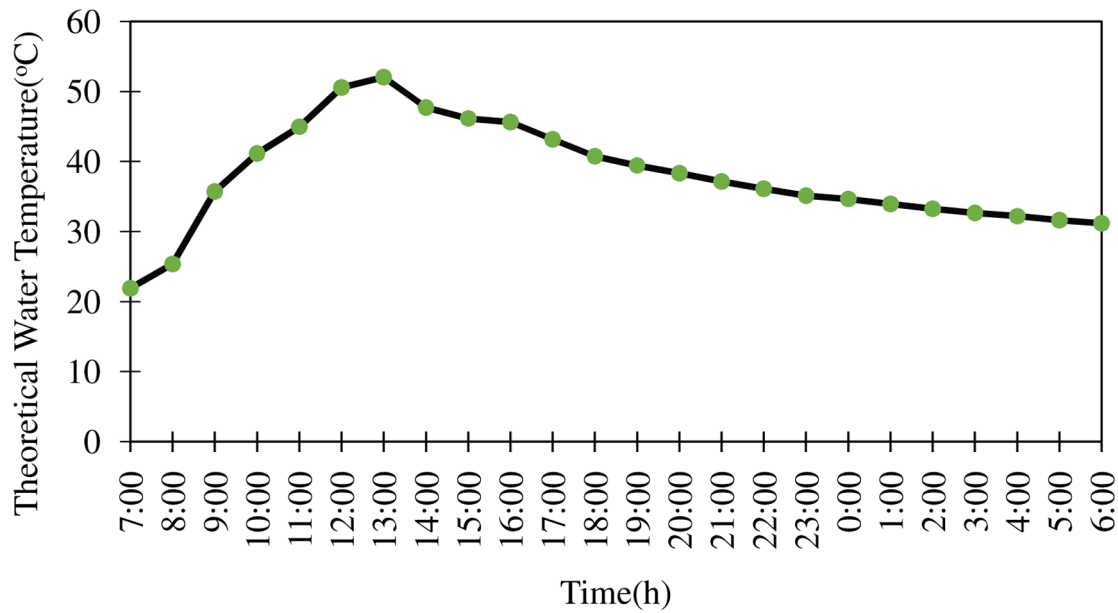

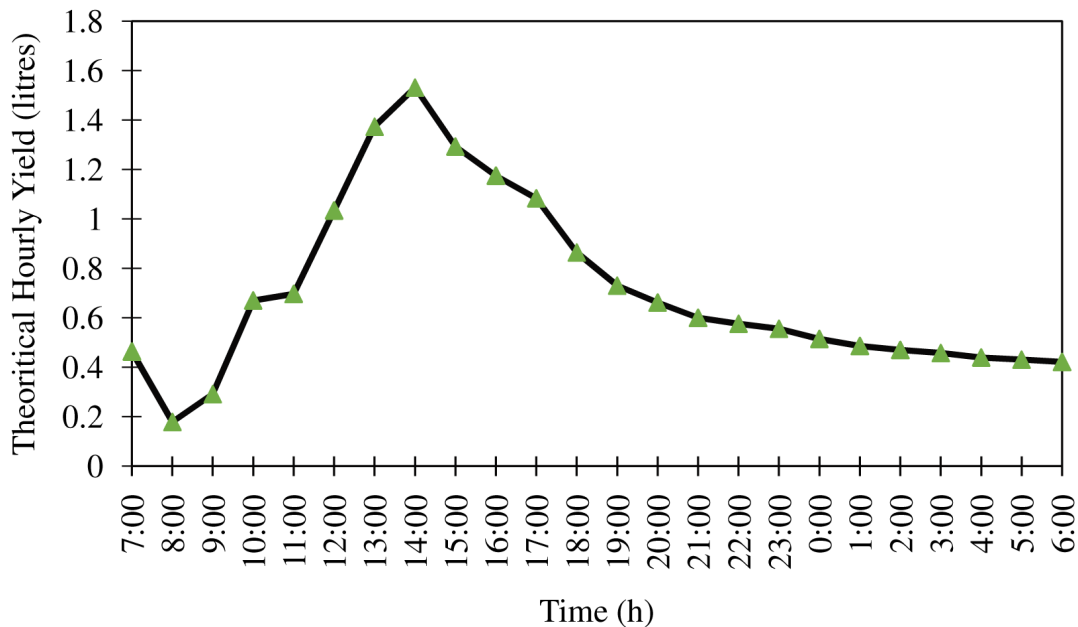Figure 4: Hourly variation of theoretical water temperature

Figure 5: Hourly variation of theoretical water yield

Table 5: Comparison among various solar still designs

S. No.	Type of Solar Still	Embodied Energy (kWh)	EPBT (years)	Capital Investment (US $)
1.	Conventional double slope passive solar still [Singh et al., 2016]	1483.90	1.43	357.41
2.	Conventional double slope multi–wick solar still [Tiwari and Selim, 1984]	2212.55	1.38	265.28
3.	Modified multi–wick double slope solar still with jute wick at 1 cm water depth [Pal et al., 2018]	1009.99	0.692	215.82
4.	Modified multi–wick double slope solar still with black cotton wick at 1 cm water depth [Pal et al., 2018]	1032.91	0.637	218.32
5.	*Triple Slope Solar Still*	915.93	*0.251*	*216.60*

Table 6: Comparison among various solar still designs on the basis of yield

S. No.	Type of Solar Still	Total Water yield in 24 hrs per m^2
1.	Conventional double slope multi–wick solar still [Tiwari and Selim, 1984]	4.5
2.	Modified multi–wick double slope solar still with jute wick at 2 cm water depth [Pal et al., 2018]	3.52
3.	Modified multi–wick double slope solar still with black cotton wick at 2 cm water depth [Pal et al., 2018]	4.5
4.	*Triple Slope Solar Still*	10.3 (theoretical)

4 Conclusion

In this work, a triple slope solar still (TSSS) has been designed, fabricated and its theoretical performance under the climatic condition of Prayagraj, (U.P.), India have been analyzed. The following conclusions can be drawn on the basis of this study:
1. The maximum theoretical yield was found to be 1.53 l/h at 14:00 h in February month under the climatic condition of Prayagraj (U.P.) and total theoretical yield was 17 litres/day.
2. The embodied energy of solar still was found to be 2595.22 MJ. The embodied energy of triple slope solar still is found to be less than double slope solar still by 9.28%.
3. The total cost for constructing the triple slope solar still was found to be Rs. 14,049. The total cost of the construction of triple slope solar still is found to be almost equal to the double slope solar still.
4. The EPBT of triple slope solar still (excluding minor components) is estimated to be around 0.202 years and when all the parts are considered then it comes out to be 0.251 years. The EPBT value of TSSS is significantly smaller than that of double slope solar still by 153.7%.

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