Journal of Thermal Analysis and Calorimetry (2023) 148:8969–8989
https://doi.org/10.1007/s10973-023-12281-3

Solar heat pipe ETC integrated with solar still system for water treatment and hot water production: novel hybrid experimental approach

Atin K. Pathak[1] · K. Chopra[1,2] · V. V. Tyagi[1] · Sanjeev Anand[1] · Richa Kothari[3] · Ahmet Sari[4,5] · A. K. Pandey[6,7]

Received: 7 September 2022 / Accepted: 23 May 2023 / Published online: 18 July 2023

Abstract

In this manuscript, the innovative design of a hybrid system is investigated for distilled water and hot water production using the heat pipe-equipped vacuum tube collector system assimilated with solar still (HTP-ETCS-SS). The proposed hybrid system is compared with traditional solar still (SS) in context of energy, exergy and financial analysis with two different depths, i.e., 40%, and 60%, and varying flow rate (4, 8, and 12 LPH). The results show a rise in distilled water productivity by 152.9%, 108%, and 51.9% with 40% depth and 162%, 152.5%, and 92.3% with 60% depth with a varying flow rate of 4, 8, and 12 LPH, respectively, in contrast to traditional solar still. The improvement in energy and exergy efficiency for distilled water output is gained between 40–22.2% and 0.7–4.1%, respectively, with the designed system. However, the system's energy and exergy efficiency lie between 64.8–42.4% and 28.4–16.4%, respectively, for both distilled water and hot water productivity. The 8 LPH flow rate is found optimum in terms of distilled productivity and hot water production. The designed system's distilled water and hot water unit costs are 0.1037$ and 0.0276$, respectively.

✉ V. V. Tyagi
vtyagi16@gmail.com

1 School of Energy Management, Shri Mata Vaishno Devi University, Kakryal, Katra, J&K 182320, India

2 School of Mechanical Engineering, Shri Mata Vaishno Devi University, Kakryal, Katra, J&K 182320, India

3 Department of Environmental Sciences, Central University of Jammu, Rahya Suchani, (Bagla) Samba, J&K 181143, India

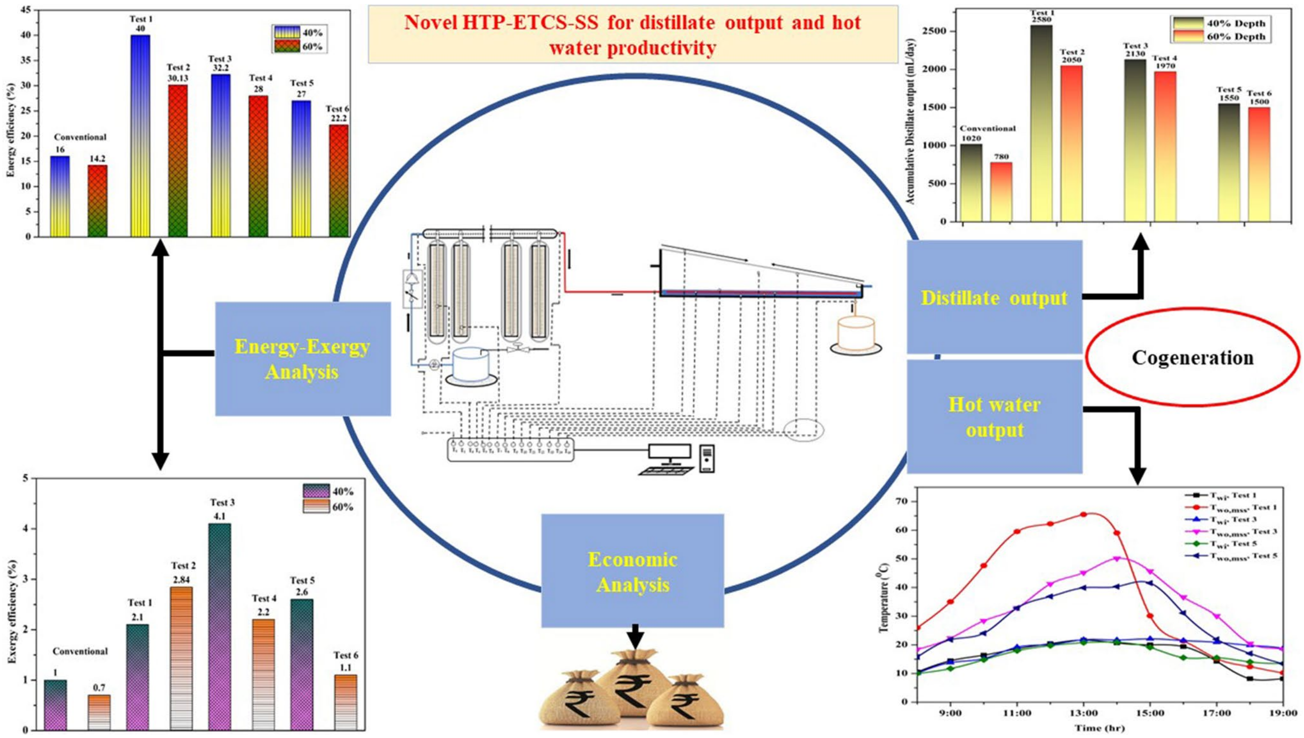
4 Department of Metallurgical and Material Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey

5 Centers of Research Excellence, Renewable Energy Research Institute, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

6 Research Centre for Nano-Materials and Energy Technology (RCNMET), School of Engineering and Technology, Sunway University, No. 5, Jalan Universiti, Bandar Sunway, 47500 Petaling Jaya, Selangor Darul Ehsan, Malaysia

7 Center for Transdisciplinary Research (CFTR), Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India

Graphical abstract



Keywords Hybrid system · Distilled water productivity · Thermal efficiency · Solar vacuum tube collector · Exergy efficiency · Heat pipe

List of symbols

ASV	Annual salvage cost/$
A	Area/m^2
P	Capital cost/$
CRF	Capital recovery cost/$
CRF	Capital recovery factor (fraction)
COD	Chemical oxygen demand/mg^{-1} L
CPL	Cost per liter/$
ETCS	Evacuated tube collector system
E_{ex}	Exergy/W
FAC	First annual cost/$
HTP	Heat pipe
Q	Heat transfer capacity/W
LPH	Liter per hour/L^{-1} h
M	Mass/kg
PCM	Phase change materials
i	Rate of interest/%
S	Salvage cost/$
SRRA	Solar resource radiation assessment
SS	Solar still
$C_{P,w}$	Water specific heat/kJ^{-1} kg^{-1} k
TDgWW	Textile degumming wastewater
TDyWW	Textile dyeing wastewater
TDS	Total dissolved solid
UAC	Uniform annual cost/$
n	Years

Subscripts

Amb	Ambient
mss	Designed solar still
ETC	Evacuated tube collector
f	Fins
g	Glass
exc	Heat exchanger
HTP	Heat pipe
inn	Inner
o	Outlet
s	Solar
vap	Vapor
w	Working fluid (water)
wi	Inlet water
wo	Outlet water

Greek symbols

λ_{fg}	Phase change heat for water evaporation/J^{-1} kg
η_{total}	Total developed system's energy efficiency

η_{th}	Developed system's thermal efficiency in context of distilled output
τ	Transmissivity
$\eta_{ex,total}$	Total exergy efficiency of the designed system
η_{ex}	Developed system's exergy efficiency in context of distilled output

Introduction

In recent years, the world per capita energy consumption increment has reached 3,260 kWh in 2018–2019 from 720 kWh in 2010 [1]. The drastic increase in energy consumption is to sustain human beings in this evolving era. The increase in a high standard of living leads to the exhaustion of natural resources [2]. Industry and households rely on freshwater and other available resources, which will get exhausted soon. Water is one of the fundamental prerequisites for the endurance of people. The per capita daily water consumption lies between 20 and 50 L for cooking and other activities [3]. The interest in freshwater is expanding all over the planet, particularly in the belt of arid areas. Industrialization and urbanization have degraded the quality of potable water worldwide. With the growing world population which would be anticipated to reach 1.6 billion by 2050; the scarcity of water also increases [4]. Various laws and agencies govern wastewater treatment technologies at different sources to make them portable worldwide. Various technologies are available for the treatment of unhealthy water. The other primary requirement of the world nowadays is hot water to carry out the daily necessities like bathing, washing, etc. The demand for hot water also escalates with an increasing standard of living, growth of population, and economic development [5]. In European Union, only 14% and in the USA 18% of the total energy consumption was utilized for hot water production in the domestic sector. The requirement for hot water is more prone in the area of cold climatic conditions [6]. The need for hot water in the Indian residential sector will be doubled by 2022 compared to 129 million/day in 2017 [7]. The maximum hot water demand is presently fulfilled by conventional electricity sources or direct fossil fuel uses.

Renewable energy sources can be better to fulfill distilled water and hot water demand, especially solar energy [8]. Solar energy can be utilized in both forms, i.e., thermal and electricity for distilled water and hot water production. Solar still is the oldest and simplest method for treating unhealthy water through the evaporation method [9]. Solar still is eco-accommodating, monetarily practical, created, worked, kept up with, and ends up being an answer for the treatment of saline/bitter water. This innovation just requires solar-based energy and less labor force to oversee and can be an appealing answer for underdeveloped, developing, and developed nations for a healthy water supply. [3]. The technology is now at an advanced stage that it can be used at the village level, in remote locations, and in industrial wastewater treatment. The main drawback of such a system is its low productivity, which is the main area to work for different researchers working on integrating external systems and modifying solar stills. Although, solar thermal collectors are the most attractive solution for water heating applications [10] and in combination with solar still for distilled water production. In the residential sector, the most common collectors used are the evacuated tube collector systems (ETCS) and flat plate solar collector systems (FPCS) [11] to fulfill hot water demand. FPCS is found to be the most widely used water heater due to its simple design, high dependability, and low maintenance. The drawback of the FPCS is their low efficiency, low-temperature output, and high initial cost. The ETCS overcomes the problem of low efficiency, temperature output, low maintenance, and initial cost. These regions made ETCS dominate the world solar market in water heating applications, over 80% of installed solar collectors are now ETCS [12]. Different researchers are working in the direction of finding newer technologies which can enhance the heat transfer rate of ETCS. The heat pipe is a modern and effective technology with an extremely high thermal conductivity rate among various other available technologies. It possesses various benefits as it is non-corrosive, high heat transfer rate, high reliability/dependability, thermal stability, and works at very low temperatures [13]. So, the possible way to fulfill the world energy demand is to shift our focus towards renewable energy sources and hybrid technologies [14]. Based on increasing demand in the household sector two major problems have been taken into consideration in this study, i.e., hot water and freshwater requirements. This leads to the need for hybrid technology for the generation of distilled (condensed) & hot water simultaneously.

In one of the articles published by Yadav and Sudhakar [15] discussed the modifications done in solar stills (single slope & double basin single slope, single, and double basin double slope, hybrid, and various other designs) so far. Sharshir et al. [16], discussed the improvement techniques utilized in tubular solar still for the desalination process. Pansal et al. [17] examined the improvement of SS on the reconciliation of photovoltaic with active SS. Essa et al. [18] utilized the ETCs as a novel vapor generator with three different water film thickness (WFT) (2, 4, and 6 mm) beneath the absorber which ultimately leads to improved energy efficiency. Maximum efficiency of 53% is reported with 2 mm WFT. Three different tubulars still diameter was examined (160, 120, and 80 mm); in this case, the highest overall efficiency was achieved with 160 mm tubular diameter of 60.2% followed by 120 and 80 mm. The best efficiency of the SS is also examined at three different slope angles, i.e., 45°, 62°, and 80°. The finest overall efficiency of 48.1% for the system is achieved at 45°. The per liter cost of distilled water production is reported as 0.01205 $\$^{-1}$Lcollector area^{-1}. Singh and Tiwari [19] designed and experimentally compared the N identical ETCS assembled with single and double basin solar still in context of energy, exergy, and production cost of distilled water from the system. An increment in the annual energy efficiency of 6.85%, exergy efficiency of 12.30%, and decrement in production by 15.19% were observed with double slope solar still at depth of 140 mm. In another study, the operation of solar still assimilated with ETCS in forced mode is examined and the highest production of 3.47 kg day^{-1} is obtained at 0.006 kg s^{-1} mass flow rate and 0.01 m depth [20]. Sampathkumar [21] and his co-workers augmented the solar still with ETC (active solar still). The result reveals that at a 40 mm water depth, the solar still produces 7.03 kg of distilled water in comparison passive still produces only 3.225 kg. A novel study [22] equipped solar still with ETC and thermoelectric modules. A thermoelectric module is utilized to deliver the electricity from the temperature difference that happened in SS because of the condensation process. The delivered electricity is utilized to run the propeller fan for prompting mechanical convection. The outcomes uncovered that by utilizing instigated convection, the highest output arrives at 1.11 kg m^{-2} h^{-1}, though the effectiveness of the framework expanded by 68%. Singh et al., [23] established the required number of vacuum tubes suitable for integration with solar still in natural mode. The best combination was found with 10 vacuum tubes and 30 mm depth, i.e., 52.5 kg water mass. The overall energy and exergy efficiency of the optimized system lies between 5.1–54.4% and 0.15–8.25%, respectively. Naghavi et al. [24] experimentally analyzed the utilization of paraffin wax integrated with ETCS. The outcomes uncover that the efficiency of the system is impacted on shady-blustery days and reaches between 34 and 36%, while on sunny days it ranges between 38 and 42%. Different heat transfer fluids (CuO, TiO_2, and MWCNT) are utilized in Heat pipe ETCS. The outcomes reveal that 15%, 5%, and 25% increments in the system's thermal efficiency have been found in August and 15%, 7%, and 25% in October, respectively. In comparison with a conventional heating system, it is found that the designed system is capable enough of saving 67.7% and 42.2% fuel, especially in the months of August and October, respectively [25]. In another study conducted by Maraj et al. [26] on ETSC-equipped heat pipe systems to analyze the annual performance and was resulted in annual efficiency of about 0.62.

Increment in distilled water and hot water demand for domestic purposes in recent years has gained popularity to fulfilling these demands through solar energy is a better option. The increment in population and availability of limited areas in the urban and rural areas turns researchers to the development of hybrid technologies. Hence, this study is focused on the advantage of a heat pipe equipped ETC System combined with solar still for distilled water and hot water productivity simultaneously as a novel and effective solution. The integration of heat pipe-equipped ETCS combined with solar still (HTP-ETCS-SS) is yet not been reported in the literature so far. Presently integration of external systems with solar still is only utilized for the enhancement of solar still productivity. Whereas this design hybrid system is novel in its dual nature which is that the utilization of solar heat for the preheating of basin water and collection of low-heated outlet water from a SS is used for other domestic heating applications (utensils, bathing, laundry, cleaning, etc.). The experimental procedure is carried out in winter when the requirement for hot water is high, and the distilled water production is less through conventional solar still. The hot water output temperature ranges between 40 and 27.8 °C with an inlet of 16–15 °C at varying flow rates between 4 and 12 LPH [11]. This shows that it has applications in the household, especially in the winter season. An improvement in distillate productivity from the designed system is found in between 51.9 and 162% in comparison to the conventional still. The variation in energy efficiency is found in the range of 64.8–42.4% and exergy efficiency in the range of 28.4–16.4%. It is suggested that the pressurized mode shows faster heat removal from beneath and increases the overall performance of the still, this will also help in decreasing the growing environmental problems and financial burden at the international level with a decrement in distilled water and hot water production cost as well. The cost of distilled (pure water) and hot water productivity is found to be 0.1037$ and 0.0276$, respectively, which is less than many other developed systems. Therefore, keeping all these points in mind, the present system is designed to produce pure and hot water for a normal household.

Experimental setup, instrumentation, and uncertainty analysis

This section is subdivided into five subcategories which deal with the description of system designing and instrumentation, wastewater characterization, uncertainty analysis, and experimental procedures. Detailed design of heat pipe equipped ETCS combined with solar still (HTP-ETCS-SS), experimental unit, and equipment has been deliberated in "System description and design" and "Experimental measurements and instrumentation" sections, respectively. The discussion on wastewater utilized in the current study and its characterization is elaborated in "Experimental procedure" section. "Wastewater characterization" section discusses the detail experimental investigation procedure, whereas "Uncertainty analysis" section provides the uncertainty analysis in performance parameters and measuring instruments during an experiment.

System description and design

The conceptual design of the constructed HTP-ETCS-SS system is demonstrated through Fig. 1. The core parts of the designed system are solar still (basin body, glass cover, HTP-ETCS, DC pump, heat exchanger, and insulated pipes).

Two solar stills have been fabricated with equal dimensions of 1 m × 1 m and kept in orientation. Out of two solar one is taken as conventional solar still as a control unit without modifications and changes for comparison whereas the latter one is integrated with HTP-ETCS. The HTP-ETCS is used as an external collector for the pre-heating of basin water. Both the still is in an L shape with an area of 1 m^2 in square shape manufactured from insulated material (fiber reinforced plastic) with 4 mm thickness. The solar still is surrounded by four sides, of which two are trapezoidal while the other two are rectangular. Both the still were kept at the horizontal plane and placed in the south direction. The solar still's inner area was black painted to augment the systems absorptivity. Pure transparent glass covers of 5 mm thickness at a slope of 45.2° concerning the horizontal surface from the front are used for condensation. Insulated vacuum rubber is utilized to keep the glass cover in position and avert leakage.

The theoretical layout of the HTP-ETC arrangement is shown in Fig. 1. It comprises 10 evacuated tubes equipped with heat pipes. The solar radiation is captured by an evacuated tube collector and heat transferred to the HTP is absorbed by a evaporation and condensation mechanism. The heat absorbed in the HTP is directly transmitted to water from the condenser of the HTP which is inserted in the manifold. On comparison with conventional ETCS and HTP equipped ETC is due to their low heat transfer capacity. HTP is equipped with the designed system to overcome this extreme shortcoming. The cold water is transferred through a copper pipe in a manifold and the flow rate was maintained by a low DC power water pump. The cold-water flow is controlled by rotameter and measured by rotameter.

Modified HTP-ETCS-SS is made up by combining conventional solar still and HTP-ETCS. The hot water output from HTP-ETCS is transferred to conventional solar still through an insulated copper pipe. The hot is circulated in the basin base at different flow rates through a heat exchanger channel made up of combining copper pipes from the thermostatic three-way valve. The heat exchanger is connected in a serpentine cross channel so that maximum transfer of heat takes place from hot water circulated from HTP-ETCS to water inside the basin (Fig. 2). The water from the serpentine heat exchanger is collected for further applications. The hot water from HTP-ETCS is initially used to pre-heat the WW is basin and finally collected in hot water tank.

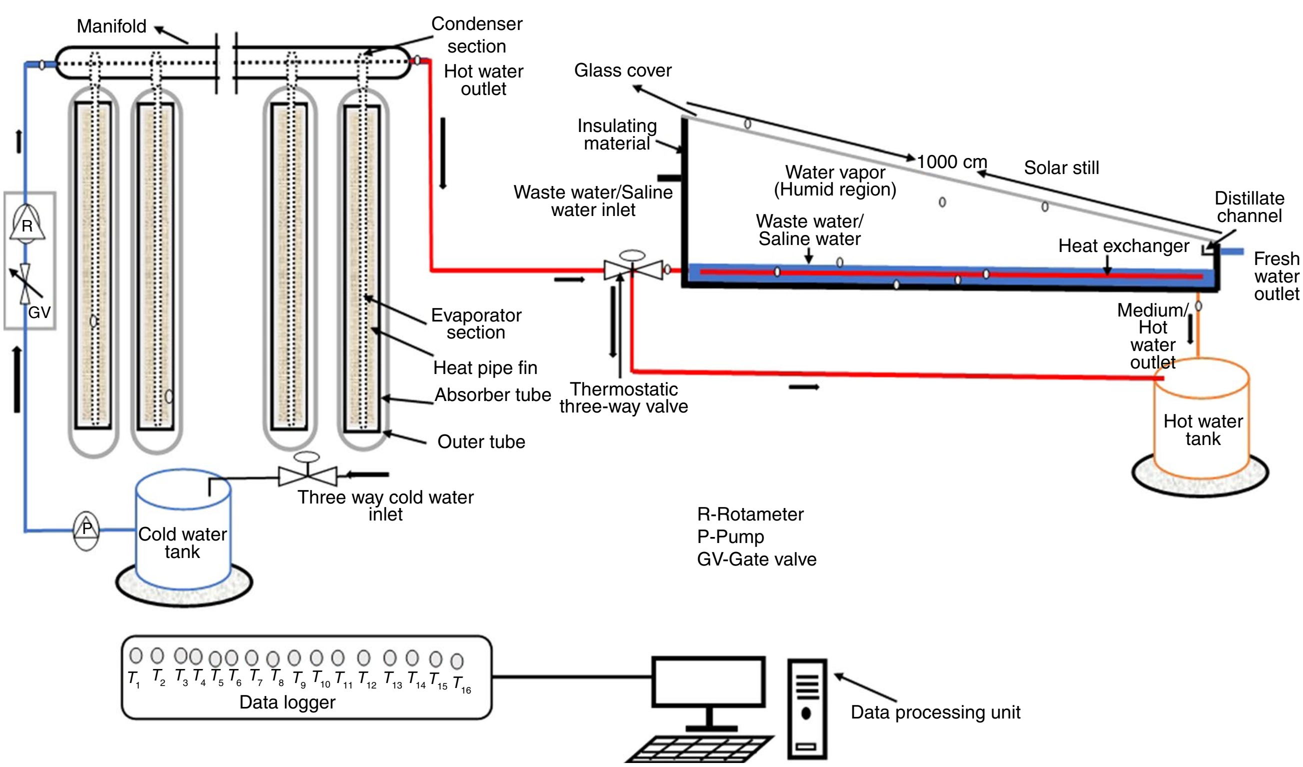


Fig. 1 Schematic representation of a developed experimental setup

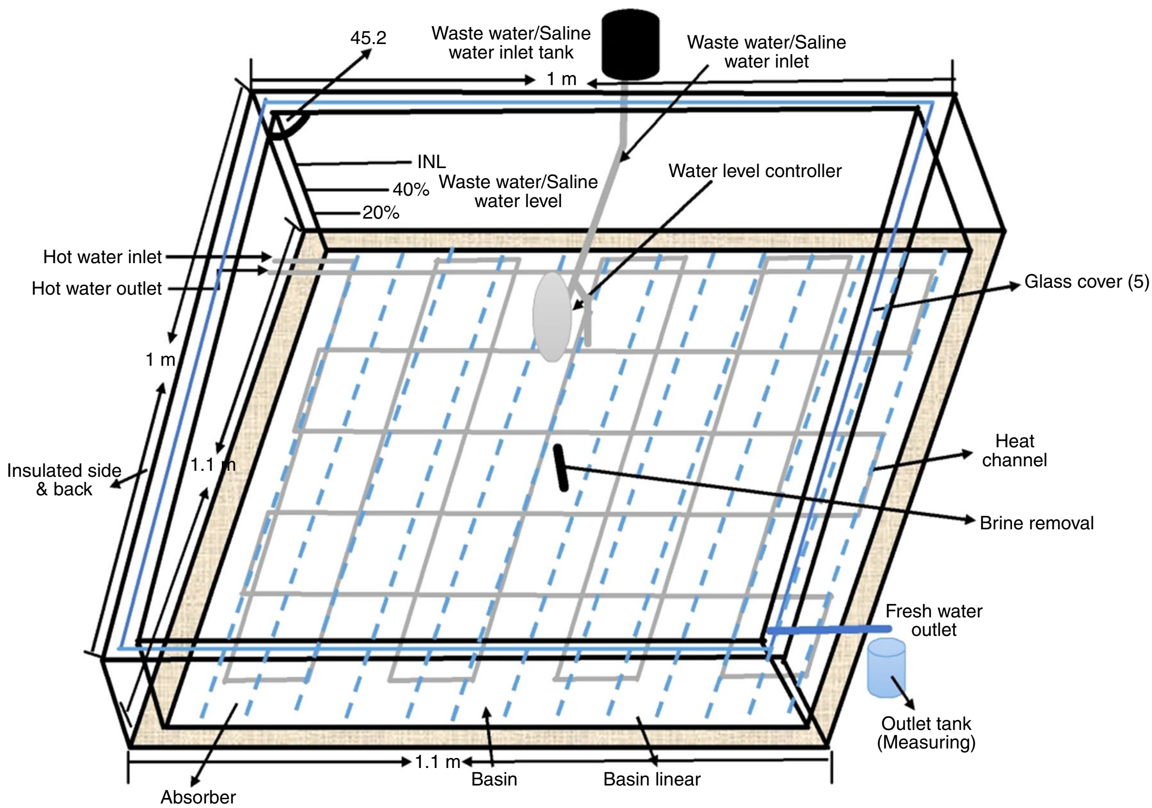


Fig. 2 Design of developed solar still assimilated with heat exchanger for hot water inlet at basin base

And, again on decrement in basin temperature the hot water pipe valves and transferred to the basin. Copper pipes are utilized to fabricate heat exchanger which leads to better heat transfer rate and act as an energy storage medium. This novel-designed system is used for both hot water and distilled water collection for domestic use.

The solar radiation transmitted from top glass cover to the basin after reflection gets absorbed and helps in addition to extra energy to the system. The transmitted solar radiation reaches the water mass from where some part of the energy is conveyed to the basin liner after absorption and reflection from the water mass. Almost all radiation that reaches the basin liner is absorbed, due to this phenomenon an increase in basin liner temperature is observed. Due to the increment in basin liner temperature, the temperature of the water also starts increasing due to the transmission of heat to water. The water starts evaporating due to the difference in the water surface temperature and inner glass cover temperature, whereas the condensation of water occurs on the inner glass cover due to the difference in outer and inner glass surface temperature through film-type condensation. The water thus condensed on the glass surface trickles to the front side due to tilt through a constant channel and is collected in an external collector through a pipe. The hot water is circulated at varying flow rates from bottom of the basin increase the temperature of basin liner and output at the endpoint. The rear wall side of the still is provided with an opening attached to the pipe for the filling of saline/brackish water in a basin. For the removal of waste collected after several run at the bottom of basin is drained through drainage system provided at the base of basin. The HTP-ETCS is fixed on an aluminum stand with a manifold and the solar still is kept on galvanized iron stand. Table 1 illustrates the specification if the designed systems.

Experimental measurements and instrumentation

In the present experimental setup, the experiment started early morning, i.e., at 07:00 AM and ended at night at 23:00 PM during winter, the data were collected after every 5-min interval. The study was conducted with three different hot water flow rates at two basin water depths. Control solar still is considered as a reference for assessment whereas developed solar still is transferred with hot water at three different flow rates. Two different water depths, i.e., 40% and 60% of basin's total capacity are taken into consideration to obtain the optimum depth for maximum production. During different studies, the temperature of various components of HTP-ETCS, SS, and HTP-ETCS-SS are measured and recorded, which is the ambient temperature (T_{Amb}), cold

Table 1 Specification of designed systems component

Component	Specification
Solar still	
Length of still	100 cm
Width of still	100 cm
Angle of glass cover	45.2°
Solar still material	Fiber-reinforced plastic
Solar still stand material	Galvanized iron
Cover material	Glass
Thickness of glass cover	0.5 cm
Heat exchanger material in modified solar still	Copper
Orientation	South
HTP-ETCS	
Number of evacuated tubes	10
Thickness of evacuated tubes	0.22 cm
Tube length of absorber	180 cm
Gap between two successive evacuated tubes	10.0 cm
Collector aperture area	75.2 cm^2
Heat pipe material	Copper
Condensing section diameter	1.4 cm
Evaporator section length	160.0 cm
Length of condenser section	6.35 cm
Condenser section length	0.952 cm
Fin material	Aluminum
Thickness of fins	0.02 cm

water temperature in HTP-ETCS (T_{wi}), hot water outlet temperature from HTP-ETCS ($T_{o,ETC}$), heat pipe temperature (T_{HTP}), fins temperature (T_f), inlet hot water temperature in SS ($T_{wi,mss}$), outlet hot water temperature from HTP-ETCS-SS ($T_{wo,mss}$), basin base temperature (T_{SSB}), inner glass cover temperature ($T_{inn,g}$), outer glass cover temperature ($T_{out,g}$), water in basin temperature (T_w), the vapor of basin temperature (T_{vap}), and heat exchanger temperature (T_{exc}). Different temperature sensors and other components used in the experiment are depicted in Fig. 3.

A *c*old-water tank of 1000 L capacity with an 18 W DC pump is used for water supply to HTP-ETCS. Water flow is maintained by valve and measured by rotameter in HTP-ETCS and HTP-ETCS-SS. The solar radiation resource assessment station (SRRA QC V1.2 201-3) installed at SMVDU, Katra, Jammu, and Kashmir is used to collect solar radiation and other meteorological data for experimental analysis. Whereas, RTD type temperature sensor is utilized with Masibus 85x++ data logger for recording temperature at various points. The distilled water produced is measured with a measuring cylinder every 15 min and collected to analyze at end of each experiment. The hot water directly from HTP-ETCS and HTP-ETCS-SS is collected in a hot water tank to be utilized for different applications. The water quality is analyzed in terms of pH, TDS, conductivity, etc. Different testing equipment utilized during different test cases for hot water production and distilled water output is datalogger, thermocouples, measuring cylinder, pH meter, TDS and conductivity meter.

Experimental procedure

The energy harvested through the HTP-ETCS is utilized in three ways. Firstly, solar radiation falling on HTP-ETCS is absorbed through evacuated tubes and conveyed to the evaporator section of a heat pipe. The evaporator section is filled with low boiling fluid which gets boiled and escalates to the condenser section. In the next phase, the energy collected in the condenser section is transferred to the manifold where direct transfer of energy takes place to flow water through the conduction process. In the third phase, the hot water produced from HTP-ETCS flowed through the heat exchanger (copper tubes) installed beneath the basin for preheating the water in a basin. The final water output was collected for further applications. The experimental procedure is as:

- An hour before starting any measurements of an experiment, the experimental setup is prepared accordingly, and the systems are cleaned properly. The water in the inlet tank and leakage are checked appropriately. Water in the basin is filled and its quantity and level are checked in both the solar still. The flow rate of the water inlet in HTP-ETCS is checked and the insulation of copper pipe for hot water transfer from HTP-ETCS to solar still is checked depending upon each test case. The hot water and distilled water output are collected in different containers.
- During each test temperature measurements are taken at the same time and ensure that the data logger is recording the measured values properly, SRRA is recording the meteorological data and solar radiation data.
- The distilled water is collected, and quantity is checked carefully and kept for quality analysis. The temperature recording is done on regular interval of hot water after pre-heating the basin water and kept in insulated water tank.
- Reiterate the Steps 1, 2, and 3.
- At the end of each day's readings, the system is prepared as the first day. The system is cleaned properly, the glass cover is cleaned, insulations are checked to prevent leakage, a hot water tank has gotten empty, and set to repeat procedure 1 for the next day’s reading.

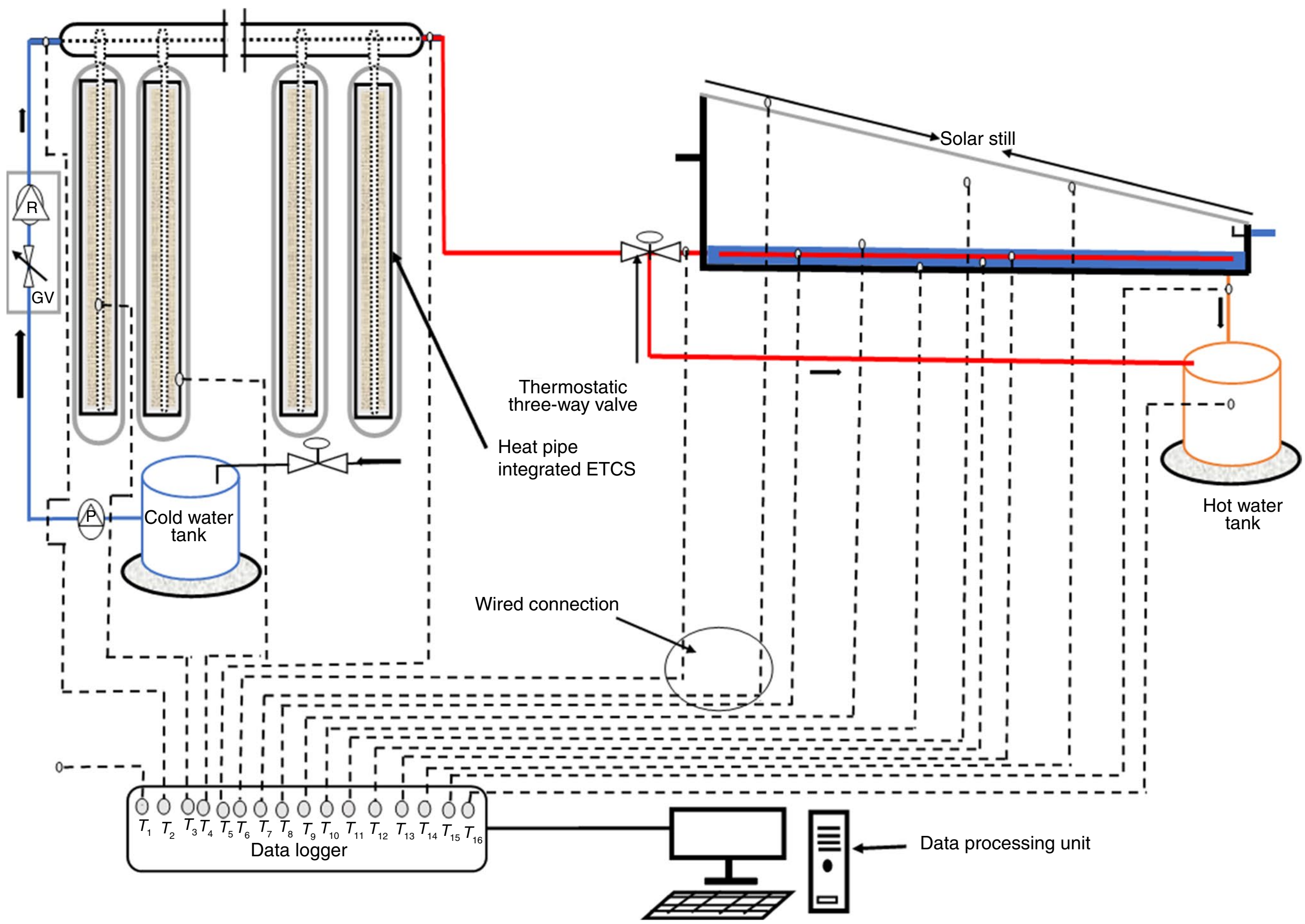


Fig. 3 Arrangements of thermocouple in an experimental setup

Wastewater characterization

The textile industry wastewater was gathered from District Panipat, situated at latitude 29.39° N, and longitude 76.96° E, from Haryana, India. The wastewater is initially pre-treated for removal of volatile and total solids particles before examination in designed system. Two different step wastewaters, i.e., degumming (TDgWW) and dyeing (TDyWW) are collected from the industry through the composite sampling method. The wastewater was collected in 20 L plastic cans for further use. To reduce the further degradation and infection in collected wastewater it is kept at 4 °C in refrigerator. The physicochemical analysis of wastewater was analysed through standard analytical process as recommended by APHA (American Public Health Association; 2012) [27]. The parameters which were examined in this study are pH, total dissolved solids (TDS), chemical oxygen demand (COD), and heavy metals. The all parameters which are considered in this study are analysed in triplicates. Heavy metal concentration is analysed by using the digestion

Table 2 Initial characterization of wastewaters

Parameters	TDgWW	TDyWW
Colour	Brownish	Blackish
Odour	Pungent	Pungent
Total coliforms/MPN-100 mL^{-1}	No detection	No detection
pH	8.62 ± 0.16	12.22 ± 0.15
TDS/mg L^{-1}	3884.7 ± 16.76	4755.1 ± 23.62
COD/mg L^{-1}	11,363.4 ± 61.66	22,367.3 ± 73.53
Cu/mg L^{-1}	0.05 ± 0.01	2.02 ± 0.05
Hardness/mg L^{-1}	1118.4 ± 55.61	1305.3 ± 24.28
Zn/mg L^{-1}	4.16 ± 0.9	7.58 ± 1.2
Fe/mg L^{-1}	3.02 ± 0.05	2.02 ± 0.06
Ni/mg L^{-1}	0.17 ± 0.02	0.03 ± 0.01
Mn/mg L^{-1}	0.18 ± 0.03	0.12 ± 0.02

method. Lab-grade chemical purchased from Hi-Media, Mumbai utilized in wastewater parametric study. The quality of wastewater is mentioned in Table 2.

Uncertainty analysis

Uncertainty is the random variability found in evaluated parameters ($Y1$; $Y2$; $Y3$;...) in each study. Important parameters which cannot be directly evaluated during different experiments can be directly evaluated as a function of $X = (Y1;\ Y2;\ Y3;...)$. Uncertainty and error analysis of the experimental results is calculated from Eq. 1 [28] and tabulated in Table 3:

$$U_x = \sqrt{\sum_i^1 \left(\frac{\partial x}{\partial_{yi}}\right)^2 U^2 yi} \tag{1}$$

Thermal performance analysis

This section deals with different thermal performance parameters analyzed during different tests in context of thermal and exergy. The energy and exergy of the HTP-ETC-SS are calculated for distilled water production, HTP-ETCS-SS for hot water output, & the total energy and exergy of the system. This section is divided into two main sub-sections first one deals with energy calculation equations for the system, whereas the second one deals with exergy calculation of the designed HTP-ETCS-SS.

Energy efficiency

The daily thermal energy efficiency $\left(\eta_{\text{HTP - ETC}}\right)$ of the HTP-ETCS equation is expressed as [29]:

$$\eta_{\text{HTP-ETC}} = \frac{Q_{\text{w,ETC}} \mathrm{d}t}{\sum I_{\text{solar}} A_{\text{HTP-ETC}} \tau_{\text{day}}} \tag{2}$$

Heat supplied to water flowing through manifold can be calculated as [11]:

$$Q_{\text{w,ETC}} = \dot{m}_{\text{w}} C_{\text{P,w}} \left(T_{\text{wo,ETC}} - T_{\text{wi,ETC}}\right) \mathrm{d}t \tag{3}$$

The ratio of hourly usable energy to hourly incident solar radiation helps in estimation of hourly energy efficiency of traditional SS [30].

$$\eta_{\text{th}} = \frac{m_{\text{ss}} \times \lambda_{\text{fg}}}{\left(A_{\text{ss}} \times I_{\text{solar}}\right) \times \Delta t} \tag{4}$$

The below equation estimates the energy efficiency of the modified SS (HTP-ETCS-SS) on hourly basis [31]:

$$\eta_{\text{th}} = \frac{m_{\text{ss}} \times \lambda_{\text{fg}}}{\left(A_{\text{ss}} \times I_{\text{solar}}\right) \times \Delta t + Q_{\text{w,ETC}}} \tag{5}$$

The total hourly efficiency of the designed system HTP-ETCS + HTP-ETC-SS) is equated as:

$$\eta_{\text{total}} = \frac{Q_{\text{w,HPT-ETC-SS}} + \left(m_{\text{ss}} \times \lambda_{\text{fg}}\right)}{\left(A_{\text{ss+HTP-ETCS}}\right) I_{\text{solar}} \times \Delta t} \tag{6}$$

Heat supplied to water flowing through manifold can be calculated as [11]:

$$Q_{\text{w,HTP-ETC-SS}} = \dot{m}_{\text{w}} C_{\text{P,w}} \left(T_{\text{wo,mss}} - T_{\text{wi,ETC}}\right) \mathrm{d}t \tag{7}$$

Exergy efficiency

Exergy output of the system in context of distilled water and hot water can be computed as [32]:

The equation of exergy balance for a closed system is computed as [33]:

$$\sum \dot{E}_{\text{ex, input}} - \sum \dot{E}_{\text{ex,output}} = \sum \dot{E}_{\text{ex,destruction}} \tag{8}$$

The exergy output of the distilled water output from conventional, as well as modified solar, still is computed as [34]:

Table 3 Detail of measuring instruments with their standard uncertainty

S. no.	Apparatus	Model	Accuracy	Range	Standard Error
1.	Thermocouple	RTD temperature sensor	± 1 °C	− 50–600 °C	± 1.3 °C
2.	Pyranometer	SRRA	± 10 W m^{-2}	0–2000 W m^{-2}	± 0.6 W m^{-2}
3.	Measuring cylinder	Borosil	± 10 mL	0–1000 mL	± 1.5 mL
4.	Rotameter	SERIES-SF-ABRWV-208	± 0.5 LPH	0–50 LPH	± 0.2 LPH
5.	TDS meter	Hanna HI82484	± 1.0 µS cm^{-1}	0–9990 µS cm^{-1}	0.8 µS cm^{-1}
6.	Conductivity meter	Hanna HI82484	± 0.5 µS cm^{-1}	0–9990 µS cm^{-1}	0.4 µS cm^{-1}
7.	pH meter	Hanna HI82484	± 0.1 pH	0–14.0 pH	0.5 pH

$$\dot{E}_{ex,output} = \frac{\dot{m}_{ss}\lambda_{fg}}{3600}\left[1 - \left(\frac{T_{Amb} + 273}{T_w + 273}\right)\right] \tag{9}$$

The exergy input of the conventional SS can be computed as [33]:

$$\dot{E}_{ex,input} = I_{solar}A_{ss}\left[1 - \frac{4}{3}\left(\frac{T_{Amb} + 273}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{Amb} + 273}{T_{sun}}\right)^4\right] \tag{10}$$

The exergy inlet in present case can be computed as [30]:

$$\dot{E}_{ex,input} = I_{solar}A_{ss}\left[1 - \frac{4}{3}\left(\frac{T_{Amb} + 273}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{Amb} + 273}{T_{sun}}\right)^4\right] + Q_{w,HTP-ETC-SS}\left(1 - \frac{T_{Amb}}{T_w}\right) \tag{11}$$

Total usable exergy of modified HTP-ETCS-SS during all test cases can be computed as [32]:

$$E_{total-product} = \frac{m_{ss}h_{fg\cdot sw}}{3600}\left[1 - \left(\frac{T_{Amb} + 273}{T_w + 273}\right)\right] + \frac{m_{ss}C_{P,w}}{3600}\left[\left(T_{wo,mss} - T_{wi,TEC}\right) - \left({}^{T_{wo,mss}}/{}_{T_{wi,ETC}}\right)\right] \tag{12}$$

Total exergy input to the modified HTP-ETCS-SS is computed as [32]:

$$E_{ex,\ input-product} = A_{a+HTP-ETC}I_t \left[1 - \frac{4}{3}\left(\frac{T_{Amb} + 273}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{Amb} + 273}{T_{sun}}\right)^4\right] \tag{13}$$

The exergy efficiency η_{ex} of the designed HTP-ETCS-SS for distilled water productivity alone is estimated as exergy of evaporated water to incident exergy:

$$\eta_{ex} = \frac{E_{ex,output}}{E_{ex,input}} \tag{14}$$

The total designed system's exergy efficiency in context of both hot and distilled water productivity can be computed as:

$$\eta_{ex,total} = \frac{E_{total-product}}{E_{ex,input,total}} \tag{15}$$

Economic analysis

Economic analysis of distilled water and hot water by the designed system (HTP-ETCS-SS) is estimated for unit cost production. The per-unit production cost for distilled water output and hot water from the designed system can be calculated as follows [32]:

$$CPL_{Distillate} = \frac{UAC}{M_{Distillate}} \tag{16}$$

$$CPL_{Hot\ water} = \frac{UAC}{M_{Hot\ water}} \tag{17}$$

The capital costs (P) of the system can be assessed by combining all types of equipment and material costs used in designing of such as ETCS, heat pipe, copper pipes, water tank, hot water storage tank, glass cover, valves, pump, rotameter, etc. To assess the capital cost (P) of the co-production of distilled water and hot water from the designed system several other parameters which are taken into account is sinking fund factor (SFF), yearly operating and repairs cost (AMC), yearly product discarded cost (ASV), first annual cost (FAC), and bank interest rate (i) [35]. First yearly cost (FAC) of fabricated system can be work out as [36]:

$$FAC = P \times (CRF) \tag{18}$$

$$CRF = \frac{i(1 + i)^n}{(1 + i)^n - 1} \tag{19}$$

The yearly product discarded value (ASV) of the fabricated system can be expressed as [37]:

$$ASV = SFF \times S \tag{20}$$

whereas sinking fund factor can be calculated as [38]:

$$SFF = \frac{i}{(1 + i)^n - 1} \tag{21}$$

whereas S is the product discarded cost of the fabricated system [38]:

$$S = 0.2 \times P \tag{22}$$

Annual maintenance cost can be computed as [39]:

$$AMC = 0.1 \times FAC \tag{23}$$

The uniform annual cost (UAC) can be computed as [32]:

$$UAC = FAC + AMC - ASV \tag{24}$$

Result and discussion

The experimental outcomes attained from conventional solar still and designed SS (heat pipe equipped vacuum tube collector joined with solar still (HTP-ETCS-SS)) have been discussed in this section. Here, the performance of designed solar has still been compared with control solar still. The conventional solar still (SS) is utilized to compare the distilled water production from the newly designed novel hot water and distilled water production unit. To further enhance the purified water output and production of hot water, the conventional solar is modified as HTP-ETCS-SS with a heat exchanger at the basin base for hot water circulation from HTP-ETCS to preheat the water in the basin to reduce the start time by increasing the basin base temperature. The water is circulated at different flow rates (4, 8, 12 LPH) at two different water depths for hot water production and circulation in modified SS and finally collected for various domestic applications. Therefore, six different combinations are considered as shown in Table 4 and compared with conventional solar still. Tests 1, 3, and 5 are assigned for hot water flow rates of 4, 8, and 12 LPH at a water depth of 40%. On the other hand, for 60% water depth, Tests 2, 4, and 6 are allocated for hot water flow rates of 4, 8, and 12 LPH, respectively. On the basis of experimental records, energy, exergy, distilled water productivity, hot water output and financial analysis of the designed system have been done and compared with the conventional system.

The disparity in solar radiation, ambient temperature, cold water inlet temperature in HTP-ETCS, hot water inlet temperature in designed from HTP-ETCS, basin base temperature, basin water temperature, vapor temperature, hot water outlet temperature from designed solar still, and inner glass temperature was discussed for considered experiments. Furthermore, energy and exergy investigation of designed systems is also presented. According to Indian water quality standards, the wastewater is analyzed, and the treatment viability of the designed system is also given with an economic analysis of the distilled water output and hot water per liter cost production.

Variation in solar insolation

The solar radiation fluctuations versus time for six different Tests are well depicted in Fig. 4. This figure shows the behaviour of solar insolation during different Tests 1–6 on different days has been found in a similar trend with fewer fluctuations. Though, because of cloudy effect, fluctuations in solar insolation were found in Test-3 and Test-5. The dramatical variations during Test-3 were reported between 10:00 to 11:00 and 14:00 to 15:00. While, during Test-5, minute variation in solar insolation is found between 10:00 to 12:00 whereas, after 13:00 sudden drop in solar radiation is till 14:00. Test-6 also showed small variation between 10:00 to 11:00 The uppermost value of solar insolation for Test-1 to 6 was reached to 916.8 (at 13:05), 902.4 (at 12:00), 961.8 (at 13:00), 974.2 (at 12:10), 936.7 (at 13:10) and 933.8 (at 12:55) W m^{-2}, respectively.

Table 4 Detail of tests

Test	Depth/%	Water flow rate
Test 1	40	4 LPH
Test 2	60	
Test 3	40	8 LPH
Test 4	60	
Test 5	40	12 LPH
Test 6	60	

Effect on different parametric temperatures

Evolution of different system temperatures like outside air (T_{Amb}), basin base (T_{SSB}), inner glass cover ($T_{inn,g}$), water in basin (T_w), and vapor of basin temperatures (T_{vap}) with time for conventional solar still, and designed solar still HTP-ETCS-SS at two different depth and various hot water flow rate (4, 8 and 12 LPH) is shown through Figs. 5a–d and 6a–d. Moreover, the variation of the inlet hot water temperature from HTP-ETCS-SS ($T_{wi,mss}$), outlet hot water temperature from HTP-ETCS-SS ($T_{wo,mss}$) with time in case of designed solar still is superimposed in Figs. 5b–d and 6b–d. It can be observed from Figs. 5 and 6 that solar radiation increases the system temperature at every subsequent hour. The system temperature increases gradually from morning till late afternoon, i.e., between 12:00 and 13:00, then a gradual reduction in all temperatures is noted unit the end of the experiment. The result reveals that the basin water temperature for all tests for the developed system was found to be control solar still. The higher temperature increases the evaporation rate of water in the basin of a designed solar still, which ultimately increases the distilled water output productivity. However, by comparing the 40% and 60% depth results, 40% depth is found more suitable in terms of distilled water output.

Moreover, in comparison to the temperature of glass and water vapour, it is established that the difference amongst water vapor and glass temperature is found maximum with tests conducted with 40% water depth in comparison to 60%. Therefore, the distilled water output productivity of

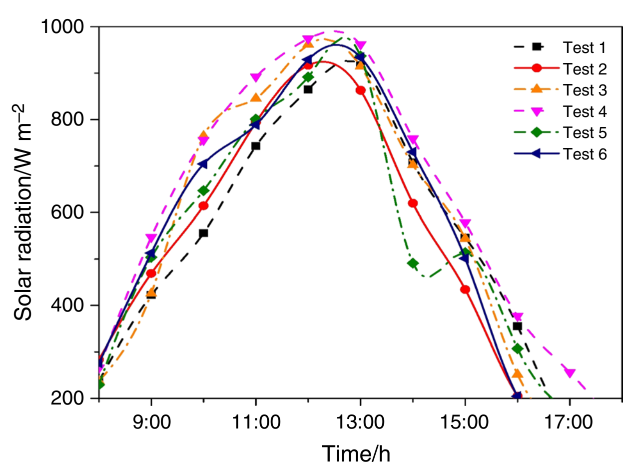


Fig. 4 Fluctuation of solar insolation versus time during different Test 1–6

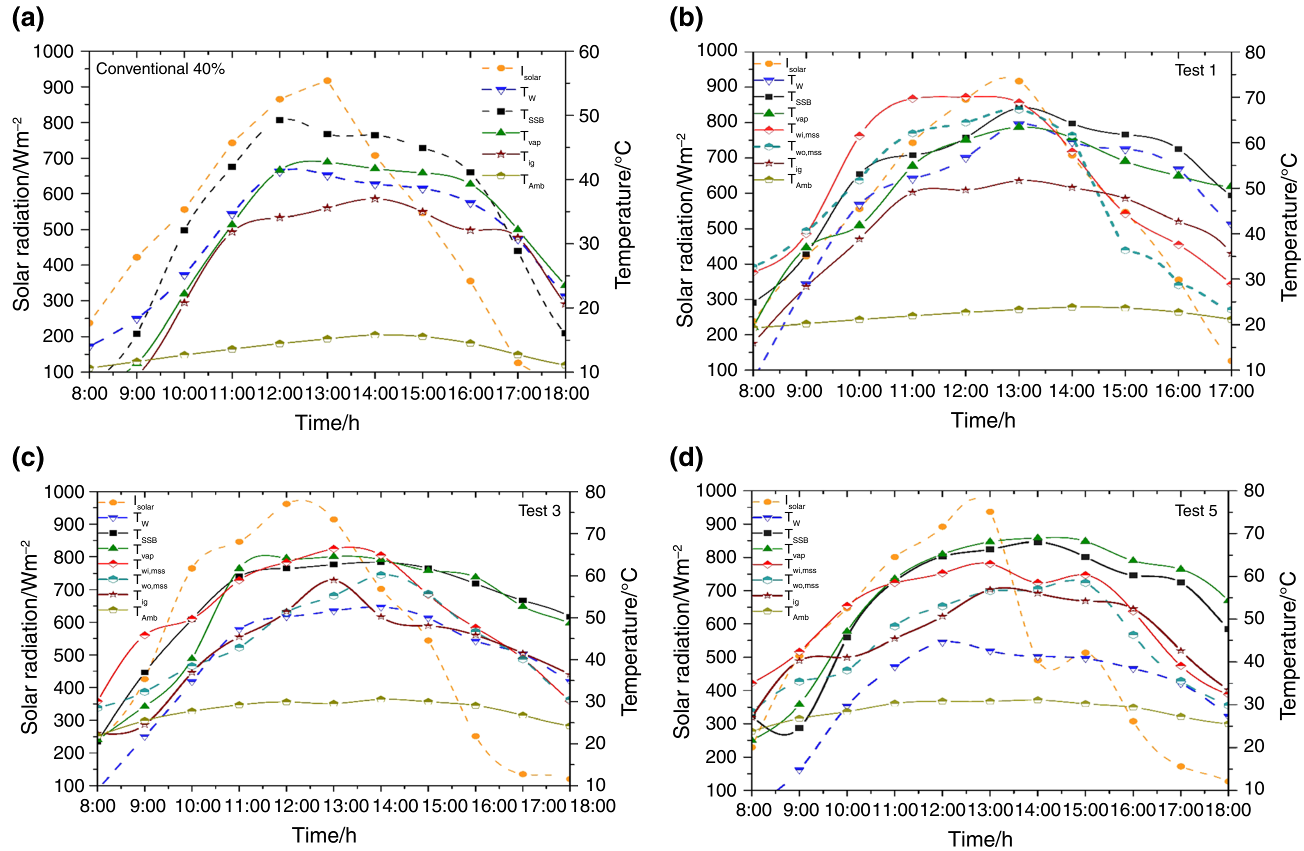


Fig. 5 Evolution of different solar still temperature of **a** conventional solar still, **b** Test-1, **c** Test-3, and **d** Test-5 of designed HTP-ETCS-SS system with time at 40% depth

the still with 40% depth is greater than 60% depth in all cases compared separately and will be greater than SS. The result shows that the water temperature for Test-1 is greater than other performed tests and SS due to low water depth and low hot water flow rate with high temperature. The heating of water starts early and leads to high distilled water output. As a result, it can be anticipated that the distilled water productivity of Test-1 will be greater than the other tests with designed still HTP-ETCS-SS or SS as will be seen later. Figure 5a–d indicates that for 40% depth, the maximum water of conventional solar still, Test-1, Test-3, and Test-5 found to be 42.7 °C, 64.1 °C, 52.5 °C, and 49.7 °C, respectively.

Figure 6a–d illustrates the different temperature nodes of solar still conventional and designed at 60% depth. It was found that the basin water temperature of designed solar still increases compared to traditional solar still. However, the lower hot water flow rate with high temperature augments the basin water temperature. This increases the difference in glass and water temperature, which increases the distilled water output against conventional solar still with the same depth. It may be noted from the obtained result that hot water flow at all flow rates helps in increasing the overall distilled water productivity in contrast to conventional solar still at 60% depth. Figure 5a–d indicates that the utmost water temperature of SS for Test-2, Test-4, and Test-6 established to be 37.7 °C, 48.3 °C, 45.5 °C, and 41.6 °C, respectively.

Effect of flow rate and depth on distilled water output

The foremost target of the designed system (HTP-ETCS-SS) is to enhance the distilled water output. Therefore, a comparative study between distilled water productivity during different tests with SS as reference is depicted in Fig. 7. The hourly distilled water production gradually increases from morning, *i.e.,* 08:00 until it reaches a maximum between 12:00 and 14:00 for considered experiments, before decreasing with time. In this section, the designed system is optimized for hot water flow rates of 4, 8, and 12 LPH at two different water depths, *i.e.,* 40%

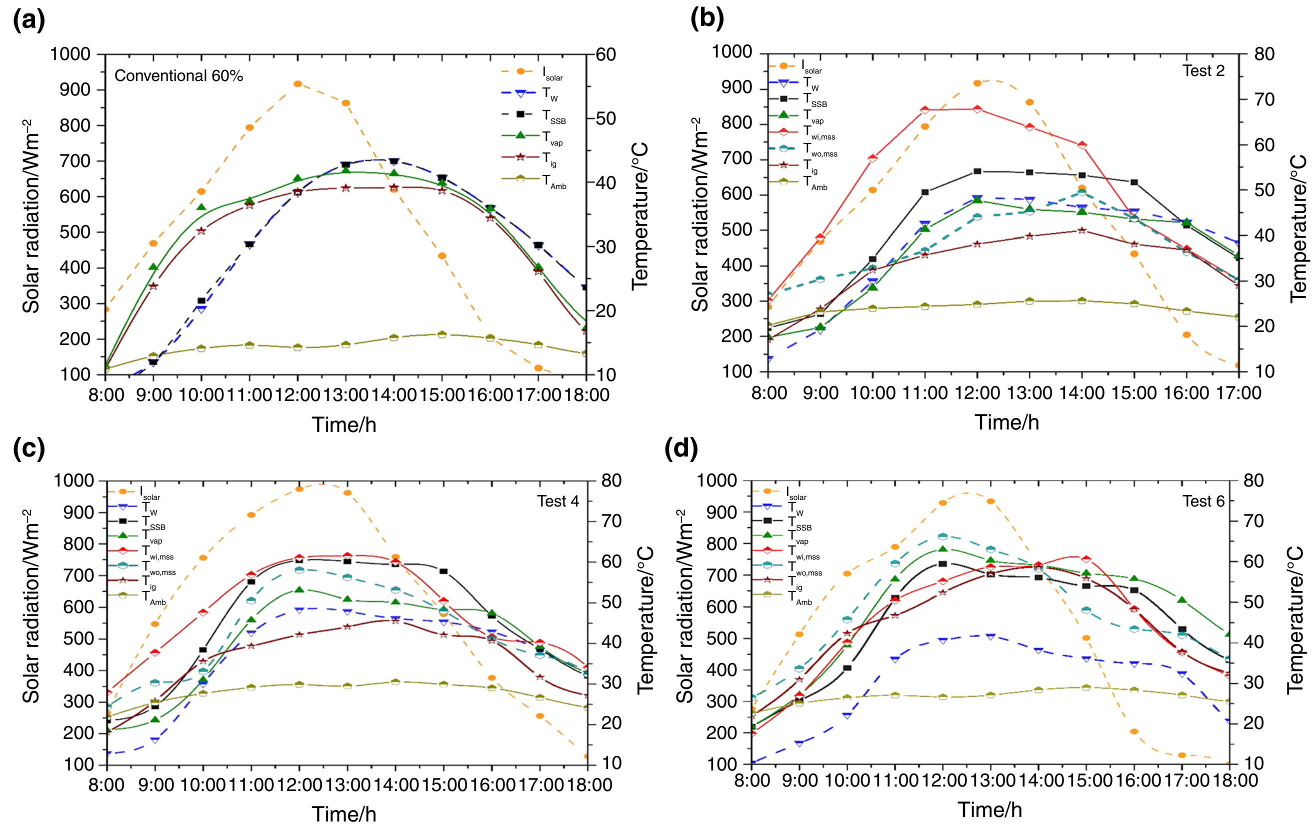


Fig. 6 Evolution of different solar still temperature of **a** conventional solar still, **b** Test-2, **c** Test-4, and **d** Test-6 of designed HTP-ETCS-SS system with time at 60% depth

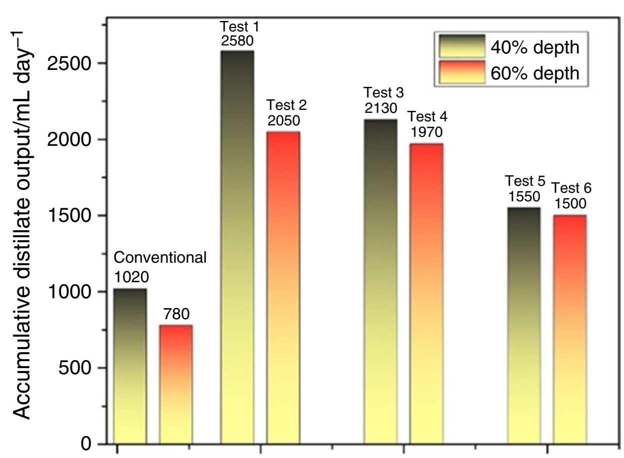


Fig. 7 Water depth and hot water flow rate impact on distilled productivity during different Test 1–6

and 60%. As the hot water flow rate increases, distilled water output decreases, but at a low hot water flow rate, the increment in distilled water output is observed at different depths by following simple thermodynamics. At low hot water flow rate, the water temperature is high, which is transferred to water in the basin and water get heated faster, whereas at 12 LPH, the water temperature is low which slowly increases the basin water temperature. The strident escalation in distilled water output is detected with an increased flow rate in the commencement owing to the efficiency of collector factor and heat removal rate from HTP-ETCS. However, after a few initial minutes (30–50 min), the decrement in temperature is observed due to a high flow rate and less conduction occurrence in the condenser of HTP-ETCS. Hence, the low flow rate, i.e., 4 LPH followed by 8 and 12 LPH is significantly considered for increasing basin water temperature, leading to enhanced distilled water output. However, after reaching a particular temperature, the effect of hot water flow rate is insignificant due to the same temperature or high basin water due to the same value of available flux and greenhouse effect in a basin, after initial increment in basin water temperature at the different hot water flow rate. When the temperature range of basin water temperature and hot water temperature is the same, the three-way valve automatically closes and diverts the hot water to a hot water storage tank for different applications. The system's performance is found optimum with a

4 LPH hot water flow rate for distilled water productivity followed by 8 and 12 LPH.

The depth of water affects the productivity of the distilled water; it can be previously observed from another study that an argument in water depth reduces the output of the distilled water [40]. A significant result is also found in the present study, but the current study's novelty lies in increasing distilled water output at high depth. The hot water flow over a cross type heat exchanger increases the water temperature, but at a lower depth, the temperature of water rises rapidly, which leads to high distilled water output concerning higher water depth temperature increases gradually with time and reaches significant evaporative water temperature in comparison to conventional depth. However, when a comparison is done between control and developed solar still (HTP-ETCS-SS) the overall distilled water output is found higher with lower depth. But the increment is reported higher with higher depth, i.e., 162%, 152.5%, and 92.3% at 4, 8, and 12 LPH, in comparison to conventional solar still. Whereas 152.9%, 108%, and 51.9% increment is reported with a lower depth of 40% at different flow rates 4, 8, and 12 LPH, respectively. Hence, this system proves to be effective for high water depth in solar still for enhanced productivity, the overall increment of the solar still can be augmented by further utilizing energy storage material. The highest distilled water productivity was obtained with Test-1, *i.e.*, 2580 mL day^{-1} followed by Test-3, Test-5, and conventional still with production of 2130, 1550, and 1020 mL day^{-1} at 40% depth. However, at 60% depth the highest distilled water productivity is found maximum with Test 2 followed by Test-4, Test-6, and conventional still, *i.e.,* 2050, 1970, 1500, and 780 mL day^{-1}.

Flow rate and water depth impact on hot water output temperatures

Another test case is examining the water depth and working fluid flow rate impact on hot water temperature. The variation in initial inlet temperature of cold water to HTP-ETCS and water outlet from modified solar still is illustrated in Fig. 8. This figure displays the disparity of inlet and outlet temperature for Test-1, 3, 5, 2, 4, and 6. The average value of inlet water temperature was 13.6, 14.3, 17.5, 15.8, 15.3, and 15.2 °C during Test-1, 2, 3, 4, 5, and 6, respectively. The increment in hot water temperature shows an inverse relationship water flow rate. The effect of water depth on hot water temperature could be observed in Fig. 8a, b. The maximum hot water temperature is gained at 40% depth at a water flow rate of 4 LPH and the minimum hot water temperature is obtained with a 4 LPH flow rate at 60% water depth. This trend is obtained due to variation in water depth during lower depth and low hot water flow rate where basin water temperature and flowing water temperature reach a common temperature faster. This occurs due to faster heating of lower mass in the basin, as it receives solar radiation and extra heat from flowing hot water from HTP-ETCS-SS flowed inside the heat exchanger installed at the base of the basin. Due to this, the three-way valve opens, and the hot water is directly transferred to the hot water storage tank. The same trend is also reported with a high flow rate. However, the trend changes with high water depth, and hot water temperature decreases as high heat transfer occurs to augment the water temperature in basin.

As seen in Fig. 8a, Tests 1, 3, and 5 attained maximum outlet temperatures of 65.5 °C (at 13:40), 50.15 °C (at

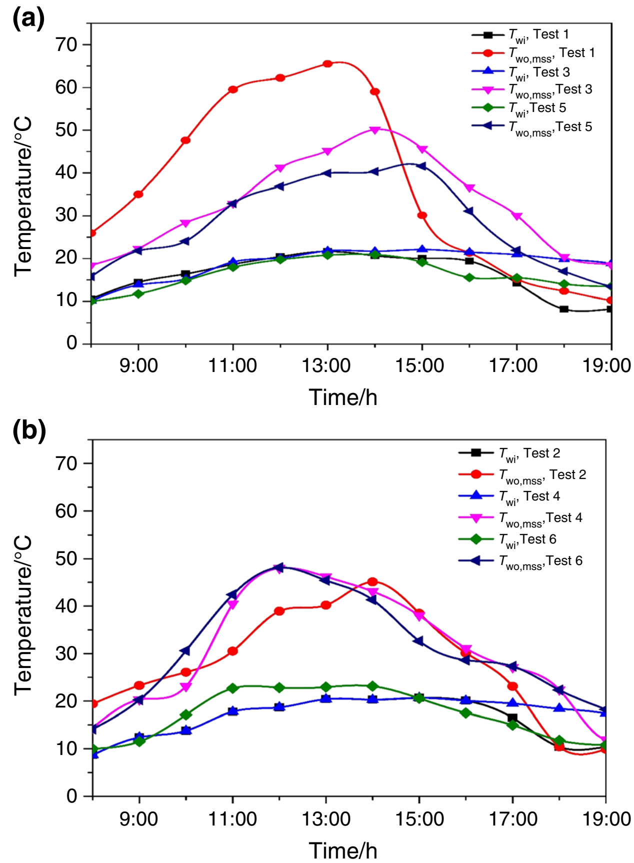


Fig. 8 Variation of inlet and outlet temperature at a different time interval during various tests 1–6 at different depths **a** 40% **b** 60%

14:35), and 41.56 °C, respectively (at 14:00). The maximum hot water temperature variation is found with a low flow rate of 4 LPH. During Test-1 high-temperature range is found in the initial hour of the experiment this phenomenon is observed due to low water depth, which takes a lesser time to heat and attain the maximum temperature according to solar radiation. Whereas, after 14:00, the temperature of the hot water flow rate decreases as the maximum heat is transferred to maintain the basin water temperature for maximum output. The same trend is also observed with Tes-3 and Test-5. But, in the case of a high flow rate, the hot water temperature decreases due to the low rate of heat transfer.

Figure 8b displays the disparity of inlet and hot water temperature at 60% water depth. The uppermost outlet temperature of 40.2 °C (at 13:10), 48.0 °C (at 12:15), and 48.56 °C (at 13:05) was obtained for Test-2, 4, and 6, respectively. Here, with this depth, water temperature at the outlet of designed solar is still low compared to low water depth. During different tests, at this depth, water requires a huge quantity of heat to increase the water temperature due to high mass. As can be observed from Test-2, data shows low hot water temperature in comparison with Test-4 and Test-6 this is due to the high-water mass in a basin which requires high energy to heat up. When the flow rate is low the transfer of heat takes more in comparison to high flow rate; hence, during a low flow rate, the hot water temperature is high, but the transfer of heat is maximum in the basin. Whereas, in the case of a high flow rate, the basin water and hot water temperature also get into equilibrium quickly. Hence, the 4 LPH shows maximum variation against 8 and 12 LPH.

The result suggested that 4 LPH with low depth and 8 LPH with high water depth is found best during an experimental performance.

Efficiencies analysis

Any modification in design, development and improvement in system output can be examined in context of useful energy and exergy output. Here in this specific section, valuation of designed HTP-ETCS-SS in comparison to SS is done.

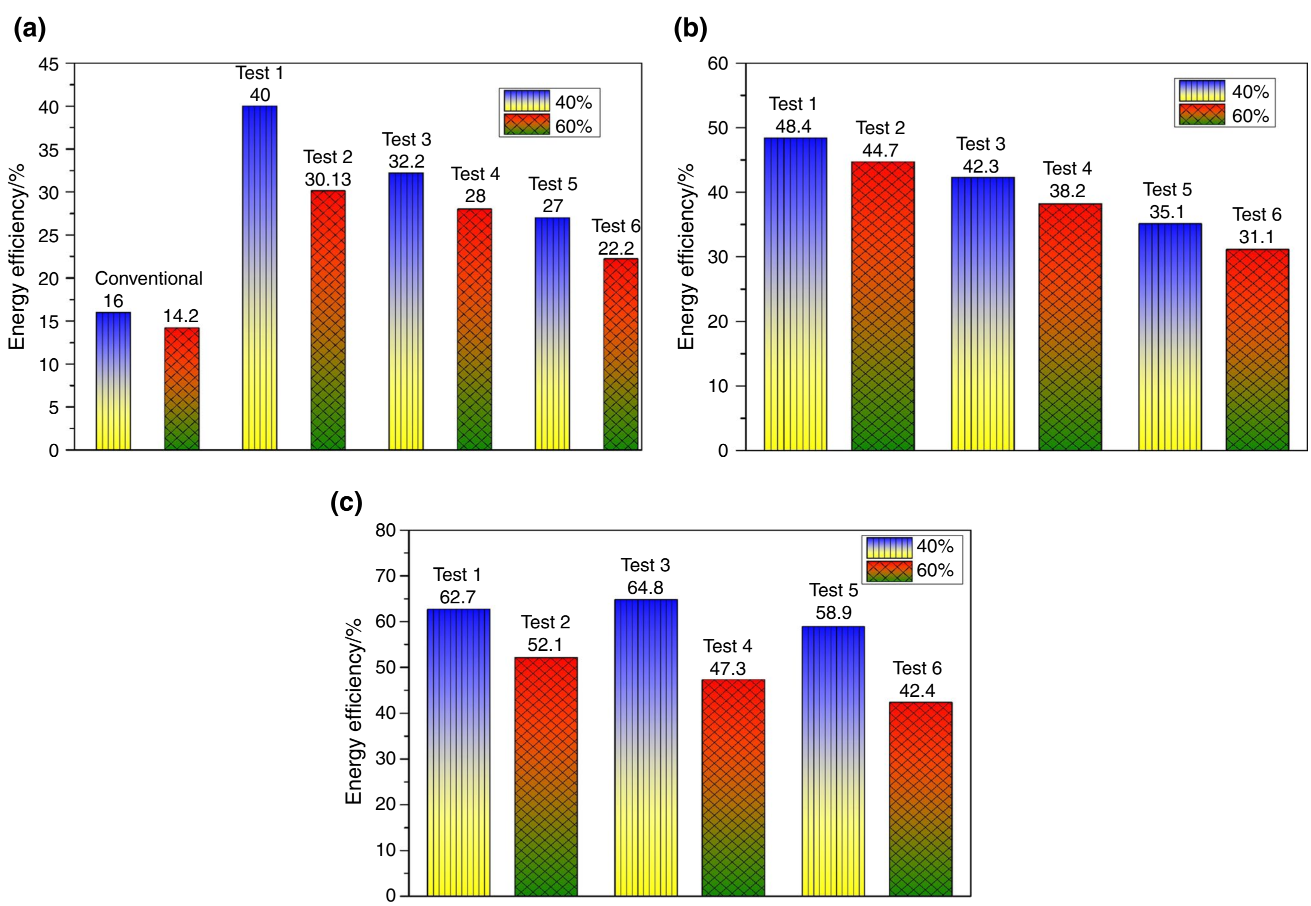


Fig. 9 The daily energy efficiency of **a** solar still for distilled water output **b** HTP-ETCS-SS for hot water productivity and **c** total system efficiency in context of (distilled water output and hot water productivity)

Variation of energy efficiency

The fluctuation in energy efficiency for each case is depicted by Fig. 9a–c. It demonstrates the energy efficiency output in terms of distilled water productivity, hot water, and total system energy (summation of distilled water output and hot water production). Figure 9a depicts that the average daily thermal efficiency with 40% depth is better than 60% depth as decreasing the water mass surges the water temperature earlier, leading to high distilled water output.

The energy efficiency of the designed system (HTP-ETCS-SS) and distilled water output with both water depth, i.e., 40% and 60%, was established to be more than control solar still. This is occurred due to additional heating of large water with flowing hot water from HTP-ETCS, which increases the water temperature, as seen from Fig. 9b. But this phenomenon affects the hot water output as the decrement in hot water temperature is observed after flowing with 60% water depth in comparison to 40% depth. This is general thermodynamics as a large water mass requires extra heat to reach the required temperature, whereas lower water mass heats faster, and common temperature is achieved for both hot water and basin water. Thus, 4 LPH is found an optimum flow rate for both distilled water output and hot water with both depths, *i.e.,* 40% and 60%.

Energy efficiency in terms of distilled water productivity from the designed system functioned at 40% depth, attained the highest value (40%) for Test-1, while with 60% depth the highest energy efficiency of 30.13% was found with Test-2. There is about 2.5 and 2 times increment in the energy efficiency of Test-1 and Test-2 when compared with control solar still. The energy efficiency output in case of 40% depth is obtained as 16%, 40%, 32.2%, and 27% with conventional, Test-1, 3 and 5, respectively. The energy efficiency output in case of 60% depth is obtained as 14.2%, 30.3%, 28.2%, and 22.2% with conventional, Test-2, Test-4, and Test-6, respectively. These results show that the designed system is suitable for energy output and productivity. It has been found from Fig. 9a that the lowest value of energy efficiency, i.e., 27% and 22.2% were obtained for Test-5 (for 40%) and Test-6 (for 60%), respectively. Whereas lowest energy efficiency of conventional solar still (for 40% and 60%), Test-4 (for 40%) and Test-5 (for 60%) was found to be 16%, 14.2%, 32.2%, and 28%, respectively.

Figure 9b depicts the energy efficiency calculated in the production of hot water collected after flowing from designed solar still. The thermal efficiency of the designed system obtained the greatest value of 48.4% for Test-1 when operating at a lower depth. In comparison, at a deeper depth of 60%, the energy efficiency was 38.2% for Tes-4. The energy efficiency of a planned system operating at 40% and 60% water depths were determined to be optimal at a mass flow rate of 4 LPH and 8 LPH, respectively, in the generation of hot water. The lowest energy efficiency values, i.e., 28.7% and 35.1%, were achieved for Test-2 and 5, respectively, with 60% and 40% depth. It is observed due to different heat transfer rates at different depths and variable flow rates. The higher depth requires high heat to heat the basin water, which is observed during 4 LPH with 60% depth; the initially hot water temperature is high, and the basin temperature is low, which leads to the transfer of high heat during this test and low hot water output. However, in other cases with the same depth, the water and hot water temperature reached equal temperature points early due to low heat during a high flow rate.

However, in the case of the total energy efficiency examination of the designed HTP-ETCS-SS, all parameters or output were considered, i.e., distilled water output and hot water production. The total energy efficiency of fabricated system is depicted in Fig. 9c. This figure demonstrates that the overall daily energy efficiency of the developed system with 40% depth is more significant than 60% depth, and the average energy efficiency is higher with a low flow rate. The daily average efficiency of the designed system with both distilled water output and hot water productivity is highest with Test-3 due to high distilled water output and hot water productivity. The average total energy efficiency was established to be 62.7%, 52.1%, 64.8%, 47.3%, 58.9%, and 42.4% during Test-1 to 6, respectively.

Exergy efficiency

This analysis is an excellent way to determine that how well a thermodynamic persuades the energy. Energy efficiency alone can't be used to figure out how well a thermodynamic system converts energy. By looking at the exergy, it is possible to cut down on the system's irreversibility, which improves the system's efficiency. Figure 10a–c determines the fluctuation in the exergy efficiency in context of distilled water output, hot water productivity, and total system exergy efficiency at varying depths (40% and 60%) with different mass flow rates, respectively.

Figure 10a shows that the average second law efficiency of conventional and designed (HTP-ETCS-SS) solar still decreases with increasing hot water flow rate. However, with 40% depth, the average second law efficiency follows the same fashion as 60% depth excluding that its uppermost exergy efficiency achieved with Test-3. It is observed that there is a marginal change in the average second law efficiency of the traditional solar still (1% with 40% depth and 0.7% with 60% depth) and the designed (HTP-ETCS-SS) solar still system 2.1%, 2.84%, 4.1%, 2.25, 2.6%, 1.1% during Test 1–6, respectively. Specifically, it's because combining the HTP-ETCS with the intended solar still augments the basin water temperature consequently rise in evaporative

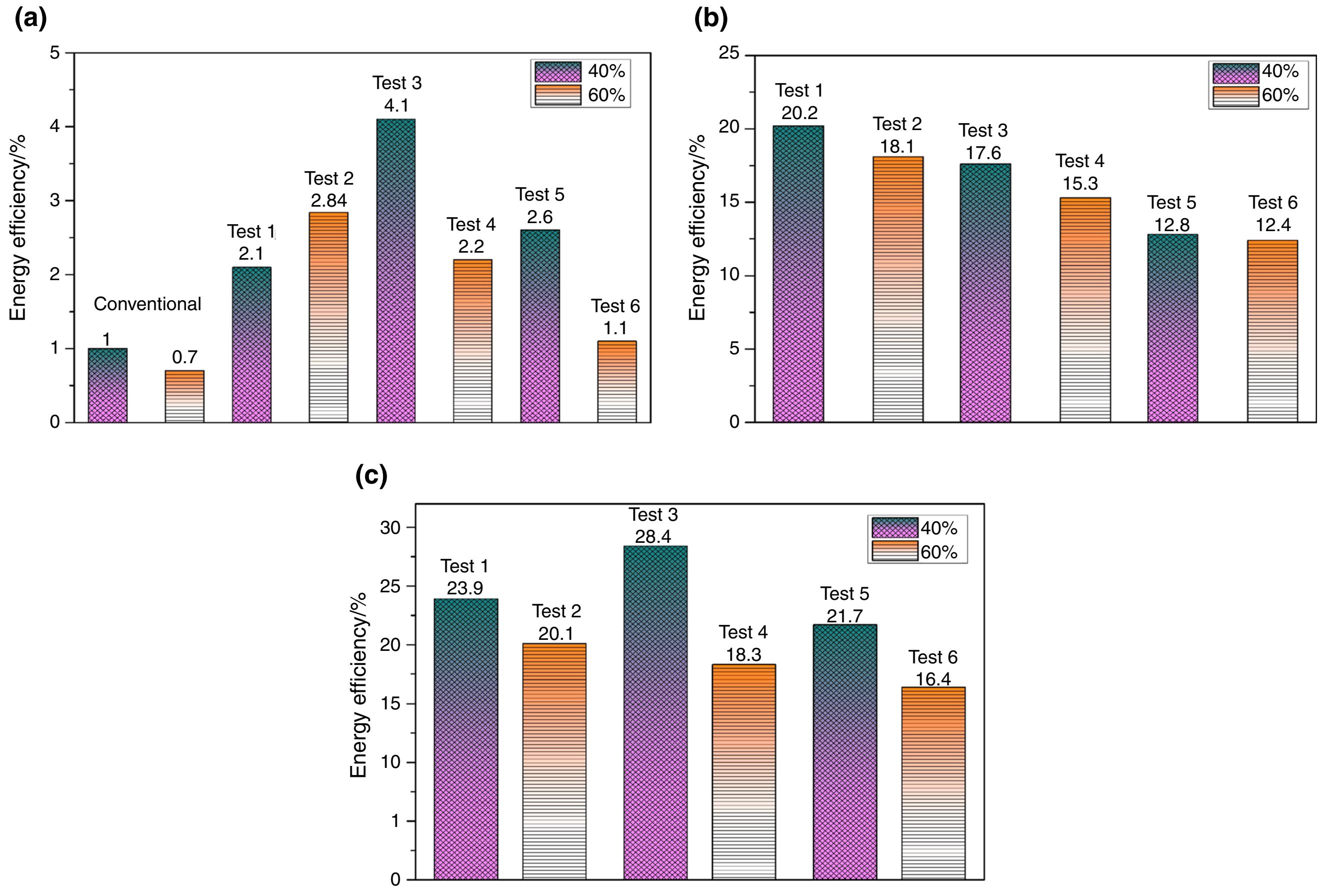


Fig. 10 The daily exergy efficiency of **a** solar still for distilled water output **b** HTP-ETCS-SS for hot water productivity and **c** total system efficiency in terms of (distilled water output and hot water productivity)

exergy, which eventually leads to a reduction in exergy losses. The highest exergy efficiency of 4.1% is achieved with Test-3 followed by Test-2, Test-4, Test-5, Test-1, Test-6, conventional solar still with 40%, and 60%, i.e., 2.84%, 2.6%, 2.2%, 2.1%, 1.1%, 1%, and 0.7%, respectively.

Figure 10b illustrates the exergy efficiency in terms of hot water productivity. Test-1 is reported with highest exergy efficiency value of 20.2%. Though it very well may be analyzed from Fig. 10b that 40% depth shows the most noteworthy exergy efficiency is a result of early heating of basin water and collection of hot water directly from HTP-ETCS to hot water tank. The exergy efficiency varies as 20.2%, 18.1%, 17.6%, 15.3%, 12.8% and 12.4% with different Test 1–6, respectively.

Figure 10c demonstrates the average total exergy efficiency of the designed SS in terms of both hot and distilled water output. It can be revealed from the figure that highest total exergy efficiency of the designed SS is reported for 40% depth. Moreover, the highest total energy efficiency of the system is found in Test-3. This rise is due to optimum production of distilled water output and hot water in this case enhances the overall exergy of the system. Whereas the noticeable rise in distilled water output in the case of 40% depth is due to high basin water temperature, distilled water yield, and hot water production as compared to 60% depth. Accordingly, the rise in evaporative exergy rates is observed with 40% depth compared to 60% depth. The average total exergy for Test-1 to 6 are 23.9%, 20.1%, 28.4%, 18.3%, 21.7%, and 16.4%, respectively.

Water quality analysis

Another aspect that is considered in the present study is the treatment of the collected textile processed wastewater Degumming (TDgWW) and Dyeing (TDyWW) from the designed system. According to the Bureau of Indian water quality standard (BIS) [41], the initial and produced water is examined in a laboratory. The quality standard which is taken into consideration is sensory indexes like colour, odour, turbidity; bacteriological indexes such as total coliform test; chemical indexes (pH, Total dissolved solids (TDS), Hardness, Chemical

Table 5 Pollutant reduction of utilized wastewater with an integrated designed system

Parameters	Standard for emission of discharge of pollutant (Textile and Dye industry) BIS [41]	Initial		Distilled water quality	
		TDgWW	TDyWW	TDgWW	TDyWW
Colour	Not detected	Brownish	Blackish	No	No
Odour	No	Pungent	Pungent	No	No
Total coliforms/MPN-100 mL^{-1}	No detection	No detection	No detection	No detection	No detection
pH	6.5–8.5	8.62 ± 0.16	12.22 ± 0.15	7.91 ± 0.1	7.13 ± 0.1
TDS/mg L^{-1}	2100	3884.7 ± 16.76	4755.1 ± 23.62	49.3 ± 6.8	30.8 ± 4.7
COD/mg L^{-1}	250–500	11,363.4 ± 61.66	22,367.3 ± 73.53	441 ± 5.2	290.5 ± 5.4
Hardness/mg L^{-1}	–	1118.4 ± 55.61	1305.3 ± 24.28	26.84 ± 2.3	14.48 ± 1.2
Cu/mg L^{-1}	0.05	0.05 ± 0.01	2.02 ± 0.05	0.01 ± 0.002	0.01 ± 0.001
Zn/mg L^{-1}	5	4.16 ± 0.9	7.58 ± 1.2	0.52 ± 0.004	0.43 ± 0.002
Ni/mg L^{-1}	–	0.17 ± 0.02	0.03 ± 0.01	0.05 ± 0.001	0.01 ± 0.001
Fe/mg L^{-1}	0.3	3.02 ± 0.05	2.02 ± 0.06	0.9 ± 0.02	0.35 ± 0.03
Mn/mg L^{-1}	–	0.18 ± 0.03	0.12 ± 0.02	0.08 ± 0.003	0.02 ± 0.002

Table 6 Capital cost investment on different components of designed HTP-ETCS-SS

S. no.	Components	Cost/US/$
1.	HTP-ETCS tubes (10)	106
2.	HTP-ETCS Manifold	134
3.	DC pump	2.4
4.	Pipes (Inlet, Outlet, Heat Exchanger)	18.65
5.	Heat exchanger	2.5
6.	Tanks (Inlet and outlet hot water)	8
7.	Valves	1.3
8.	Insulation material	1.6
9.	Solar still unit	100.15
10.	Glass cover	33.38
11.	Solar still stand	20.03
12.	Paint	2.6
13.	Rotameter	6.01
14.	Construction cost	45
15.	Miscellaneous	30
Total		511.62

Table 7 Economic analysis of the designed HTP-ETCS-SS system for distilled water, and hot water productivity

S. no.	Parameter	Value	Unit
1.	m_{ss}	639	Lm^{-2}
2.	$m_{wo,mss}$	2400	Lm^{-2}
3.	n	15	Year
4.	i	0.09	%
5.	SFF	0.034	–
6.	CRF	0.124	–
7.	P	511.62	$
8.	FAC	63.440	$
9.	S	102.324	$
10.	ASV	3.479	$
11.	AMC	6.344	$
12.	UAC	66.305	$
13.	$CPL_{Distilled\text{-}water}$	0.137	$
14.	$CPL_{Hot\text{-}water}$	0.0276	$

oxygen demand (COD)), and toxic indexes Cu, Fe, Mn, Ni, Zn. The removal efficacy of the system is illustrated in Table 5. The result is the average removal of all pollutants during different tests. It indicates that the system is capable enough of removing all those pollutants and maintaining the quality of water according to the standards.

Economic analysis of the HTP-ETCS-SS

The most crucial aspect in designing any solar still system is its economics and acceptance on a large scale. The economics of solar stills are mainly depended on the distilled water output rate. But, here in this study, the benefit of HTP-ETCS-SS is the co-production from the system in form of distilled and hot water output and this makes system more economical and viable. The system output directly governed by the area of installation, the climatic condition, yearly solar days, solar radiation intensity, ambient temperature, and other factors are taken into consideration. The output from developed HTP-ETCS-SS is used to determine fluctuation cost, capital cost, and fixed cost. It was found that there is a relationship between operating and maintenance costs and the variable cost of the designed HTP-ETCS-SS system [42]. The system was

Table 8 Discussing different previous work studies and comparing with current work

S. no.	System description	Efficiency of the system		Distilled water productivity/ Lm^{-2} day^{-1}	Hot water productivity/ Lm^{-2} day^{-1}	Unit cost/$	References
		Energy	Exergy				
1.	Solar still assimilated with FPC and PTC with packed bed	16.24%	–	2.775	–	0.22	[3]
2.	Spiral tube based solar water heater (SWH) assimilated with solar still in passive mode	–	–	4.4	–	0.23	[14]
3.	Solar still combined with double evacuated superconducting gas tube with heat storage device	–	9.2%	10.138	–	0.239	[32]
4.	Solar desalination system combined with parabolic concentrator (PCB-SDS)	51.83%	4.8%	8.33	–	0.21	[35]
5.	Tubular solar still with parabolic concentrator	28.54%	–	3.53	–	0.024	[43]
6.	An ETCS with a heat pipe and solar still that is combined as a hybrid system (HTP-ETCS-SS)	64.8%	28.4%	2.13	80	0.137	Present Work

installed on the roof of SMVDU Campus, Katra (J&K), India (32.9915°N, 74.9318°E) where the total average sunny days is considered as 300 days in a year [35]. The economic parameters which are taken into consideration are calculated based on the Indian situation, where. The economic parameters considered and calculated here are based on Indian situation, where the interest rate per year (i) is assumed as 9%, life period of the system (n) is considered as 15 years, rate of inflation is 3% and daily average solar radiation 5.91 kW hm^{-2} day^{-1}. The cost investment of different components for the construction of HTP-ETCS-SS is illustrated through Table 6.

Economic analysis of the designed systems, solving methodology, and various other parameters involved is illustrated through Table 7. It explains the estimated cost involved in different components in designing HTP-ETCS-SS co-generation system. Test-3 is taken into consideration while calculating the economics behind the designed HTP-ETCS-SS system due to its standard distilled water output and hot water production. The main objective of manufacturing and operation process of any newly designed system is to keep the costs lower.

Table 8 illustrates the comparison between the present work distilled water productions, efficiency, exergy, distilled water output cost with previous work. The current system has an efficiency greater than the conventional SS and other SS due to their co-generation potential. By utilizing more robust materials and prominent control system which will lead to increment in system efficiency which will also lead to decrement in the unit cost of the system productivity and payback period. The unit cost of distilled water and hot water is found to be 0.1037$ and 0.0276$, respectively. The overall cost of total productivity (distilled water and hot water) is found to be 0.0218$.

Conclusions

The foremost motive of the presented research work is to design a novel hybrid heat pipe equipped with ETCS combined with solar still (HTP-ETCS-SS) and to study the distilled water output and hot water productivity simultaneously. To study the impact of HTP-ETCS on solar still hot water is circulated at different flow rates (4, 8, 12 LPH) at different depths (40% and 60%). The system that has been developed and installed may successfully eliminate the issues of distilled water (drinking water) and hot water demand for an average household. Based on the performance of the designed HTP-ETCS-SS system, the following conclusion can be drawn:

- The integration of HTP-ETCS eliminates the problem of pre-heating and the initial time to start the distilled water production.
- The hot water produced from HTP-ETCS helps in increasing the heat transfer rate of basin water and could also be utilized for various household practices (washing, bathing, kitchen, etc.) during winter and summer.
- The overall accumulative distilled water output for conventional solar still at 40 and 60% depth, HTP-ETCS-SS during different tests 1–6 are nearly 1020 mL, 780 mL, 2580 mL, 2050 mL, 2130 mL, 1970 mL, 1550 mL, and 1500 mL, respectively, leading to an improvement of 152.9%, 162%, 108%, 152.5%, 51.9%, and 92.3%, respectively, contrasted with conventional solar still at varying depth of 40% and 60%.
- The first law efficiency of the control system and designed HTP-ETCS-SS system at 40 and 60% depth and varying flow rate in designed system is 14.2–16% and 22.2–40%, respectively.

- The exergy efficiency of the conventional solar still and designed HTP-ETCS-SS system at varying flow rate of 4, 8, and 12 LPH at different 40% and 60% is found in between 0.7 and 4.1%.
- The overall (total) energy and exergy efficiency of the designed system HTP-ETCS-SS for both hot water and distilled water output at different flow rates and depths lies between 42.4–64.8% and 16.4–28.9%, respectively.
- According to the output potential in terms of distilled water, hot water, energy, and exergy hot water flow rate of 8 LPH at 40% depth is found suitable for household applications.
- The quality of wastewater treated during different tests was tested in terms of toxicology, physical, biological, and chemical index finally match the quality/standard of discharge water.
- The unit cost of hot water and distilled water produced from the designed system is 0.0276$ and 0.1037$, respectively. The overall cost of the total productivity, i.e., amalgamation of hot water and distilled water simultaneously is 0.0218$.
- The per unit cost of distilled water production can be reduced by utilizing different energy storage material which will also impactfully increase the output, useful energy and exergy output as well.

Acknowledgements Mr. Atin K. Pathak, Senior Research Fellow (SRF) under Inspire fellowship scheme by Department of Science and Technology, Ministry of Science and Technology (Govt. of India), New Delhi, India is gratefully acknowledged for financial assistance.

Author contributions AKP**:** Investigation, Data Curation, Writing-Original draft preparation, KC**:** Formal Analysis, Validation, VVT: Conceptualization, Formal Analysis, Validation, Supervision, SA: Software, visualization, Validation, RK: Data Curation, Supervision Methodology, AS: Reviewing and Editing, Resources, AKP: Resources, Reviewing and Editing.

Declarations

Conflict of interest The authors unveil no genuine or possible irreconcilable situation in a monetary or individual relationship with others or associations that might have seemed to impact the work revealed in this paper.

References

1. Kober T, et al. Global energy perspectives to 2060–WEC's World Energy Scenarios 2019. Energy Strat Rev. 2020;31: 100523.
2. Panchal H, et al. Annual performance analysis of adding different nanofluids in stepped solar still. J Therm Anal Calorim. 2019;138(5):3175–82.
3. Madiouli J, et al. Experimental study and evaluation of single slope solar still combined with flat plate collector, parabolic trough and packed bed. Sol Energy. 2020;196:358–66.
4. Pugsley A, et al. Global applicability of solar desalination. Renewable Energy. 2016;88:200–19.
5. Sharma A, Pathak A. Evacuated tube solar collector's importance and innovations in wide range applications. Int J Sci Technol Adv. 2016;2(4):39–44.
6. Fuentes E, Arce L, Salom J. A review of domestic hot water consumption profiles for application in systems and buildings energy performance analysis. Renew Sustain Energy Rev. 2018;81:1530–47.
7. Chopra K, et al. Experimental performance evaluation of a novel designed phase change material integrated manifold heat pipe evacuated tube solar collector system. Energy Convers Manage. 2019;198: 111896.
8. Smyth M, et al. Experimental performance characterisation of a hybrid photovoltaic/solar thermal façade module compared to a flat integrated collector storage solar water heater module. Renew Energy. 2019;137:137–43.
9. Narayanan SS, Yadav A, Khaled MN. A concise review on performance improvement of solar stills. SN Appl Sci. 2020;2(3):1–15.
10. Pugsley A, et al. Performance evaluation of the senergy polycarbonate and asphalt carbon nanotube solar water heating collectors for building integration. Renew Energy. 2019;137:2–9.
11. Chopra K, et al. Thermal performance of phase change material integrated heat pipe evacuated tube solar collector system: an experimental assessment. Energy Convers Manage. 2020;203: 112205.
12. Chopra K, et al. Global advancement on experimental and thermal analysis of evacuated tube collector with and without heat pipe systems and possible applications. Appl Energy. 2018;228:351–89.
13. Wang H, et al. An integrated heat pipe coupling the vapor chamber and two cylindrical heat pipes with high anti-gravity thermal performance. Appl Therm Eng. 2019;159: 113816.
14. Taamneh Y, et al. Extraction of drinking water from modified inclined solar still incorporated with spiral tube solar water heater. J Water Process Eng. 2020;38: 101613.
15. Yadav S, Sudhakar K. Different domestic designs of solar stills: a review. Renew Sustain Energy Rev. 2015;47:718–31.
16. Sharshir SW, et al. A mini review of techniques used to improve the tubular solar still performance for solar water desalination. Process Saf Environ Prot. 2019;124:204–12.
17. Pansal K, et al. Use of solar photovoltaic with active solar still to improve distillate output: a review. Groundw Sustain Dev. 2020;10: 100341.
18. Essa MA, et al. Performance analysis for an inclined tubular still desalination integrated with evacuated tube collector. Sol Energy. 2021;224:361–72.
19. Singh D, Tiwari G. Exergoeconomic, enviroeconomic and productivity analyses of basin type solar stills by incorporating N identical PVT compound parabolic concentrator collectors: a comparative study. Energy Convers Manage. 2017;135:129–47.
20. Kumar S, Dubey A, Tiwari G. A solar still augmented with an evacuated tube collector in forced mode. Desalination. 2014;347:15–24.
21. Sampathkumar K, Arjunan T, Senthilkumar P. The experimental investigation of a solar still coupled with an evacuated tube collector. Energy Sour Part A Recov Util Environ Eff. 2013;35(3):261–70.
22. Shafii MB, et al. Examination of a novel solar still equipped with evacuated tube collectors and thermoelectric modules. Desalination. 2016;382:21–7.
23. Singh RV, et al. Performance of a solar still integrated with evacuated tube collector in natural mode. Desalination. 2013;318:25–33.

24. Naghavi M, et al. Thermal performance of a compact design heat pipe solar collector with latent heat storage in charging/discharging modes. Energy. 2017;127:101–15.
25. Daghigh R, Zandi P. Improving the performance of heat pipe embedded evacuated tube collector with nanofluids and auxiliary gas system. Renew Energy. 2019;134:888–901.
26. Maraj A, et al. Energy performance analysis of a forced circulation solar water heating system equipped with a heat pipe evacuated tube collector under the Mediterranean climate conditions. Renew Energy. 2019;140:874–83.
27. Association APH, et al. Standard methods for the examination of water and wastewater, vol. 2. American Public Health Association; 1912.
28. Taylor JR. An introduction to error analysis: The study of uncertainties in physical measurements. University Science Books; 1997.
29. Sharafeldin M, Gróf G. Experimental investigation of flat plate solar collector using CeO2-water nanofluid. Energy Convers Manage. 2018;155:32–41.
30. Hassan H. Comparing the performance of passive and active double and single slope solar stills incorporated with parabolic trough collector via energy, exergy and productivity. Renew Energy. 2020;148:437–50.
31. Tiwari G, et al. Exergoeconomic and enviroeconomic analyses of partially covered photovoltaic flat plate collector active solar distillation system. Desalination. 2015;367:186–96.
32. Zhou X, et al. Experimental investigation and economic analysis on a solar pure water and hot water hybrid system. Appl Therm Eng. 2021;195: 117182.
33. Petela R. Exergy of undiluted thermal radiation. Sol Energy. 2003;74(6):469–88.
34. Deniz E. Energy and exergy analysis of flat plate solar collector-assisted active solar distillation system. Desalin Water Treat. 2016;57(51):24313–21.
35. Pathak AK, et al. Experimental investigation of designed solar parabolic concentrator based desalination system for textile industry wastewater treatment. Energy Environ. 2022;33(5):870–96.
36. Sharshir SW, et al. Performance enhancement of stepped double slope solar still by using nanoparticles and linen wicks: energy, exergy and economic analysis. Appl Therm Eng. 2020;174: 115278.
37. Hassan H, Ahmed MS, Fathy M. Experimental work on the effect of saline water medium on the performance of solar still with tracked parabolic trough collector (TPTC). Renew Energy. 2019;135:136–47.
38. Abd Elbar AR, Yousef MS, Hassan H. Energy, exergy, exergoeconomic and enviroeconomic (4E) evaluation of a new integration of solar still with photovoltaic panel. J Clean Prod. 2019;233:665–80.
39. Esfahani JA, Rahbar N, Lavvaf M. Utilization of thermoelectric cooling in a portable active solar still—an experimental study on winter days. Desalination. 2011;269(1–3):198–205.
40. Dubey A, Kumar S, Arora A. Enviro-energy-exergo-economic analysis of ETC augmented double slope solar still with 'N'parallel tubes under forced mode: Environmental and economic feasibility. J Clean Prod. 2021;279: 123859.
41. BIS. *Indian standard specifications for drinking water*. Bureau of Indian Standards, New Delhi (2012).
42. Gorjian S, et al. Experimental performance evaluation of a stand-alone point-focus parabolic solar still. Desalination. 2014;352:1–17.
43. Elashmawy M. An experimental investigation of a parabolic concentrator solar tracking system integrated with a tubular solar still. Desalination. 2017;411:1–8.