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# Energy matrices, exergo-economic and enviro-economic analysis of an active single slope solar still integrated with a heat exchanger: A comparative study

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ABSTRACT

This paper presents an analysis of energy matrices, production cost of water and electricity, exergo-economic and enviro-economic analyses of an active single slope solar still integrated with a heat exchanger under optimized conditions on the bases of energy and exergy. Analyses have been done considering four climatic conditions (a, b, c and d) for each month of year for three cases: (i) N – partially covered Photovoltaic Thermal Flat Plate Collectors Single Slope Solar Still (Partially – PVT – FPC – SS – SS), (ii) N – fully covered Photovoltaic Thermal Flat Plate Collectors Single Slope Solar Still (Fully – PVT – FPC – SS – SS) and (iii) N – Flat Plate Collector Single Slope Solar Still (FPC – SS – SS). We report that the cost of potable water is lowest for case (i) followed by case (iii) and then case (ii) at the interest rate of 2% and 5%. However, case (ii) performs better for electricity generation followed by case (i) and the computed kWh per unit cost (exergo-economic parameter) based on energy is highest for case (ii) i.e. 1.73 kWh/₹.

## 1. Introduction

From the dawn of human civilization water has played an important role in the growth and development of human beings. Enormous expansion of human activities has diversely affected not only water but land and air as well. From the beginning of $20^{th}$ century a series of work has been done towards the sustainable development of energy resources and water management.

Agencies like United Nations Development Programme (UNDP), World Bank (WB) and World Health Organization (WHO) have been keenly involved across the world for supporting various projects related to the sources of fresh water for the consumption purposes. Several researchers and policy makers have interacted to identify water based research priorities in United Kingdom (UK) [1]. Their findings revealed that interaction with other key sectors (agriculture and energy) is necessary to obtain sustainability in water sector.

Water has innumerable applications such as drinking, domestic use, irrigation, generation of hydro–electricity and industrial usage for the extraction of thermal heat, and for most of its usage, water does not have a viable substitute, which makes it an indispensable commodity. The conventional distillation methods (simple distillation, fractional distillation, steam distillation), purification methods (filteration, sedimentation, chlorine disinfection) and desalination methods (reverse osmosis, electrodialysis, thermal desalination) are energy intensive and emit Green Houses Gases ($GHG_s$). Therefore switching to renewable energy resources for the distillation of water is the need of the hour.

Solar distillation is a sustainable and attractive option to meet the rising demand for the fresh water. Solar still is an apparatus used for converting brackish, impure or hard water into potable water by using solar energy. Solar stills are broadly classified as passive and active solar stills. The drawback of passive solar distillation unit is the lesser yield of distilled water in comparison to active distillation system. The yield from passive solar still is between 2 and 5 l/$m^2$/day. This marks them uneconomical in comparison to other active solar distillation systems. Prior work includes the classification of solar still [2], improvement techniques for productivity [3], designs [4], active single slope solar still [5,6], and condensers with solar still [7]. Active solar stills are divided into nocturnal distillation and high temperature distillation. In high temperature distillation, thermal energy is supplied into the basin of solar distillation system through some external sources e.g. by incorporating flat plate collectors, solar concentrator, photovoltaic thermal collectors, evacuated tubular collector etc. As warm/hot water is fed into the basin of solar still the evaporation is increased and higher yield is obtained.

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Rai and Tiwari [8] studied single basin solar distillation unit coupled with flat plate collector and have reported a 24% higher daily yield (distilled water) compared to a conventional single slope solar distillation system. Hamadou and Abdellatif [9] have studied solar distillation unit by circulating heat transfer fluid at the basin of solar still and found that the yield was not proportional to the rate of heat transferred. Tiris et al. [10] experimentally studied solar still unit by incorporating two flat plate collectors and reported that an average growth of 100% in yield (distilled water) from the solar distillation unit was obtained in comparison to conventional solar still (passive). Badran et al. [11] examined single slope solar distillation unit integrated with flat plate collectors (FPC) and reported that an upsurge of 231% yield when tap water was fed for the purification. Dwivedi and Tiwari [12] made comparison between active and passive double slope solar still and found that energy efficiency was lower and exergy efficiency was higher in active double slope solar still. Sinha et al. [13] reported that the active solar distillation system is an alternative investment for solar hot water system and annual operating cost of the solar hot water system was higher than the active solar still because of higher initial investment in solar water heater. Yousef H. Zurigat [14] studied comparison between regenerative solar desalination unit and conventional solar still and then its performance was evaluated. He found 20% higher productivity in regenerative solar still, and if wind velocity rises from 0 to 10 m/s then productivity is 50% higher than the conventional solar still. Abdel Rehim and Lasheen [15] have conducted experimental and theoretical work on solar still integrated with solar concentrator and heat exchanger using serpentine oil as a working fluid. The economic analysis of the modified system has been done and the productivity was increased by 18%. El-Sabaii [16] has done transient mathematical modeling for the active single slope solar distillation unit with and without sensible storage (sand) in the basin liner and reported that daily productivity ($P_d$) of 4.005 kg/m$^2$/day with efficiency of 37.8% is obtained by using 10 kg of sand compared to daily productivity of 2.852 kg/m$^2$/day with a daily efficiency of 27% without storage. Tiwari and Dhiman [17] have done transient analysis of the single slope solar still coupled with the heat exchanger by including the effect of the proposed system parameters. It was observed that internal convective and radiative heat transfer coefficient could be considered as constants during the performance of the single slope solar still. Kabeel et al. [18] have reviewed the improvement of performance in the solar still through effectual heat exchange mechanism. Sharshir et al. [19] have enhanced the performance of solar still by using nano–fluids. They have used graphite and copper oxide micro–flakes and the results show that productivity is enhanced by 44.91% and 53.95% respectively, when compared with the passive solar still (without micro flakes). When water over glass cover is fed the yield is improved by 47.80% and 57.60% respectively for graphite and copper oxide micro flakes for the proposed system. Panchala and Patel [20] have studied different designs of solar still with different climatic parameters. Kumar and Tiwari [21] proposed and validated the active solar distillation system for remote locations, which are not connected by power grids for electricity. Solar still was integrated with two flat plate collectors ($FPC_s$) (one partially covered with semitransparent PV module) arranged in series to get high temperature of water and stated an increase in yield (distilled water) by 3.5 times over the passive solar still. They studied energy pay–back time of the system, which lies in between 3.9 and 23.9 years. Mukherjee and Tiwari [22] have compared the economic analysis among different designs of conventional solar still viz. single slope fibre reinforced plastic and double slope fibre reinforced plastic solar distillation unit, and double slope concrete distillation unit. They found that the cost of distill water from conventional solar still is minimum i.e. ₹ 0.15/l. Fath et al. [23] presented the thermal economic analysis between the two solar still configurations, the pyramid and the single slope distillation unit; yearly performance showed that single slope solar distillation unit was more efficient and economical. Lesourd [24] has analyzed the economics of renewable energy resources integrated with grid. Tiwari et al. [25] have studied exergo-economic and enviro economic analyses of an active single slope solar distillation system and compared with prior results obtained by researchers. Energetic and enviro economic analysis of hybrid PVT array have been studied by Rajoria et al. [26]. They have taken two different designs (case (1) and case (2)) and found case (2) has lesser solar cell temperature and high electrical efficiency, additionally, higher average outlet air temperature was obtained. Exergo economic study of power plants operational on various fuels was studied by Rosen and Dincer [27], and they established a co–relation between thermodynamic and economics. They also demonstrated the merit of third law of thermodynamics and extended electrical utility.

The prior research show that in an active solar stills saline, brackish, impure or hard water is circulated in the thermal collectors which corrodes the tubes as a result, the life span of collectors reduces significantly. Thus, to overcome this problem a novel solution i.e. N – identical thermal collectors are integrated with a helically coiled heat exchanger to the single slope solar still is carried out. The three thermal collectors, which are integrated to the single slope solar still are:

1. Partially covered Photovoltaic thermal Flat Plate Collectors (Partially – PVT – FPC). ($A_c$ = 1.365 m$^2$; $A_m$ = 0.605 m$^2$)
2. Fully covered Photovoltaic thermal Flat Plate Collectors (Fully – PVT – FPC). ($A_c$ = 0 m$^2$; $A_m$ = 2 m$^2$)
3. Conventional Flat Plate Collectors (FPC). ($A_c$ = 2 m$^2$; $A_m$ = 0 m$^2$)

With the help a of heat exchanger, fluid (water) is allowed to flow in the thermal collectors and subsequently increases the life span of thermal collectors (cases (1–3)). The above mentioned cases (i–iii) have been numerically computed on the bases of energy and exergy for four climatic conditions (a), (b), (c) and (d) for each month of a year. The objectives of the research work are as follows:

1). Annual analyses of yield (distilled water), overall thermal energy (thermal and electrical), overall thermal exergy, solar radiation and electrical energy for three cases (i–iii) have been computed with the help of a model developed based on thermodynamics in MATLAB. Then, energy matrices, production cost of water (Rs/kg) and electricity (Rs/kWh), exergo–economic (₹/kWh) and enviro–economic analysis are studied on the bases of energy and exergy.
2). Comparisons have been made among three cases (i–iii) on the bases of energy and exergy for the climatic condition of New Delhi, India.

## 2. System description

Fig. 1(a–c) represents the schematic view of the active solar distillation systems (cases (i–iii)) and Fig. 1(d) represents a cross sectional view of the helically coiled heat exchanger (Copper). N – identical thermal collector cases (1–3) are connected in series and the outlet is connected to the basin of the single slope solar still. The working fluid (water) flows inside the helical coiled heat exchanger, and the thermal energy is transmitted from warm/hot water to the impure water kept in the solar still. The three configurations, cases (1–3) are designed such that warm/hot water flows inside the tubes beneath the upper layer. Thus, thermal energy is extracted through water from all the three configurations (cases (1–3)).

The thermal collectors are aligned in series, i.e. the outlet of former collector is the passage (inlet) for the later collector and so on to obtain higher water temperature. Thus, N – similar thermal collectors cases (1–3) remains in a closed loop with an active single slope solar distillation. A DC motor is integrated to the active solar distillation systems. It helps water (fluid) to overcome the pressure drop in connecting pipes so that water circulates with higher velocity in comparison to the natural mode circulation. DC motor is operated by electrical energy generated by photovoltaic module whereas, in case (3) electrical energy is supplied to the motor.