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A novel cogeneration system for sustainable water and power production by integration of a solar still and PV module

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HIGHLIGHTS

- A solar still integrated with evacuated tubes and semitransparent photovoltaic are proposed.
- Effect of basin water depth, number of ETC and types of PV modules are investigated.
- Performance of proposed systems is compared with similar systems.
- Using 30 tubes, the maximum distillated yield is obtained 2.76 kg for the depth of 0.07 m.
- The maximum electrical energy is achieved for the HIT with value of 70.47 W/m^2.

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ABSTRACT

Present work is an attempt to propose and analyze a new solar still equipped to semitransparent photovoltaic and evacuated tube collector in natural mode. The system performance is investigated from various aspects such as distilled water yield, instantaneous and daily electrical power production, instantaneous and daily energy and exergy efficiencies considering six types of photovoltaic module as well as various basin water depths and number of tubes. Results show that type of photovoltaic module does not have a significant effect on distilled water yield. However, it is revealed that increasing the number of tubes could increase the water yield. It is found that for a specific number of tubes, maximum water yield in a day occurs for basin depth of 0.07 m. Also, the higher number of tubes increases the distillate yield. The maximum water production (4.77 kg/m^2·day) is achieved for the basin depth of 0.07 m and 30 numbers of tube. It is revealed that for the HIT photovoltaic module type the maximum instantaneous and daily electrical power are 70.48 W/m^2 and 483.2 Wh/m^2, respectively. Also, maximum daily energy and exergy efficiencies are calculated 6.86% and 16.65%, respectively, for basin depth of 0.07 m and tubes number of 10.

1. Introduction

Water is a fundamental human need. Each person on earth requires at least 20 to 50 l of clean, safe water a day for drinking, cooking, and simply keeping themselves clean. Polluted water isn't just dirty-it's deadly. Despite of developing countries' efforts, there are many regions where healthy drinking water is scarce. More than 700 million people still lack ready access to improved sources of drinking water; nearly half are in sub-Saharan Africa [1]. This can cause lots of diseases related to the unhealthy water. Impure and unhealthy water is much available around us which can be purified and become healthy. One of the methods for purification of water is distillation. The distillation process utilizes a heat source to vaporize water. The object of distillation is to separate pure water molecules from contaminants with a higher boiling point than water. In the distillation process, water is first heated until it reaches its boiling point and begins to evaporate. The stable temperature ensures continued water vaporization, but prohibits drinking water contaminants with a higher boiling point from evaporating. Next, the evaporated water is captured and guided through a system of tubes to another container. Finally, removed from the heat source, the steam condenses back into its original liquid form. Contaminants having a higher boiling point than water remain in the original container. This process removes most minerals, most bacteria and viruses, and any chemicals that have a higher boiling point than water. For this reason, distillation is sometimes valued as a method of obtaining pure drinking water.

Distillation process needs energy to run, which can be obtained using the renewable energy sources such as solar. Solar powered distillation of water can be defined as measures to separate and extract clean

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water by vaporization. This can be particularly useful to turn seawater, brackish or even contaminated water into clean water safe for drinking.

Aybar [2] proposed a solar based distillation system producing distilled water and hot water simultaneously. The system is modeled and analyzed theoretically and effects of inlet water mass flow rate as well as solar radiation rate on the performance of the system are investigated. Maximum and average hot water temperatures are obtained 60 and 40 °C suitable for domestic consumption, respectively. Ibrahim and Elshamarka [3] developed a theoretical model for a basin liner equipped with an air-cooled condenser instead of conventional distillation system with a glass. Also, the results are experimentally investigated to compare with theoretical results. Results show that the performance of the modified system is better than the conventional one. As the production potential of passive solar distillation systems is low, there are several researches in literature studying the feasibility of improving the active solar distillation systems. To improve the common solar still performance two solutions could be considered; one, using auxiliary system, the temperature within the basin line would be increased, e.g. the method “two-phase thermosyphon heat pipe” is used for improving the performance of solar collector [4]. Another way is use of heater for preheating the inlet temperature of the basin line. The preheating process could be done via Evacuated Tube Collector (ETC) and Flat Plate Collectors (FPC) both of which has its own advantages and disadvantages. Not only is the design of FPC simple, but also the operating and maintenance cost of this method is lower. However, FPCs are not able to follow the solar irradiation resulting in a lower efficiency. In addition, heat loss via convection is another disadvantage for FPCs. On the other hand, ETC systems have not the two disadvantages of FPCs as the ETC is cylindrical as well as the existence of vacuum in the gap between the two cylinders. ETC has lots of applications using the solar energy. Mehmet Esen [5] experimentally investigated a solar cooker, integrated with ETC. The effect of using different refrigerant in ETC is analyzed and it is revealed that besides the environmental condition, type of refrigerant has a great influence on solar cooker performance.

Morad et al. [6] experimentally compared the performance of a double slope solar distillation system in passive and active modes with and without cover cooling. Effects of basin depth water and upper glass thickness on the daily production are investigated. It is found that in the active mode daily water production is 22.3% more than that of the passive one. Singh et al. [7] analyzed the performance of an active solar distillation system equipped with evacuated tube. The daily and instantaneous water and electricity production as well as the energy and exergy efficiencies are investigated. When the number of tubes is kept to be 10, the maximum production of safe water occurs at the minimum water depth in the basin. The effects of tube number and water depth on the performance of the system are investigated and optimized. The Semitransparent photovoltaic module is used in building industry with the purpose of producing electricity and heating. Vats and Tiwari [8] measured the temperature of a building equipped with semitransparent photovoltaic and opaque photovoltaic systems. Air duct is considered to be installed in a façade or inclined. It is observed that there are maximum (18.0 °C) and minimum (2.3 °C) rise in room air temperature for semitransparent photovoltaic thermal (SPVT) roof without air duct and opaque photovoltaic thermal (OPVT) facade with air duct respectively.

Nayak and Tiwari [9] measured theoretically and experimentally the temperature of greenhouse and PV module by installing a photovoltaic module on the greenhouse roof. Results show that there is a good agreement between the temperature calculated by the theoretical model and that found in experimental analysis. Net annual electrical production is reported 716 kWh. Also, annual output thermal exergy is calculated for the PV module to be 12.8 kWh. The exergy efficiency is found to be 4% in the case of PV module.

Since there are so many regions where availability of both healthy water and electrical power is low, present work is an attempt to investigate producing distilled water and electrical power, simultaneously, by means of a solar still equipped with the evacuated tube collector in natural mode and semitransparent photovoltaic module instead of using the glass in the conventional solar still. To the best of our knowledge, there is not similar study in literature. The electrical and thermal energy as well as the exergy efficiency has been evaluated for solar still integrated with ETC and PV module. Effect of water depth in the basin of solar still and number of ETC and six different types of PV modules (i) m-Si, (ii) p-Si, (iii) amorphous silicon (a-Si), (iv) cadmium telluride (CdTe), (v) copper indium gallium diselenide (CIGS), and (vi) a heterojunction comprised of a thin a-Si PV cell on top of a c-Si cell (also known as HIT) on electrical power and watery yield has been calculated.

2. System description and assumptions

The proposed system is illustrated in Fig. 1a. Referring to this figure, the system consists of a solar still integrated with ETC and semitransparent PV module where basin water of solar still is connected to the ETC. Due to high temperature water in ETC and density difference at different parts of ETC, hot water with low density moves to the top of the tube while water with lower temperature and higher density moves to the bottom. Consequently, water with high temperature enters the basin. As shown in Fig. 2a, a semitransparent PV module with 30° slope is installed on a solar still. It is assumed that there is not any air leakage from the system. Also, the basin is painted in black color to absorb the maximum level of sun radiation.

When the solar radiation is received by the PV module, part of the radiation is absorbed by the PV resulting in produce electricity while some remained parts are absorbed by water in the basin. The tubes with a 1.4 m length and inner diameter of 0.047 m (with an equal distance from each other) are installed with a slope of 45° on the diffuse reflector while connecting to the basin. The tubes consist of two symmetry cylinders. The inner cylinder is full of water and the gap between the two cylinders is vacuumed in order to prevent the heat loss. In addition, the outer surface of inner cylinder is painted in black color to absorb the maximum possible sun radiation.

In the present work, the system is simulated and modeled using the numerical solving methods in MATLAB software. The module efficiency ($\mu_{r,m}$) and temperature coefficient ($\beta_{r,m}$) in the standard test condition for the six PV modules are listed in Table 1. Also, the specifications of the solar still and ETC are listed in Table 2. Basin water mass flow is assumed to be 30, 70 and 120 kg for water depth of 0.03, 0.07 and 0.12 m, respectively.

Considering the glass on the solar still, fractional solar fluxes are assumed $\alpha'_w = 0.34$, $\alpha'_b = 0.36, 0.33, 0.31$ for 0.05, 0.10 and 0.15 m water depth, respectively [10].

3. Modeling of solar still integrated with ETC and SPVM

The energy balance equation for each component of the systems is performed using the following assumptions;

(a) Solar distillation unit is vapor leakage proof.
(b) Temperature dependent heat transfer coefficients have been considered,
(c) Side heat loss from the solar still is neglected,
(d) There is no thermal stratification across the water depth,
(e) Initial values of water and condensing cover temperatures have been used to determine the values of internal heat transfer coefficients,
(f) System operates in quasi-steady state regime during the day,
(g) (j) Water level in the solar still basin is assumed to be constant,
(h) Water temperature inside the ETC is assumed to be constant along the tube,
(i) Heat capacities of semitransparent PV module and basin are negligible.