A Novel Hybrid PV/T System for Sustainable Production of Distillate Water from the Cooling of the PV Module

Angham Fadil Abed<sup>1</sup> Dhafeer Manee Hachim<sup>2</sup> and Saleh E Najim<sup>3</sup>

<sup>1</sup>Engineering College, Mechanical Department, University of Kufa, Najaf, Iraq
<sup>2</sup>Engineering Technical College, Najaf, Al-Furat Al-Awsat Technical University, Najaf, Iraq
<sup>3</sup>Engineering College, Mechanical Department, University of Basrah, Basrah, Iraq

E-mail: angham.alshebly@uokufa.edu.iq

Abstract. A large portion of incident solar radiation on photovoltaic (PV) panels is transformed into heat; thus, reducing photovoltaic panel power. The photovoltaic module's efficiency depends primarily on the ambient temperature, the temperature of the module, the incoming intensity of the solar radiation, and the composition of the PV material. Depending on the type of solar cells used, PV panel efficiency typically drops by 0.5 for each degree rise in temperature. The cooling technique is also beneficial to maintain the cell at the operating temperature and should be such that, with a uniform distribution, it holds the average cell temperature to its minimum values. The supply of drinking water is increasingly declining with increasing population, growth, and environmental pollution. Therefore, it is appropriate to concentrate on available distilling water. Due to its low cost, energy, and ability requirements, solar still is one of the promising technologies available for water purification. The current work attempts numerically to suggest and analyze the production of distilled water, electric power, and heating water for domestic by utilizing a simple passive cooling technique for a new hybrid PV/T. The present work benefits from the unwilled heat of PV panel to obtain freshwater without the construction of solar still by putting a glass cover on the original frame of PV. The system's performance is investigated from various aspects such as distilled water yield, production of electrical and thermal power instantaneously, and daily by considering three types of mass flow rate in inner wick and four types in the outer wick. Results show that the mass flow rate of inner wick does not significantly affect the temperature of PV and distilled water yield, but the mass flow rate in outer wick has affected distilling water. The production of water was maximum for the CPVWD module and is increased by about 65.73% more than that for the PVWD. The CPVWD module is found to display the highest electrical efficiency while the PVWD shows the lowest value. Good agreement between the present results and previous works was found.

Keywords. Hybrid PV/T, System sustainable, Distillate water, PV module.

1. Introduction
Demanding for current energy is fossil fuels and nonrenewable sources, and it is expanding at a fast rate besides being greenhouse gas emitters. Solutions to meet the current energy challenges are based on using sources of renewable energy. Solar energy is a clean and inexhaustible renewable energy resource with zero waste generation and no carbon dioxide emissions. Researches have been done over the years to be benefiting from enormous solar resources. Photovoltaic panels (PV) are among the...
most important techniques, but its efficiency remains low as much of the solar energy is transformed into thermal energy [1]. Photovoltaic cells (PV) are renewable energy devices that transform incident sunlight into electrical energy DC. During this energy conversion process, these cells only transform a portion of the incoming solar radiation into useful output energy while the rest is lost as heat wasting. Hence, this wasted heat increases the cell temperature. As the photovoltaic cell temperature increases, the open-circuit voltage and fill factor decrease, leading to a decrease in the conversion efficiency of the PV system [2]. The smallest unit is termed as a solar cell, and they are arranged in parallel and series to build a PV module. PV arrays consist of PV modules that are connected in series and parallel. Indeed, PV power plants shares have increased worldwide, and many countries are now planning to increase the proportion of alternative energies in electricity generation. It is found that the performance of PV decreases as the temperature of the PV module increase. For every 1 °C rise in solar cell temperature, the efficiency of crystalline silicon solar cells decreases by 0.5%, and this efficiency reduction change with the cell type [3,4]. Consequently, a cooling system is needed to remove this heat by using cooling fluids, such as air and water, in forced or natural convection withdraws the heat from the PV panel and using it in different implementations and to obtain stability in the production of electrical energy at the same time. In this case, the PV panel is called a hybrid PV/T [4]. Photovoltaic–thermal (PV/T) represents an integration of PV technology and solar thermal technology, which simultaneously transform the incident radiation into electricity and heat and gains popularity. The PV/T module employ in many applications. It can be utilized in the industrial field, domestic using and preheating water or air. Building façades and roofs can be integrated with PV/T air systems, and with the addition of the electrical load, they can provide air ventilation for the building.

On the other hand, PVT/water systems employ a water heat exchanger placed in the photovoltaic backside. It is in thermal contact with it, suitable for space and water heating, etc. [5]. Thermal, electrical, and energy efficiencies are the measure of the performance of the hybrid PV/T system. Since the material used for the manufacturing of PV cells is sensitive to change in temperature, therefore, the electrical efficiency of the system mainly depends upon the cell temperature. Whereas thermal efficiency usually comprises the ratio of a beneficial heat gain [6][7].

The demand for freshwater has increased due to population explosions and rapid industrial development worldwide, while the supply of pure water declines day by day. To solve this problem, a sustainable source for water distillation is a solution. Economic factors, however, maybe the conventional distillation of brackish or brackish waters, which can be found respectively in deserts and seashore. Therefore, solar energy is a possible distillation alternative by using the stills in such locations, despite being a much less efficient energy source than fossil fuels or electric power [8]. Solar stills are one of the systems for direct solar desalination in which solar radiation is directly applied to generate desalinated water. Solar still is simple to produce and requires no professional labor and maintenance; therefore, it is considered an active source for freshwater production for both domestic and agricultural domestic fields. The solar radiation mechanism still is when the solar radiation is falling on the glass cover of still. Brackish, or wastewater also starts to evaporate in the black painted basin. The water that has evaporated rises to the glass cover's cooler inner surface and is condensate as freshwater. The evaporated water condenses and runs down over the bottom cover glass surface due to the gravity where it can be deposited into freshwater. Solar still has two forms, passive and passive. There are several ways to heated the water in the basin, but the most preferred approach is either directly combining the basin with the panel or using a heat exchanger [9,10].

Yari et al. [11] studied a new integration of a solar still equipped with semi-transparent PV and evacuated tube collectors in a natural mode. Their system applied various basin water depths and many tubes and six types of PV modules. They concluded that the PV module form does not affect pure water productivity. Maximum water yield (4.77 kg / m2.day) for tube number 30 and basin depth of 0.07 m was achieved. Hedayati-Mehdiabadi et al.[12] investigated the efficiency of PV/T connected to stepped cascade still. The freshwater yield increase was 20 % to hit 5.71 kg/(m2.day) with a daily energy efficiency of 26 % from the proposed system. The system's maximum energy efficiency can be obtained at a PV/T collector area of 1.3m² and 0.03 kg/min of desired brackish water flow. In order to perform the process of desalination and generate electricity, Manokar et al.[13] studied the efficiency
of an integration of a PV panel fixed at the basin of solar still. Their results suggest that the PV-still freshwater yield is 7.3, 4.4, and 3.7 kg, respectively, with sidewall and bottom insulation, PV plus still with sidewall insulation, and PV plus still without any insulation. Pournaj et al.[14] studied a hybrid PV / T active solar system in which a solar PV is operated by Peltier (Thermo Electric Cooler) device to increase freshwater production during evaporation and condensation processes. The proposed device has an average thermal efficiency improvement of 30 % compared to CSS. Naroei et al. [15] investigated the efficiency of combining stepped solar still with photovoltaic thermal water collector (PVT) numerically and experimentally. The results showed that the desired collector and mass flow rate of PVT water was 1.33 m² and 0.068 kg/min, respectively. More than two times, the CSS efficiency and a 20 % improvement in the pure water yield are increased by the proposed method. Al-Nimr et al. [16] suggested a novel PV/T distillation system with a combined PV/T cell fixed at the base of basin solar still under the water to be treated. An internal reflector is also used in the basin area to focus the solar radiation, and the novelty of using PV / T cells submerged underwater and outside finned condenser, which increases the rate of evaporation due to increase in water temperature. A fan is added and placed above the water's surface to rapidly lift the water vapor from the basin and force it into the condensing chamber. A fan was operated by PV / T immersed, and the condensation processes increased in the daytime. PSS productivity is measured at about 6.8 kg/day at a solar radiation rate of 1000 W/m² with an efficiency of 56.5 %. However, it has 4.07 kg/day productivity and 28.6% efficiency in CSS. Kumara et al.[10] experimentally tested a hybrid photovoltaic/thermal ( PV / T) single slope active solar still and a conventional passive solar still with three different water depths (0.05 m, 0.10 m, and 0.15 m). In order to achieve higher distillate water output, a nickel-chrome heater (NiCr) was used and operated by solar photovoltaic ( PV) in the suggested hybrid still. Their findings show that the system's daily yield is six times greater than the conventional passive yield. It is evident from the experimental analysis that the overall electrical and thermal performance of the proposed hybrid active (PV / T) solar was still increased to around 25 % higher than the conventional passive one. The evaporative cooling concept is well known and has been implemented in many industrial and industrial applications. However, the cooling of PV panels using evaporative cooling is minimal, and there is very little research on the use of evaporative cooling for PV panels. Evaporative cooling has a high potential in dry and hot climates to regulate the temperature of the PV panels built under these conditions[17]. In evaporative cooling, employing wetted wicks decreases the thermal inertia and increases heat transfer by evaporation-condensation [18]. Haidar et al.[17] investigate the influence of the evaporative cooling of solar photovoltaic ( PV) panels by designing a simple and efficient experimental setup. The back surface of the PV panel was moistened and open to the ambient. Water was supplied from a tank by gravity to the back of the PV panel. The PV panel temperature was reduced to more than 20 °C, and the efficiency of electric power generation was improved by around 14 % compared to the PV reference panel. The effect of evaporative cooling on the output of PV panels was theoretically investigated by Haidar et al. [19]. Their model includes ambient air being blown inside a duct, a water layer flowing inside the same duct, and heat transfer between the air and PV. The influence of heat and mass transfer was studied, and a decrease in the temperature of the PV panel to about 6 °C was expected. The thermal and electrical efficiency of a PV panel cooled by an evaporative chimney was evaluated by Lucas et al. [20] experimentally. The temperature drop reached 8 °C, and the mean electrical efficiency increase was in the range of 4.9-7.9 %, with an average ambient temperature of less than 30 °C. A passive thermal regulation method was developed by Chandrasekar et al.[21] with heat spreaders combined with cotton wicks to regulate the temperature of the PV module during its operation. Two flat PV modules use one thermally controlled flat PV module and reference PV without cooling, and the PV module's thermal and electrical efficiency was also compared with the results of the PV module without a cooling system. The PV module temperature was reduced to approximately 12%, and the electrical output was increased by 14 % using the established cooling system. Basic equations of energy balance were applied for the PV module to calculate the coefficient of thermal loss, which was found to increase because of the influence of fins and evaporative cooling in humid cotton wicks.

The authors best survey, and from the previous literature review, there are many areas where healthy water and electric power supply is low. Present work is a numerical attempt to investigate producing
distilled water, electrical power, and heating water for domestic and straightforward use, by using a simple passive cooling technique for a hybrid PV/T. The proposed PV/T system was used to benefit from unwilled heat and employ it to produce distilled water and heat water for different domestic use. A cooling system was provided on the PV panel's back surface using a cotton wick to cool the panel and produce pure water. The present paper assumes a coupling is concentrated on integrating the PV with a simple solar still consist of glass cover placed on the PV back surface original aluminum frame without using an extra construction for solar still, i.e., the PV can represent a source for electricity, pure water for drinking, and heating water for domestic using. The benefit of this cooling method is; (i) the solar still does not occupy space other than the space used by the PV(PV provide electricity and transform to a simple solar still by adding a glass cover to the frame of PV), (ii) In the pervious studies there is a thermal medium between the PV and the still used to pass the energy from the auxiliary part to the still, combined with the still as solar collectors, PV, resulting in various system efficiencies leading to a reduction in overall system performance while here we overcome this problem. Hence a new novel coupling technique of a PV panel in this work which benefits from the heat losses from the panel to evaporating the water flowing in wetted cotton wick and obtain pure water without using the power of the PV as used in previously coupling techniques of solar still with PV, i.e., from the same PV module we obtain pure water and electricity. Also, (iii) the PV is not costly, does not need maintenance, has a very long operating time, and even if the PV power is low, this integration will help obtain pure water.

2. System description

2.1. Experimental setup

A sectional view of the hybrid (PV/T) is shown in Figure 1. With the same peak power, two PV modules are included in the experimental setup. The first test PV module (PVREF) is considered a reference module, and the other PV test modules are provided with a distillation and cooling system (PVWD, CPVWD). The experimental rig (PV panel with 30° slope is installed, and latitude angle 32.1) is built at Najaf-Iraq. A piece of the plain wick (inner wick) with 0.01 mm thickness of porous cotton was directly settled to the back surface to do the second module (PVWD). A layer of 6 mm thick commercial back glass sheet inclined at nearly 30° to the horizontal covers the panel, and it is pasted (by using silicon) to the frame of the PV module without exceeding it. Plastic pipes of 15mm diameter are inserted in two bores drilled on the same sidewall of the PV frame. The first fitting bottom (15mm diameter) pipe is used for the collection of distilled water. The other top (15mm diameter) pipe is used to supply brackish water. A slot of approximately 0.75 mm was longitudinally cutting on the surface of this pipe to insert the wick ends and allow arrived water from a controlled container by valve to the cotton wick. A hole of about 0.5 cm diameter is made in the bottom wall of the PV frame to discharge the excessive water. Another porous back wick (back wick) is fixed on the back glass cover outer surface to make the (CPVWD) module. The top ends of this wick are inserted in a pipe fixed in the top of the cover with a slot of the same size as mentioned previously for PVWD. The hybrid PV modules are fixed by an iron stand, as explained in Figure (1). A set of thermocouples is used to measure the module's temperature; some are attached at three different positions on the panel back surface, two are fixed to the back wick surface, and another is assigned for the back glass cover inner surface and humid air. While a separate thermocouple is used to measure the ambient temperature. The thermocouple sensors (type-T) were linked to the thermocouple data logger and calibrated with an accuracy of ±1 Co. The data logger is programmed and connected to the computer to record the temperatures with a 5 min. A solar power meter (Type SR 11) with an accuracy of ±5 W/m² is used to measure the total solar radiation on an inclined surface close to the test module. The graduated 500 ml capacity vessel is used to measure and collect the condensate water on a manual record (one hour).

3. Uncertainty analysis

The error occurs in the measurement devices during each experiment, and it can be considered a difference between the measured value and the actual value. In general, errors in every experiment are
calibration, human errors, experiment conditions, uncontrolled variables, ambient conditions, measurement tools, etc. So, uncertainty is classified into two types: systematic and random errors. By reviewing of manufacture datasheet or data of measurement devices calibration, systematic errors could be calculated. The random errors could be calculated by utilizing statistical processes. Random error sources are undistinguished and may happen due to many factors like human mistakes or ambient conditions, and it is always uncountable. Systematic errors are not varied, but random errors are varied for the experiment of unchangeable conditions. In this study, the uncertainty of the second type is considered since it is supposed that all the measurement devices are uniformly distributed. The equation of standard uncertainty can be expressed as [9]:

$$u = \frac{a}{\sqrt{3}}$$

(1)

Where u expressed as the value of standard uncertainty and a is the accuracy of the measuring devices. The uncertainty values connected by tests are recorded in Table (1).

| Instruments Range | Ranges | Accuracy | Instruments standard uncertainty | Parameter Measured |
|-------------------|--------|----------|----------------------------------|--------------------|
| Thermocouple      | 0–100 °C | 1°C | 0.6°C | Temperature of Panel |
| Solar power meter TES1333R | 0-1999 W/m² | 5 W/m² | 2.8 W/m² | Global Radiation |

**Table 1. Standard uncertainty, accuracy, and ranges of instruments.**

![Figure 1. Set up of experiment.](image)
3.1. CFD modeling

In this research, simulation and modeling for the hybrid (PV/T) with an uncooled system and a cooling system with desalination were studied. The hybrid system consists essentially of the following components:

1. Photovoltaic uncooled panel (PVREF) consisting of the following elements (Figure 2a):
   - Photovoltaic cells are submerged in an EVA (ethylene-vinyl-acetate) polymer layer.
   - A layer of glass for protection of the PV cells (front glass-cover).
   - A layer of Tedlar for protective underneath PV cells.

2. A photovoltaic panel with desalination (PVWD) which consist of the following components (Figure 2b):
   - Photovoltaic panel with the same layers as in (PVREF).
   - A piece of the porous cotton wick (inner wetted wick) was directly connected to the PV panel's back surface, and water was allowed to flow and wet this wick to obtain pure water.
   - A back glass cover (as a condensation surface) below the PV panel with enclosed air space. This cover putting in the original frame of PV without extra construction for an air closed cavity.

3. A cooling photovoltaic panel with desalination (CPVWD), which consists of the same components as PVWD with extra back wetted wick (outer wetted wick) of the same type as used in PVWD attached to the back surface of the back glass cover (Figure 2c).

The design parameters and thermophysical properties that are used in the simulation are given in Table 2. In order to ensure that the solar rays are normal to the surface at most times of day, the system is inclined at an angle of 30°. Through a distribution pipe (top pipe), the feed water goes and then absorbed by the inner wick layer (capillary action) on the back surface of the PV panel, creating a water layer all over the wick. Solar energy warms the panel and inner wick layer. Some of the water on the wick evaporates and condenses when it touches the cool back glass cover, and some of the water is subtracted out of the module. The condensate flows into a condensate pipe (bottom pipe) and is extracted from the cavity side. The remainder of the feed water, which is hot water, flows into another collection opening that produces the remaining water opening in the center of the lower PV frame, and the hot water is removed from this opening. This technique was used to obtain pure water. To reduce the temperature of PV, which was raised during the distillation process, the study presents a solution to enhance the cooling of a PV by allowing the back or outer wick to be wetted by water from the same tank, as shown in Figure 2c.
Figure 2. Cross-sectional view and types of heat transfer modes of a) photovoltaic module (PVREF), b) photovoltaic module with desalination (PVWD) and c) cooling photovoltaic module with desalination (CPVWD).
### Table 2. The materials, items, symbols, and values of the hybrid modules used in the modeling and simulation.

| Part            | Materials          | Items         | Symbols | Values (m) |
|-----------------|--------------------|---------------|---------|------------|
| PV glass cover  | Glass              | Thickness     | $t_{fg}$| 0.0032     |
|                 |                    | Length        | $l_{fg}$| 0.539      |
|                 |                    | Width         | $w_{fg}$| 0.66       |
| PV solar cells  | Silicon            | Thickness     | $t_{sc}$| 0.00018    |
|                 |                    | Length        | $l_{sc}$| 0.539      |
|                 |                    | Width         | $w_{sc}$| 0.66       |
| PV back sheet   | Tedler             | Thickness     | $t_{t}$ | 0.00018    |
|                 |                    | Length        | $l_{t}$ | 0.539      |
| Wick            | Cotton             | Thickness     | $t_{w}$ | 2.1E-4     |
| Backglass cover | Commercial glass   | Length        | $l_{bg}$| 0.539      |
|                 |                    | Width         | $w_{bg}$| 0.66       |

### 4. Mathematical modeling

Figure 2 Displays the thermal processes on the hybrid system. Using time-dependent energy balance and mass balance equations, the system is modeled, and the equations are simulated using Comsol 5.3.

The energy balance equation can be expressed with the following assumption:

1. The flow in the proposed modules is 2-D, unsteady, and laminar.
2. There is no water vapor leakage between the back glass cover and PV original frame.
3. Coefficients of heat transfer temperature-dependent have been taken.
4. The nodal approach (the temperature of each solar panel layer is assumed to be spatially constant) is considered.
5. Thermal losses have been ignored on the lateral sides.
6. Water vapor on the wick surface is saturated.
7. Evaporation flux is equal to Condensation flux.
8. Variable properties (change with temperature).
9. Radiation to the ground is negligible.

The equation of the heat balance for each PV / T component can be express as:

#### 4.1. For PVREF

- **Glass layer:**

  \[
  M_{fg} C_{fg} \frac{dT_{fg}}{dt} = R_{fg} - Q_{rfg-sky} - Q_{cfg-amb} - Q_{cofg-sc}
  \]  

- **Solar cells**

  \[
  M_{sc} C_{sc} \frac{dT_{sc}}{dt} = R_{sc} - Q_{cosc-fg} - Q_{cosc-t} - Q_{ele}
  \]

Where\[22]:

\[
Q_{ele} = IA_{m} \dot{\zeta}_{ref} \left[ \left( 1 - \beta_{p} (T_{sc} - T_{sc,ref}) \right) \right]
\]

- **Tedler layer**

  \[
  M_{t} C_{t} \frac{dT_{t}}{dt} = R_{t} + Q_{cosc-t} - Q_{ct-amb}
  \]
4.2. For PVWD:
The distillation system is placed on the rear side of the PV panel in the present work, except for the Tedler layer; for this module, all equation balances applied to PVREF were applied here.

- Tedler layer

\[ M_t C_t \frac{dT_t}{dt} = R_t + Q_{cond} - Q_{ct-w} \]  

6)

- Inner porous wick layer

\[ M_w C_w \frac{dT_w}{dt} = Q_{ct-w} - Q_{rw-bg} - Q_{ew-ma} - Q_{cw-ma} + C_{in} T_{in} - C_w m_e T_{w-ex} \]  

7)

Where

\[ Q_{ew-ma} = m_{ew} h_{evp} = = -3600 \times D_{AB} / L \int_0^L \frac{dC}{dy} h_{evp} A_m \]  

8)

Where[13]

\[ m_e = m_{in} - m_{ew} \]  

9)

- Moist air

\[ M_{ma} C_{ma} \frac{dT_{ma}}{dt} = Q_{ew-ma} + Q_{cw-ma} - Q_{cma-bg} - Q_{cdma-bg} \]  

10)

\[ Q_{cdma-bg} = Q_{ew-ma} \]  

11)

- Backglass cover

\[ M_{bg} C_{bg} \frac{dT_{bg}}{dt} = Q_{cdma-bg} + Q_{cma-bg} - Q_{cbg-amb} \]  

12)

4.3. CPVWD

The above energy balance equations that were applied for PVWD are applied for this module except for equations for back glass cover and back or outer wetted wick and can be written as:

- Backglass cover

\[ M_{bg} C_{bg} \frac{dT_{bg}}{dt} = Q_{cdma-bg} + Q_{cma-bg} - Q_{cbg-bw} \]  

13)

- Back or outer porous wick layer

\[ M_{bw} C_{bw} \frac{dT_{bw}}{dt} = Q_{cbg-bw} - Q_{cbw-amb} + C_{w} m_{in} (T_{w,in} - T_{w,ex}) \]  

14)

4.4. Thermal and electrical efficiency

The electric efficiency for the modules can be written as follows:[22]

\[ \zeta_{ele} = \frac{Q_{ele}}{I_{Am}} \]  

15)

Where \( Q_{ele} \) is calculated from Eq.10. For the PVREF module, it does not generate any useful thermal power. The thermal efficiency for PVWD and CPVWD is calculated as:[23]

\[ \zeta_{th} = \frac{C_w (m_{in} T_{w,in} - m_e T_{w,ex})}{I_{Am}} \]  

16)

4.5. Heat transfer coefficients used in Energy balance equations

1) Radiative heat transfer coefficient

The coefficient of radiative heat transfer between the front glass cover of the PV module and the sky may be given by the following equation[22]:

\[ h_{fg-sky} = \sigma e_{fg} \frac{(T_{fg}^4 - T_{sky}^4)(T_{fg}^2 + T_{sky}^2)}{T_{fg} - T_{sky}} \]  

17)
The internal radiation heat transfer coefficient for PV/T can be determined from the equation of radiation between two parallel flat plates as follow [22]

\[ h_{rl-j} = \frac{\sigma (T_i + T_j)}{\varepsilon_i + \varepsilon_j} \]

2) Convective heat transfer coefficient

The external convective heat coefficient produce from the wind effect and can be described for all modules by the following relation:[22]

\[ h_{ci-amb} = 5.7 + 3.8v_w \]

3) Conductive heat transfer coefficient

The conductive heat transfer is effected via the adjacent panel components. In this case, the heat transfer coefficient is expressed by the following relation between two adjacent components i and j [22]:

\[ h_{ci-j} = \frac{1}{\frac{\varepsilon_i}{k_i} + \frac{1}{\varepsilon_j k_j}} \]

4.6. Governing Equations

Flow and energy equations are modeled on continuity, momentum, energy, and mass transfer conservation principles. The heat transfer process begins when solar energy is incident on the PV. In the proposed PV / T, flow is deemed incompressible, unsteady, 2D, and laminar, and the following equations are applied.

1- Conservation of Mass Equation

The continuity equation represents the conservation of mass for the air mixture, and it can be expressed as

\[ \frac{\partial \rho}{\partial t} + \nabla (\rho u) = 0 \]  

2- Conservation of Momentum Equations

The momentum equation for the mixture represents the Navier-Stokes equations and can be given as

\[ \rho \left( \frac{\partial u}{\partial t} + u \nabla u \right) = -\nabla p + \nabla \left( \mu (\nabla u + (\nabla u)^T) \right) + F + \left( \rho - \rho_{ref} \right) g \]

Where \( u \) is the velocity of the fluid, \( p \) is the pressure of the fluid, \( \rho \) is the density of the fluid, and \( \mu \) is the dynamic viscosity of the fluid. The various terms refer to the inertial forces applied to the fluid (first term), friction forces (second), viscous forces (third), and external forces (forth)).

3- Conservation of Energy Equation

\[ \rho C_p \frac{\partial T}{\partial t} + \rho C_p u \nabla T + \nabla q = q_o \]

Where

\[ q = -K \nabla T \]

and \( q_o \) represent heat source

4.7. Equations of Concentration

In pore space, the transport of diluted species is regulated by diffusion and convection, as defined in the following equation:
\[
\frac{\partial c}{\partial t} + u \nabla c = \nabla (D \nabla c) + R
\]  

(26)

C is the species (mol/m3) concentration, D indicates the coefficient of diffusion (m2/s), R is the species' expression of reaction rate (mol/(m3 · s)), u is the velocity vector (m/s). The first expression on the left side of Equation (26) refers to the species' accumulation. The second expression on the right side of Equation (26); represents a term in the sink or source, usually because of a chemical reaction.

4.8. Boundary conditions

To simulate the continuity, momentum, energy, and concentration equations, appropriate boundary conditions were defined at all boundaries. Boundary conditions of moist air for PVWD can be written as following[24,25]:

i) Inner porous wick Surface: At the inlet \( m = m_{\text{w}i} \), \( T = T_{\text{w}i} \), at outlet \( p = 0 \), along the surface of the wick, \( T = T_{\text{w}} \) and \( c = C_{\text{w}} = P_{\text{sat}}/(R.T_{\text{w}}) \)

ii) Inner surface of back glass cover: \( u=0, v=0, T=T_{\text{bg}}, c=C_{\text{bg}}|T=T_{\text{c}}, \Phi=100\% \)

Where, \( C_{\text{bg}}=P_{\text{sat}}/(R.T_{\text{bg}}) \).

iii) Back porous wick surface: At the inlet \( m = m_{\text{bw}i} \), at outlet \( p = 0 \), along the surface of the back wick, \( T = T_{\text{bw}} \) and \( c=C_{\text{bw}}=P_{\text{sat}}/(R.T_{\text{bw}}) \).

iv) Sidewalls: no-slip, thermal insulation, no flux.

v) Convection heat transfer between the front glass cover and the ambient and can be described by Eq.20

vi) Radiation on the top glass cover, which can be written as in Equations 17 and 18 and radiation between the back surface of the wick and inner surface of the back glass cover, which can be found in Equation 19.

5. Use of Comsol multiphysics

Comsol multiphysics is a versatile interacting environment used to model and solve all sorts of problems concerning science and engineering. With this program, traditional models for one form of physics can be easily extended into multiphysics models that solve coupled physics phenomena [26]. The previously mentioned model equations (system of partial differential equations) describing coupled fluid flow, heat, and mass transfer in proposed modules were solved using the finite element software, COMSOL Multiphysics®version5. The coupled partial differential equations for continuity, momentum, energy, and concentration and the boundary condition are molded and solved simultaneously in an iterative procedure using the heat transfer module(laminar flow with transient heat transfer and transient mass transfer). Based on the environmental data, the solar irradiance and the temperature of ambient varied throughout the day. In order to simulate more realistic boundary conditions instead of constant boundary conditions that are often used to simplify numerical simulation, the input boundary condition varied with time. The values are also written as an equation for the external convection heat transfer coefficient that varies with the wind velocity at each time step. Also, the efficiency of the PV panels is influenced by the temperature, so the conversion efficiency of the PV panels is also dynamically varied at each step time using the temperature information from the running steps.

6. Code validation

Firstly, a mesh convergence test is performed to investigate the mesh size results' independence for the hybrid systems. The finite element meshing of the computational domain of proposed hybrid modules (PVREF, PVWD, CPVWD) is accomplished, and one of these modules (PVWD) is displayed in Figure 3. Different types of non-uniform grid systems are checked with elements: 37,117; 45,283; 51,155; 63,409; 73,203; 85,670 and 107,097 for PVWD. The grid size was calculated by increasing the meshing number until the criterion \([p-(p+1)]/p < 10^{-3}\) was obtained. Here \( 'p' \) stated the calculated temperature using the current mesh size, and \( 'p+1' \) resembles temperature at the next mesh size. Parameters of supervision are chosen as cell temperature, and productivity inside the closed space was checked for the grid independence test. It was found that there was no substantial change between 73,203 and 85,670 meshing in cell temperature value and productivity, but time intolerable. Thus, the
PVWD with 73,203 domain elements is considered for numerical analysis for saving time as no difference in result by increasing the number of elements over the taken value. For productivity, the grid test result is shown in Figure 4. Secondly, to validate the model and numerical simulation methods used in this study for PVREF, a comparison is made with the numerical simulation results deduced by Silimin [22]. The solar system is a conventional air collector hybrid PV/T based on the usage of a tow photovoltaic monocrystalline module type “Siemens SP75”. At the standard rating conditions, this PV module reaches 75W as an electrical capacity. The experimental study's climatic conditions and design parameters of Ref. [27] are used to assess and compare the energy efficiency of the hybrid module in this numerical simulation model for this validation setup. The simulated cell and tedler temperature values and their corresponding Silimin[22] values are shown in Fig.5 during the test day. It is observed from this figure that there is a strong agreement between the results. Another comparison was made in Fig.6 with the experimental results of the same work for tedler, moist air, and back glass temperatures. Note that a good agreement between the simulated and experimental results for the present work, where the maximum error is about 19%.

![Figure 3. Meshing of PVWD domain with various element.](image-url)

![Figure 4. Productivity grid testing with the number of elements.](image-url)
Figure 5. The simulated results of solar cells and tedler temperatures during the test day for PVREF.

Figure 6. Comparison between the experimental and simulated results of tedler, moist air, and back glass temperatures during the test day for PVWD.

7. Experimental variation of weather conditions
For a sunny day of 9 November 2019, the experimental climatic data of Iraq-Najaf was used in numerical simulation. The geographical coordinates of the location of the site are latitude 32°.1 N, longitude 44°.19 E, azimuth 0°, and altitude 6 m. The following figure (Figure 7) involves the variation of the measured climate, which comprises the incident solar irradiance and ambient temperature on the 9th day of this month. The intensity of solar radiation hits high values, greater than 900 W/m² between 11:00 and 12:00, then decreases gradually till 4:00 pm. The range of the ambient temperature is between 20 and 34°C.
8. Results and discussion
This work's main objective is to benefit from unwanted heat-producing from panels to obtain freshwater production, cooling of PV panel, and obtaining hot water for different domestic using. Freshwater production attaches with the rate of evaporation of brackish water in the wetted inner wick and the rate of condensation of the evaporated vapor of water. With an increase in brackish water temperature and the temperature difference between brackish water and moist air, the rate of evaporation increases. The condensation rate increases with the temperature differential increases between the moist air and the back glass, the differential between the glass and ambient air, and the outside air velocity [9]. The numerical results were carried out from 9:00 hours until 16:00 hours. Therefore, it is essential to investigate and evaluate the temperatures of the modules to understand their behavior well.

8.1. Temperature distribution
The thermal performance of the proposed hybrid (PV/T) at unsteady conditions was investigated. The evolution of the PV panel, wicks, humid air, and back glass cover, and ambient temperatures with time for all hybrid modules is shown in Figure (8). It can be seen that the temperatures of the PV panel (Tucumber layer) are the highest in the modules (except for PVREF) and much higher in the PVWD. The PV solar cells are the hottest components for PVWD and CPVWD modules; their maximum value reaches 67 °C and 59 °C for the PV with desalination(PVWD) and the cooling PV desalination (CPVWD) respectively and 66 °C for PVREF. The Addition of a back or outer wick above the outer surface of the back glass cover in the CPVWD module causes a quick decrease in the temperature of all components of CPVWD due to the evaporative cooling effect between the outer wetted wick and the ambient. The maximum temperature difference of the solar cell layer between PVREF and CPVWD modules is 7.6 °C between 10:30 am, and 11:00 am which represents a 12.8% reduction in temperature. For PVWD, the maximum temperature difference between the inner wick and moist air is about 3.9 °C while for
CPVWD, it is about 10.16 °C and this corresponding to a reduction in temperature by about 5.9% and 17.4%, respectively; thus, it leads to the improved evaporation rate of the inner wetted wick. Also, it can be observed from Figure 8 the high difference in temperature between moist air and back glass cover for CPVWD as compared with PVWD, and this causes augment in condensation rate. All the component temperatures of the proposed modules are higher than the temperature of the ambient. Figure 9 indicates streamlines and isotherms of PVWD and CPVWD modules at 11:45 am at the inner and outer mass flow rate of 0.000416 kg/s and 0.00133 kg/s. The streamline figures indicate that there is one recirculating region in tow modules, rotate in a clockwise direction. It can be noted that humid air concentrate near the back glass cover and back surface of the inner wick and moves from the inner wick towards the back glass cover. The results indicate that there are gradual changes in temperature contours near the wick surface and the back glass cover due to condensation and evaporation phenomena. It can also be seen as the effect of outer wick in decreasing the back glass cover temperature.

![Figure 8](image-url)

**Figure 8.** The hourly evolution for temperature components in PVFER, PVWD, and CPVWD.
8.2. Variation of hourly and daily distillate outputs

The influence of employing PV as a simple solar still is represented by an hourly yield of freshwater. Figure 10a illustrates a comparison of the yielding hourly of the PVWD and CPVWD for a mass flow rate in inner and outer wicks are 0.000416kg/s and 0.00133 kg/s, respectively. The findings illustrate that the distillate output in the CPVWD is higher than that in the PVWD. This is because of the good evaporating properties of the outer or back wick used to enhance the rate of water evaporation in the CPVWD. The capillary property and low thermal capacity of wetted wick increase the wick evaporation rate. Furthermore, observations show that during the morning time, the distilled water was minimal. This is because the water had not been heated up yet. While the highest distilled water productivity was provided at approximately 11 am, and then starts to decline. This is due to the high solar radiation incident and the high surrounding and ambient temperature through this time of day (Fig. 7). Besides, the temperature of water feed to the wicks has minimal in the morning, requiring time to heat up. Figure 10b shows the variation of hourly accumulative water productivity for CPVWD and PVWD versus day hours from 9 am to 4 pm. It is clear from this figure that the accumulated amount of distilled water from CPVWD is higher than that for PVWD. The daily productivity of CPVWD at 4 pm was about 1541.54ml/m², while the corresponding for the PVWD is nearly 930.13 ml/m². This means that the productivity of CPVWD is increased by about 65.73% more than that for the PVWD.
Figure 10. Variation of water productivity for PVWD and CPVWD a) hourly variation, b) accumulative variation.

8.2.1. The daily efficiency of the still. When we consider a PV as a solar still, it is important to calculate the still efficiency. The efficiency of solar still is an important factor in assessing the performance of still systems. The daily efficiency, $\zeta_d$, can be calculated by the summation of the condensate production every hour $m_{ew}$, multiplied by the latent heat $h_{fg}$, hence the result is divided by the average daily solar radiation $I(t)$ over the whole area $A$ of the system [28].

$$\zeta_d = \frac{\sum m_{ew} \times h_{fg}}{\sum A m \times I}$$

(27)

Results showed that CPVWD daily efficiency is about 21%. While the PVWD daily efficiency is about 12.44%.

8.3. The effect of mass flow rate variation

Figure 11 shows the mass flow rate variation in inner wick with productivity for PVWD and CPVW. It can be seen that the change in mass flow rate has a low effect on productivity for the two modules (PVWD α CPVWD). Also, the same behavior can be seen in Figure 12 for solar cell temperature compared with PVREF. It is observed that the average temperature of the solar cell for PVREF is higher. CPVWD shows the lowest average temperature that can be assigned to the cooling
The evaporative cooling effect is provided on the back glass cover's outer side due to the evaporation of water from the cotton wick structure. As already stated, the system produces hot water for domestic use while producing distilled water from the feed water, and this effect can be seen in Figure 13, which shows the variation of mass flow rate in inner wick with time for the temperature of the outlet water. It can be seen that the varying mass flow rate has little influence on outlet water temperature because the difference in values of the mass flow rate was taken very simple; therefore, the variation effect was very simple. Be careful in taken values of inner mass flow rate because excessive in it will destroy the capillary effect of wick and cause a mixing of distilled and brackish water. The effect of varying mass flow rates on outer wick with productivity for CPVWD was depicted in Figure 14. It can be seen clearly with increasing the mass flow rate, the amount of yield will increase because of the good effect of outer wick in increasing the enclosed cavity's condensation rate. As a result, productivity will be increased. Figure 15 demonstrates the variation of average back glass temperature for CPVWD with time for variable mass flow rate in the outer wick. The average module temperature decreases with the increaser in the mass flow rate. As the mass flow increases, the fluid velocity increases, leading to an increase of convection heat transfer between back wick and ambient. In this case, the reduction in back glass temperature was 10.9%, which shows the back cooling method's effectiveness.

**Figure 11.** Variation of mass flow rate in inner wick productivity.

**Figure 12.** Variation of mass flow rate in inner wick with average temperature of solar as compared with PVREF.

**Figure 13.** Variation of mass flow rate in inner wick with the average temperature of outlet water.
8.4. Performances of energy
The variations of the hourly electric power generated for each module per unit area, which proves mathematically in Equation (3), are shown in Figure 16. The values reached for the CPVWD, the PVREF, and the PVWD modules are 115.19W/m², 112.56W/m², and 111.5 W/m². For the first module (PVREF) and the second module (PVWD), the almost match's electric power hourly steps of the other modules. The third module (CPVWD) shows the maximum value of electrical efficiency. The hourly variations in thermal energy for each hybrid PV / T module per unit area are illustrated in Figure 17. For each proposed module, the maximum thermal power values are 399.32W/m², 235.46 W/m² for CPVWD, and PVWD, respectively. In terms of thermal power produced the CPVWD the most effective system. For each module, Figure 18 indicates the comparative variations in electrical efficiency for each hour. The daily electrical efficiency averages for CPVWD, PVREF, and PVWD are 12.99 %, 12.77 %, and 12.72 %, respectively. For each module, Fig.19 shows the comparative hourly variations of thermal efficiencies. The daily thermal efficiency averages are 43.66 % and 25.83
\%, respectively, for CPVWD and PVWD. Figure 20 shows the different calculated average daily efficiencies in this research. In contrast with other modules, CPVWD demonstrates the highest efficiencies.

\[\text{Figure 16. The simulated values of electrical power each module during the test day.}\]

\[\text{Figure 17. The simulated values of thermal power for each module during the test day.}\]

\[\text{Figure 18. The hourly variation of electrical efficiency for each module.}\]
9. Conclusions
The fundamental purpose of this research is to benefit from the high temperature of the PV panel in obtaining freshwater by using hybrid modules and reducing the negative effect of high temperature by using the evaporating cooling technique. A comparative thermal and electrical system performance analysis between three PV/T modules is presented numerically. The model equations are heat and mass transfer and were solved using COMSOL Multiphysics® version 3.5. The studied PV/T modules are an uncooled photovoltaic panel (PVREF), a photovoltaic panel with desalination (PVWD), and a cooling, photovoltaic panel with desalination (CPVWD). The novelty of the developed modules is its capability to benefit from the high temperature of the PV panel in producing freshwater without solar still constructing. The analysis of the results between all the modules proposed gave us some findings on the modules tested’ thermal and electrical behaviors. The results show that the daily average thermal and electrical energy efficiencies are: 12.77% for PVREF, 25.83% and 12.72% for PVWD, 43.66% and 12.99% CPVWD, respectively. The following results can be drawn from the study:

- Adding back or outer wick to the CPVWD increases the water productivity by about 65.73% over the PVWD. Also, the average daily efficiency for the CPVWD is about 21%. While for PVWD is approximately 12.44%.
Temperature differences between the inner wick and moist air and between moist air and back glass cover in CPVWD are higher than PVWD, resulting in higher condensation rates.

CPVWD shows the lowest average temperature of the solar cell, which can be attributed to the cooling effect caused by the outer wick.

For CPVWD, the maximum reduction in the temperature of the solar cell layer was about 12.8%.

Increasing the mass flow rate in the inner wick has a low effect on productivity for the tow modules (PVWD α CPVWD), while increasing the mass flow rate in the outer wick will raise the productivity because of the good effect of the outer wick in increasing the condensation rate inside the enclosed cavity.

For values of mass flow rate in inner wick used in this research, little variation in outlet water temperature was observed.

The CPVWD module is found to display the highest electrical efficiency.

The PVWD shows the lowest electrical efficiency.

| Nomenclature | Description |
|--------------|-------------|
| PV/T | photovoltaic/thermal |
| RMSD | root mean square percent deviation |
| PVREF | uncooled photovoltaic panel |
| CPVWD | Cooling photovoltaic panel with desalination |
| PVWD | photovoltaic panel with desalination |
| PSS | Passive solar still |
| Symbols | |
| A | area of PV panel(m²) |
| C | concentration(mol/m³) |
| C_s | specific heat capacity of component i (J kg⁻¹ K⁻¹) |
| C_t | the conversion factor of thermal power plant |
| h_no | conductive heat transfer coefficient (W m⁻² K⁻¹) |
| h_i | radiative heat transfer coefficient (W m⁻² K⁻¹) |
| h_c | convective heat transfer coefficient (W m⁻² K⁻¹) |
| h_e | Evaporative mass transfer coefficient (m/s) |
| h_amb | Condensation mass transfer coefficient (m/s) |
| h_p | latent heat of vaporization(j/kg) |
| I_t | thickness of component i (m) |
| I | solar irradiance (W m⁻²) |
| M_i | mass of component i (kg) |
| m | mass flow rate (kg s⁻¹) |
| Q_e | useful electric power (W) |
| Q_t | temperature of component i (°C) |
| P | pressure(N/m²) |
| t | time (s) |
| Q_co | conductive heat transfer(W) |
| Q_C | convective heat transfer(W) |
| Q_r | radiative heat transfer(W) |
| Q_x,y | evaporative mass transfer(W) |

| Greek symbols | Description |
|---------------|-------------|
| R_i | Solar energy absorbed by component i |
| Q_{cd} | condensation mass transfer(W) |
| ζ | efficiency |
| K | thermal conductivity (W m⁻¹ K⁻¹) |
| τ | transmissivity |
| α | absorptivity |
| e | emissivity |
| β_p | Stefan-Boltzmann coefficient(W m⁻² K⁻⁴) |
| β | packing factor |

Subscripts
- amb: ambient
- sc: solar cell layer of PV
- fg: front glass layer of PV
- t: tedler layer of PV
- bg: back glass cover
- w: inner wick, wind, water
- bw: back or outer wick
- ma: moist air
- sky: sky
- th: thermal
- d: daily
- in: inner
- ex: outer
- p: constant pressure
- x, y: Axes

10. References
[1] S S Chandela and Tanya Agarwal 2017 Review of Cooling Techniques Using Phase Change Materials for Enhancing Efficiency of Photovoltaic Power Systems (Renewable and Sustainable Energy Reviews) vol 73 pp 1342–1351
[2] A B Ahmer Baloch, M S Haitham Bahaidarah, Palanichamy Gandhidasan and A Fahad Al-Sulaiman 2015 Experimental And Numerical Performance Analysis Of A Converging Channel Heat Exchanger For PV Cooling (Energy Conversion and Management) vol 103 pp 14–27
[3] M Chandrasekar, S Rajkumar and D Valavan 2015 A Review on the Thermal Regulation Techniques for Non-Integrated Flat PV Modules Mounted on Building
Top (Energy Build) vol 86 pp 692–697

[4] H A Ali Al-Waelia , K Sopiana, A Hussein Kazemb and T Miqdam Chaichane 2017 Photovoltaic/Thermal (PV/T) Systems (Status and future prospects Renewable and Sustainable Energy Reviews) vol 77 pp 109–130

[5] M Sakhr Sultan and M N Ervina Efzan 2018 Review on Recent Photovoltaic/Thermal (PV/T) Technology Advances and Applications (Solar Energy) vol 173 pp 939–954

[6] Sourav Diwanial, Sanjay Agrawal and S Anwar Siddiqui1 and Sonveer Singh 2019 Photovoltaic–Thermal (PV/T) Technology: A Comprehensive Review on Applications and its Advancement (International Journal of Energy and Environmental Engineering)

[7] C Good, J Chen, Y Dai and A Grete Hestnes 2015 Hybrid Photovoltaic/Thermal Systems in Buildings—A Review (Energy Proced) vol 70 pp 683–690

[8] S Y Munzer Ebaid and Handri Ammari 2015 Modeling and Analysis of Unsteady -State Thermal Performance of a Single -Slope Tilted Solar Still (Renewables) vol 2 p19

[9] Ayman Refat Abd Elbar and Hamdy Hassan 2020 An Experimental Work on the Performance of New Integration of Photovoltaic Panel with Solar Still in Semi-Arid Climate Conditions (Renewable Energy) vol 146 pp 1429–1443

[10] B Praveen Kumara, D Prince Winston, P Pounraja, A Muthu Manokar, Ravishankar Sathyamurthyd,e,f and A E Kabeel 2017 Experimental Investigation on Hybrid PV/T Active Solar Still with Effective Heating and Cover Cooling Method (Desalination)

[11] M Yari, A E Mazareh and A S Mehr 2016 A Novel Cogeneration System For Sustainable Water And Power Production By Integration Of A Solar Still And PV Module (Desalination) vol 398 pp 1–11

[12] F S and F S E Hedayati-Mehdiabadi 2017 Energy Analysis Of A Stepped Cascade Solar Still Connected To Photovoltaic Thermal Collector (Int J Automot Mech Eng.) vol 14 pp 4805–4825

[13] A M Manokar, D P Winston, A E Kabeel and R Sathyamurthy 2017 Sustainable Fresh Water and Power Production by Integrating PV Panel in Inclined Solar Still (J.Clean Prod) vol 172 pp 2711–2719

[14] P Pounraj, D P Winston, A E Kabeel, B P Kumar, A M Manokar, R Sathyamurthy and S C Christabel 2018 Experimental Investigation On Peltier Based Hybrid PV/T Active Solar Still For Enhancing The Overall Performance (Energy Convers Manag) vol 168 pp 371–381

[15] M Naroei, F Sarhaddi and F Sobhnamayan 2018 Efficiency of a Photovoltaic Thermal Stepped Solar Still (experimental and numerical analysis, Desalination) vol 441 pp 87–95

[16] A Moh'd Al-Nimr and A Wahib Al-Ammari 2016 A Novel Hybrid PV-Distillation System (Sol Energy) vol 135 pp 874–883

[17] Zeyad A Haidar, Jamel Orfi and Zakariya Kaneesamkandi 2018 Experimental Investigation of Evaporative Cooling for Enhancing Photovoltaic Panels Efficiency (Results in Physics)

[18] A K Kaushal a, M K Mittal a and D Gangacharyulu b 2017 An Experimental Study of Floating Wick Basin Type Vertical Multiple Effect Diffusion Solar Still with Waste Heat Recovery (Desalination) vol 414 pp 35–45

[19] Z A Haidar, J Orfi, H Oztöp and Z Kaneesamkandi 2016 Cooling of Solar PV Panels Using Evaporative Cooling (J. Therm. Eng.) vol 2 pp 928–933

[20] M Lucas, F Aguilar, J Ruiz, C Cutilias, A Kaiser and P Vicente 2017 Photovoltaic
Evaporative Chimney as a New Alternative to Enhance Solar Cooling (Renewable energy) vol 111 pp 26–37

[21] M Chandrasekar and T Senthilkumar 2015 Experimental Demonstration of Enhanced Solar Energy Utilization in Flat PV (Photovoltaic) Modules Cooled by Heat Spreaders in Conjunction with Cotton Wick Structures (Energy) pp 1–10

[22] Mohamed El Amine Slimani, Madjid Amirat, Ildikő Kurucz, Sofiane Bahria, Abderrahmane Hamidat and Wafa Braham Chaouch 2016 A Detailed Thermal-Electrical Model of Three Photovoltaic-Thermal (PV/T) Hybrid Air Collectors and Photovoltaic (PV) Module: Comparative Study Under Algiers Climatic Conditions (Energy Conversion and Management)

[23] Hikmet Ş Aybar 2006 Mathematical Modeling of an Inclined Solar Water Distillation System (Desalination) vol 190 pp 63–70

[24] Salman H Hammadi, Dhafer Manea H and Hussein Ali Jabar 2015 Experimental Study of the Performance of Tubular Solar Still In Najaf City (International Journal of Energy and Environment (IJEE)) vol 6 pp 587–596

[25] Kh Md Islam and T Fukuhara 2007 Production Analysis Of A Tubular Solar Still (Doboku Gakkai Ronbunshuu B) vol 63 no 2 pp 108–119

[26] COMSOL Multiphysics Reference Manual 2015 version 5.0 COMSOL Software License

[27] AS Joshi, A, Tiwari GN, I Dincer and BV Reddy 2009 Performance Evaluation of a Hybrid Photovoltaic Thermal (PV/T) (Glass-To-Glass) System (Int. J. Therm Sci.) vol 48 pp 154–64

[28] Z M Omara, A E Kabeel, A S Abdullah and F A Essa 2016 Experimental Investigation of Corrugated Absorber Solar Still with Wick and Reflectors (Desalination) vol 381 pp 111–116