Solar Driven Agricultural Greenhouse Integrated with Desalination System: Energy-Water-Food Nexus

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Abstract

This study presents the effective performance of a sustainable solar driven agricultural greenhouse (GH) self-reliant of energy and irrigation water via desalination. The GH is furnished with infrastructures such as; (i) - an inlet condenser for cool air exchanger and partial water production, (ii) - an internal cavity for crop production (iii) - roof transparent solar distillers (TSD) for solar desalination and partial shading and (iv)- a thermal chimney for natural air ventilation. A mathematical model is developed to predict the performance of the sustainable GH system. A coupled approach of MATLAB/Simulink and computational fluid dynamics (CFD) based on three simulation models were used: solar radiation, thermal energy balance and CFD model. Two parametric studies were carried out. The first one analyzed the effects of different air velocity on the system thermal performance and natural ventilation rate. The second study assessed the effects of different covering material on the transmitted solar radiation. Results from the model shows that 8.5 MJ/m².day of total solar radiation is transmitted into the GH. The greenhouse air temperature is lowered by 5°C and humidified by 20%, to satisfy the required conditions necessary for plant growth. Maximum water yield of 11.5 L/m².day was obtained, aided by the addition of Al-metal
Additionally, 2.6 kWh/m².day of power is consumed by the air-cooling condenser.

At air velocity of 0.3 m/s, there is a natural tendency of air to flow by draft, due to air temperature difference of up to 4 °C. Furthermore, glass and EVA cover materials transmit 52 and 48 % of solar radiation into the GH respectively. The proposed system will enable the parallel production of water and food and enhance economical plant productivity.

**Keywords:** Sustainable greenhouse; Desalination; Condenser; Solar distillers; Natural ventilation
Solar driven agricultural greenhouse integrated with desalination system represent one of the best applied example of the energy-water-food nexus. This integrated system not only provide its own irrigation water, it also provide a controlled environment necessary for food production and has the potential to generate electrical energy via photovoltaic (PV) cells [1]. The UN world water development report 2015 states that by 2050, an increase in 55 % of global water demand will be observed, and the world's agricultural sector will be required to generate 60 % more food, reaching up to 100 % in the developing nations [2]. The 2017 World Health Organization (WHO) reports that, with the prevailing climate change situation, more than 50 % of the world population will exist in high water stress areas by 2030 [3]. The intensifying water crisis is also associated to food production since agriculture accounts for 70 % of all freshwater usages [4], hence fresh water supply is one of the most significant future issues [5]. The evident increasing demand for food, energy and water, coupled with the ever-increasing scarcity of land resources, this study aims to tackle these issues by proposing the investment of solar energy into desalination and greenhouse systems. An agricultural greenhouse (GH) is an enclosed transparent house used to protect
crops from critical ambient climate conditions and pests, and provide the opportunity
to adjust the indoor microclimate suitable for crop growth and production, both in terms
of quantity and quality [6]. GH enables year-round crop production and improves the
yield and quality of crops through control of the physical environmental factors such as
light, water, temperature, relative humidity, CO2 concentration, and ventilation [7]. GH
technology can guarantee the sustainable and secure food production by increasing the
production yield up to ten times more [1], and decreasing the 11.8 m³/d per capita water
requirements by 80 % compared to conventional cultivation [2, 3]. However, GH
energy consumption can be up to one hundred times more [8]. Thus, one of the
substantial technical challenges of GHs is management of energy consumption [9].
Renewable energy technologies provide access to the secure and environmentally
sustainable supply of energy and can be cost-effective as well [10]. For sustainability,
solar thermal appears to be the most sustainable energy resource [11]. Since the GH
itself functions as a solar collector, solar energy utilization can lead to a reduction in
production cost [12].

All GH systems, irrespective of physiographical location, consist of essential
climate control mechanisms and components, and depending on their design and
complexity, they are capable of providing a major or minor amount of environmental
control, and consequent plant growth and productivity. The major fundamental GH
microclimate environment is strongly reliant on available solar radiation, temperature
manipulation, humidity control, CO₂ concentration and air ventilation [13, 14].

Temperature management is essential to influencing plant growth and development,
with an average range of 17°C to 27°C, over which there is a near linear positive
response in terms of increased growth [15]. Humidity (RH) in GHs is controlled to
ensure adequate transpiration and also reduces fungal infection. As a general guide, it
is often recommended that GH RH be maintained within the range 60-90 % suitable for
healthy plant growth. CO₂ enrichment is also vital in GH production with most plants
showing a positive response to increased CO₂ levels up to 1,000 - 1,500 ppm [13, 15].

Ventilation is necessary during summer periods to prevent excess rise of GH
temperature above the ambient air. The rate of ventilation varies between 20 and 180
air changes per hour [3].

Agricultural GHs have shown great complexity and diversity depending on its
location across the globe. For cold climates, GH are specifically designed to provide a
warmer environment for crops to grow, such as the so-called active (or heated)
greenhouses equipped with several heating devices. Meanwhile, GH combined with shading, ventilation (passive GH), or cooling systems are used in hot climates to control the inner environment. Ghani et al. [16] comprehensively reviewed several GH designs features in hot and arid climates. The review involved GH shape, dimensions, orientation, cooling methods, and the renewable technologies applicable in GHs. Due to the continuous increase in energy prices and climate concerns, the energy consumption in GH systems became one of the main challenges especially in hot climate [17]. In general, two methods can be used to reduce the energy consumption of agricultural GH systems. These methods are the integration of semi-transparent photovoltaic (PV) and solar distillation units on the GH roof [18, 19]. Several integrated GH systems utilizing solar radiation above plant needs have been documented. Yano et al. [20] established two prototypes of semi-transparent photovoltaic (PV) modules proposed for GH roof applications. The yearly electrical energy production estimate showed that these PV modules are potentially suitable for GHs in high solar radiation regions, where electrical energy production could be high. Yohannes and Fath, [21] developed an agriculture GH model with in-built Transparent Photo-Voltaic (TPV) panels to be energy self-sufficient and produce irrigating water for the hot
environmental conditions of Abu Dhabi, UAE. Hassan et al. [19] investigate the effect of cooling system condenser properties on the interior climatic conditions inside a GH integrated with on-roof TPV. The results demonstrate that the GH satisfy the required micro-climatic conditions for plants growth and be self-sufficient of irrigating water during a hot day for Abu Dhabi, UAE.

Many studies are concerned with the integration of a solar distillers with a GH system. Fath and Abdelrahman [22] studied the numerical performance of a GH covered with on-roof transparent solar still at 30° inclination. The GH shows to withstand harsher environmental conditions when integrated with an on-roof solar still. Radhwan [23] developed a stepped-solar-still for GH heating and humidification. The total daily yield of the solar stills is about 4.92 L/m², and the daily average efficiency is about 63%. Chaibi [24] performed a numerical and experimental deviation study of a small water desalination module to be placed on a GH roof, and obtained a 25% deviation between calculated and measured water production. Mari et al. [25] conduct an experimental and theoretical study to examine the performance of 28 on-roof solar still integrated into a GH. Results revealed approximately 52% reduction in solar radiation inside the GH, the theoretical model also overestimate the water yield by
approximately 15% higher than the measured one. Radhwan and Fath [26] experimentally investigate the thermal performance of an agricultural GH consisting of 24 on-roof solar stills distillation system. For the summer condition of Jeddah, Saudi Arabia, the results showed that the temperatures inside the GH are 8–10° (at GH inlet) and 3–6° (at GH outlet) below ambient temperature. The relative humidity inside the GH is found to vary between 20% and 35% above ambient conditions, satisfying the comfort zone of the plant growth. They obtained a relatively small water production range from 1.7 to 2.5 L/d, mainly due to relatively high glass temperature. A solar GH with built-in water desalination system and humidification-dehumidification (HDH) system was analytically studied [27]. This integrated system uses the excess solar radiation (excess of the crop requirement) to desalinate water and reduce the cooling load of the greenhouse. The results showed that, by controlling the fresh-air ratio and condenser by-pass ratio, the interior climate of the GH will satisfy the comfort zone for plant growth. The system can produce about 8.6 kg/m².day of water. Rabhy et al. [28] developed an experimental and numerical analyses of a transparent solar distiller suitable for agricultural GH. The system results show about 37.5% of irrigation water can be produced, whiles the power consumption of the GH cooling system can be
reduced by 60%. Other developed integrated system include the ‘Watergy’ GH system, developed for integrated water treatment, solar thermal energy collection and advanced food production suitable in the arid and Mediterranean regions [29]. De Zwart [30] also developed a system called ‘Sunergy’, which is a semi-closed GH that is closed during periods with high solar radiation, to enable harvesting of solar energy at moderately high temperatures, and allows ambient air exchange during cloudy days and at night, for dehumidification. Seawater GH is another strategy developed based on solar distillation units for arid countries in the Middle East to challenge the high temperature, water salinity, and water scarcity problems. These concepts were examined using both experimental setups [31] and energy and mass balance models [32]. The main conclusions of this studies were that semi-transparent solar still modules can be integrated into a GH roof in order to control the solar radiation and produce fresh water, which could meet the irrigation demand of GHs.

The main contribution of this study is to integrate all the elements of energy-water-food nexus into a system capable of producing food, water and reducing energy consumption, while also cutting costs and improving the quality of the combined services. A sustainable GH system is developed, which was integrated with transparent
solar distillers (TSD) and equipped with a chilled water condenser at the entry of the GH cavity. The design concepts are based on micro-climate control strategies, renewable energy water production sources and application of innovative covering materials. Firstly, it presents and uses a method to couple MATLAB/Simulink with computational fluid dynamics (CFD) for GH climate modelling. The MATLAB model were used to predict surface temperatures, condenser effects, water production and power consumption, which were then used as boundary condition in the CFD model to determine the micro-climatic condition of the GH cavity. Secondly, the effects of different operating parameters on the micro-climatic conditions inside the GH (air temperature and relative humidity), water production and electrical power consumption of the GH are investigated. The simulations are carried out to evaluate the performance of the GH for the metrological conditions of a Mediterranean climate. Furthermore, the GH model was analyzed for its natural ventilation performance. This developed model will provide the basis for further investigation and designing next generation GHs, for sustainable agriculture in the MENA-GCC and other water-stressed regions.

2. Materials and methods

2.1 System Description
The conceptual configuration of the GH is demonstrated in Fig. 1. Briefly, the GH system consists of an interior glass covered plant cavity, a chilled water condenser at the entry of the GH cavity, a vertical and inclined riser, set of transparent solar distillers placed on the risers, a thermal chimney and a vertical down comer channel. The GH structure was designed facing the south in order to receive maximum solar radiation while minimizing heat loss. Geometrical dimension of the GH is given in Table 1.

Ventilation fresh air (a1) at ambient condition enters the GH through an inlet condenser. In the condenser, the air is partially cooled and humidified, depending on the ambient temperature and relative humidity. The cool air (a2) then mixes with the bypassing air and moves through the interior GH cavity (a1), where it gains heat and water vapor through convection and plant transpiration. The heated air then leaves the GH cavity through an outlet condenser (a3), where it gets cooled to saturation condition and condense the water derived from plants transpiration. The cool air (a4) then mixes with the bypassing air and flow through the vertical (a5) and inclined risers (a6), to gain extra heat from solar stills and glass covers. Depending on the seasonal condition, the heated air then either leaves the GH to the atmosphere through a thermal chimney or partially recirculated from the down comer (a7) into the GH cavity to mix with the fresh
ambient air. In the current paper, the outlet condenser is not active (switched off) and no air recirculation through the down comer.

The integrated transparent solar distiller is illustrated in Fig. 2. The solar distillers are oriented to face the south with a cover tilt angle of 30°, which is equal to the solar latitude angle of the target study area [28]. The solar distillers are designed to be transparent to enable solar light reach plant region for photosynthetic process. Further, the solar distillers will serve as partial shading thereby reducing the GH cooling load and utilize the excess solar radiation (above plant need) for water desalination. The solar still desalination works based on evaporation and condensation [2]. Solar radiation passes through the glass cover and converts the saline water into vapor. The water vapor flows up and condenses on the inner surface of the inclined cover due to temperature differences. The purely desalinated water is then collected via the distillation trough [33]. Due to the low gained output ratio (GOR) of solar still desalinations, an aluminum (Al) metal net is added to the base of the distillers to enhance productivity by increasing the absorption of solar radiation. A parametric study is performed to determine the effect of net area ratio on the total solar radiation transmitted into the GH cavity.

2.2 Model Development
In this sustainable GH analysis, an integrated approach of MATLAB/Simulink and ANSYS-CFD models are used in three steps of calculations. The process is summarized as follows; Firstly, a transient mathematical model was used to calculate the instantaneously incident global solar radiation received by the GH covers based on a Clear Day Solar Flux Model [27, 34]. Secondly, a transient thermal model based on energy and mass balance equations were used for each component of the GH system to predict the thermal behavior of the system. The equations were solved using MATLAB. Finally, a 2-D ANSYS-CFD model was then developed to determine the microclimatic condition (in terms of air velocity, temperature, relative humidity and water vapor) within the GH cavity.

Fig. 3 shows briefly the system methodology. The calculated solar radiation by the clear sky model and the ambient conditions (of temperature, RH, wind speed) were used as inputs for the thermal model. The glass surface temperatures and condenser air temperature predicted by the thermal model were used as input for the boundary condition of the CFD model. The continuity, energy, species and mass transport equations were solved numerically. The CFD model methodology will be explained in Section 2.2.3.
2.2.1 Solar Radiation Model

The instantaneous overall solar radiation incidental on the inclined surface of the GH depends on the declination & solar altitude angle, latitude and surface inclination angle. In this model, the instantaneous global solar radiation incident on each GH surface is predicted according to Eqns. 1-6 [27, 34].

\[ I_\beta = I_{B\beta} + I_{D\beta} + I_{R\beta} \]  

\[ I_{B\beta} = A e^{-k * sec \theta_z} \cos \theta_z \]  

\[ I_{D\beta} = C * A e^{-k * sec \theta_z} * 0.5(1 - \cos \beta) \]  

Where \( I_\beta \) is the incident global solar radiation, \( I_{B\beta} \) is the direct beam radiation, \( I_{D\beta} \) is the diffused radiation, \( I_{R\beta} \) is the reflected solar radiation.

The zenith angle \( (\theta_z) \) on an inclined surface of the GH is calculated according to Eqn.4,

\[ \cos \theta_z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega \]  

Declination angle \( (\delta) \) is calculated as below,

\[ \delta = 23.45 \sin \left( 360 \frac{284 + n}{365} \right) \]  

To calculate the total solar radiation received on the GH and TSS components, the Eqn. below is used,
\[ s_t = \sum A_i I_i \]  

Where \( A_i \) and \( I_i \) represent the area and the total incident radiation reaching the \( i^{th} \) section. The values of \( A \), \( k \) and \( C \) are 1069 W/m\(^2\), 0.205 and 0.134 respectively for 21\(^{st}\) June giving from the ASHRAE model [35]. Solar radiation inside the GH is calculated based on the above equations using the transmissivity of each cover material layer and water.

2.2.2 Thermal Model

To predict the transient surface temperature of the GH cover components, heat air exchange, condensed water from moist air condenser, yield produced from the TSS and the electrical power consumed by the condenser are achieved from the equations of energy and mass balance. The mathematical model is developed with the following assumptions [36]:

(1) Clear sky solar radiation model is applied
(2) Air is assumed transparent for long and short-wave radiation and its absorptivity is neglected
(3) Plant thermal properties are equivalent to that of water due to the high content of water in the plant
(4) Relative humidity and temperature of circulating air are presumed to be uniform.

(5) GH component temperatures are lumped (i.e. same throughout).

(6) Temperature of earth below the ground is assumed constant at 15 °C and evaporation of the floor is negligible.

(7) GH is assumed to be properly insulated with no leakage through the walls.

(8) Thermal analysis is based on quasi-steady state conditions inside the greenhouse due to transient behavior for short time intervals and heat transfer is one-dimensional.

The main governing equations are listed below, Eqns. 7-11, [19, 27]

For transient temperature change for each GH and TSD components;

\[
\frac{dT}{dt} = \frac{1}{M \cdot C_p} \left( \sum Q_{in} - \sum Q_{out} \right) \tag{7}
\]

For air flow, Eqn 8 applies;

\[
m_a (h_o - h_{in}) = \left( \sum Q_{in} - \sum Q_{out} \right) \tag{8}
\]

For condensed water from the condenser;

\[
m_c = m_{\text{cond}} (w_{in} - w_{out}) \tag{9}
\]

From the TSD, the produced distillate is calculated as follows;

\[
m_{TSD} = \frac{Q_e}{h_{fg}} \tag{10}
\]

The electrical power is calculated as follows;
\[ \text{power} = \frac{m_{\text{cond}}(h_{\text{in}} - h_{\text{out}})}{COP} \]  \tag{11}

The input data for the thermal model are the calculated solar radiation and the climate metrological data of temperature, relative humidity and wind speed. Fig. S1 (supplementary material) illustrates the universal energy and water vapor fluxes within the GH, which were used to define the mass balance and energy balance equations of the proposed model. Fig. S2 (supplementary material) illustrates the flow chart of the mathematical model procedure.

2.2.3 CFD Model

2.2.3.1 Governing Equations

To study the internal climatic condition of the GH cavity, heat transfer processes are solved using the CFD code (ANSYS Fluent). The flow inside the GH was considered as two-dimensional, an-isothermal, fully turbulent and incompressible flow. The CFD code uses the finite volume method for solving the governing equation of fluid flow and heat transfer based on mass, energy and momentum conservation, i.e. the Navier–Stokes equation. The transport equation of air flow based on the Navier–Stokes equation is given by [37]:

\[ \frac{\partial \rho \psi}{\partial t} + \nabla \cdot (\rho \psi \mathbf{v}) = \nabla \cdot (\Gamma \nabla \psi) + S_m \]  \tag{12}
Where $\rho$, $t$, $\psi$ and $\nabla$ are the density, time, concentration variable and divergence operator respectively. $\vec{v}$ and $\Gamma$ are the velocity vector and diffusion coefficient. The source term, $S_m$ is added due to crop transpiration.

The Energy Equation balance is giving by equation 13 [22];

$$
\frac{\partial}{\partial x_i} \left[ u_i (\rho e + p) \right] = \frac{\partial}{\partial x_i} \left[ \left( K + \frac{C_p \mu_i}{\rho \tau} \right) \frac{\partial T}{\partial x_i} - \sum h_j J_j \right] + S_h
$$

(13)

Where $e$, $K$ and $h_j$ represent the total fluid energy, thermal conductivity and and species sensible enthalpy respectively.

The species transport equation and conservation equation for air and water vapor fraction was activated using the mass fraction of H2O (w/w) described by equation 14 [38].

$$
\frac{\partial}{\partial t} \left( \rho Y_{H_2O} \vec{v} \right) = \frac{\partial}{\partial t} \left[ (\rho D_{H_2O} + \frac{\mu_t}{S_{ct}}) \frac{\partial Y_{H_2O}}{\partial t} \right] + S_{H_2O}
$$

(14)

Where $S_{H_2O}$ represent water vapor added or removed from the air due to condensation or evaporation. The constant $D_{H_2O}$ is the diffusion coefficient of water vapor into air which is equal to $2.88 \times 10^{-5}$; $S_{ct}$ is the turbulent Schmidt number which is equal to 0.7.

To account for turbulences, the standard $k-\varepsilon$ model with wall function was used [39].

This model solves for turbulent kinetic ($k$) and the rate of dissipation of energy ($\varepsilon$) in
unit volume and time. This model has been used in GH CFD simulations with success, providing good agreement with experimental results [40]. The equations for $k$ and $\varepsilon$ are giving below, respectively.

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \tag{15}
\]

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_3 \varepsilon G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \tag{16}
\]

From the equations, $G_k$ and $G_b$ represent the generated turbulence kinetic energy due to mean velocity gradients and buoyancy respectively, $Y_M$ represents the dilation fluctuation contribution in compressible turbulences. The constants are giving below [22].

\[ C_{1\varepsilon} = 1.44, C_{2\varepsilon} = 1.92, C_\mu = 0.09, \sigma_k = 1.0, \sigma_\varepsilon = 1.3 \]

The plant was considered as porous media with the source term governed by the Darcy–Forchheimer equation which include the viscous loss term and inertial resistance loss term [41].

The Darcy law is giving by;

\[
S_i = -\left( \frac{\mu}{\alpha} u + C_2 \frac{1}{2} \rho |u| u \right) \tag{17}
\]

Where $\alpha$ and $C_2$ represent the permeability and inertial resistance factors of the porous medium, whose values are chosen to represent the crop under consideration.

2.2.3.2 Geometry creation and grid generation
The 2D computational domain was created using ANSYS Design Modeler 18.2.

The geometrical characteristics of the GH were assigned according to what is presented in Table 1. A 2D structured mesh was generated using Ansys Mesh workbench, which consist of approximately 71,000 cells. A structured Cartesian mesh was chosen to limit the numerical diffusion of errors and facilitate calculation convergence.

Four different element sizes of the structural grids are used to test the grid independence; including the coarse (0.5 m), medium (0.3 m), fine (0.1 m) and very fine (0.05 m). Two of the simulation parameters, air velocity out (V_{out}) and pressure in (P_{in}), are selected to evaluate the effect of the grid density. The V_{out} and P_{in} calculated from the coarse and medium grid deviate significantly, while the fine and very fine grid represent similar results. Therefore, the fine grid system was used to conduct our simulations, considering the efficiency and computing accuracy. The quality of the grid was checked by applying the skewness parameter. The skewness parameter indicates how ideal a cell shape is. The mesh used gave a maximum skewness parameter of 0.5, which falls into the “good” range, according to the Ansys Fluent manual [42].

2.2.3.3 Method of solutions and boundary conditions

Academic ANSYS FLUENT V18.2 was used to carry out the CFD analysis. The
computational domain was meshed using a two-dimensional structured mesh with 71,748 cells. The CFD code solves the transport equation using the finite volume method for each cell. To account for pressure velocity coupling, the SIMPLE algorithm was used [41]. The CFD numerical model parameters are enumerated in Table 2. The convergence criterion is set to $10^{-6}$ for the continuity, momentum and turbulence equations, and $10^{-8}$ for the energy equation.

The glass cover and air temperature variations, which were predicted by the thermal model, were considered as the boundary conditions for the CFD model. The interior GH cavity were simulated in the CFD model for full day, in an hourly quasi-steady-state condition. The main working fluid in this simulation is a mixed species of water vapor and air, whose density depends on the operating pressure while the specific heat, thermal conductivity and viscosity were taken as a function of temperature. The plant region is simulated as porous material with viscous resistance $\alpha^{-1} = 2.532$ m$^{-2}$, inertial resistance $C_2 = 1.6$ m$^{-1}$ and porosity of 40%. The participating solid material in the porous media calculation is considered as a fully developed tomato plant whose properties are detailed in Table 3. Thermo-physical properties of other materials like glass, water and ground are giving in Table 4 [43, 44].
2.2.4 Parametric study

The general performance of the GH system on four different air velocities (0.6, 0.5, 0.4, 0.3 m/s) were examined. Four different cover materials were also studied; (a) glass, (b) Ethylene vinyl acetate film (EVA), (c) polyethylene (P.E), (d) polyvinyl chloride film (PVC), whose optical properties are given in Table 5 [43, 45].

3. Results and discussion

3.1 Model Validation

To validate this model, the interior GH temperature and relative humidity is firstly compared between simulation and published data of [27] for the ambient condition of 21st June. Fig. 4 shows the simulation and validation data of the average air temperature and relative humidity inside the GH cavity. The trend of the air temperature (Fig. 4a) shows close agreement especially during solar hours, the difference between the simulation and validation values was always less than 1°C. Regarding the relative humidity (Fig. 4b), the agreement was particularly good during the solar hours, the maximum difference between both values occurred after midnight, when the validation values dropped more quickly than those predicted by the CFD model. In all cases, the maximum relative humidity difference was less than 7%. A good comparison between
the two values suggest that the simulation of temperature and relative humidity propagation inside the GH interior is successful. Therefore, in view of the validation results of the model, the CFD model proved to be a satisfactory predictive model that could be used to predict the temperature and airflow distributions in GHs. Hence, the CFD can therefore, be a very useful tool in the study of the internal microclimatic conditions of the GH system.

3.2 Effect of TSD on transmitted solar radiation

The key for designing transparent GHs is to get enough solar radiation into the GH. The threshold of solar intensity required for plants photosynthetic process is 8.5 MJ/m².day [46, 47]. During the summer, excess solar radiation about twice the plant need is available. To utilize the excess solar intensity, this study integrates transparent solar distillers into GH roof. To improve productivity of the distillers, an Al-metal net were added to the base of the solar distillers to increase solar absorptivity and decreases transmissivity into the GH. Fig. 5 shows the effect of the Al-metal net on the transmitted solar radiation and the daily variation of the direct solar radiation reaching the GH. Firstly, we study the effect of the Al-metal net area ratio to the solar still base. In Fig. 5a, when the net area ratio is zero (i.e. no metal net added), 14 MJ/m².day of total solar
radiation is available during the day. By increasing the net-area ratio, the total solar radiation transmitted into the GH decreases, reaching the required threshold of 8.5 MJ/m².day at a net area ratio of 0.75. Fig. 5b present hourly variation of the transmitted solar radiation into the GH through each cover, for the maximum radiation day of 21st June, with glass cover material. The solar intensity varied in a sinusoidal way with total available direct solar radiation of 8.5 MJ/m².day, the maximum value of 250 W/m² recorded during solar hours. The solar distillers reduce the transmitted solar radiation by ~50%. These solar intensity data were then used to compute the temperature on individual roof and wall of the GH using the standard ASHRAE model.

3.3 GH system operational performance

The operational performance of the GH in terms of air temperature, relative humidity, freshwater production and power consumption of the air-cooling condenser are analyzed. The evolution of these factors throughout the day for the examined air velocity are presented.

Fig.6 illustrate the hourly variation of the average air temperature in the GH cavity for the 21st of June, for the four examined air velocity and the ambient temperature. In all cases, the GH air temperature is lower than the ambient temperature because of the
effect of condenser air-cooling, and the solar distillers serving as a partial shading.

While the ambient air temperature varies between 24°C to 31°C, the GH (cavity) average air temperature varied from 20°C to 26°C. During this day, as the sun rose around 6:00 AM, GH temperature began to rise until it reached 26°C. As the sun set, around 6:00 PM, the solar radiation intensity and ambient temperature dropped, the GH air temperature also dropped accordingly to a value below 22°C. Despite the change in air velocity, the GH air temperature were similar, satisfying the required condition needed for plant growth.

In Fig. 7, the average air relative humidity inside the GH cavity and the ambient for the four examined air velocities are giving. The GH air relative humidity is 15 to 20% higher than that of the ambient. This is because the air gets humidified in the condenser and from plant transpiration. The ambient relative humidity varies between 45% and 80%, in the GH it varies between 60% and 90%. The relative humidity obeys the sinusoidal trend with its minimum value at midday. Favorably, lower relative humidity at mid-day aid the air-cooling condenser in reducing the high ambient air temperature. The difference of the average air relative humidity among the examined air velocities are not important, since the mechanism of vapor transfer remains the same.
In all cases, the air relative humidity inside the GH cavity is within the satisfactory values (comfort zone) for plants growth.

Fig. 8 presents the hourly accumulated water production from the TSD and the condenser for the examined air flow rates. The addition of Al-metal net enhances the productivity of the TSD, producing averagely over 60% of the accumulated water. The major difference in water production from the examined air velocities is found in the condenser distillate, since the condensed water production depends on the mass flow rate of air passing through the condenser. At air flow rate of 0.3 m/s, over 9 L/m².day of water is produced. The distillate water production increases with an increase in air flow velocity, an additional 2.5 L/m².day of water production was observed at increasing air flow velocity from 0.3 to 0.6 m/s. Overall, the GH system is capable of producing freshwater which exceed the average irrigation water demand of a GH (2 L/m².day) [28, 48],

Fig. 9 shows the accumulated power consumed by the air-cooling condenser for the examined air flow rates. At air flow rate of 0.3 m/s, 1.3 kWh/m².day of energy is consumed by the air-cooling condenser to produce 2.7 L/m².day of fresh water. Increasing the air flow rate from 0.3 m/s increases the energy consumption by 0.43
kWh/m².day for each step increase. This is due to the increase in mass flow rate of air passing through the condenser. At 0.6 m/s, the energy consumption is about 2.6 kWh/m².day, producing 5.4 L/m².day of fresh water. Integrating an agricultural GH with transparent solar distillers decreases power consumption for air cooling by approximately 60% [28]. For all examined air flow rates, the condenser consumed reasonable amount of energy for air cooling and distillate production, these results are consistent with Hassan et al. [19]

3.4 Optimal growing conditions

An appropriate microclimate for plant growth and development is characterized by the solar light availability, when it is up to 8.5 MJ/m².day, the temperature range varying between 14 and 28 °C, RH of 60 – 90% and air velocity between 0.2 to 0.5 m/s.

In order to assess the efficiency of each examined air flow rate, distributions and profiles for air velocity, temperature and humidity for the mid-day at a flow rate of 0.5 m/s are presented. Fig. 10 shows the CFD simulation results for GH air temperature, velocity vectors and relative humidity contours at 12 P.M of 21st June with glass cover material. At this time, the ambient air temperature is 304 K, the outside relative humidity is 46 % and the wind speed is 0.5 m/s.
Fig. 10a indicates the temperature distribution inside the GH cavity. The GH air temperature in the plant region is slightly cooler than the ambient air, with an average GH air temperature of 299 K. This is due to the cooling effect created by the inlet condenser. The CFD model also shows the solar distiller region (roof) of the GH as the hottest surface, which intercepts majority of the solar radiation. The GH air temperature is uniform for most of the GH cross section, with the left region of the cross section slightly warmer. This is due to the air heating by convection and plant transpiration as it passes through the GH cavity, and transferring the heat to the GH roof, which becomes warmer than other regions in the GH.

Fig. 10(b) and (c) show the relative humidity and water mass fraction contours predicted by the CFD model at 12 P.M for the same set of boundary conditions. Fig. 10b shows an increase in humidity immediately after the condenser, since the air gets humidified in the condenser unit. As the air flows in the plant region, the air becomes warmer and humidified from plant transpiration. The average air relative humidity in the plant region is 62%, which is higher than the ambient RH of 45%. The water mass fraction (Fig. 10c) also increases in a streamwise direction in the plant zone, due to water vapor generated inside the plant region. The water mass fraction was slightly
higher in areas with higher air temperatures (Fig. 10a), since hot air holds more water vapor.

Fig. 10d illustrate the air velocity vectors developed inside the GH at 12 P.M for the 21st June. The air velocity depends on the opening area, which is 1 m², with an average air velocity of 0.5 m/s at the inlet opening. In the plant region, the air velocity is damped due to high resistance of plant to air flow. This causes a strong stream of air to flow over the plant, while a weaker stream flow under the plant (as seen from the stream function contours). The average air velocity in the plant region varies between 0.1-0.2 m/s, which perfectly suits plant growth conditions.

3.5 Natural ventilation performance

This sustainable GH will aim to rely on natural ventilation driven by two mechanisms, namely the wind induced pressure field around the GH and the buoyancy force induced by the warmer and more humid air in the GH riser. Natural ventilation is effective if the outside temperature is low compared to GH riser air temperature, where the difference in density between the inside and outside air causes natural draft [49]. Air temperature and humidity differences between the inside and outside of a GH produce forces that drive flow. The natural tendency for hot and humid air to rise and
accumulate towards the upper part of a space leads to stable stratification, and this has
a significant influence on the flow patterns within the GH. The determining factor in
the form of the vertical stratification is the location of the openings. The warm and
humid air will flow out over the upper area of the opening and the cool air will enter
through the lower area of the opening.

Buoyancy driven ventilation is significant only at low wind speeds. At low wind
speed, the buoyancy effect is the main driving force of ventilation in a GH with plant.
To evaluate the natural ventilation of this GH, the temperature field on the inclined riser
generated by the four different air velocities is shown in Fig.11. During the day, the air
temperature at the inclined riser (T_a6) is higher than the ambient air temperature at
wind speed of 0.3 and 0.4 m/s. At speed of 0.3 m/s, the air temperature at the inclined
riser is 4 °C higher than the ambient. This is due to the absorbed solar radiations by the
solar stills and dissipated subsequently as latent and sensible heat inside the GH. During
the non-solar hours, the outside air is warmer than the inside GH due to the cooling
effect created by the condenser. To achieve natural ventilation at night, the condenser
may have to be turned OFF. Hence, natural ventilation could be maintained in the GH
especially during the daytime. This conditions also satisfy the air exchange rate of 0.7
3.6 Covering material parametric study

GH sustainability depends largely on cover material, as it influences the GH microclimate and protect plants from adverse weather conditions. The evolution of basic factors such as transmitted solar radiation, interior air temperature and water production for each examined cover material are presented. Fig. 12a present the instantaneous total solar radiation transmitted into the GH cavity for the examined cover materials for the maximum radiation day of 21st June. The highest transmitted solar radiation is achieved with the glass and EVA cover, with 52 and 48 % solar radiation transmitted into the GH respectively. The PVC cover allows lower transmittance (~ 30 %) due to its high absorptivity, which may become less in winter season. The air temperature and relative humidity differences inside the GH cavity for the studied cover materials are not significant (data not shown), because the main mechanism of heat transfer is from convection of the entering air stream and the effect of air-cooling condenser. For water production, Fig. 12b shows the accumulated water production for the examined cover materials. Less water is expected to be produced from the transparent solar distillers for PVC and P.E covers due to high material
absorptivity and low transmitted solar radiation. Although sufficient amount of fresh water is expected to be produce from the air-cooling condenser unit.

4 Conclusions

In this study, a newly developed solar driven agricultural greenhouse for air cooling, and solar energy application for irrigation water production is presented. The potentials of using an integrated TSD-GH system was investigated, combining water production and agricultural farming in the same area. The potential harmony between solar radiation availability and the demand for irrigation water is illustrated. A new coupled approach of MATLAB/Simulink and CFD modelling methodology was developed to predict the performance of the sustainable GH system. This approach takes advantage of the strength of each tool to study, with accuracy, the full functionality and requirement needed to operate a sustainable GH integrated with solar desalination system. The calculations are implemented for the external environmental condition of 21st June, representing the maximum radiation day of Borg-El-Arab, Egypt.

In general, the excess solar radiation was utilized, allowing 8.5 MJ/m².day of solar intensity threshold for plant photosynthetic process. An AL-metal net was added to trap the excess solar radiation for enhanced desalination water production. A parametric
Study was carried out to investigate the effect of different air flow velocity and covering materials. Increasing the air velocity by 0.1 m/s increases the water production by 0.75 L/m².day, and power consumption by 0.43 kWh/m².day. At wind speed of 0.3 m/s, air temperature at the inclined riser is 4 °C higher than the ambient condition. At this condition, there is a tendency of the air to flow by natural draft, hence reducing the fan power. At air velocity of 0.5 m/s (base line), the average air temperature and relative humidity in the GH cavity were 26 °C and 62 % respectively, at 12:00 of the maximum radiation day. For different covering materials, the highest transmitted solar radiation is achieved with glass and EVA cover, with 52 and 48 % solar radiation transmitted into the GH respectively.

In general, to overcome the MENA-GCC drought, this GH is designed to reach a water autonomous irrigation situation by investigating the potential of providing conventional and nonconventional water sources for a water efficient GH. This self-sustainable GH will allow sufficient cooling to enable crop production in the extreme summer climate of the Mediterranean regions. The proposed system will also allow parallel production of food and water and enhance plant productivity. The desalination components may perhaps enable regional progress in GH production into arid and
MENA-GCC regions. In the next step of this research, a comprehensive economic analysis and development of an experimental model are proposed. The economic analysis will include the capital and operating cost of the integrated system. The major capital cost will include building construction, cooling system, transparent solar distillers, irrigation system, water storage tank, fan ventilation systems, lightening and other machinery and equipment. Operational cost will consist of labor cost, material input, marketing, fertilizer and repair and maintenance cost. The experimental validation will be built along the shores of the Mediterranean Sea in Borg Al-Arab Egypt, using cost effective and sustainable materials.

**Declarations**

**Availability of data and materials**

All data generated or analyzed during this study are available from the corresponding author on reasonable request.

**Competing interests**

The authors have declared no conflict of interests.

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Authors' contributions

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References

1. H. Esmaeli and R. Roshandel, “Optimal design for solar greenhouses based on climate conditions,” Renew. Energy, vol. 145, pp. 1255–1265, 2020.

2. N. Shekarchi and F. Shahnia, “A comprehensive review of solar-driven desalination technologies for off-grid greenhouses,” Int. J. Energy Res., vol. 43, no. 4, pp. 1357–1386, 2019.

3. A. Entezari, R. Z. Wang, S. Zhao, E. Mahdinia, J. Y. Wang, Y. D. Tu, and D. F. Huang, “Sustainable agriculture for water-stressed regions by air-water-energy management,” Energy, vol. 181, pp. 1121–1128, 2019.

4. J. Farfan, A. Lohrmann, and C. Breyer, “Integration of greenhouse agriculture to the energy infrastructure as an alimentary solution,” Renew. Sustain. Energy Rev.,
599  vol. 110, no. August 2018, pp. 368–377, 2019.

600  5. T. Sakamoto, T. Ogawa, H. Nada, K. Nakatsuji, M. Mitani, B. Soberats, K. Kawata,
601  M. Yoshio, H. Tomioka, T. Sasaki, M. Kimura, M. Henmi, and T. Kato,
602  “Development of Nanostructured Water Treatment Membranes Based on
603  Thermotropic Liquid Crystals: Molecular Design of Sub-Nanoporous Materials,”
604  Adv. Sci., vol. 5, no. 1, Jan. 2018.

605  6. J. I. Montero, E. J. Van Henten, J. E. Son, and N. Castilla, “Greenhouse
606  engineering: New technologies and approaches,” Acta Hortic., vol. 893, pp. 51–64,
607  2011.

608  7. G. Giacomelli, N. Castilla, E. Van Henten, D. Mears, and S. Sase, “Innovation in
609  greenhouse engineering,” Acta Hortic., vol. 801 PART 1, no. July 2015, pp. 75–88,
610  2008.

611  8. G. L. Barbosa, F. D. Almeida Gadelha, N. Kublik, A. Proctor, L. Reichelm, E.
612  Weissinger, G. M. Wohlleb, and R. U. Halden, “Comparison of land, water, and
613  energy requirements of lettuce grown using hydroponic vs. Conventional
614  agricultural methods,” Int. J. Environ. Res. Public Health, vol. 12, no. 6, pp. 6879–
615  6891, Jun. 2015.
9. R. H. E. Hassanien, M. Li, and W. Dong Lin, “Advanced applications of solar energy in agricultural greenhouses,” Renewable and Sustainable Energy Reviews, vol. 54. Elsevier Ltd, pp. 989–1001, Feb-2016.

10. IRENA 2015 "Renewable Energy in the Water, Energy & Food Nexus"

11. J. J. Cartelle Barros, M. Lara Coira, M. P. de la Cruz López, and A. del Caño Gochi, “Assessing the global sustainability of different electricity generation systems,” Energy, vol. 89, pp. 473–489, Sep. 2015.

12. G. K. Ntinas, V. P. Fragos, and C. Nikita-Martzopoulou, “Thermal analysis of a hybrid solar energy saving system inside a greenhouse,” Energy Convers. Manag., vol. 81, pp. 428–439, 2014.

13. A. M. Syed and C. Hachem, “Review of Design Trends in Lighting, Environmental Controls, Carbon Dioxide Supplementation, Passive Design, and Renewable Energy Systems for Agricultural Greenhouses,” J. Biosyst. Eng., vol. 23, no. 1, pp. 28–36, 2019.

14. A. Yano, A. Furue, M. Kadowaki, T. Tanaka, E. Hiraki, M. Miyamoto, F. Ishizu, and S. Noda, “Electrical energy generated by photovoltaic modules mounted inside the roof of a north–south oriented greenhouse,” Biosyst. Eng., vol. 103, no. 2, pp.
15. A. Al-Ibrahim, N. Al-Abbadi, and I. Al-Helal, “PV greenhouse system - System description, performance and lesson learned,” Acta Hortic., vol. 710, pp. 251–264, 2006.

16. S. Ghani, F. Bakochristou, E. M. A. A. ElBialy, S. M. A. Gamaledin, M. M. Rashwan, A. M. Abdelhalim, and S. M. Ismail, “Design challenges of agricultural greenhouses in hot and arid environments – A review,” Engineering in Agriculture, Environment and Food, vol. 12, no. 1. Elsevier B.V., pp. 48–70, Jan-2019.

17. A. Marucci and A. Cappuccini, “Dynamic photovoltaic greenhouse: Energy efficiency in clear sky conditions,” Appl. Energy, vol. 170, pp. 362–376, May 2016.

18. M. Cossu, A. Yano, Z. Li, M. Onoe, H. Nakamura, T. Matsumoto, and J. Nakata, “Advances on the semi-transparent modules based on micro solar cells: First integration in a greenhouse system,” Appl. Energy, vol. 162, pp. 1042–1051, Jan. 2016.

19. G. E. Hassan, A. H. Salah, H. Fath, M. Elhelw, A. Hassan, and K. M. Saqr, “Optimum operational performance of a new stand-alone agricultural greenhouse with integrated-TPV solar panels,” Sol. Energy, vol. 136, pp. 303–316, 2016.
20. A. Yano, M. Onoe, and J. Nakata, “Prototype semi-transparent photovoltaic modules for greenhouse roof applications,” Biosyst. Eng., vol. 122, pp. 62–73, 2014.

21. T. Yohannes and H. Fath, “Novel Agriculture Greenhouse That Grows Its Water And Power: Thermal Analysis,” Cancam, 2013.

22. H. E. S. Fath and K. Abdelrahman, “Micro-climatic environmental conditions inside a greenhouse with a built-in solar distillation system,” vol. 171, pp. 267–287, 2004.

23. A. A. M. Radhwan, “Transient performance of a stepped solar still with built-in latent heat thermal energy storage,” Desalination, vol. 171, no. 1, pp. 61–76, 2005.

24. M. T. Chaibi, “Validation of a simulation model for water desalination in a greenhouse roof through laboratory experiments and conceptual parameter discussions,” Desalination, vol. 142, no. 1, pp. 65–78, Jan. 2002.

25. E. G. Mari, R. P. G. Colomer, and C. A. Blaise-Ombrecht, “Performance analysis of a solar still integrated in a greenhouse,” Desalination, vol. 203, no. 1–3, pp. 435–443, 2007.

26. A. Radhwan and H. E. S. Fath, “Thermal Performance of Greenhouse with Built-in Solar Distillation System: Experimental Study,” Ninth Int. Water Technol. Conf.,
27. A. H. Salah, G. E. Hassan, H. Fath, M. Elhelw, and S. Elsherbiny, “Analytical investigation of different operational scenarios of a novel greenhouse combined with solar stills,” Appl. Therm. Eng., vol. 122, pp. 297–310, 2017.

28. O. O. Rabhy, I. G. Adam, M. Elsayed Youssef, A. B. Rashad, and G. E. Hassan, “Numerical and experimental analyses of a transparent solar distiller for an agricultural greenhouse,” Appl. Energy, vol. 253, no. July, p. 113564, 2019.

29. H. J. J. Janssen, T. H. Gieling, S. L. Speetjens, J. D. Stigter, and G. Van Straten, “Watergy: Infrastructure for process control in a closed greenhouse in semi-arid regions,” Acta Hortic., vol. 691, no. May 2014, pp. 821–828, 2005.

30. H. F. De Zwart, “The sunergy greenhouse - One year of measurements in a next generation greenhouse,” in Acta Horticulturae, 2011, vol. 893, pp. 351–358.

31. A. M. Al-Ismail and H. Jayasuriya, “Seawater greenhouse in Oman: A sustainable technique for freshwater conservation and production,” Renewable and Sustainable Energy Reviews, vol. 54. Elsevier Ltd, pp. 653–664, Feb-2016.

32. E. Farrell, M. I. Hassan, R. A. Tufa, A. Tuomiranta, A. H. Avci, A. Politano, E. Curcio, and H. A. Arafat, “Reverse electrodialysis powered greenhouse concept for
water- and energy-self-sufficient agriculture,” Appl. Energy, vol. 187, pp. 390–409, 2017.

33. C. B. Maia, F. V. M. Silva, V. L. C. Oliveira, and L. L. Kazmerski, “An overview of the use of solar chimneys for desalination,” Sol. Energy, vol. 183, pp. 83–95, 2019.

34. P. Amarananwatana and C. Sorapipatana, “An Assessment of the ASHRAE Clear Sky Model for Irradiance Prediction in Thailand Nuntiya,” Asian J. Energy Environ, vol. 08, no. 02, pp. 523–532, 2007.

35. S. Rabia, 2017 ASHRAE Handbook Fundamentals SI.pdf.

36. Abdullahi, K., Salah, A.H., Fath, H.E.S., 2019. Transient operational performance of integrated solar greenhouse – Desalination system: Case study of Mediterranean mild winter condition. p. 030006. https://doi.org/10.1063/1.5117037

37. D. Piscia, J. I. Montero, E. Baeza, and B. J. Bailey, “A CFD greenhouse night-time condensation model,” Biosyst. Eng., vol. 111, no. 2, pp. 141–154, 2012.

38. I. Janajreh, H. E. S. Fath, and S. S. Raza, “Thermal performance of solar-distillation integrated greenhouses,” 2012.

39. D. Piscia, P. Muñoz, C. Panadès, and J. I. Montero, “A method of coupling CFD
and energy balance simulations to study humidity control in unheated greenhouses,” Comput. Electron. Agric., vol. 115, pp. 129–141, 2015.

40. T. Boulard and S. Wang, “Greenhouse crop transpiration simulation from external climate conditions,” vol. 100, pp. 25–34, 2000.

41. J. Chen, F. Xu, D. Tan, Z. Shen, L. Zhang, and Q. Ai, “A control method for agricultural greenhouses heating based on computational fluid dynamics and energy prediction model,” Appl. Energy, vol. 141, no. 1, pp. 106–118, 2015.

42. “ANSYS Fluent Theory Guide, 2017.

43. C. Baxevanou, D. Fidaros, T. Bartzanas, and C. Kittas, “Yearly numerical evaluation of greenhouse cover materials,” Comput. Electron. Agric., vol. 149, no. August 2016, pp. 54–70, 2018.

44. X. He, J. Wang, S. Guo, J. Zhang, B. Wei, J. Sun, and S. Shu, “Ventilation optimization of solar greenhouse with removable back walls based on CFD,” Comput. Electron. Agric., no. October, pp. 0–1, 2017.

45. A. Marucci, D. Monarca, M. Cecchini, A. Colantoni, A. Manzo, and A. Cappuccini, “Films for Mediterranean Greenhouse : A New Sustainable Technology,” vol. 2012,
46. W. Baudoin, R. Nono-Womdim, “Good agricultural practices for greenhouse vegetable crops: Principles for mediterranean climate areas,” agris.fao.org.

47. A. H. Salah and G. E. Hassan, “Performance Improvement of Roof Transparent Solar Still Coupled With Agriculture Greenhouse,” Int. Conf. New Trends Sustain. Energy-ICNTSE, vol. 3, no. 1, pp. 151–154, 2016.

48. N. Katsoulas, A. Sapounas, F. De Zwart, J. A. Dieleman, and C. Stanghellini, “Reducing ventilation requirements in semi-closed greenhouses increases water use efficiency,” Agric. Water Manag., vol. 156, pp. 90–99, 2015.

49. C. R. Chu, T. W. Lan, R. K. Tasi, T. R. Wu, and C. K. Yang, “Wind-driven natural ventilation of greenhouses with vegetation,” Biosyst. Eng., vol. 164, pp. 221–234, 2017.
| Symbol | Description                                      | Symbol | Description                                      |
|--------|--------------------------------------------------|--------|--------------------------------------------------|
| A      | apparent solar irradiation                       | a      | mean height of plants                            |
| Bc     | breadth of channel, m                            | C      | diffuse radiation factor                        |
| C2     | inertial resistance                              | COP    | Coefficient of Performance                      |
| Cp     | specific heat, J/kg K                           | D_{w2o}| vapor-air diffusion                             |
| e      | Total fluid energy                               | H_{s}  | height of south wall, m                          |
| H_{N}  | height of north wall, m                          | h_{fg} | heat of vaporization of water, J/kg             |
| h_{j}  | Sensible enthalpy                                | h_{in} | enthalpy of inlet air, J/kg                      |
| h_{out}| enthalpy of outlet air, J/kg                      |        |                                                  |
| I_{B}β | direct beam solar radiation, W/m²                | I_{β}  | incident global solar radiation, W/m²           |
| I_{D}β | diffused solar radiation, W/m²                   | I_{ref}| reflected radiation W/m²                        |
| K      | thermal conductivity                             | k      | atmospheric extinction coefficient               |
| L_{b}  | Length of TSD base, m                            | LAI    | leaf area index                                  |
| L      | length of the greenhouse, m                      | k_{p}  | plant leaf Characteristic length, m             |
| M      | Mass, kg                                        | m_{a}  | mass flow rate of air, kg/s                      |
| m_{c}  | mass flow rate of water, kg/s                    | m_{cond}| mass flow rate of air through the condenser, kg/s|
| Pr_t   | Prandtl number                                   | Q_{e}  | Evaporated heat, W                              |
| Q_{in} | inlet heat to any component                      | Q_{out}| outlet heat from any component                  |
| r_{a}  | plant aerodynamic resistance, s/m                | r_{s}  | plant stomata resistance, s/m                    |
| S      | Source term                                      | Sc     | Schmidt number                                   |
| s_{h}  | horizontal space between TSDs, m                 | s_{c}  | vertical space between TSDs, m                   |
Table 1. Greenhouse geometrical dimensions.

|                | L    | $\beta_{\text{TSD}}$ | $30^\circ$ |
|----------------|------|----------------------|------------|
| $W$            | 1 (m)| $L_b$                | 0.75 (m)   |
| $H_S$          | 2.5 (m)| $h_w$             | 1 (cm)    |
| $H_N$          | 4.5 (m)| $S_h$              | 0.5 (m)   |
| $B_c$          | 1.5 (m)| $S_r$              | 0.75 (m)  |
| $th_g$         | 3 (mm)|                    |            |
**Table 2. CFD parameters used.**

| CLASSIFICATION          | METHOD                  | Under factor | relaxation factor | Parameter |
|-------------------------|-------------------------|--------------|------------------|-----------|
| Solver settings         | Pressure-based solver   | Pressure     | 0.3              |           |
| Pressure-Velocity Coupling | SIMPLE                | Density      | 1                |           |
| Energy discrete scheme  | Second order upwind     | Mass Force   | 0.9              |           |
| Momentum discrete scheme| Second order upwind     | Momentum     | 0.7              |           |
| k discrete scheme       | First order upwind      | H₂O          | 1                |           |
| e discrete scheme       | First order upwind      | Energy       | 1                |           |
| H₂O scheme              | Second order upwind     | Turbulent Viscosity | 1      |           |
|                         |                         | k and e      | 0.8              |           |
### Table 3. Plant parameters.

| Parameter | Value details |
|-----------|---------------|
| $a$       | 1 (m)         |
| $LAI$     | 3             |
| $C_{p,p}$ | 2130 (J/kg. K) |
| $\alpha_p$ | 0.4         |
| $\varepsilon_p$ | 0.92        |
| $\rho_p$  | 700 (kg/m$^3$) |
| $k_p$     | 0.173 (W/m.K) |
| $L_p$     | 0.03 (m)      |
| $r_a$     | 50(day) to 5000(night) (S/m) |
| $r_s$     | 250 (S/m)     |
|        | Glass | Water | GROUND |
|--------|-------|-------|--------|
| $\varepsilon_g$ | 0.92  | $\varepsilon_w$ | 0.4733 | $\varepsilon_{gr}$ | 0.93 |
| $\alpha_g$ | 0.06  | $\alpha_w$ | 0.3    | $\alpha_{gr}$ | 0.4 |
| $\tau_g$ | 0.9   | $\tau_w$ | 0.68   | $\tau_{gr}$ | 1 (W/m².K) |
| $\rho_g$ | 2500 (kg/m³) | $\rho_w$ | 1 (Ton/m³) | $\rho_{gr}$ | 1680 (kg/m³) |
| $C_{p,g}$ | 750 (J/kg.k) | $C_{p,w}$ | 4186 (J/kg.k) | $C_{p,gr}$ | 1187.8 (J/kg.k) |
| $K_g$ | 1.2 (W/m.K) | | $K_{gr}$ | 2.15 (W/m.K) |
### Table 5. Material’s thermal and optical properties.

| Material  | Density $\rho$[kg m$^{-3}$] | Specific heat $C_p$[J kg$^{-1}$ K$^{-1}$] | Emissivity | Absorptivity | Transmissivity |
|-----------|-----------------------------|------------------------------------------|-------------|--------------|----------------|
| Glass     | 2500                        | 750                                      | 0.92        | 0.06         | 0.9            |
| P.E       | 923                         | 2300                                     | 0.7         | 0.1          | 0.85           |
| EVA       | 926                         | 2600                                     | 0.89        | 0.02         | 0.89           |
| PVC film  | 900                         | 2550                                     | 0.91        | 0.1          | 0.8            |