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RESEARCH ARTICLE

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Modeling and optimization of poultry house passive cooling strategies in semiarid climates

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Summary

Meeting hygrothermal and air quality requirements in livestock dwellings is crucial for upholding production quality standards. However, ventilation and air-conditioning in such enclosures is very energy-intensive, especially amidst climate change and intensifying summer conditions. This is due to large surface areas, livestock densities, and contaminants' generation rates. Hence, striving for more efficient passive cooling techniques is always a desired goal to reduce the anthropogenic emissions of the agricultural sector without compromising production quality. In this study, the energy savings' potential of two passive systems in a poultry house located in the semiarid climate of Beqaa Valley, Lebanon, was compared. The first system is the conventional stand-alone direct evaporative cooler (DEC), which evaporatively cools the outdoor clean air to temperatures close to its wet bulb. The second system combines with the DEC, an earth-to-air heat exchanger (EAHE) that sensibly precools the ambient air and reduces its wet-bulb temperature. This can increase the cooling capacity of the DEC, which can save substantial amounts of energy while achieving similar, if not better, indoor conditions. To conduct this study, simplified mathematical models were developed for the DEC, EAHE, and the poultry house space, assuming a well-mixed air volume. After sizing the systems, simulation results showed that the stand-alone DEC system was not able to meet relative humidity requirements at all times unlike the proposed hybrid EAHE/DEC system. Moreover, the hybrid EAHE/DEC system resulted in 40% reduction in air and water consumption rates compared with the DEC system during the summer season.

KEYWORDS
direct evaporative cooler, earth-to-air heat exchanger, energy efficiency, poultry welfare, sustainable cooling

1 | INTRODUCTION

The agricultural sector in the Middle East and North Africa (MENA) region suffers from a scarcity of natural resources, shortage of arable land and water, and degradation of what is already in use due to unfavorable and worsening climate conditions.[1] Driouech et al[2] predicted a 0.2°C to 0.5°C increase in temperature in the next decade as well as increased dryness and humidity in the northwestern and eastern regions, respectively. With the simultaneous increase in meat and dairy consumption, sustainable development of livestock farms in the agricultural sector (ie, dairy farms and layer/broiler houses) is a must.[3] This includes meeting air-conditioning and ventilation requirements. In other words, livestock and farm workers should be provided with a comfortable thermal environment and good breathable air quality acquired at minimal energy consumption. A survey in poultry houses in Egypt[4] showed increased risks of lung disease (coughing, wheezing, etc.) in farm workers, due to increased exposure to ammonia (NH_3) generated from poultry litter. Another study in poultry houses[5] revealed that heat stress combined with increased ammonia levels in the bloodstream of laying hens led to decreased immunity and hormonal imbalance. Hence, in layer houses—constituting the largest production margin in the market,[6] meeting thermal and air quality requirements is important. This means that average indoor temperatures should range between 20°C and 24°C,[7] relative humidity (RH) between 55% and 75%, and contaminants' concentration kept lower than 2500 and 25 ppm for exhaled CO_2 and NH_3.[8,9] This guarantees low bird mortality rates and life cycle costs while increasing profitability.[10]

Passive cooling techniques conventionally used in poultry houses are swamp coolers or direct evaporative coolers (DECs) that supply conditioned fresh air to the poultry house via typical tunnel or cross-ventilation air distribution systems.[11,12] In the DEC, air is passed between water-soaked pads, which absorb the heat from the fresh air in order to evaporate.[13] This lowers the air temperature to near its wet-bulb temperature (WBT) while adding moisture. The advantage of evaporative coolers is the fact that they are nearly passive systems since they are driven by pumps and fans.[14] Moreover, they do not use compressors or polluting refrigerants compared with conventional cooling systems, which reduces energy consumption and anthropogenic carbon emissions.[15,16] The DEC has shown merit in poultry houses located in arid climates where the ambient WBT is low and the air humidification does not result in the violation of RH requirements.[17,18] Their performance begins to deteriorate in the case of semiarid climates and becomes completely inefficient in hot and humid climates.[19-21] In these cases, the high WBT, combined with the high heat loads—typically found in poultry houses, requires large amounts of supply fresh air in order to meet thermal and RH requirements. On the one hand, this increases the water and electricity consumption of the DEC. On the other, the high flow rate leads to an increase in the air velocity at the bird level, causing them discomfort as well as litter and dust disturbance.[22] Consequently, in the hot semiarid and humid climates of the MENA region, the use of stand-alone DEC might not be enough. Dağtekin et al[23] used the DEC in a tunnel-ventilated poultry house in Adana, Turkey, characterized by semiarid climate. They found that the DEC was not efficient during summer afternoons, where indoor temperatures peaked beyond 28°C and RH beyond 80% above the allowed maxima. In a recent study, Al-Assaad et al[24] have coupled the conventional DEC with tunnel ventilation in the Beqaa region of Lebanon characterized by semiarid climate. Similar to Ref.,[23] they found that while indoor temperatures did not go above 25°C, the indoor RH levels exceeded their maximum allowable limit throughout most of the cooling season and reached a maximum value of 86.7% during the peak month of July. Long-term exposure to higher temperatures and RH results in the hens suffering from heat stress and possible suffocation, and risks their survival rate.[25-27] Moreover, a high humidity content in the air can moisten the poultry house bedding possibly injuring the chickens' feet and increasing manure's NH_3 production.[28,29]

Therefore, it is important to look for solutions that enhance the DEC effectiveness. A possible solution is to lower the WBT of the ambient fresh air entering the DEC, which is possible through sensible precooling. In order to maintain the sustainability of the ventilation system, passive cost-effective strategies are sought such as underground pipe heat exchangers that make use of the earth as a heat sink due to its constant year-round temperature.[30] Such systems are known as earth-to-air heat exchangers (EAHEs). Using a blower fan only, the EAHE passes the ambient air into a long pipe underground buried at a certain depth (optimally around 4-5.5 m).[31] The air then releases its heat, which is dissipated in the surrounding soil through convection and conduction.[32] The EAHE has been used as a stand-alone system in buildings and agricultural facilities for several decades. Ghosal et al[33,34] studied the performance of an EAHE in a greenhouse and found that temperatures were 3 to 4°C lower than the case without the EAHE. Morshed et al[35] studied the cooling performance of an EAHE in a poultry farm located in the hot desert areas of South Iraq. They found that under wet soil, the supply air temperature was reduced by 7 to 8°C and mitigated the heat stress of birds. The EAHE has also been successfully coupled with the DEC in buildings and in the agricultural sector, mainly greenhouses. Bansal et al[36,37] showed that an EAHE with an efficient blower, assisting an evaporative cooler, can increase comfort hours in buildings compared with the stand-alone EAHE and reduces the energy consumption compared with conventional air-conditioning. Tahery et al[38] successfully coupled an EAHE to reduce the water consumption of a stand-alone DEC, conditioning greenhouses located in different climate zones in Iran. Their results showed that the EAHE reduced the DEC water consumption by 17% to 49% from climates 1 to 4, respectively. Therefore, since the performance of the hybrid system showed significant merit for commercial and greenhouse buildings, this work investigates for the first time, the performance of the hybrid EAHE/DEC for poultry houses.

While the integration of the EAHE can enhance the performance of the DEC in semiarid climates, the operation of the EAHE imposes additional pressure drop on the supply airflow, which increases the system's electrical consumption. Moreover, meeting poultry house hygrothermal and air quality requirements at all times can often be at the expense of energy consumption. Therefore, the performance of the hybrid system must be optimized to meet the requirements inside the poultry house at reduced energy consumption. To the authors' knowledge, no research tackling poultry house ventilation has compared the performance of a hybrid EAHE/DEC to a stand-alone DEC for similar poultry house space conditions. Moreover, no previous research has tried to minimize the operating costs of these passive systems while simultaneously considering the comfort of farm workers and layers. The aim of this work is to properly design the conventional stand-alone DEC and the proposed hybrid EAHE/DEC systems implemented for a poultry house located in the semiarid Beqaa region in eastern Lebanon. The systems' operating conditions are then optimized to meet the poultry house environmental constraints at minimal water and electricity consumption. The optimized performance of each system is then compared in terms of the created indoor conditions and the resulting operating cost in order to determine the most cost-effective strategy for poultry house ventilation in semiarid conditions. This is achieved by developing mathematical models of the *DEC* and *EAHE* systems combined with a lumped space model. The models are used to predict the temperature, humidity, and contaminants' concentration hourly variation inside a typical poultry house located in the Beqaa region during the midday of each month of the cooling season (May through September).

2 | SYSTEM DESCRIPTION

The poultry house under consideration was an aviary-type layer house containing 1600 sixty-five-week-old chickens, weighing 1.8 kg each. Figure 1A shows a schematic of the poultry house and the installed DEC and EAHE systems. The poultry house had dimensions of 13.2 m (length) × 11.8 m (width) × 3 m (height) and was assumed air-tight with minimal infiltration ($\mathrm{ACH}_{\mathrm{inf}} < 0.2$). The walls, floor, and ceiling were constructed with 200-mm hollow block concrete bricks. The ceiling was additionally insulated on the outside with a 30-mm layer of polystyrene foam. A 50-mm layer of pine nut shavings lined the floor, serving as a bedding material for the laying hens. The detailed composition of the envelope (material density, specific heat, and convective heat transfer coefficient) can be seen in Ref..[24] Table 1 presents the heat load generated by the hens as well as the pollutants generated due to their respiratory activities (CO_2) and water vapor (H_2O) and manure (NH_3).

To meet the aforementioned environmental constraints, a hybrid passive ventilation system is implemented. The air was distributed via a tunnel ventilation system. As shown in Figure 1A, the clean cool fresh air is supplied at the ceiling level and the room air is discharged to the ambient from the side wall using exhaust fans. The ventilation system integrates the conventional DEC with an assistive EAHE consisting of several pipes (N_{pipes}) of radius R, length L, buried underground at a burial depth z (Figure 1A). The operation of this system depends on the ambient conditions. For moderate temperatures, it operates in natural ventilation mode (dotted line in Figure 1A) where both the EAHE and DEC are bypassed. In this case, the ambient air at state (I) is directly supplied at a flow rate $\dot{m}_{NV}$ to the poultry house, after which the air is exhausted at (II). The corresponding psychrometric process of the ventilation air is shown in Figure 1B. For higher temperatures, the passive ventilation system is operated in mixed mode (solid line in Figure 1A): The ambient air at state (1) is entirely diverted towards the EAHE at a supply flow rate of $\dot{m}_{\mathrm{sup}}$ in order to benefit from its maximum cooling potential. In the EAHE, $\dot{m}_{\mathrm{sup}}$ is divided between the EAHE pipes where it is sensibly cooled to state (2). The air is then diverted between the DEC and its bypass with a fraction β. In the DEC, the air is cooled and humidified until it reaches state (3) and mixed with the bypassed airflow forming the supply air at state (4). The psychrometric process is shown in Figure 1C with the corresponding state points shown in Figure 1A. To determine the effectiveness of the hybrid system in meeting the required indoor conditions, the stand-alone DEC (dashed line in Figure 1A) is also studied. It is operated as follows: A fraction β of the ambient air at state (A) bypasses the DEC, whereas the remainder of the supply flow rate ($\dot{m}_{\mathrm{sup}}$) enters the DEC wet channels to be cooled and humidified. The DEC outlet air at state (B) is mixed with the bypassed ambient air, forming the supply air stream at state (C). The cool clean ventilation air removes the space load, dilutes the indoor contaminants, and is exhausted at (D). The psychrometric process is shown in Figure 1C with the corresponding state points shown in Figure 1A.

Note that well-mixed conditions were considered, which is a valid assumption for smaller poultry house establishments.[24] Due to the variation of the ambient temperature and RH levels, the operation of both stand-alone DEC and hybrid systems in the natural and mixed ventilation modes differs. Thus, in order for the systems to meet the space requirements at minimal water and electricity cost, motorized dampers control the bypass fraction on the DEC in order to provide the optimal operating conditions ($\dot{m}_{\mathrm{sup}}, \beta$) on an hourly basis for both stand-alone DEC and hybrid EAHE/DEC systems.

3 | METHODOLOGY

To compute the hourly variation of poultry house temperature, RH, contaminants' concentration, as well as air and water consumption, simplified mathematical models were developed for the DEC and the EAHE as well as the tunnel-ventilated space.

The output peak load from the space model was used to calculate the flow rate of supply air. The flow rate was then used as input into the mathematical modeling of the *DEC* to size its components such as channel width, length, gap size, and number of channels for the *DEC*. The EAHE was then sized (pipe material, length, thickness, diameter, burial depth, and number of pipes) according to specific constraints and coupled with the sized DEC unit. After

TABLE 1 Heat and mass generation rates from the laying hens

Sensible load	**7.51 W[39]**
Latent load	3.30 W[39]
CO_2 generation rate (respiratory activities)	75.9 g/day·hen (summer conditions)[40]
H_2O generation rate (respiratory activities)	2.1 g/hr·hen (summer conditions)[39]
NH_3 generation rate (manure)	0.47 g/day·hen (summer conditions)[41]

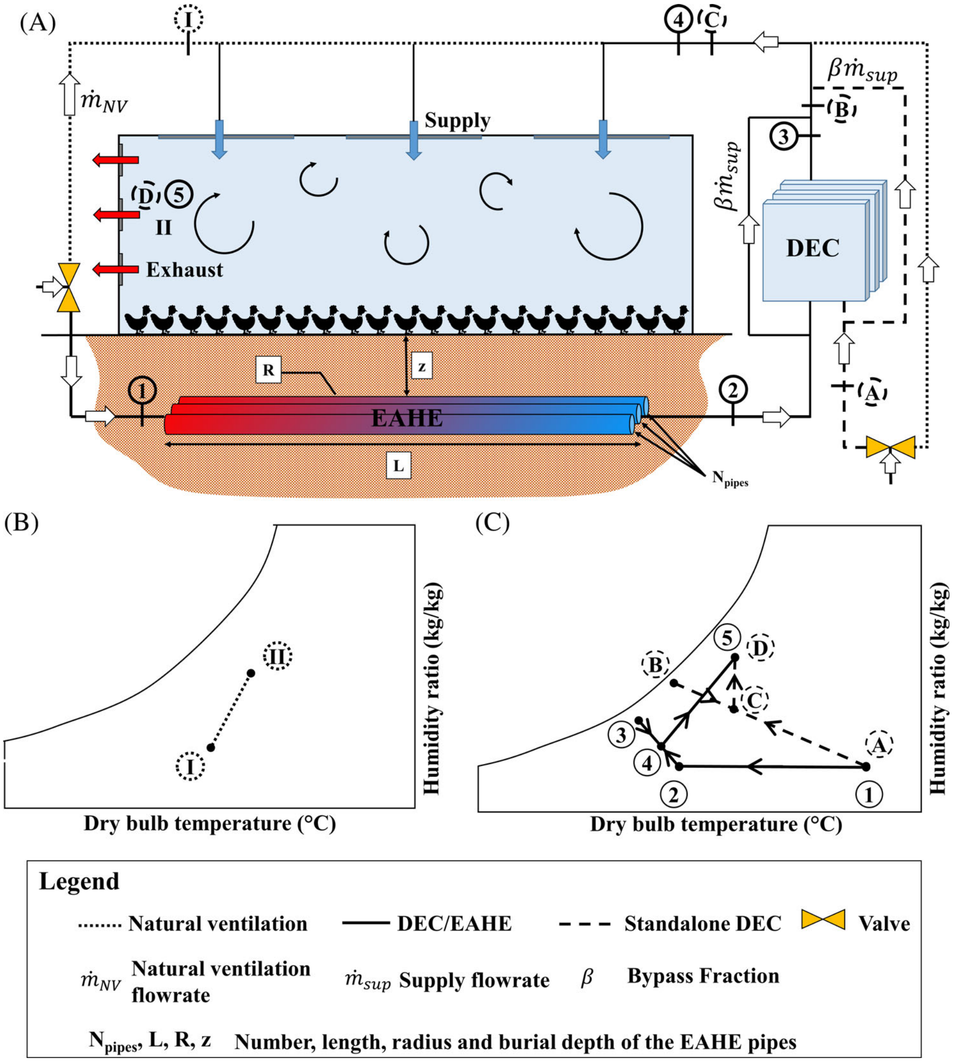

FIGURE 1 Schematic of the A, *DEC* and *EAHE* units integrated with a tunnel air distribution system and B, the associated psychrometric process

sizing these units, the mathematical models were coupled with a genetic algorithm optimizer to calculate the required hourly variation of the bypass fraction on the EAHE and DEC and the poultry supply flow rate. They are regulated to meet the thermal environment requirements of the poultry house at minimal electricity and water consumption. The poultry house space model along with the mathematical models of *DEC* and *EAHE* units is presented in the following subsections.

3.1 | Poultry house space model

A simplified mathematical model that solves for the energy and mass balance equations was developed for the poultry house. It was used to obtain the hourly variation of the cooling load, temperature, RH, and contaminants' concentrations, assuming no infiltration. Equation (1) represents the energy balance equation for the space as follows:

$$\rho_{\text{air}} V_{\text{PH}} C_{p_{\text{air}}} \frac{dT_{\text{PH}}}{dt} = \dot{m}_{\text{sup}} C_{p_{\text{air}}} \left(T_{\text{sup}} - T_{\text{PH}}\right) + Q_{\text{oh}} + Q_{\text{conv}}(t) \tag{1}$$

The left side of Equation (1) represents the transient term for the heat stored in the poultry house. The first term on the right-hand side represents the net convective heat flow, Q_{oh} (W) is the sensible heat generation due to the metabolic activity of occupied hens, and Q_{conv} (W) is the convective heat exchange between the space and the poultry house envelope (walls, floor, and ceiling). The model of Yassine et al[42] was adopted to solve for the walls' inner surface temperatures. T_{PH} (°C) is the space temperature, which should optimally be equal to 24°C. T_{sup} (°C) and $\dot{m}_{\text{sup}}$ (kg/s) are the inlet supply temperature and mass flow rate from the *DEC* and *EAHE*. ρ_{air} (kg/m^3) is the air density, V_{PH} (m^3) is the volume of the poultry, and $C_{p_{\text{air}}}$(J/kg K) is the specific heat of air. The mass balance of moisture and contaminants in the space are given in Equation (2) as follows:

$$\rho_{\text{air}} V_{\text{PH}} \frac{dC_{\text{species},i}}{dt} = \dot{m}_{\text{sup}} \left(C_{\text{sup},i} - C_{\text{species},i}\right) + C_{\text{gen},i} \tag{2}$$

The terms on the left-hand side of Equation (2) represent the transient storage term for species (H_2O, CO_2, NH_3) in the space. The first term on the right-hand side represents the net mass transfer into the space. The second term on the right-hand side of Equation (2) represents the contaminants' generation rate in the space (CO_2 and NH_3) and moisture generation rate.[39] C_{species} (ppm) and C_{sup} (ppm) are the concentrations of species (i denotes either CO_2, NH_3, or H_2O) in the space and supply air, respectively. Note that for the water vapor, $C_{\text{sup},i}$ (ppm) is taken as input from the *DEC* humidified air.

3.2 | DEC model

Figure 2 illustrates a detailed schematic of the *DEC* unit, which is composed of consecutive wet channels with cooling pads wetted with water originating from a tank. Channel width w, length L, gap size e, velocity u_d, and number of channels N_{channels} are the main components to be sized. The DEC mathematical model is solved based on heat and mass transfer between the cooling air in the wet channels and the water film. It gives the cooling air and water film temperature variations ($T_{\text{ca}}(x)$ and $T_{\text{wa}}(x)$, respectively) as well as the variation of the humidity content of the cooling air $\omega_{\text{ca}}(x)$ in the x-direction (Figure 2). Equation (3) presents the energy balance between the cooling air and the water, whereas Equation (4) presents the mass balance between the cooling air and the water:

$$\frac{\partial T_{\text{ca}}(x)}{\partial x} = \underbrace{\frac{h_{\text{ca}} A}{C_{p_{\text{ca}}} \dot{m}_{\text{ca}} L_{\text{ch}}} \left(T_{\text{wa}} - T_{\text{ca}}\right)}_{\text{sensible}} + \underbrace{\frac{C_{p_{\text{wv}}} \partial \omega_{\text{ca}}(x)}{C_{p_{\text{ca}}} \partial x} \left(T_{\text{wa}} - T_{\text{ca}}\right)}_{\text{latent}}, \tag{3}$$

where h_{ca} (W/m^2·K) is the convective heat transfer coefficient of the cooling air. $\dot{m}_{\text{ca}}$ (kg/s) is the mass flow rate of cooling air that exits the DEC and is supplied to the poultry house, L_{ch} (m) is the length of the channel. Cp_{wv} (J/kg·K) and Cp_{ca} (J/kg·K) are the specific heat of water vapor and moist cooling air, respectively. A (m^2) is the area through which the heat and mass exchange occurs:

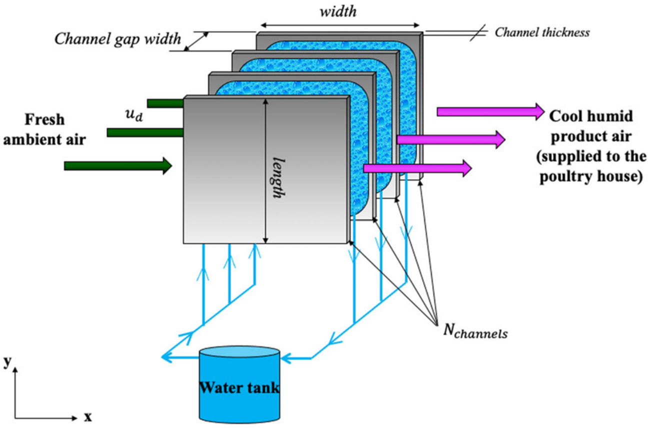

FIGURE 2 Schematic of the *DEC* system

$$\frac{\partial \omega_{\mathrm{ca}(x)}}{\partial x}=\frac{h_{\mathrm{m}}\rho_{\mathrm{ca}}A}{L_{\mathrm{ch}}\dot{m}_{\mathrm{ca}}}(\omega_{\mathrm{sat}}-\omega_{\mathrm{ca}}), \tag{4}$$

where $\omega_{\mathrm{sat}}$is the saturation humidity at the water film temperature. h_{m} is the mass transfer coefficient according to the Lewis relation.

Moreover, the energy balance of the water film is given in Equation (5) as follows:

$$\frac{\partial T_{\mathrm{wa}}(x)}{\partial x}=\frac{h_{\mathrm{ca}}A}{\dot{m}_{\mathrm{wa}}C_{p_{\mathrm{wa}}}L_{\mathrm{ch}}}\left[(T_{\mathrm{ca}}-T_{\mathrm{wa}})-\left(\frac{C_{p_{\mathrm{wv}}}-C_{p_{\mathrm{wa}}}}{C_{p_{\mathrm{ca}}}}T_{\mathrm{wa}}+\frac{h_{\mathrm{fg}}}{C_{p_{\mathrm{ca}}}}\right)(\omega_{\mathrm{sat}}-\omega_{\mathrm{ca}})\right], \tag{5}$$

where $\dot{m}_{\mathrm{wa}}$ is the water mass flow rate of the cooling pad, $C_{p_{\mathrm{wa}}}$ is the specific heat capacity of water (J/kg K), and h_{fg} is the latent heat of vaporization of water (J/kg). The water consumption of the system is given by

$$\mathrm{WCR}=\frac{\dot{m}_{\mathrm{ca}}}{\rho_{\mathrm{wa}}}(\omega_{\mathrm{amb}}-\omega_{\mathrm{out,ca}})\times 3600\times 1000, \tag{6}$$

where *WCR* (L/h) is the water consumption of the *DEC* system, and ω_{amb} (kg/kg$_{\mathrm{air}}$) and $\omega_{\mathrm{out,ca}}$ (kg/kg$_{\mathrm{air}}$) are the specific humidity ratios of the ambient air entering the *DEC* and the cooling air exhausted from the *DEC*, respectively.

3.3 | EAHE model

The EAHE is composed of a number of pipes made of a characteristic material buried at a specific depth (z) beneath the soil (Figure 1A). The soil temperature can be used for cooling applications in the summer and for heating applications in the winter due to its constant year-round temperature. In the summer of Beqaa, the ambient air passing through the EAHE is sensibly cooled, and its WBT is inherently reduced. The performance of the EAHE depends on the pipe material and dimensions, length and cross-sectional area, burial depth, soil properties, and temperature as well as the airflow temperature.

The soil temperature $T(z,t)$ varies throughout the year depending on the outside weather conditions and with depth according to Equation (7)[31]:

$$T(z,t)=T_{\mathrm{m}}-A_{\mathrm{wa}}\exp\left\{-z\left(\frac{\pi}{365\alpha}\right)^{0.5}\right\}\cos\left\{\frac{2\pi}{365}\left[t_e-t_0-\frac{z}{2}\left(\frac{\pi}{365\alpha}\right)^{0.5}\right]\right\}, \tag{7}$$

where z is the soil depth, and α is the soil thermal diffusivity. Equation (7) takes as input T_{m}, which is the mean annual ground surface temperature ($z=0$), A_{wav} is the amplitude of the temperature profile at the surface, t_0 is the phase constant of air and is related to the time elapsed from the beginning of the year at which the air temperature reaches its minimum value in the year and the phase angle difference between the air and soil surface temperature. t_{e} is the time elapsed from the beginning of the year. This model has been validated with experimental measurements of ground temperatures and showed good agreement with errors lower than 5%. Moreover, it has been shown to give satisfactory results for different climate zones, where the soil was heavy and dry or heavy and moist.

Once the soil temperature at the burial depth z is determined, the 1D model of Derbel et al[32] was used to determine the pipe outlet temperature T_{outair}as seen in Equation (8):

$$T_{\mathrm{outair}}=T_{\mathrm{amb}}(t)-\{T_{\mathrm{amb}}(t)-T(z,t)\}\left(1-e^{-\sigma L_{\mathrm{tu}}}\right) \tag{8}$$

The above equation is the analytical solution to the differential equation obtained by equating the energy transferred between the airflow inside the pipe and that conducted to the surrounding soil, which are both combined by considering the thermal conductance. The different terms in Equation (8) represent the following: T_{outair} is the outlet air temperature from the tube, T_{amb} is the ambient air temperature, $T(z,t)$ is the soil temperature, L_{tu} is the length of the tube, and σ is the ratio of overall heat transfer coefficient (air + pipe + soil) over the ventilation mass flow rate and specific heat of air.[32]

3.4 | System optimizer

The operation of the stand-alone DEC and hybrid EAHE/DEC systems is optimized in order to regulate the supply air conditions at minimal operating cost. For this reason, an operation strategy is adopted where the supplied flow rate ($\dot{m}_{\mathrm{sup}}$) and the bypass fraction on the DEC (β) are optimized on an hourly basis in order to minimize its water consumption (*WCR*) as well as the system's electricity consumption (*EC*). Due to the nonlinearity of the problem, a genetic algorithm is used as the search method to determine the optimal system operating conditions. An objective function (J) is thus defined that follows the approach presented by House and Smith.[43] Accordingly, J is written as the sum of two competing cost categories: the system operating costs (consumed air and water) as well as the penalty terms that reflect the poultry thermal and air quality constraints. These constraints are introduced into the objective function as additional costs,[44] that increases the system's cost when they are violated, driving the search algorithm towards the optimal solution.[45] The constraints on indoor temperature (T_{PH}) and relative humidity (RH_{PH}) are combined into the cost function via the temperature-humidity index (THI_{PH}) that evaluates the heat stress for laying hens.[25,46] The *THI* has been extensively used in the evaluation of the thermal environment in livestock dwellings and has been the basis for strategic control of any adopted ventilation system.[28] By limiting this index to a maximum of 72%, the poultry temperature and RH ranges of 20-24°C and 55%-75%], respectively, are ensured. In addition, acceptable air quality is achieved by having the CO_2 and NH_3 concentrations below the set points of 2500 and 25 ppm, respectively. The objective function (*J*) is thus defined as follows:

$$J = J_1 + J_2 + J_3 + \delta_{\mathrm{elec}}(E_{\mathrm{c}}) + \delta_{\mathrm{water}}(WCR) \tag{9}$$

$$J_1 = \delta_{THI}\left(\exp\left(\frac{THI}{THI_{\mathrm{set}}}\right) - 1\right) \tag{9a}$$

$$J_2 = \delta_{co_2}\left(\exp\left(\frac{C_{CO_2}}{C_{CO_2,\mathrm{set}}}\right) - 1\right) \tag{9b}$$

$$J_3 = \delta_{NH_3}\left(\exp\left(\frac{C_{NN_3}}{C_{NH_3,\mathrm{set}}}\right) - 1\right) \tag{9c}$$

where the first term represents the thermal constraints cost (Equation (9(a))), and the second and third terms represent the air quality constraints costs that reflect the indoor CO_2 (Equation (9(b))) and NH_3 (Equation (9(c))) concentrations, respectively. The last two terms represent the actual monetary cost of the consumed electricity and water for each studied system. The poultry house constraints are included in the objective function as normalized deviations from their respective maximum threshold values. In addition, the use of the exponential function for the control terms imposes large penalties on *J* when the poultry thermal and air quality constraints are not met, forcing the search algorithm towards the optimal solution.[45] The weighting factors δ_i are chosen to give all the different components of the objective function equal contribution. In this case, since the constraints terms are normalized, their weighting factors (δ_{THI}, δ_{CO2}, and δ_{NH3}) are set to unity.[47] The other weighting factors (δ_{elec} and δ_{water}) represent the actual cost for electricity and water in adopted Lebanon (0.13 \$/kWh and 2 \$/m^3, respectively).[48] The population size of the search algorithm is set to 60 individuals with a maximum generation number of 100. The crossover fraction and function tolerance are set to 0.8 and 10^{-14}, respectively.

4 | SOLUTION METHODOLOGY

The simulations were conducted during the summer months from May to September. The midday of each summer month was selected as the typical representative day. The weather data for the summer season based on a typical meteorological year (TMY) was used as input into the DEC, EAHE, and poultry house space models.[49] Figure 3 illustrates the hourly variation of the ambient temperature T_{ambient} (°C), RH_{ambient} *(%)*, and T_{wb} (°C) for the midday of each summer month.[49] The geometrical and thermal properties of the building envelope, hourly ambient conditions, and internal sensible and latent loads, as well as hens' and manure contaminants generation rates were taken as inputs for the poultry space model. The output gave the hourly variation of the cooling load for the summer season presented in Figure 4. The peak load was found during August (97.8 W/m^2), which is a typical load found in poultry houses during summer in the Mediterranean region.[50] A maximum flow rate ($\dot{m}_{\mathrm{max}}$) of 7.5 kg/s was found enough to remove it while maintaining the air quality requirements and without causing discomfort to the laying hens through the draft generated by high indoor air velocities[51,52] The sized system is shown in Table 2.

In the case of the hybrid system, the same DEC unit was used (Table 2). $\dot{m}_{\mathrm{max}}$ from the DEC (7.5 kg/s) was used to size the EAHE pipe length, thickness, burial depth, and number of pipes, based on the following constraints:

- Burial depth 3 to 5 m, adequate for summer conditions in Mediterranean climates.[53] In the case of this work, a burial depth of 4 m was chosen.
- Number of pipes and pipe radius such that the maximum velocity in the pipe at the highest flow rate of 7.5 kg/s is 2 to 3 m/s.[54] In the case of this work, 10 pipes were chosen with a radius of 0.26 m.
- The pipe length depends on the availability of land for excavation and should be close to the poultry house length (13.2 m). In the case of this work, a length of 14 m was chosen (Table 2).

The EAHE pipe material chosen was PVC having a density of 1380 kg/m^3, a specific heat of 900 J/kg K, and a thermal conductivity of 0.16 W/m K. This material is commonly used in EAHE applications.[54] The soil in the inland region of Lebanon is classified as sandy clay loam with the following thermal properties: thermal diffusivity α_s of 0.316×10^{-6} m^2/s, thermal conductivity of 0.5 W/m K, and heat capacity of 1.59×10^3 kJ/m^3 K.

Figure 5 illustrates the optimization strategy of the sized stand-alone DEC and hybrid EAHE/DEC systems. At each time step, the possibility of operating the systems in the natural ventilation mode is tested. This is achieved when the indoor conditions of temperature and RH are met without exceeding the maximum allowable flow rate ($\dot{m}_{\max}$) of 7.5 kg/s. In order to reduce the fan's EC during the natural ventilation, $\dot{m}_{\text{sup}}$ is chosen as the lowest possible flow rate that does not degrade the air quality. When natural ventilation is not able to meet the poultry house cooling load, either the stand-alone DEC or the hybrid EAHE/DEC can be operated. In order to reduce their water and electricity consumption, the operating parameters ($\dot{m}_{\text{sup}}$, β) are optimized as follows: the genetic algorithm seeds the supply flow rate ($\dot{m}_{\text{sup}}$) and the bypass fraction β on the DEC. They are then used in the EAHE/DEC models along with the other geometrical inputs and weather and soil properties to get the supply air conditions. These models also calculate the DEC water consumption and the pressure drop on the airflow in both the EAHE and DEC in order to determine the blower fan electrical consumption. The supply air conditions are then used as input to the space model along with the space characteristics and solar radiation data. The space model yields the indoor air conditions and CO_2 and NH_3 concentrations, which are used to evaluate the thermal and air quality levels inside the poultry. The objective function is then evaluated, and the calculations are repeated until the optimal solution is reached that gives the required thermal and air quality inside the poultry at minimal energy.

A numerical model was developed to simulate the discretized energy and mass balances of the poultry space model, *DEC* and *EAHE* models. The numerical model implemented an implicit first-order time integration scheme. A time step of 100 seconds was adopted after conducting a time-step independence test. A steady periodic solution was sought and was reached after a simulation period of 8 days. The convergence criterion was set when the residuals of the temperature between two consecutive iterations at repeated one-day cycle from previous cycle were less than 10^{-5}°C.

To make sure the EAHE model is able to predict the energy balance between soil and air, the model was validated with the experimental data of Ozgener et al.[55] They investigated the performance of an EAHE made of PVC in heating and cooling applications of greenhouses in the Mediterranean climate of Turkey. Their soil had fairly similar thermal properties as that of the Beqaa in Lebanon while being slightly more conductive. Their EAHE was buried at 3 m, and had a diameter of 0.56 m and a length of 25 m. For a constant inlet temperature of 39.8°C and an airflow rate of 1.8 kg/s, they measured the outlet air temperature from the EAHE. The soil having a constant temperature of 27.5°C reduced the outlet air temperature to 34.8°C. Taking the inputs (pipe dimensions, properties, soil temperature, properties, and mass flow rate) from their study into the developed EAHE model in this work, the outlet temperature from the

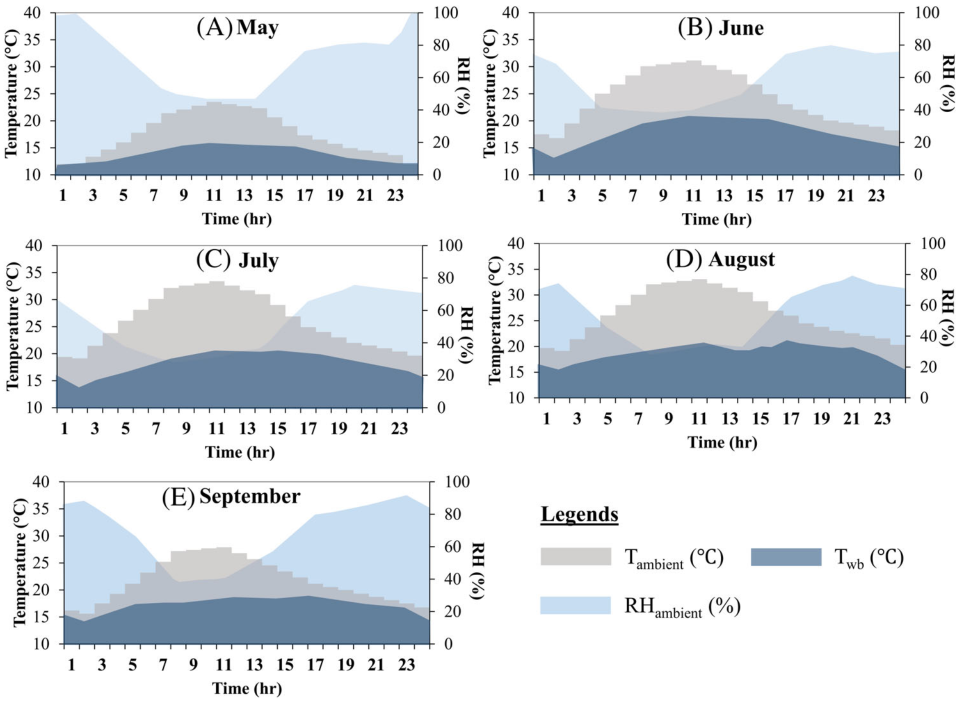

FIGURE 3 Hourly variation of the ambient temperature T_{ambient} (°C), RH_{ambient} *(%)*, and T_{wb} (°C) for the midday day of A, May; B, June; C, July; D, August; and E, September according to TMY (EU science hub)

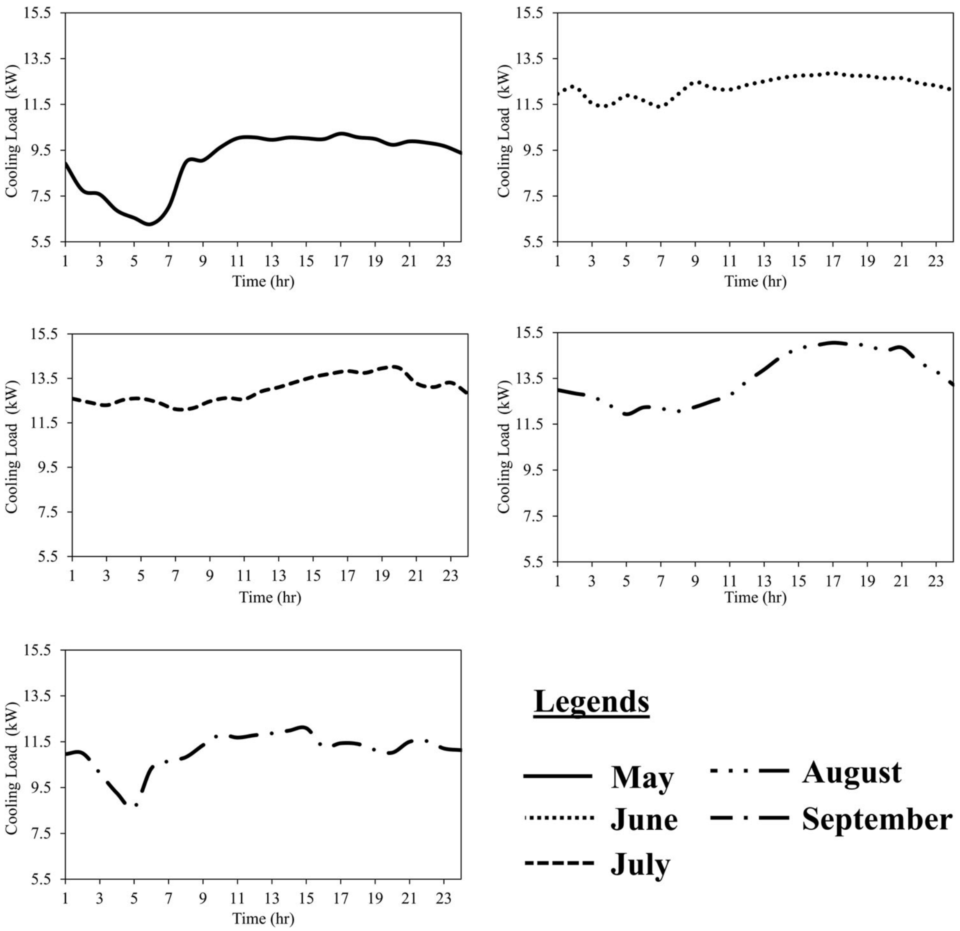

FIGURE 4 The load variation (kW) on hourly basis for each summer month

TABLE 2 Geometric and operational parameters of the *DEC* and *EAHE* units for each compartment in the poultry house

Parameter	*DEC*	*EAHE*
Channel length (m)	2	-
Channel width (m)	2	-
Channel gap thickness (m)	3.0×10^{-3}	-
Sheet thickness (m)	0.5×10^{-3}	-
Pipe length (m)	-	14
Diameter (m)	-	0.52
Pipe thickness (m)	-	2.55×10^{-2}
Depth (m)	-	4
Number of channels	410	-
Number of pipes	-	10

model was equal to 33.8°C, similar to the experimentally measured value by Ozgener et al[55] with a relative error of 3%. On the other hand, the DEC outlet conditions from the developed model were validated against the experimental data of Bishoyi et al.[56] They investigated the performance of a DEC with height, length, and width of 87, 61, and 10 cm, respectively. For inlet air conditions of 32°C, 84% RH, their DEC apparatus yielded a supply temperature of 30.08°C. Taking these conditions, as well as the same DEC geometry as inputs, the developed DEC model yielded a supply temperature of 29.73°C, resulting in 1.17% error with the experimental readings. Therefore, the predictions of the developed EAHE and DEC models in this work are reliable.

5 | RESULTS AND DISCUSSION

In this section, the performance of the tunnel air distribution system with the *DEC* and *EAHE* is evaluated based on their ability to maintain a comfortable thermal environment for the laying hens as well as good air quality. Due to the nature of the generic algorithm, each optimization run was repeated several times in order to ensure convergence to the optimal solution. This was achieved by comparing the different results in terms of indoor conditions and operating cost. Consequently, the solutions that showed better compliance with the space constraints and has the lowest operating cost were reported here.

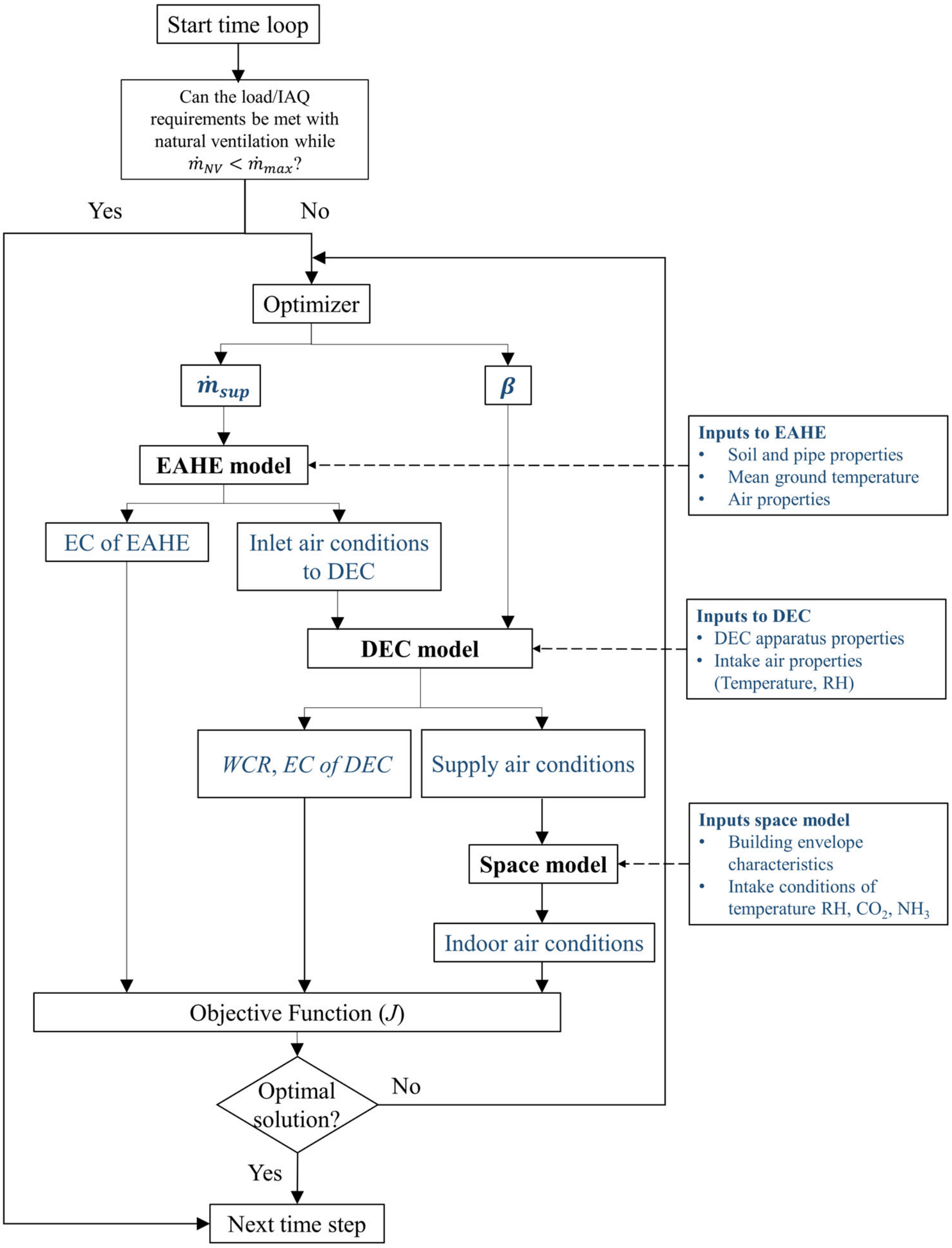

FIGURE 5 Solution methodology flow chart

5.1 | Performance of stand-alone DEC and hybrid EAHE/DEC

The performance of the passive ventilation system was optimized on an hourly basis for a representative day of each month of the summer season in the Beqaa region based on the operation strategy presented in Section 4. Figure 6 shows the optimization results in terms of operating conditions ($\dot{m}_{sup}$, β) as well as the operation window of the stand-alone DEC and hybrid EAHE in either the natural or mixed ventilation mode. The operation of the stand-alone DEC and hybrid EAHE/DEC differed between the months of moderate ambient conditions (May and September) and those with high ambient conditions (June, July, and August).

For the stand-alone DEC system during the month of May (Figure 6A), the required $\dot{m}_{sup}$ varied between 1.38 and 3.91 kg/s throughout the entire day. The hourly variation of the $\dot{m}_{sup}$ followed that of the cooling load (Figure 4): the minimum $\dot{m}_{sup}$ was needed during the nighttime when the load was still low and increased with increasing ambient conditions until it reached a maximum during peak load. As for β, it can be seen that the ambient conditions were cool enough to allow natural ventilation (β=100%) between 19:00 hour and 9:00 hour, when the poultry cooling load was low (Figure 4). Accordingly, $\dot{m}_{sup}$ around 2.2 ± 0.7 kg/s was needed to meet the poultry thermal and air quality requirements. As the cooling load increased with the ambient conditions, the DEC operation was necessary to provide the

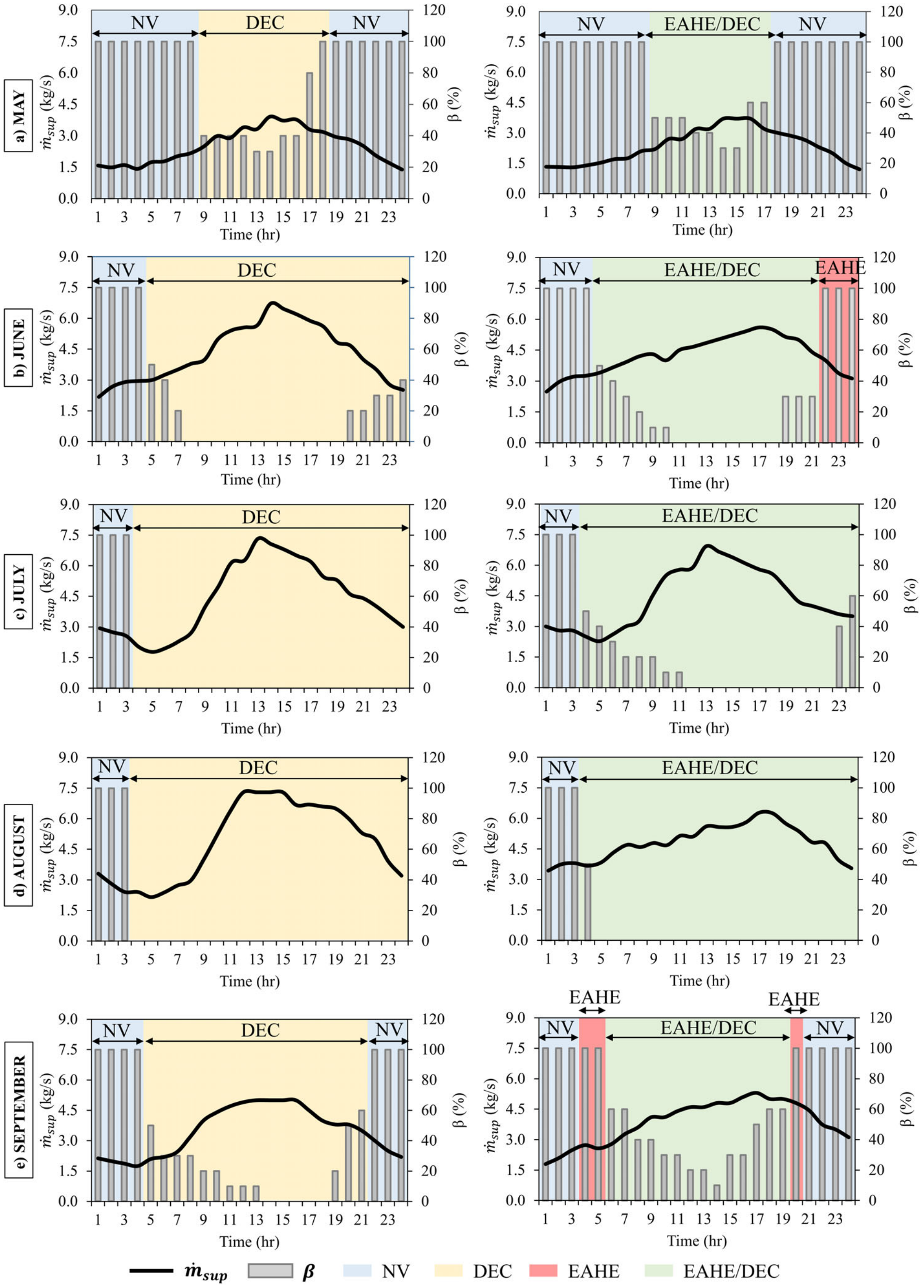

FIGURE 6 Hourly variation of the air supply flow rate and the bypass fractions for the stand-alone *DEC* and hybrid EAHE/DEC for the months of A, May; B, June; C, July; D, August; and E, September

needed supply air conditions. Thus, it was operated with β around 40% where the minimum β is needed at peak hour. Similar trends of the operating conditions can be seen for the month of September (Figure 6E) but with higher flow rate values (4.65 ± 0.4 kg/s) and lower β levels ($20 \pm 20\%$) due to the higher load of the poultry module. For the hybrid EAHE/DEC during May, $\dot{m}_{\text{sup}}$ showed an hourly variation pattern similar to that of the DEC: It ranged between a minimum of 1.2 kg/s needed during nighttime and a maximum of 3.7 kg/s during the peak load period. In addition, the hybrid EAHE/DEC operated in the NV mode, similar to the stand-alone DEC. However, during daytime, when the cooling load was increasing, the EAHE/DEC operated in mixed ventilation mode, where the ventilation airflow is cooled in its entirety in the EAHE, reducing thus the DEC inlet air temperature and enhancing its cooling performance. Consequently, a lower supply temperature was possible with the hybrid system, leading to the operation of the DEC with higher β around 50% and lower flow rate as compared to the stand-alone DEC. Moreover, the operating parameters of the hybrid EAHE/DEC followed comparable trends during the month of September, where the EAHE was able to operate alone ($\beta = 100\%$) between

4:00 hour-6:00 hour and 19:00 hour-20:00 hour. Moreover, during daytime, the EAHE assisted the DEC by increasing possible β to 40 ± 17%, reducing thus the electrical and water consumption of the DEC (Figure 6E).

For the stand-alone DEC during the month of August (Figure 6D), the system operated in NV mode ($\beta = 100\%$) during the early hours of the day (1:00 hour - 3:00 hour) with a flow rate of 2.73 kg/s. For the remainder of the day, the DEC was completely operated (β 0%), with $\dot{m}_{\mathrm{sup}}$ that followed the variation of the cooling load, similar to May. However, the higher levels of $\dot{m}_{\mathrm{sup}}$ were necessary, where it increased from 2.38 kg/s during daytime to 7.3 kg/s during peak load period. Thus, a higher average $\dot{m}_{\mathrm{sup}}$ of 5.2 ± 2 kg/s was needed during August- the peak load month. As for the hybrid EAHE/DEC, its operating parameters was similar to the stand-alone DEC: It operated in the NV mode ($\beta = 100\%$) during the same period (1:00 hour-3:00 hour), and the DEC was completely operated ($\beta = 0\%$) for the remainder of the day. However, due to the assisting effect of the EAHE, the needed $\dot{m}_{\mathrm{sup}}$ in this case was considerably lower, where it varied around 5 ± 0.8 kg/s. For the remaining months of high ambient conditions, June (Figure 6B) and July (Figure 6C), the operating parameters of the DEC and EAHE/DEC systems had similar patterns as those of August. However, lower $\dot{m}_{\mathrm{sup}}$ and higher β due to lower cooling loads of these months. For example, during June (Figure 6B), the average $\dot{m}_{\mathrm{sup}}$ varied around 4.3 ± 1.4 kg/s with β around 12.5 ± 17.1% for the DEC and around 4.2 ± 0.9 kg/s with β around 27.5 ± 35% for the EAHE/DEC. Moreover, during July (Figure 6c), the average $\dot{m}_{\mathrm{sup}}$ varied around 4.7 ± 1.8 kg/s with β of 0% for the DEC and around 4.6 ± 1.5 kg/s with β around 14.3 ± 20% for the EAHE/DEC.

Table 3 shows the resulting averages of the hourly variation of the air temperature (T_{PH}), RH (RH_{PH}), CO_2 ($C_{co_2,\mathrm{PH}}$), and NH_3 ($C_{NH_3,\mathrm{PH}}$) concentration inside the poultry house obtained by the two systems. It can be seen that both the stand-alone DEC and the hybrid EAHE/DEC provided T_{PH} with average values ranging between 22.5°C and 23.7°C, well within the temperature allowable range. As for the poultry RH levels, the stand-alone DEC resulted in RH_{PH} around 53.6 ± 4.0% 67.4 ± 7.0% during the moderate months of May and September, compliant with the humidity requirements. However, during high humidity months of June, August, and July, RH_{PH} levels exceeded 75% (Table 3). On the other hand, the hybrid EAHE/DEC system provided an average hourly RH_{PH} below 75% throughout the entire cooling season. This indicated that the EAHE assisted the DEC in creating an indoor environment that is more compliant with the poultry constraints. Finally, it was noticed that both systems were able to meet the air quality requirements with $C_{co_2,\mathrm{PH}}$ and $C_{NH_3,\mathrm{PH}}$ well below the allowable limits of 2500 ppm and 25 ppm, respectively (Table 3). Based on the above, it is clear that for most of the cooling season, the stand-alone DEC system for poultry house ventilation applications in semiarid climates was able to satisfy the thermal and air quality requirements but failed to satisfy RH requirements at all times. In fact, the RH was higher than 75% for several hours during the day for the majority of the cooling season. This can harm production quality and increase bird mortality rates by causing bird suffocation. This is a typical outcome of using evaporative cooling in such climates. The performance of the stand-alone *DEC* in poultry house of Mediterranean climate was studied by.[23] They reported similar results to this study where the *DEC* was most effective during mornings and evenings, whereas during the afternoon, the poultry's *RH* reached a maximum of 88%. In another study applying DEC for poultry houses in several cities in Morocco,[14] the city of Errachdieh—having similar climate to Beqaa, it was found that the DEC supply temperatures ranged between 12°C and

TABLE 3 Average hourly values of the poultry house temperature, RH, and CO_2 and NH_3 concentrations for all considered months

Month	May	June	July	August	September
DEC					
T_{PH} (°C)	22.5 ± 0.8	23.2 ± 0.6	23.7 ± 0.2	23.6 ± 0.3	23.2 ± 0.4
RH_{PH} (%)	53.6 ± 4.4	70.8 ± 12.0	72.0 ± 12.1	76.1 ± 9.3	67.4 ± 7.0
$C_{co_2,\mathrm{PH}}$ (ppm)	1523 ± 380.0	1055.0 ± 220.0	1102.0 ± 326.0	1028.1 ± 281.0	1230.0 ± 312.0
$C_{NH_3,\mathrm{PH}}$ (ppm)	3.6 ± 1.2	2.1 ± 0.7	2.23 ± 1.0	2.00 ± 0.9	2.64 ± 1.0
EAHE/DEC					
T_{PH} (°C)	22.5 ± 0.7	23.1 ± 0.7	23.6 ± 0.3	22.8 ± 1.0	23.4 ± 0.7
RH_{PH} (%)	51.6 ± 4.0	67.0 ± 10.5	67.6 ± 11.4	75.4 ± 7.8	63.8 ± 4.3
$C_{co_2,\mathrm{PH}}$ (ppm)	1630.0 ± 460.0	1030.0 ± 147.0	1050.0 ± 227.0	945.0 ± 103.0	1115.3 ± 243.0
$C_{NH_3,\mathrm{PH}}$ (ppm)	4.0 ± 1.5	2.0 ± 0.4	2.1 ± 0.7	1.7 ± 0.3	2.27 ± 0.7

22°C during the cooling season, similarly to what was obtained in this work (Figure 6). This yielded satisfactory thermal environment in their poultry house. However, they stated that RH in some cases were high, deeming the stand-alone system as unreliable in more humid regions. By integrating the EAHE with the DEC, the inlet temperatures into the DEC were reduced while maintaining constant humidity ratio. This enhanced the wet-bulb efficiency of the DEC while reducing the supply airflow humidity.

5.2 | Reduction in electricity/water consumption

Figure 7 shows the hourly variation of the operating cost for the midday of each summer month and highlights the time periods when the indoor RH constraints were not met. It is clear that the variation of the operating cost depends mainly on the operating conditions of the systems. For the moderate month of May (Figure 7A), during natural ventilation hours, the operating cost consisted only of

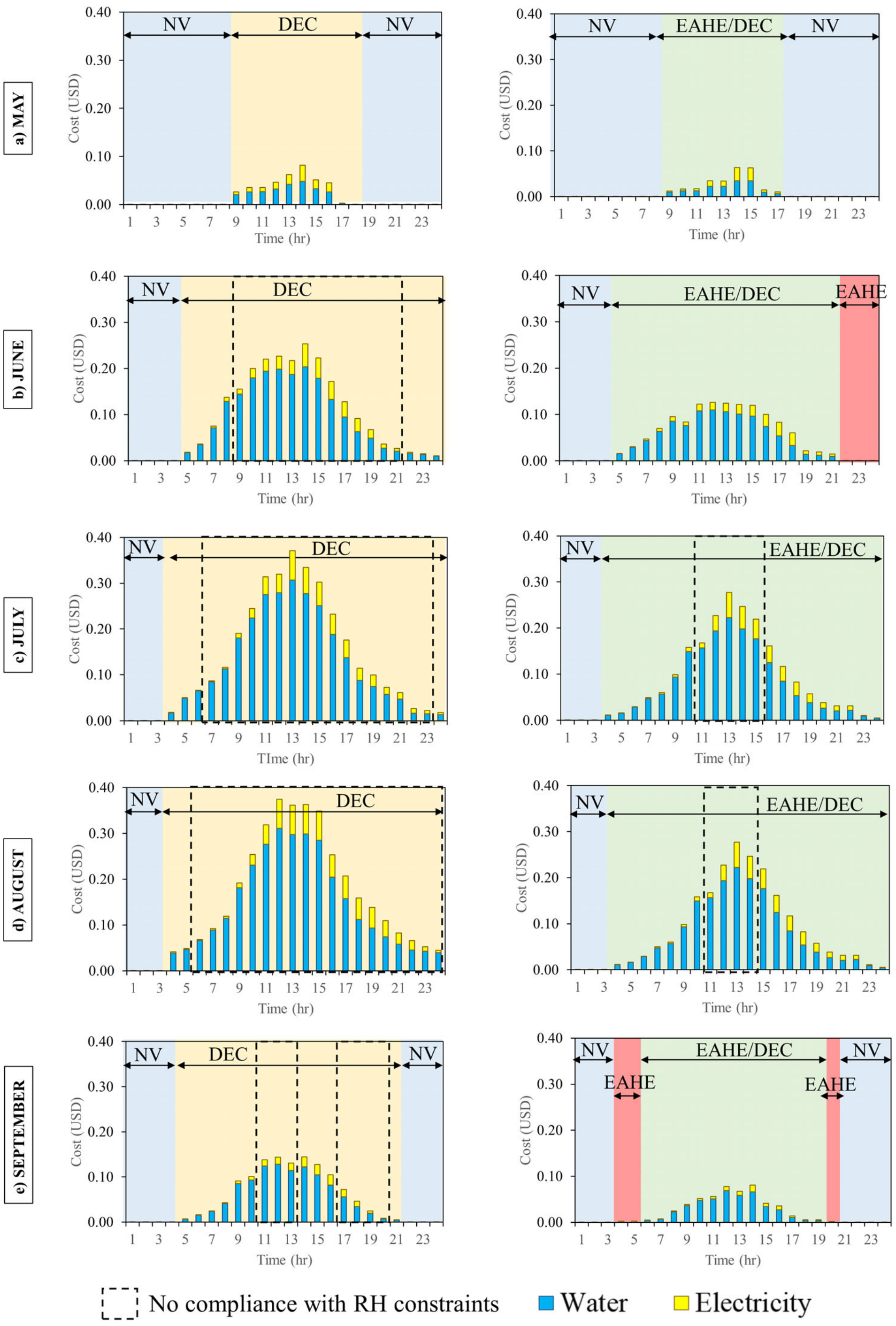

FIGURE 7 Hourly variation of the operating cost for the optimized performance for both stand-alone DEC and hybrid EAHE/DEC with the periods of no compliance with the RH constraints for the months of A, May; B, June; C, July; D, August; and E, September

the price of the consumed electrical energy to operate the fans at minimal pressure drop. As the ambient temperatures increase during the day, the DEC was operated, increasing thus the operating cost, which follows a similar pattern to that of the $\dot{m}_{\text{sup}}$ (Figure 6A). The stand-alone DEC was able to meet the poultry house thermal and air quality constraints throughout the entire day, in both natural and mixed ventilation modes. The same behavior was noted for the hybrid EAHE/DEC. However, the operating cost of the hybrid system was 31% lower than that of the conventional DEC, which is attributed to the lower $\dot{m}_{\text{sup}}$ and higher β (Figure 6A). The same pattern can be seen for the month of September (Figure 7E). However, due to the higher humidity levels in comparison with May, the stand-alone DEC was not able to meet the indoor RH constraints during peak hours. As for the hybrid system, it achieved indoor conditions that are more compliant with the constraints during the entire day. This highlights the importance of the EAHE in enhancing the DEC performance as well as reducing the system operating cost, which reached 60% during this month.

For the months having higher ambient temperatures and RH (ie, August) (Figure 7D), the indoor RH was only met in the natural ventilation mode, unlike the stand-alone DEC. Moreover, the operating cost followed a similar trend to that of the supplied flow rate (Figure 6D) and was 85% higher than that of May. This was expected since higher flow rates were needed in the peak month of August. On the other hand, the hybrid EAHE/DEC was more effective in meeting the RH constraints, which were violated only during the peak hours (during 5 hours only). In addition, the hybrid system was also able to lower the operating cost by 34% during the peak month. It should be noted that the temperature, and CO_2 and NH_3 concentrations were within their respective limits during all the months and for both systems. Similar trends can be observed for the months of June (Figure 7B) and July (Figure 7C).

During the cooling season of the inland region of Lebanon, it can be seen that the hybrid EAHE/DEC was superior to the conventional DEC. On top of providing better indoor conditions, the hybrid system was also able to lower the water consumption by 41%, its electrical energy consumption by 33%, leading to an overall savings of 40% in the system operating cost as compared to the conventional stand-alone DEC.

6 | CONCLUSION

This study investigated the performance of two passive cooling techniques, the DEC and the EAHE/DEC, in meeting the thermal and air quality requirements in a tunnel-ventilated poultry house located in the Beqaa region, East Lebanon. Mathematical models were developed for the DEC and the EAHE as well as the poultry house space considering the uniform conditions of temperatures and pollutants' concentration. The models were coupled to size the system (DEC and EAHE) and optimize the hourly performance of the DEC and EAHE/DEC systems. Genetic algorithm was used to determine the optimal supply flow rate and bypass fraction on the DEC needed to meet the poultry house thermal and air quality requirements at minimal operating cost. The latter consisted of the cost of the water and electrical energy consumed by the ventilation systems. Based on the optimal performance of both stand-alone DEC and hybrid EAHE/DEC systems, it can be concluded that

1. Both systems were able to meet the poultry house requirement in temperature and species concentrations,
2. The hybrid EAHE/DEC was better at meeting the poultry house relative humidity constraints, where the maximum allowable limit of 75% was respected over the entire cooling season,
3. The hybrid EAHE/DEC achieved considerable water and electrical energy savings of 41% and 33%, respectively, as compared to the stand-alone DEC.
4. The optimized operation of the hybrid EAHE/DEC resulted in 40% reduction in the ventilation system operating cost as compared to the stand-alone DEC.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

NOMENCLATURE

ACH	air change per hour (h^{-1})
AREC	Agriculture Research and Education Center
A	direct evaporative cooling channel area (m^2)

A_{wav}	temperature wave amplitude at the ground surface (°C)
C_{gen}	concentration of species generated in the compartment (mg/s)
C_{p}	specific heat (J/kg K)
C	concentration in air (ppm)
DEC	direct evaporative cooling
EAHE	earth-to-air heat exchanger
e	DEC channel gap size (m)
EC	electrical energy consumption (kWh)
h	convective heat transfer coefficient (W/m^2 K)
h_{fg}	latent heat of vaporization of water (J/kg)
h_{m}	mass transfer coefficient (m/s)
I	horizontal solar radiation (W/m^2)
J	objective function
L	length (m)
$\dot{m}$	supply flow rate (kg/s)
N_{channels}	number of channels in DEC unit
Q_{conv}	internal heat gain from compartment envelope (W)
Q_{oh}	internal heat gain from hens (W)
R	radius (m)
RH	relative humidity (%)
th	pipe thickness (mm)
t	time (s)
T	temperature (°C)
t_0	phase constant of air (hr)
t_{e}	time elapsed from the beginning of year (hr)
T	temperature (°C)
T_{wa}	water film temperature (°C)
T_{wb}	wet-bulb temperature (°C)
u_{d}	velocity of air in DEC channels (m/s)
V_{PH}	poultry house compartment volume (m^3)
w	DEC channel width (m)
WBT	wet-bulb temperature (°C)
WCR	water consumption of the DEC system (l/hr)
z	depth (m)

Greek symbols

α	thermal diffusivity (m^2/s)
δ	objective function weighting factors
ρ	density (kg/m^3)
σ	ratio of overall heat transfer coefficient over the ventilation mass flow rate and specific heat of air (m^{-1})
ω	specific humidity ratio (g/kg)

Subscripts

ambient	ambient
ch	channel
CO_2	carbon dioxide
co	cooling air
i	species index (CO_2, NH_3, H_2O)
mean	mean annual ground temperature
NH_3	ammonia
out	outlet
PH	poultry house
sat	saturation
set	set point
sup	supply
wa	water
wav	wave amplitude at the ground surface
wv	water vapor

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