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Effect of Greenhouse Design Parameters on the Heating and Cooling Requirement of Greenhouses in Moroccan Climatic Conditions

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ABSTRACT Protected crop production is rapidly expanding in the Mediterranean Basin, and particularly in Morocco. Increased local and overseas demand for these products led to a rapid development in greenhouse usage encouraged by government policies. The aim of this study is to investigate key design parameters that affect the thermal behavior and the heating/cooling energy need of a greenhouse situated in Agadir (Morocco). The parameters include the cladding material characteristics, shape, orientation, and air change rate. The greenhouse is modeled by a developed thermal model using TRNSYS software. The model considers the presence of the plants inside the greenhouse by adding the heat and humidity gain into the heat and water balance of the greenhouse using an evapotranspiration sub-model. The effect of evapotranspiration on the greenhouse thermal behavior was also examined in this study. A validation of the current TRNSYS simulation and evapotranspiration model was made using previous studies from the literature, and the comparison showed fair agreement. The relative error of the annually heating demand obtained by this model is 1.66%, and the evapotranspiration model used in this study shows relative deviation less than 6.5%. The results of this study indicate that the East-West greenhouse orientation is the optimum orientation as it can reduce the annual cost of air-conditioning of the greenhouse by 9.28% compared to North-South orientation. Quonset shape is the optimum greenhouse shape in Morocco as it can save 14.44% of annual cost of air-conditioning instead of the Even-span shape.

INDEX TERMS Greenhouse design parameters, greenhouse thermal modeling and simulation, greenhouse heating and cooling requirement, greenhouse thermal behavior, plant evapotranspiration, TRNSYS software.

NOMENCLATURE

A_p :	Plants surface area (m^2).
ACAC:	Annual Cost of Air-Conditioning (MAD/year.m^2)
C :	thermal capacitance (JK^{-1})
COP_h :	coefficient of performance of heating (-)
COP_c :	coefficient of performance of cooling (-)
$\hat{c}$:	electricity cost (MAD/year.m^2)
E_h :	greenhouse heating requirement ($kWh/year.m^2$)
E_c :	greenhouse cooling requirement ($kWh/year.m^2$)
ET :	evapotranspiration rate ($mmday^{-1}$)
ET_o :	reference evapotranspiration ($mmday^{-1}$)
G :	soil heat flux ($MJm^{-2}h^{-1}$)
h_{ai-ci} :	internal convective heat transfer coefficients of the greenhouse covering ($Wm^{-2}K^{-1}$)
h_e :	external convective heat transfer coefficients of the greenhouse covering ($Wm^{-2}K^{-1}$)
h_{ai-s} :	convective heat transfer between indoor greenhouse air and the soil ($Wm^{-2}K^{-1}$)
K_c :	crop coefficients
K_t :	a unit conversion
LAI :	leaf area index (m^2m^{-2})
m_{ET} :	added humidity ratio by the plants to the greenhouse environment due to the evapotranspiration (kg/h)

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m_v :	is the mass transfer rate of water due to ventilation (kg/h)
m_{inf} :	is the mass transfer rate of water due to infiltration (kg/h)
$\dot{Q}_{surf}$:	convective gain from all surfaces (W)
$\dot{Q}_{inf}$:	infiltration gains (W)
$\dot{Q}_{vent}$:	ventilation gains (W)
$\dot{Q}_{ET}$:	internal convective gains due to the occupants (crops in this case)(W)
$\dot{Q}_{solair}$:	fraction of solar radiation entering the zone through external windows which is immediately transferred as a convective gain to the inside air (W)
R_n :	net radiation (W/m^{-2})
s :	Slope of the saturation vapor pressure curve $(kPa°C^{-1})$
T_{ai} :	inside air temperature (°C)
T_{ci} :	inner cover surface temperature (°C)
T_{amp} :	amplitude of surface temperature (°C)
T_{mean} :	mean surface temperature (°C)
T_g :	ground temperature at a certain depth (°C)
T_s :	soil temperature (°C)
t_{now} :	current day of the year
t_{shift} :	day of the year corresponding to the minimum surface temperature
v :	air velocity (ms^{-1})
V :	greenhouse volume (m^3)
VPD :	Vapor pressure deficit (kPa)

Greek Letters:

α :	thermal diffusivity of the ground (m^2/s)
λ :	Latent heat of vaporization $\left(MJkg^{-1}\right)$
ρ :	air density $\left(kgm^{-3}\right)$
χ :	moisture capacitance multiplier (-)
ω_i :	inside air humidity ratio (kg/kg)
γ :	psychrometric constant $(MJkg^{-1})$
r_a :	aerodynamic resistance (sm^{-1})
r_c :	canopy resistance (sm^{-1})

Acronym

PE :	Polyethylene
PVC :	Polyvinyl chloride
PC :	Polycarbonate
PMMA :	Polymethylmethacrylate
PHS :	Polycarbonate hollow sheets

I. INTRODUCTION

The greenhouse is a transparent construction to the incident solar radiation that creates a suitable microclimate for crops and protects them from external environments to rise their production and quality. The key design parameters that affect the thermal behavior and the heating/cooling energy need of a greenhouse are: the cladding material characteristics, shape, orientation and air change rate [1].

Greenhouse food production shows a high ability to ensure food security [2], [3]. Greenhouse cultivation occupies a particular place in the agricultural field and has been widely used by farmers in many parts of the world [4], [5]. About 115 countries adopt the greenhouses in their commercial vegetable cultivation [6]. In tropical regions, the greenhouse is among the popular options for agricultural production enhancement [7].

Morocco occupies an important strategic link between Europe and Africa. Solar radiation in this country ranges from 5.28 to 6.33 kWh/m^2/day [8]. Horticulturally, Morocco is mainly considered as an important source of vegetables and citrus fruits for Europe. The greenhouse surface area is expanding rapidly in Morocco, from 2800 ha in 1988 up to 10000 ha in 2000 [9]. About half of the protected area in Morocco is dedicated to tomato cultivation [10].

Energy management presents one of the main challenges of greenhouse. Many different models and tools have been used to calculate heating and cooling requirements in greenhouses. Ahamed *et al.* [11] developed a quasi-steady state time-dependent thermal model to determine the heating load of a greenhouse located in Saskatoon. In another study, they developed a thermal model for Chinese style solar greenhouses named "CSGHEAT" to estimate their time-dependent heat energy demand and obtained a good results with relative root means square error (rRMSE) and average percent error equal to 11.5% and 8.7%, respectively [12]. This model was compared by a TRNSYS model [13]. It was found that some assumptions such as fixed infiltration rate and schedule for moisture gain and thermal blanket in TRNSYS give high errors for the heating requirement estimation. Ha *et al.* [14] developed a greenhouse Building Energy Simulation (BES) model to determine the greenhouse energy requirement under the climatic conditions of Republic of Korea using TRNSYS according to the type of greenhouse, region, and designed internal air temperature. Rasheed *et al.* [15] studied the impact of using different thermal screen materials and thermal screens control strategies on greenhouses heating need using BES model adopting TRNSYS 18 software. This model was validated experimentally (Nash-Sutcliffe efficiency coefficients of 0.84 and 0.78) which make the model appropriate for greenhouse thermal simulations. They found that using multi-layer night thermal screens can save 20%, 5.4%, and 13.5% of heating energy consumption instead of using the Polyester, Luxous, and Tempa screens respectively. This model was used in another study by Rasheed *et al.* [16] to determine the greenhouse design parameters impact on its energy saving efficiency. A greenhouse oriented east-west with a gothic-shaped roof and covered with double-glazing of Polymethylmethacrylate, is the best configuration under the climate of South Korea.

Greenhouse inside air temperature depends mainly on the outside climatic conditions (ambient temperature and solar radiation) and greenhouse design parameters [1]. To build a perfect thermal model, estimation of accurate solar radiation and heat transfer coefficients is crucial, as these parameters impact significantly the energy and mass balance of the greenhouse [17]–[19]. Greenhouse shape and orientation have a significant impact on the total solar radiation received by the greenhouse which eventually affects the indoor air temperature [20]–[24]. Considering the contributions and effects of plants is one of the main challenges of greenhouse energy analysis [25], [26]. The presence of the crops has a crucial role in the greenhouse microclimate which has been examined in the current study.

Several simulation tools are available to obtain detailed information on the heat and mass transfer mechanisms inside the greenhouse. Energy simulation software including EnergyPlus and TRNSYS, could be used for predicting and estimating the energy loads of different types of buildings [1]. TRNSYS software was adopted for the transient simulation of the indoor greenhouse climate in several research [27]. This software showed high performance in this field [28]–[33]. Due to the dynamic nature of plant transpiration, modelling the thermal behaviour of a greenhouse using building software is more complicated. Studies that used this kind of software modeled the greenhouse without considering crops inside or assuming a constant evapotranspiration rate which leads to huge inaccuracies in greenhouse heating/cooling energy requirement [13].

In the current study, this problem was solved by implementing an evapotranspiration sub-model in the greenhouse modeling. It is based on a mathematical model to determine the evapotranspiration rates within inside a greenhouse using the Stanghellini model [34]. This sub-model helps to simulate the greenhouse with presence of crops inside by adding the heat and humidity gain into the heat and water balance of the greenhouse. The Stanghellini evapotranspiration model showed good results and considered more appropriate for determining of the evapotranspiration rate (ET) inside greenhouse [34]–[38].

A validation of this novel greenhouse thermal model developed in this study and the evapotranspiration model, was made using previous studies from the literature.

The objective of this work is to introduce a comprehensive TRNSYS model capable of predicting accurately heating and cooling loads for a Greenhouse application. Moreover, greenhouse design parameters affecting the thermal behavior and the heating/cooling energy need of a greenhouse situated in Agadir (Morocco) are investigated in detail. These parameters are the cladding material (their types, single and double glazing, thickness of double glazing, gap gas type), shape, orientation, and air change rate. Optimization of the design parameters was carried out by considering annual energy costs as the main performance metric.

II. METHODOLOGY

A. GREENHOUSE DESCRIPTION

The greenhouse geometry was drawn in SketchUp software with Trnsys3d extension, and then imported into TRNSYS (type56, TRNBuild) (Fig. 1). The geometry materials properties are provided in Table 1.

TABLE 1. Frame and floor characteristics.

Parameters	Value
Floor solar absorptance	0.6
Longwave emission coefficient of the floor	0.9
Floor thermal conductivity	0.55 W/m.K
Frame thermal conductivity [39]	58 W/m.K
Specific heat capacity of the floor	1 kJ/kg K
Specific heat capacity of the frame [39]	465 J/kg K
Floor density	1100 kg/m^3
Frame density [39]	7850 kg/m^3

TABLE 2. Covering material properties.

Cover characteristics	PE [41]	PVC [41]	PC [41]	PMMA [16]	PHS [39]
Solar transmittance	0.86	0.91	0.78	0.82	0.86
Solar reflectance	0.10	0.07	0.14	0.12	0.06
Visible radiation transmittance	0.89	0.92	0.75	0.92	0.82
Visible radiation reflectance	0.08	0.07	0.15	0.07	0.13
Thermal radiation transmittance	0.18	0.06	0.02	0.00	0.1
Thermal radiation emission	0.79	0.62	0.89	0.98	0.9
Conductivity ($Wm^{-1}K^{-1}$)	0.33	0.13	0.19	0.19	0.06
Thickness (mm)	0.10	0.10	10	10	10

Windows were created within walls and represent almost 99% of their surface using SketchUp. The radiative and thermal properties of the covering materials was calculated by Window 7.7, a software presented by Berkeley Lab, Berkeley, CA, and then transferred into the window library in TRNSYS (W4-lib). The covering materials used in this study were not available in the Window database, so these materials were created using material proprieties available in the literature (Table 2 and 3).

The Meteonorm database was used to generate the outside climatic conditions of the studied city (the incident solar radiation and ambient temperature). The undisturbed ground temperature variation through the year described by the following correlation and imported into Type56 as a boundary condition for the floor [40]:

$$T_{amb}.exp\left[-depth.\left(\frac{\pi\alpha}{365}\right)^{0.5}\right] .cos\left\{\frac{2\pi}{365}.\left[t_{now}-t_{shift}-\frac{depth}{2}.\left(\frac{365\alpha}{\pi}\right)^{0.5}\right]\right\} \quad (1)$$

where T_{mean} is the mean surface temperature, T_{amb} is the amplitude of surface temperature, α is the thermal diffusivity of the ground, t_{now} is the current day of the year and t_{shift} is

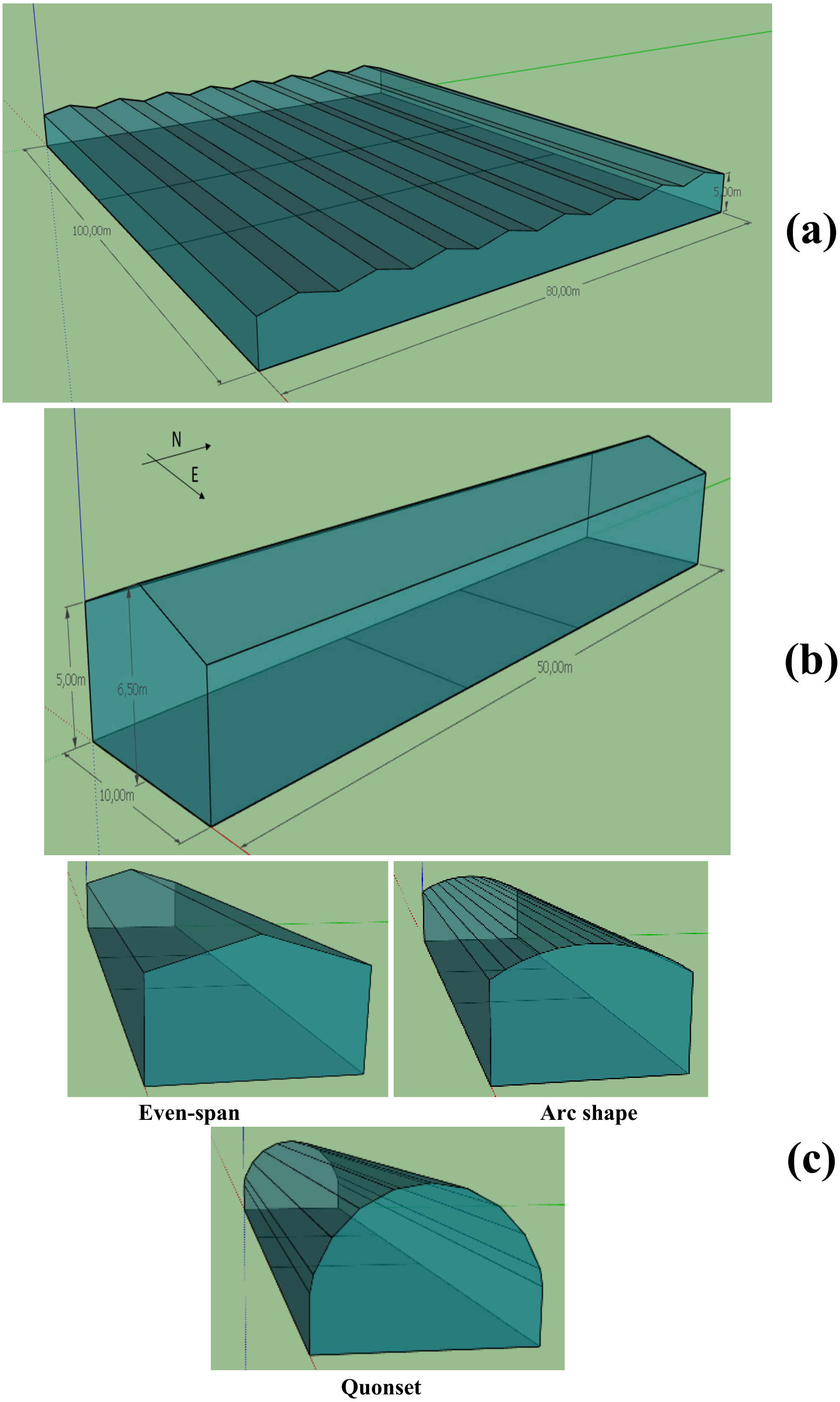

FIGURE 1. Greenhouse geometries used in the investigation: (a) SketchUp drawing of the greenhouse used for the covering materials and air change tests. (b) SketchUp drawing of the greenhouse used for the orientation tests. (c) SketchUp drawing of the greenhouse used for the greenhouse shape tests.

TABLE 3. Gap proprieties.

Gape	Conductivity (W/m.K)	Viscosity (kg/m.s)	Cp (J/kg.K)	Density (kg/m^3)	Prandtl
Air	0.024	0.000017	1006.10	1.29	0.72
Argon	0.016	0.000021	521.92	1.78	0.67
Krypton	0.0087	0.000023	248.09	3.73	0.67
Xenon	0.0052	0.000021	158.34	5.86	0.65

TABLE 4. Different configurations proposed for the investigations.

Examined parameters	Different scenarios
Covering materials	*Different materials:* Polyethylene (PE) - Polyvinyl chloride (PVC) - Polycarbonate (PC) - Polymethylmethacrylate (PMMA) - Polycarbonate hollow sheets (PHS) *Different gap thickness of double PE:* single, 1mm, 2mm and 3mm *Different gap type of double PE:* Air, Argon, Krypton and Xenon
Greenhouse orientation	Two different greenhouse orientation, East-West and North-South orientation.
Greenhouse shape	Even-span - Arc shape – Quonset
Air change rate	1, 2, 3, 4, 5, 6, 7, 8, 9 and 10

the day of the year corresponding to the minimum surface temperature.

B. EXAMINED SCENARIOS

The current greenhouse model was adopted to investigate the impact of greenhouse design parameters, including covering materials, their thickness and gap type, orientation, shape and air change rate, on its thermal behavior and energy need for heating and cooling. Different configurations were proposed for this study, they are given in Table 4.

C. MODELING

The TRNSYS software was developed to simulate physical processes related to collection, storage, and use of solar energy. It consists of connecting a selected set of modules from its library, each module has inputs and outputs. A single multi-zone building (type56) is one of this modules, which can link to a weather data file in order to simulate the thermal behavior and heating/cooling requirement of the building. Alternatively, in this work, this module can be used to simulate a greenhouse as it can solve its heat balance equations.

A schematic layout of this model of greenhouse on TRNSYS is presented in Fig 2.

The energy balance for an arbitrary building geometry is presented by the following equation:

$$C\frac{dT_{ai}}{dt} = \dot{Q}_{surf} + \dot{Q}_{inf} + \dot{Q}_{vent} - \dot{Q}_{ET} + \dot{Q}_{solair} \quad (2)$$

Here, the $\dot{Q}_{surf}$ is the convective gain from all surfaces, the $\dot{Q}_{inf}$ and $\dot{Q}_{vent}$ are the infiltration and ventilation gains, $\dot{Q}_{ET}$ is the energy flux lost due to evapotranspiration, $\dot{Q}_{solair}$ is the fraction of solar radiation entering the zone through external windows which is immediately transferred as a convective gain to the inside air.

The internal and external convective heat transfer coefficients of the greenhouse covering [41]:

$$h_{ai-c} = 1.247\,(T_{ai} - T_{ci})^{1/3} \quad (3)$$

$$h_e = 7.2 + 3.8v \quad (4)$$

The convective heat transfer coefficients between indoor greenhouse air and the soil [25]:

$$h_{ai-s} = 1.7\,|T_{ai} - T_s|^{1/3}; \quad T_{ai} < T_s \quad (5)$$

$$h_{ai-s} = 1.3\,|T_{ai} - T_s|^{1/4}; \quad T_{ai} \geq T_s \quad (6)$$

The evapotranspiration convective heat flux $\dot{Q}_{ET}$ needs to be defined using an integrated user define module. It can be obtained by the following equation:

$$\dot{Q}_{ET} = ET \cdot \lambda \cdot \rho \cdot A_p \quad (7)$$

The mass balance for the greenhouse air node is given by [27]:

$$\chi \cdot \rho \cdot V \cdot \frac{d\omega_i}{dt} = \mathrm{m}_{inf} + m_v + m_{ET} \quad (8)$$

where χ is the moisture capacitance multiplier, ρ is the air density, V is the greenhouse volume, ω_i is the inside absolute air humidity ratio, m_v is the mass transfer rate of water due to ventilation, m_{inf} is the mass transfer rate of water due to infiltration, m_{ET} is the mass transfer rate of water due to evapotranspiration.

The moisture gains due to the evapotranspiration are equal to:

$$m_{ET} = \dot{Q}_{ET}/\lambda \quad (9)$$

D. GEOGRAPHICAL SITE AND CULTURE

Solar radiation in Morocco ranges from 5.28 to 6.33 kWh/m^2/day [8]. The outside climatic conditions (the incident solar radiation and ambient temperature) of Agadir (Morocco) are given by the Meteonorm database and are shown in Figure 3.

Tomato is an important vegetable crop in the world belongs to family of the Solanaceae [42], [43]. It is a fast-growing crop and sensitive to harsh climate. High humidity with

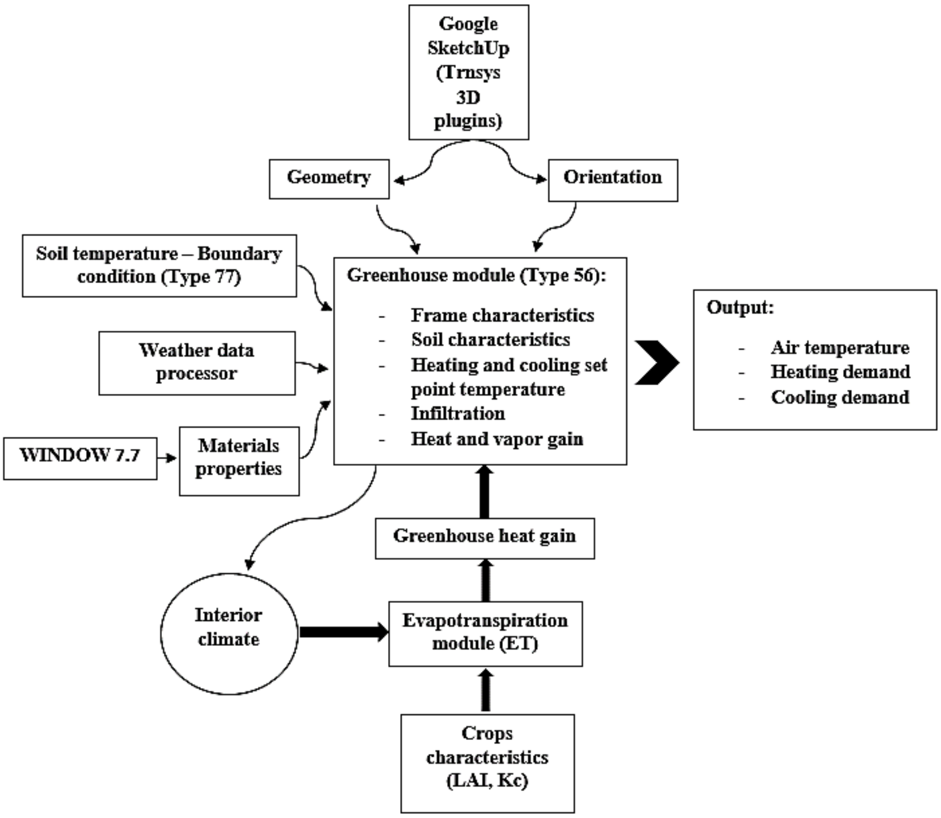

FIGURE 2. Diagram of this greenhouse model on TRNSYS.

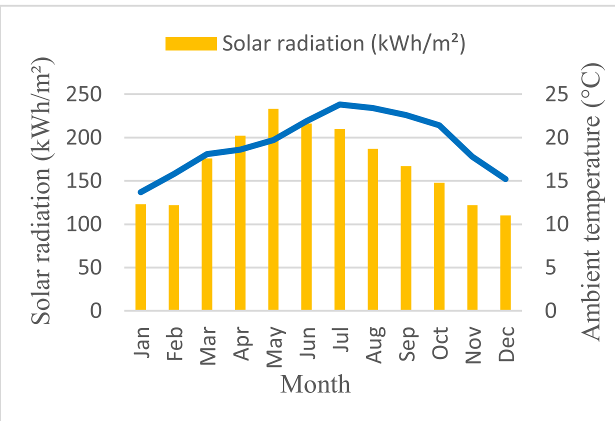

FIGURE 3. Solar radiation and ambient temperature of Agadir.

temperature above 25°C leads to a drop in yield [43], [44]. High night temperature and high humidity accompanied with low sunlight results an intense vegetation growth and low fruit productivity [43], [44]. Table 5 shows the optimum temperature for tomato growth.

High humidity results in a higher incidence of diseases and pests and rotting fruit. Therefore, dry climates are recommended for tomato cultivation. A relative humidity of 75% is considered optimal [45]. It allows to have fruits of good caliber and without defect of coloring.

E. EVAPOTRANSPIRATION ANALYSIS

Evapotranspiration (ET) represents the water loss from the plant to the air through evaporation and transpiration. It is associated to the supply water for the irrigation, the water stored variation in the soil, and the water amount evacuated from the greenhouse [37]. The evapotranspiration rate inside the greenhouse systems is dominated by plant transpiration and depend on the climatic conditions and the plant growth stage [46].

The estimation of ET implicates determining the reference evapotranspiration (ET_o) and the crop coefficient (K_c) which depend on the growth stage and the type of the crop. Several models have been evaluated in previous studies to predict the evapotranspiration rate (ET) under greenhouse conditions. High weather data quality is needed to have a high accuracy of evapotranspiration calculation [47]. Stanghellini [34] revised the Penman-Monteith model to represent greenhouse conditions, where wind speeds are typically $< 1.0\ m.s^{-1}$:

$$ET_o = 2.LAI.\frac{1}{\lambda}.\frac{s.(R_n - G) + K_t.\frac{VPD.\rho.c_p}{r_a}}{s + \gamma.\left(1 + \frac{r_c}{r_a}\right)} \quad (10)$$

$$ET = K_c \cdot ET_o \quad (11)$$

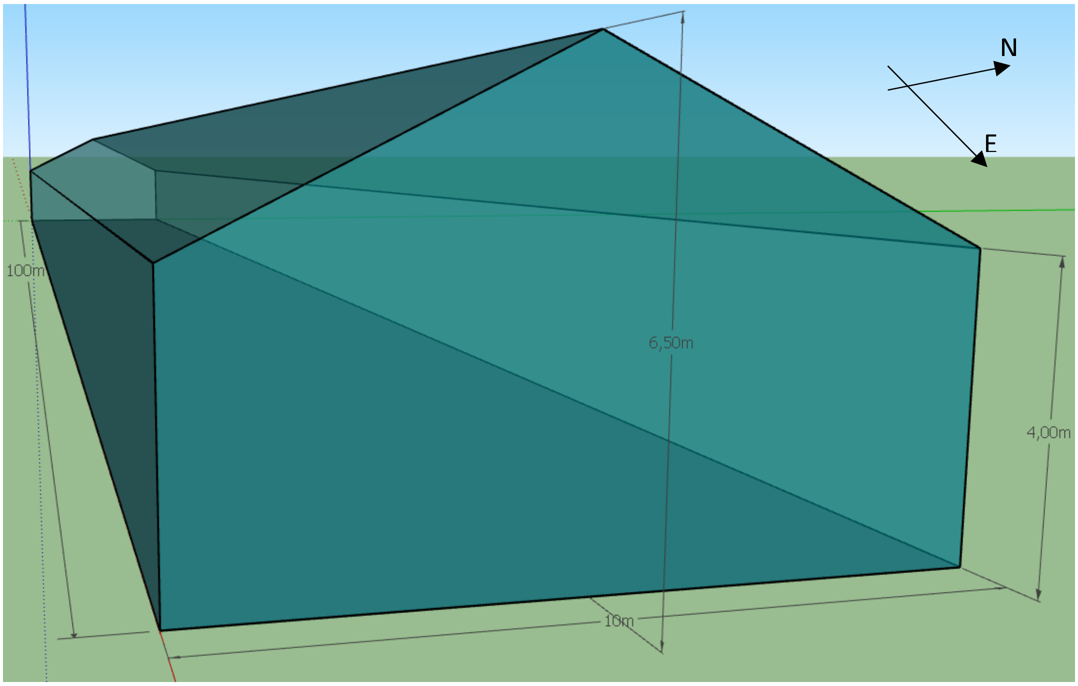

FIGURE 4. SketchUp drawing of the conventional greenhouse geometry used for the validation.

TABLE 5. Optimum temperature for tomato growth [44].

Time	Optimum temperature for tomato growth
Daytime	18-25°C
Nighttime	10-20°C

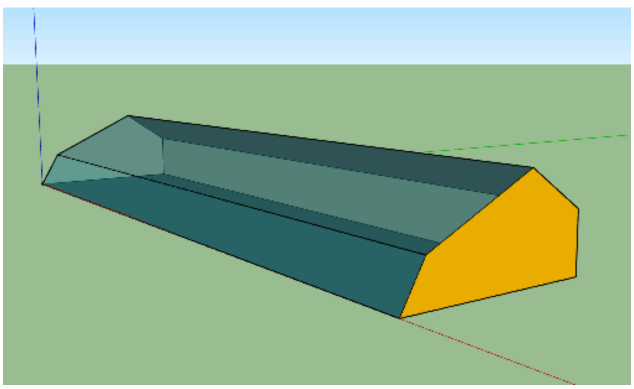

FIGURE 5. SketchUp drawing of the Chinese-style solar greenhouse geometry used for the validation.

where ET_o is the reference ET ($mmday^{-1}$). K_c is the crop coefficient and LAI is the leaf area index (m^2m^{-2}) was defined as the ratio of total leaf area (m^2) to ground area (m^2).

F. TRNSYS SIMULATION VALIDATION

In this section, a validation of the current model was made using previous studies from the literature. Ahamed *et al.* [11], [48] developed a quasi-steady state thermal model "GREENHEAT" to estimate the heating demand for year-round production of a conventional greenhouse. This model showed a great performance and validated with actual heating data collected from a commercial greenhouse located in Saskatoon [11]. In other study they developed a simulation model to estimate the hourly heating requirements in a Chinese style solar greenhouse (CSGHEAT) [12], [13]. The model was validated with experimental data, and the predicted result was found to be in good agreement with the measured data. The results obtained for the conventional greenhouse (GREENHEAT) by Ahamed *et al.* [48] and for Chinese style solar greenhouse (CSGHEAT) by Ahamed *et al.* [13], were adopted to validate the current thermal model (TRNSYS).

The first validation was made using a study made by Ahamed *et al.* [48]. They estimated the heating demand of a single-span greenhouse (1000 m^2) located in Saskatoon (52.13°N, 106.62°W), Saskatchewan, Canada. The greenhouse roof is covered with the air inflated double-layer polyethylene film, and the twin-wall polycarbonate (8 mm) enclosed the sidewall. The span width, the sidewall height, and the ridge height were 10 m, 4 m, and 6.5 m, respectively (Fig. 4). The hourly weather data of Saskatoon for 2015 from the National Solar Radiation Database (NSRDB) were used for the simulation.

The thermal curtain was considered to be in operation during the night to reduce the long-wave radiation heat loss through the transparent cover. Supplemental lighting is important for the winter greenhouse at high northern latitudes to maintain the optimum photoperiod for plants. Therefore, the supplemental lighting was considered to be turned on between 7 AM to 10 PM. The natural gas operated CO_2

generator was considered in operation for the entire sunlight period, and the air circulation system was considered to be effective for all the times. The input parameters for the simulation of heating requirements are listed in Table 6.

The second validation was made using a study made by Ahamed *et al.* [13]. They estimated the heating demand of a typical Chinese-style solar greenhouse (30 m × 7 m, 3.5 m height at the ridge) (Figure 5) located in Saskatoon (52.13°N, 106.62°W), Saskatchewan, Canada. The angle of the south roof in CSG is relatively high near the ground for effective use of the indoor growing area and bent to reduce the slope after a certain height. The lower part has an angle of 60° near the ground, and the upper part has an angle of 26°. The angle is 34° for the nontransparent north roof. The south roof of the greenhouse is glass-covered, and the other three walls and north roof are nontransparent. Table 7 shows the physical and thermal properties of the materials used for the simulation. The typical meteorological year (TMY) data files of Saskatoon (52.13°N, 106.62°W) from the Canadian weather year for energy calculation (CWEC) were used [49].

The thermal blanket was considered as external shading device which covered the south roof only for the nighttime, and the additional thermal resistance was assumed to be 0.37 m^2 K/W. The heating set-point temperatures for the day and night were considered as 21°C and 18°C, respectively, and the optimum relative humidity was considered at 80%. The cooling mode was set at 23°C of indoor temperature, and dehumidification mode was effective at 81% of indoor RH.

The infiltration rate was considered at 0.5 air changes per hour (ACH). The supplemental lighting was considered at 30 Wm^{-2}, which would be turned on when solar radiation would reach below 250 Wm^{-2}, and the lighting was considered to be turned off from 10:00 pm to 6:00 am, thereby 16 h of photoperiod was maintained in the greenhouse. The CO_2 supply to the greenhouse could contribute to the heating of the greenhouse when CO_2 is produced by combustion of fossil fuel, quite often natural gas. The heat gain from the CO_2 generator was simulated based on the CO_2 supply rate 4.5 $gm^{-2}h^{-1}$ and the CO_2 production rate 2.7 kg per kg of fuel, and the net heating value of natural gas was considered at 38.0 MJm^{-3} of gas. The CO_2 generator was considered in operation for daytime from 6:00 am to 7:00 pm.

III. RESULTS AND DISCUSSIONS

A. VALIDATION

1) TRNSYS SIMULATION MODEL

Ahamed *et al.* [48] found that annually heating demand of a greenhouse tomato is 1486 MJ/m^2 using GREENHEAT model. The annually heating demand given by TRNSYS simulation is 1462 MJ/m^2, with 1.66% of difference. Figure 6 showed the Monthly heating demand for greenhouse tomato obtained by Ahamed *et al.* [48] and TRNSYS simulation. From April to September, the monthly heating demand had negligible values, so for comparison purposes, the results obtained for these months are excluded from the analysis. The

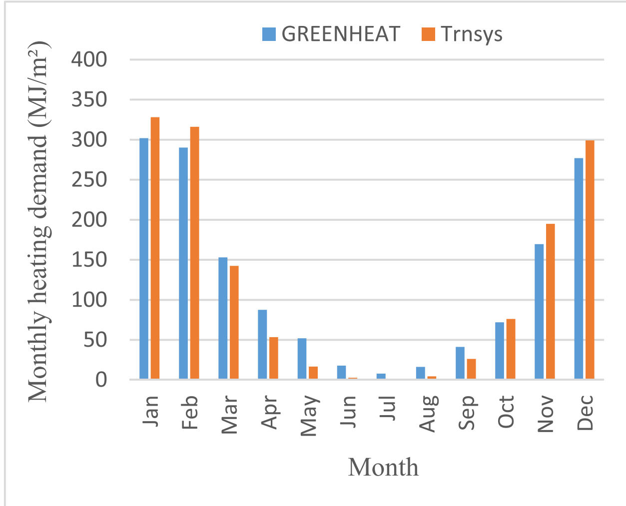

FIGURE 6. Monthly heating demand (MJ/m^2).

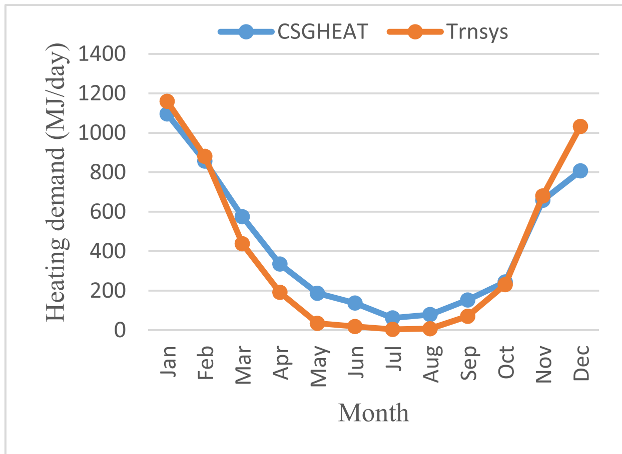

FIGURE 7. Monthly average daily heating requirement predicted by TRNSYS simulation and CSGHEAT.

comparison between the results obtained by GREENHEAT and TRNSYS gives relative error inferior then 8.95% in the cold months (except November had 14%) with the average difference of 8.9%. Previous studies reported that the average percent error in simulation close to 10% is reasonably acceptable for greenhouse thermal modeling [11]. Therefore, it can be concluded that the current simulation mode can predict the energy requirement of conventional greenhouses with good accuracy. Figure 7 compares the simulated average daily total heating requirement in each month in the study greenhouse by TRNSYS and CSGHEAT. The comparison between the results obtained by CSGHEAT and TRNSYS gives average difference of 11.5%. Therefore, it can be concluded that the current model can be used to predict the energy requirement Chinese Solar Greenhouses (CSG).

2) EVAPOTRANSPIRATION MODEL

A study was made by Pamungkas *et al.* [37], where good results were obtained for estimation hourly evapotranspiration rate. We used this study to validate the current

TABLE 6. Constant values of different parameters used for the first validation [48].

Parameters	Value	Units
Greenhouse characteristics		
Infiltration rate per hour	1.0	(-)
Thermal conductivity of plywood (19 mm)	0.12	(W m^{-1} K^{-1})
Thermal conductivity of polystyrene insulation (65 mm)	0.03	(W m^{-1} K^{-1})
Soil characteristics		
Thermal conductivity of soil	1.4	(W m^{-1} K^{-1})
Soil temperature	15	(°C)
Plant characteristics		
Average leaf area index of tomato	3	(-)
Characteristic length of tomato leaf	0.027	(m)
Covering characteristics		
Thermal air conductance of the air spaces	3.85	(W m^{-2}·K^{-1})
Poly cover (6 mils)		
Emissivity of IR barrier poly cover	0.2	(-)
Transmissivity to solar radiation	0.75	(-)
Transmissivity to long-wave radiation	0.29	(-)
Thermal conductivity	0.33	(W m^{-1} K^{-1})
Polycarbonate (8 mm twin-wall)		
Emissivity of polycarbonate	0.65	(-)
Thermal conductivity	0.2	(W m^{-1} K^{-1})
Transmissivity to solar radiation	0.78	(-)
Transmissivity coefficient to long-wave radiation	0.03	(-)
Other parameters		
Installed lighting wattage	50	(W m^{-2})
Heat conversion factor	0.75	(-)
Lighting allowance factor	1.2	(-)
Number of recirculating fans	12	(-)
Rated power of motors	375	(W)
Motor efficiency	0.9	(-)
Motor load factor	1.0	(-)
Motor use factor	1.0	(-)
Net heating value of fuel	38	(MJ m^{-3} of gas)
Rate of CO_2 supply in greenhouse	4.5	(g m^{-2} hr^{-1})
CO_2 production rate	2.7	(kg kg^{-1} of fuel)

model. Table 8 shows the ET calculated and measured by Pamungkas *et al.* [37] and TRNSYS model for different hourly values measured of air temperature, solar radiation, and relative humidity in the period of February 26-March 10, 2014. Pamungkas *et al.* [37] mentioned that crop coefficients were nearly equal to 1 current their study. The wind speed measured inside the greenhouse during the experiments was lower than 0.5 ms^{-1}. The maximal relative deviation

TABLE 7. Physical and thermal properties of the materials used for the second validation [13].

Surfaces	Materials	Thermal Properties
South roof	Single layer glass (0.04 m)	U = 5.86 W m^{-2}.K g-value = 0.85 Convection coefficient = 11 kJ h^{-1} m^{-2} K^{-1} (inside), 64 kJ h^{-1} m^{-2} K^{-1} (outside)
North roof and end walls	Plywood (0.013 m), extruded polystyrene insulation (0.065 m), and plastic sheet (from outside to inside).	U= 0.25 W m^{-2}.K Longwave emission coefficient = 0.9 Convection coefficient = 11 kJ h^{-1} m^{-2} K^{-1} (inside), 64 kJ h^{-1} m^{-2} K^{-1} (outside)
North wall	Galvanized steel (0.002 m), sand (0.152 m), extruded polystyrene insulation (0.065 m), plywood (0.013 m), and steel (0.002 m) (from outside to inside).	U= 0.23 W m^{-2}.K Solar absorptance = 0.8 Longwave emission coefficient = 0.9 Convection coefficient = 11 kJ h^{-1} m^{-2} K^{-1} (inside), 64 kJ h^{-1} m^{-2} K^{-1} (outside)
Floor	Plaster/Clay (0.1 m)	U= 2.61 W m^{-2}.K Solar absorptance = 0.8 Longwave emission coefficient = 0.9 Convection coefficient = 4.5 kJ h^{-1} m^{-2} K^{-1}

is 6.5%, which mean that the model has an acceptable precision.

B. GREENHOUSE THERMAL BEHAVIOR

After the creation of the greenhouse model using TRNSYS, several simulations were performed to determine the greenhouse thermal behavior. For a comprehensive analysis, the air temperature of the greenhouse under different material at three consecutive days referring to the four seasons of the year in Morocco (21-23 of March, June, September and December), were presented (figures 8-11). In addition, to show the effect of the plant's evapotranspiration on the greenhouse thermal behavior, the inside air temperature was presented with and without presence of tomatoes crops inside the greenhouse.

The results show that the inside air temperature varies according to the climate and the season of the year and is generally higher than ambient temperature for all the studied covering materials due to the greenhouse effect. PHS covering material provides the higher inside temperature significantly for all the time which can exceed 45°C at summer. The lower inside temperature showed by PE with a low difference with PVC. A marginal difference between PC and PMMA covering materials was observed. The inside air temperature in an empty greenhouse is higher than in a greenhouse full of mature tomato crops (LAI up to 3) for all the season under all the studied covering materials. This decrease of the temperature can be explained by the evapotranspiration phenomenon of the crops, which cools the air. Higher value of crop coefficient (K_c) and leaf area index (LAI) leads to a high evapotranspiration flux and crops area, which implies a high energy absorbed by the plants leaf from the air. The same outcome was discussed in previous studies [25], [26].

C. GREENHOUSE HEATING AND COOLING REQUIREMENT

1) GREENHOUSE COVERING MATERIAL

Several covering materials are widely recognized on the market and selecting the appropriate choice of materials to satisfy local requirements helps reduce the greenhouse operating costs. Figure 12 shows the heating and cooling requirements of different greenhouse covering materials. The heating and cooling demand vary according to the climate and the months of the year; the maximal cooling loads occur during the month of July while the maximal heating loads are observed in January. During winter months, the cooling needs are generally negligible independently of the covering material, the same for the heating loads in the summer months. The annual heating demand of the greenhouse covered by PHS, PC, PMMA, PVC and PE for a year-round production of tomato are 91.9, 111.6, 120.9, 125.2 and 129.8 MJ/m^2, respectively. These results are in agreement with the trend of the heating and cooling load reported by a previous study (Rasheed *et al.*, 2018), in which PE showed the highest annual heating demand (750 MJ/m^2.yr), under Daegu (latitude 35.53° N, longitude 128.36° E) climatic conditions, compared to the other materials. In this study, PHS shows the low annual heating energy demand (91.9 MJ/m^2) and the high annual cooling demand (202.6 MJ/m^2). The greenhouses in Morocco are generally covered by 0.2mm PE, the simulated results indicated that the annual heating and cooling requirement in a greenhouse cover by 0.2mm PE was around 129.8 MJ/m^2 and 134,3 MJ/m^2 respectively. Therefore, using PHS as a covering material at Agadir (Morocco) can reduce by 29.2% the annual heating demand by comparison to PE. On the other hand, PHS have the higher annual cooling demand, so it cannot be decided that this material is the suitable for the greenhouse covering. The suitable covering material should be optimal for both the heating and cooling requirement. Therefore, an economic analysis, taking into account both the heating and cooling demand and their cost, was made and discussed in the coming sections.

The effect of different material thicknesses, including 1, 2 and 3mm of double layered PE in addition to single PE, is also investigated in this study. The thickness of each sheet is 0.1 mm; therefore, the overall thickness of the materials is determined by the air gap between them. Figure 13 shows the heating and cooling energy demand of the greenhouse

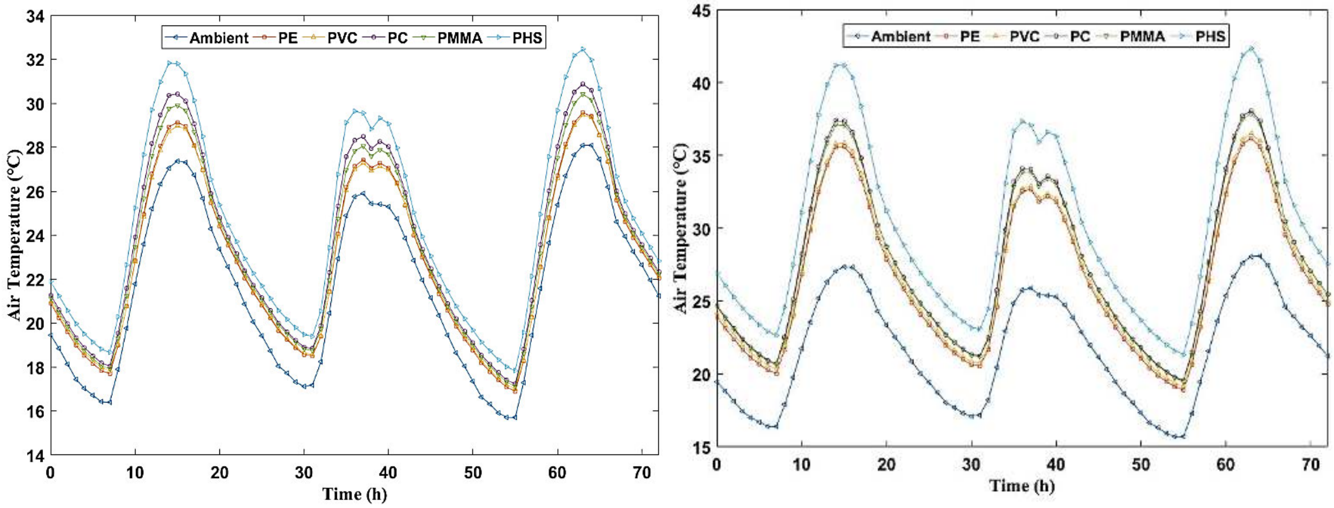

FIGURE 8. Ambient and inside greenhouse temperature at 21-23 September for each covering material for a full (right) and empty (left) greenhouse.

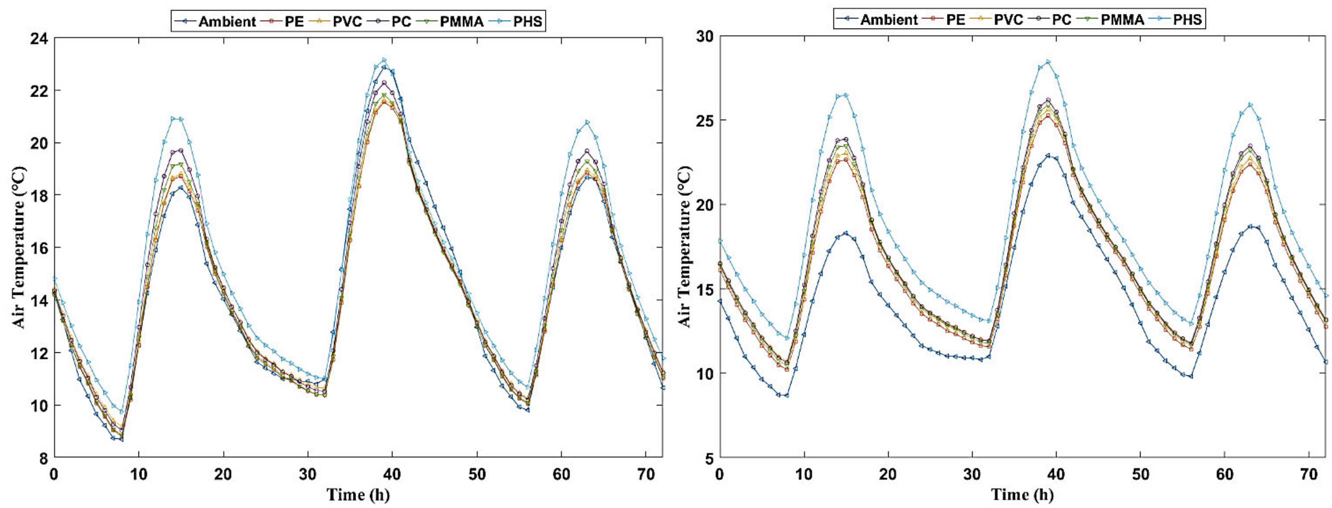

FIGURE 9. Ambient and inside greenhouse temperature at 21-23 December for each covering material for a full (right) and empty (left) greenhouse.

TABLE 8. ET calculated by Pamungkas *et al.* [37] and TRNSYS modelisation.

Temperature (°C)	Solar radiation ($MJm^{-2}h^{-1}$)	Relative humidity (%)	ET (mmh^{-1}) by [37]	ET calculated (mmh^{-1})	Relative error (%)
25.4	0.33	60.15	0.1111	0.1081	2.742
26.3	0.43	51.43	0.1367	0.137	0.204
27.7	0.56	37.74	0.1711	0.1809	5.697
21.6	0.17	71.05	0.07081	0.06804	3.925
27.05	0.46	39.61	0.1603	0.1646	2.664
28.1	1.01	32.76	0.2370	0.2451	3.396
22.3	0.102	52.06	0.1032	0.09656	6.505

covered with PE with different gap thicknesses. It has been noticed that the heating demand decreases, and the cooling demand increases significantly when the cover thickness is increased. This outcome was as well confirmed by previous studies [16], [50], which highlighted that Double-layered PE reduces heat loss through the coverings and the internal

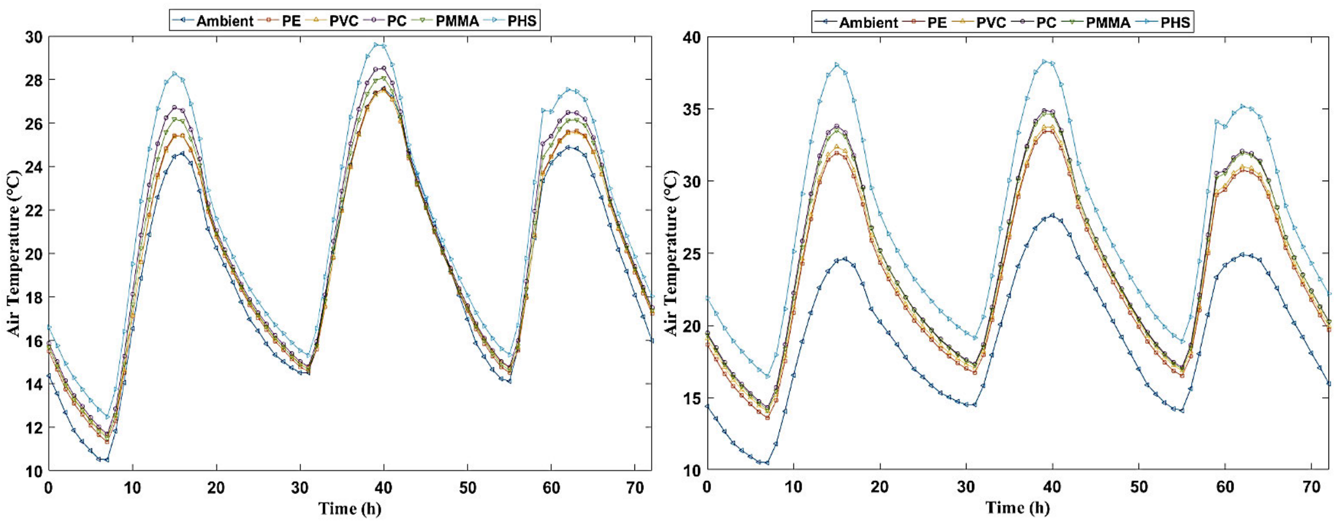

FIGURE 10. Ambient and inside greenhouse temperature at 21-23 March for each covering material for a full (right) and empty (left) greenhouse.

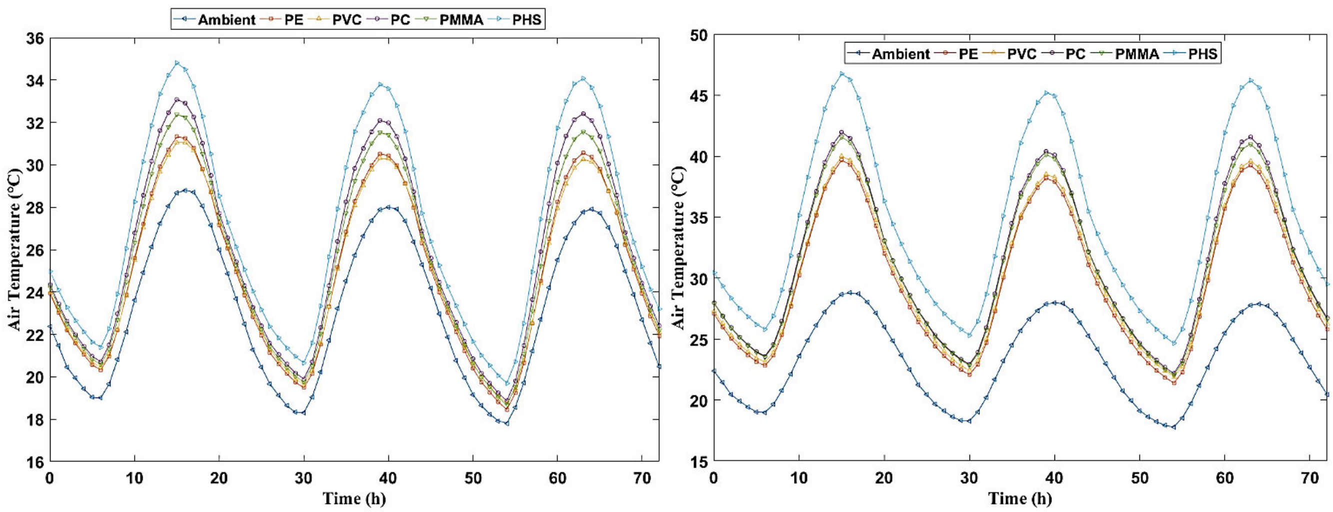

FIGURE 11. Ambient and inside greenhouse temperature at 21-23 June for each covering material for a full (right) and empty (left) greenhouse.

temperature was 2–5°C higher than that of the single-layered greenhouse [16]. The same authors investigated the effect of different thicknesses of a double layered material, they found that the heating demand decreases significantly when the cover thickness increases [16]. In this study, a 20.5% reduction in the heating energy requirement was observed when the single PE covering replaced by a Double PE (3mm gap thickness) covering. On the other hand, in the cooling demand point of view, the Double PE (3mm gap thickness) have a higher cooling requirement than single PE, so it cannot be decided which material is the optimum. Therefore, an economic analysis was made and discussed in the coming sections in order to find the optimum gap thickness.

In addition to the gap thickness, gap gas type was also investigated. Figure 14 shows monthly heating and cooling demand of the greenhouse for different gas type of double PE, the gases are: air, Argon, Krypton, and Xenon. Xenon showed the lowest annual heating energy demand (98.5 MJ/m^2) and the highest annual cooling demand (194.9 MJ/m^2), while air showed the highest annual heating energy demand (113.2 MJ/m^2) and the lowest annual cooling demand (169.6 MJ/m^2). By using Xenon as a gap in double PE at Agadir (Morocco), it possible to reduce by 13% the annual heating demand. On the other hand, Xenon shows the highest annual cooling demand, so it cannot be decided which gap gas type is the optimum. Therefore, an economic analysis was made and discussed in the coming sections in order to find the optimum gap gas type.

2) GREENHOUSE ORIENTATION

Figure 15 shows the monthly heating and cooling energy demand of the greenhouse for the orientations: E-W and N-S. The heating load during the winter months is higher

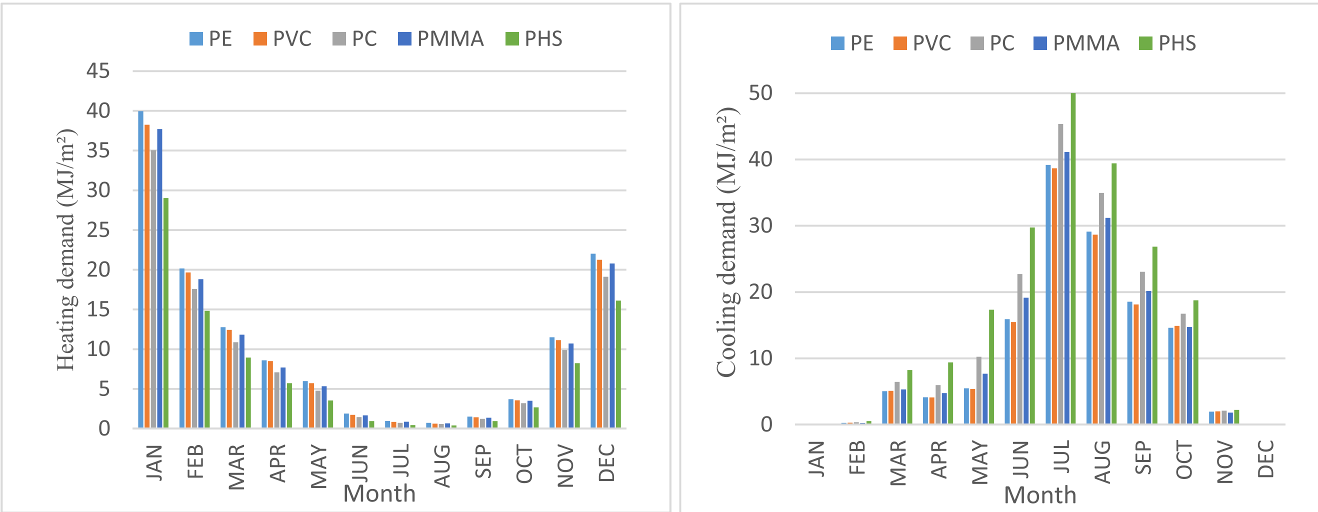

FIGURE 12. Monthly heating and cooling demand of the greenhouse for different materials.

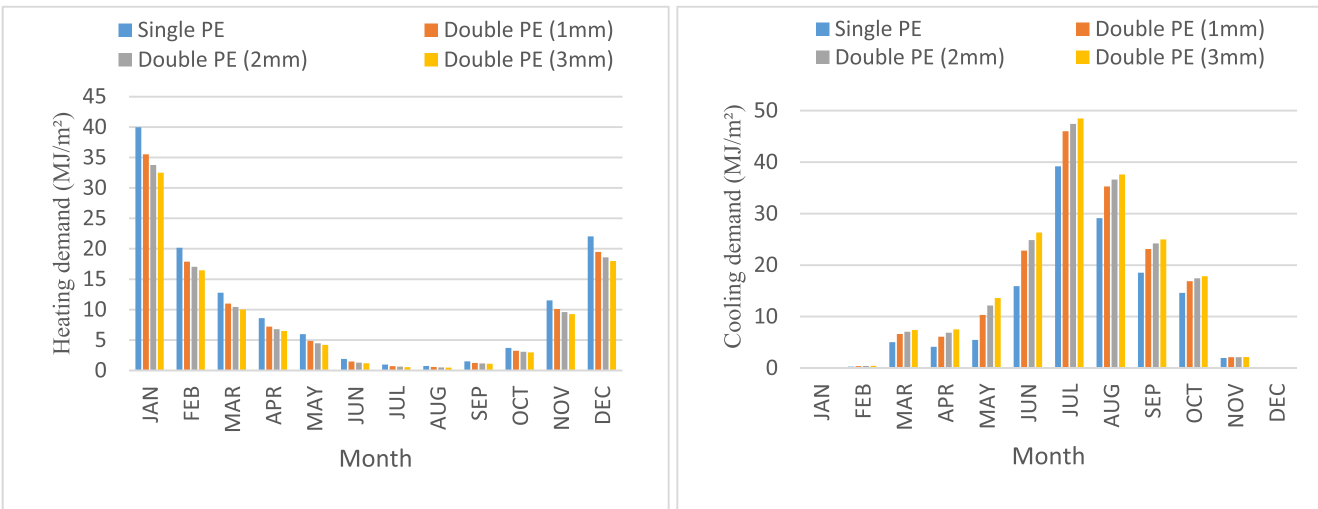

FIGURE 13. Monthly heating and cooling demand of the greenhouse for different gap thickness of double PE.

in the N-S oriented greenhouse than in the E-W oriented greenhouse; the opposite trend can be observed during the summer months. Overall, the required cooling load during summer and heating load during winter, respectively, are lower for an E-W orientation. Stanciu *et al.* [24] compared these two orientations of a greenhouse located at Romania. They found that E-W orientation gives higher heating demand and lower cooling demand in summer and lower ones in winter in comparison to a N-S orientation, which confirmed the results obtained by the current study.

3) GREENHOUSE SHAPE

An analysis was carried out by performing three simulations separately for the three different greenhouse shapes, thereby calculating the monthly heating and cooling energy requirement to keep the optimum inside air temperature for each shape, the results are reported in Figure 16. The annual heating energy demand for the Arc, Even-span and Quonset shapes are 162.7, 153.8 and 154.6 MJ/m^2, respectively. Annual cooling demand was around 145.06, 167.5 and 126.8 MJ/m^2, for Arc, Even-span and Quonset, respectively. The arc shape showed lowest energy consumption than other shapes from heating point of view, while the Even-span showed better performance from cooling point of view. Therefore, it cannot be decided which shape is the optimum for the greenhouse, and an economic analysis was made and discussed in the coming sections in order to find the optimum greenhouse shape.

4) GREENHOUSE AIR CHANGE RATE

The heating and cooling requirements of the greenhouse were calculated for different air change rates and are reported

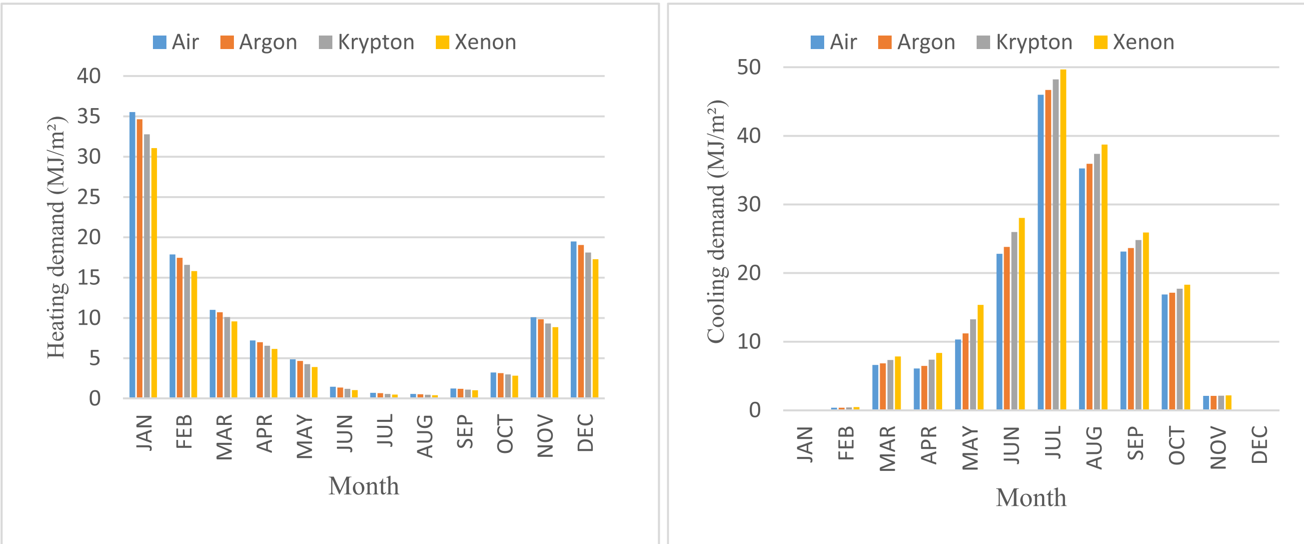

FIGURE 14. Monthly heating and cooling demand of the greenhouse for different gas type of double PE.

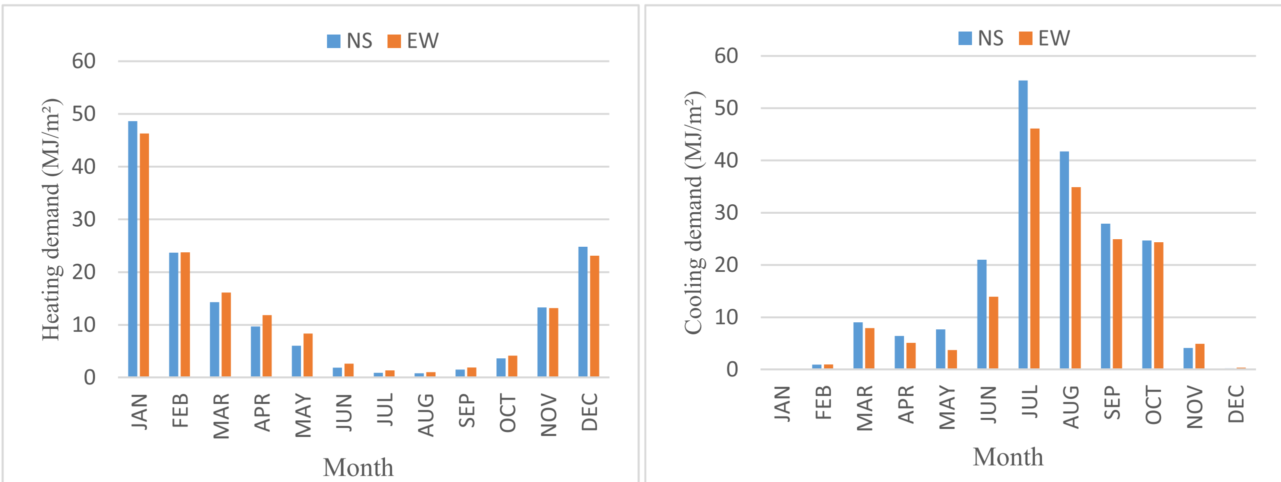

FIGURE 15. Monthly heating demand of the greenhouse for different greenhouse orientation (MJ/m^2).

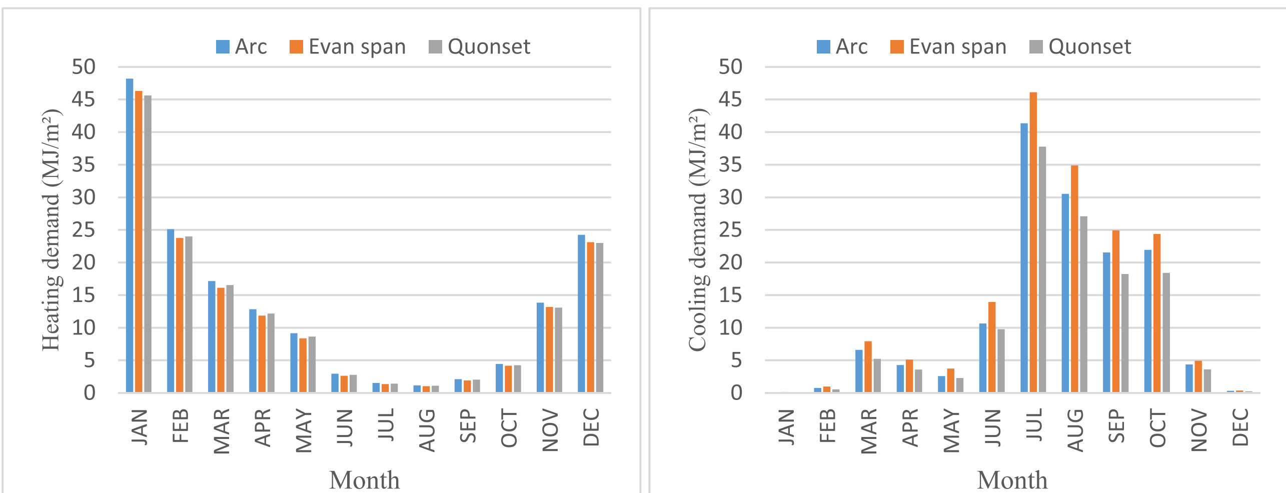

FIGURE 16. Monthly heating and cooling demand of the greenhouse for different greenhouse shape.

in Figure 17. It is observed that the annual heating and cooling demands increase significantly with the increase of air change rate. By increasing the greenhouse air change rate from 1 to 2, 3, 4, 5, 6, 7, 8, 9 and 10 h^{-1}, the greenhouse annual

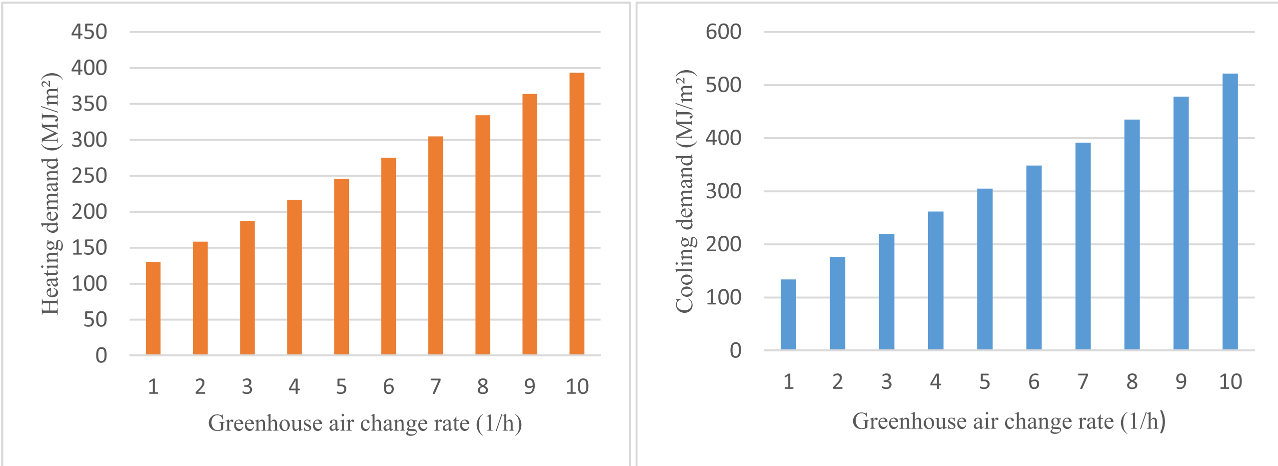

FIGURE 17. Annually heating and cooling demand of the greenhouse for different greenhouse air change rate.

heating demand increase by 21.8%, 44.07%, 66.5%, 89.04%, 111.65%, 134.31%, 157%, 179.72% and 202.46%, respectively, and the greenhouse annual cooling demand increase by 31.52%, 63.4%, 95.45%, 127.61%, 159.82%, 192.08%, 224.36%, 256.69% and 289.02%, respectively. As conclusion, the air change rate should be minimized as much as possible to reduce the heating and cooling energy requirement.

D. ANNUAL COST OF AIR-CONDITIONING

In order to determine the optimal greenhouse configuration within the scope of this study, an economic analysis was performed. A commercial heat pump (coefficient of performance COP of heating equal to 3.5 and COP of cooling equal to 2.5) was adopted to cover the heating and cooling requirement of the greenhouse. The electricity cost in Morocco ranges from 0.9-1.2 MAD/kWh [51].

The Annual Cost of Air-Conditioning (ACAC, MAD/year.m^2) was calculated for each scenario to achieve the purpose of this study. This indicator required the heating and cooling energy requirement of the greenhouse (E_h and $E_c(kWh/year.m^2)$, respectively), the COP of heating and cooling, and the electricity cost $\hat{c}$ (a value of 1.1 MAD/year.m^2 was assumed for this study).

The annual cost of air-conditioning is:

$$ACAC = \left(\frac{E_h}{COP_h} + \frac{E_c}{COP_c}\right) \times \hat{c} \tag{12}$$

Figure 18 shows the annual cost of air-conditioning of the greenhouse for different materials. PHS covering material showed the higher value of the annual cost by 32.78 MAD/year.m^2, while PVC showed the lower value of 27.16 MAD/year.m^2. Using PVC as a greenhouse covering material could save 2.12% of the annual cost of air-conditioning of the greenhouse in Morocco instead of using PE. The PVC greenhouse covering material is the optimum material for the Morocco climate condition.

Figure 19 shows the annual cost of air-conditioning of the greenhouse for different gap thickness of double PE. It has been noticed that the annual cost of air-conditioning of the greenhouse increases significantly when the cover thickness increased. Single PE showed the lower value of the annual cost by 27.75 MAD/year.m^2. It can be concluded that using single sheet of PE is suitable for greenhouse covering in Morocco compared to Double PE.

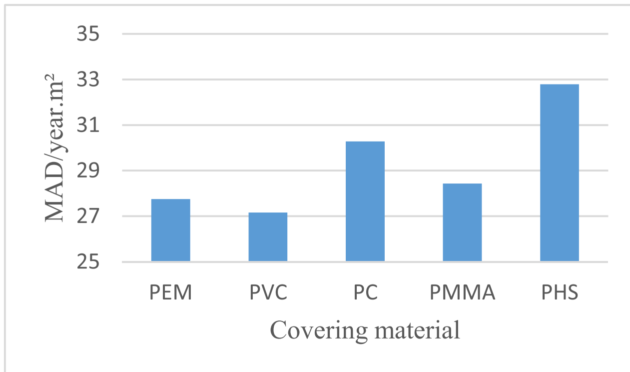

FIGURE 18. Annual cost of air-conditioning of the greenhouse for different materials.

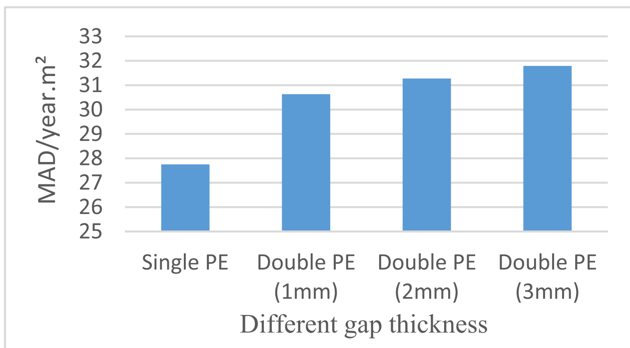

FIGURE 19. Annual cost of air-conditioning of the greenhouse for different gap thickness of double PE.

Figure 20 shows the annual cost of air-conditioning of the greenhouse for different gas type of double PE. Using air as gap gas in double PE showed the lower value of the annual cost by 30.63 MAD/year.m^2, which makes it the optimum

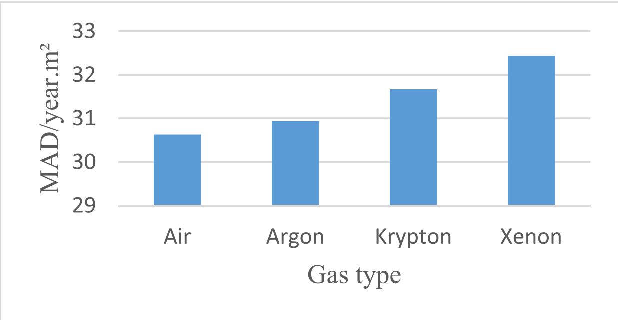

FIGURE 20. Annual cost of air-conditioning of the greenhouse for different gas type of double PE.

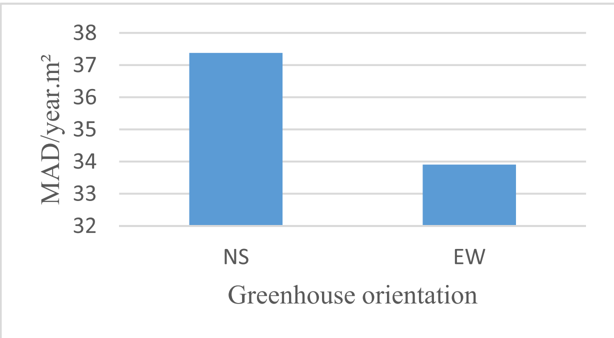

FIGURE 21. Annual cost of air-conditioning of the greenhouse for different greenhouse orientation.

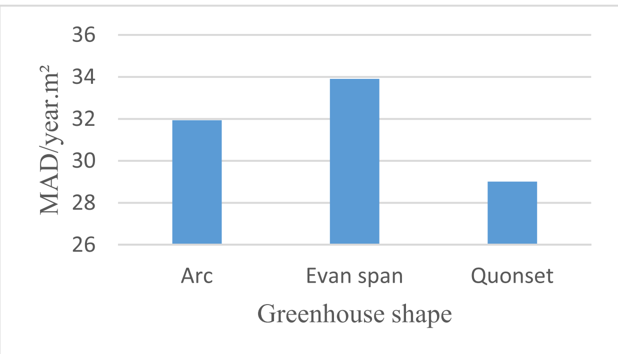

FIGURE 22. Annual cost of air-conditioning of the greenhouse for different greenhouse shape.

gap gas type for a greenhouse in Morocco, compared to Argon, Krypton and Xenon.

Figure 21 shows the annual cost of air-conditioning of the greenhouse for different greenhouse orientation. East-West greenhouse orientation could save 9.28% of the annual cost of air-conditioning of the greenhouse in Morocco compared to North-South orientation, which makes it the suitable greenhouse orientation for Morocco climate condition.

Figure 22 shows the annual cost of air-conditioning of the greenhouse for different greenhouse shape. The results indicated that Quonset shape showed the lower annual cost by 29.01 MAD/year.m^2 compared to Even-span and arc shape, which mean that is the optimum shape for Moroccan greenhouses. Using Quonset shape for greenhouse in Morocco can save 14.44% of annual cost of air-conditioning instead of using Even-span shape that used widely in this country.

IV. CONCLUSION

An investigation of the greenhouse design parameters that affect the thermal behavior and the heating/cooling energy need of a greenhouse situated in Agadir (Morocco) was studied extensively using dynamic simulation. A validation of the current TRNSYS simulation model was made using previous studies from the literature. The relative error of the annually heating demand obtained by this model is 1.66%. The comparison between the results obtained by GREENHEAT and TRNSYS gives the average difference of 8.9% in the cold months where the heating demand is important. The evapotranspiration model used in this study shows relative deviation less than 6.5%, which mean that the model has an acceptable precision. Examined parameters include cladding material (their types, single and double glazing, thickness of double glazing, gap gas type), shape, orientation, and air change rate, was made in this study. The inside air temperature varies according to the climate and the season of the year, and it is higher than ambient temperature for all the studied covering materials due to the greenhouse effect. The inside air temperature in an empty greenhouse showed a higher temperature value then a greenhouse full of mature tomato crops (LAI up to 3) for all the seasons under all the studied covering materials.

Based on the comparative results from the study, the following conclusions can be retained:

- Using PHS as a covering material instead of 200μm PE that is widely used at Agadir (Morocco), can reduce 29.2% of annual heating demand.
- The heating demand decreased and the cooling demand increased significantly when the cover thickness increased. A 20.5% reduction in the heating energy requirement was observed when the single PE covering replaced by a Double PE (3mm gap thickness) covering.
- Using Xenon as a gas gap in double PE at Agadir (Morocco), can reduce 13% of annual heating demand.
- The arc shape showed better performance than other shapes from heating point of view, while the Even-span showed better performance from cooling point of view.
- Using PVC as a greenhouse covering material could save 2.12% of the annual cost of air-conditioning of the greenhouse in Morocco instead of using PE, which mean the PVC is the optimum material for the Morocco climate condition.
- It can be concluded that using single sheet of PE is suitable for greenhouse covering in Morocco compared to Double PE.
- Using air as gap gas in double PE showed the lower value of the annual cost by 30.63 MAD/year.m^2, which makes it the optimum gap gas type for a greenhouse in Morocco, compared to Argon, Krypton and Xenon.
- East-West greenhouse orientation is the optimum orientation as it can save 9.28% of the annual cost of air-conditioning of the greenhouse in Morocco compared to North-South orientation.

- Quonset shape is the optimum greenhouse shape in Morocco as it can save 14.44% of annual cost of air-conditioning instead of using Even-span shape that is widely used in the country.

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