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Article

Development and Optimization of a Building Energy Simulation Model to Study the Effect of Greenhouse Design Parameters

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Abstract: Energy management of the greenhouse is considered to be one of the most important challenges of greenhouse farming. Energy saving measures need considered, besides applying energy supplying techniques. To address this issue, a model was developed to simulate the thermal environment of a greenhouse using a Transient Systems Simulation Program (TRNSYS 17) as a building energy simulation (BES) platform. The model was calibrated by modifying the input parameters to minimize the uncertainties obtained from the results. Nash-Sutcliffe efficiency coefficients of 0.958 and 0.983 showed good agreement between the computed and experimental results. The proposed model was used to evaluate the effects of greenhouse design parameters, including roof shape, orientation, double-glazing, natural ventilation, coverings and their thickness, on its energy conservation capacity. It was found that the most suitable design for a greenhouse located in Daegu (latitude 35.53° N, longitude 128.36° E) South Korea would be east-west (E-W) oriented, with a gothic-shaped roof and double-glazing of PMMA (Polymethylmethacrylate) covering. Natural ventilation reduced the inside temperature of greenhouse, thereby reducing the energy demand of cooling. The model developed can help greenhouse farmers and researchers make pre-design decisions regarding greenhouse construction, taking their local environment and specific needs into consideration.

Keywords: energy conservation; structural modeling; heating load; cooling load

1. Introduction

In severe climatic conditions, different heating and cooling systems are used to achieve the desired microenvironment in a greenhouse; however, this combination tends to cause an increase in energy consumption. Although the value of higher crop yields that can be obtained in a well-controlled modern greenhouse compared to outdoor cultivation is recognized, there are concerns that the greenhouse sector has become one of the most energy-intensive sectors in the agriculture industry, because of its high energy input [1]. According to one recent report from South Korea, greenhouse heating costs have increased to 30–40% of total production costs [2]. Reduction of energy consumption in greenhouse farming is the most significant challenge facing both researchers and growers, and as energy demand increases, both are focusing on ways to manage, save, produce, and store energy [3]. Various technologies, particularly renewable energy, are being utilized globally to fulfill energy requirements in buildings in general, including in the agriculture sector [4].

Most of the existing studies have focused on applying different renewable energy sources in greenhouses, aiming to reduce the cost of energy production for economical crop growth [5,6]. Experimental analyses undoubtedly provide the most reliable data; however, the results obtained from such analyses are often site-specific and may be valid only for the particular climatic conditions under evaluation, in addition to being expensive [7]. Researchers have used modeling and simulation to analyze solar energy and geothermal energy, and different heating and energy storage systems with the aim of providing a more environmentally sustainable and economically feasible method of heating in greenhouses. Several studies have used the transient systems simulation program (TRNSYS) to investigate the feasibility of utilizing solar energy to heat greenhouses. Usually solar irradiation is high in summer and low in winter; this has inspired researchers to develop the concept of seasonal storage of energy to compensate for energy demand during heating periods [8]. Voulgaraki and Papadakis [9] presented studies of solar heating and seasonal storage for such a system, including thermal and economic analysis for the whole system. Carlini et al. [10] verified the feasibility of a “photovoltaic greenhouse” and further analyzed the influence of the climate outside the greenhouse, the choice of plants cultivated, the choice of construction materials, wind conditions, altitude, and slope exposure on energy balance. Attar et al. [11] also presented a greenhouse solar heating system, discussing the parameters that influence seasonal storage systems. Vadiie and Martin [1] studied feasibility of the evolution of solar energy to fulfil the energy demand of greenhouses, discussing options to minimize energy demand and maximize the utilization of solar energy. Asdrubali et al. [12] described a solar energy system for greenhouse heating and compared simulation results with real energy consumption. Chargui et al., and Sungbok et al. [13,14], who evaluated the applicability of geothermal energy for heating and cooling greenhouses, analyzed the on-demand utilization of energy stored in the earth. Moreover, Hoes et al., and Vadiie and Martin [15,16] studied the influence of the “closed greenhouse” concept from the perspective of energy management. Different aspects of energy management in greenhouses are important in different contexts. Dalamagkidis et al. [17] designed a scheme to optimize of heating, cooling, humidification, and dehumidification in greenhouses. Kolokotsa et al. [18] developed a fuzzy logic controller system and studied the efficiency of greenhouses while considering all the external parameters that influence their internal environments. Serir et al. (2012) [19] estimated the heat transfer coefficient of greenhouse covering materials in order to evaluate the thermal behavior of unheated greenhouses. Lee et al. [20] studied the optimal selection of heating and cooling facilities for greenhouses. Ishigami et al. studied [21] environmental control in greenhouses by calculating their heat balance and fogging systems. Zhang et al. [22] developed a model to study the soil heat storage in greenhouse and validated results of their model with experimental data. Park et al. [23] studied the cooling and heating load in greenhouses using plant hot water. Therefore, we decided to propose a Building Energy Simulation (BES) model to study the greenhouse design parameters, which will help researchers and growers to take pre-design decisions under local weather conditions.

Apart from using novel energy conservation technologies, evaluating and optimizing greenhouse design parameters can affect fuel consumption positively and reduce energy demands. The evaluation of greenhouse design parameters has the potential to reduce energy demand. Energy supply techniques were modeled without considering the potential effects of various greenhouse design parameters on energy efficiency. There are some studies that analyze greenhouse design parameter. Mathala et al. developed a mathematical model to study these parameters, comparing the inside temperature for each one. However, this study did not calculate energy demand and ignored different covering materials typically used in greenhouses to reduce heat loss [24]. Gupta et al. [25] used an Auto-Cad tool to study the total solar fraction inside a greenhouse at different orientations to determine the best ones; while this study covers a very important design parameter, this model cannot be used to study the other parameters for decision making. Sethi [26] also studied the different shapes and orientations of greenhouses by using mathematical modeling based on solar radiation transmission through different shapes and orientations, and also validated the model using experimental results. These studies do not consider other greenhouse design parameters or estimate the total energy requirement for both heating

and cooling periods by taking the seasonal requirement into account. As many BES models have been developed and validated, this tool provides an opportunity for researchers to analyze agricultural buildings efficiently and evaluate different parameters, while accounting for local weather conditions.

TRNSYS is a versatile component-based program that provides tools to simulate both simple and complex energy flows in buildings. It was first developed in 1975 for the simulation of thermal systems but has since undergone continuous development to become a hybrid simulator by including photovoltaic, thermal solar, and other energy systems [13]. TRNSYS consists of a series of programs and add-ins that carry out simulation under user-defined conditions. It can easily be connected with many other programs, such as ANSYS Fluent, Matlab, and Excel, for coupled simulations and pre- and post-processing; such versatility has made TRNSYS an effective program to carry out energy systems simulations.

The main scope of this study is to provide a reliable BES model (using TRNSYS 17) to study how various aspects of greenhouse design affect energy conservation. It is important to determine energy demand to estimate annual operating cost for greenhouse crop production. The energy demand is highly dependent on greenhouse design parameters, which influence the internal environment of the greenhouse based on the availability of solar radiation in the greenhouse. Therefore, efforts have been made to correctly estimate the effect of solar radiation on the internal environment of a greenhouse. This was done by calibrating the proposed BES model based on a detailed examination of the methods used to calculate solar radiation on a tilted surface of the greenhouse. The BES model was successfully validated with the experimentally obtained results, and statistical analyses were carried out on the calibration and validation results to determine the reliability of the proposed model. The calibrated and validated BES model was then used to evaluate the effect of various greenhouse design parameters, including: Greenhouse shape, orientation, glazing, use of natural ventilation; which includes different roof and side vents openings, covering materials including; polyethylene (PE), polyvinyl chloride (PVC), horticulture glass (HG), polymethylmethacrylate (PMMA), and polycarbonate (PC), and the thickness of the covering material. All simulations were conducted for a single span greenhouse. The selection of the optimum greenhouse design can reduce its energy demand. This tool provides an opportunity for researchers and growers to analyze agricultural buildings efficiently and evaluate their different parameters while accounting for their local weather conditions.

2. Materials and Methods

2.1. Experimental Greenhouse

The single-span experimental greenhouse had a rectangular based, round roof, and was covered with a double-layered PE material, as shown in Figure 1. The dimensions of the greenhouse were 22 m × 8.4 m × 4 m, with a total volume and floor area of 556.8 m³ and 184.8 m², respectively; these specifications are shown in Figure 2. The experimental greenhouse was located in Daegu (latitude 35.53° N, longitude 128.36° E, elevation 48 m), South Korea. Necessary information and data from the site were collected to use as input data in the BES model. Weather data were recorded for one year starting from 1 January 2016; their characteristics are presented in Table 1. The temperature inside the greenhouse was measured at different locations along the central line, and the mean of these measured temperatures were used for comparison with the BES results for validation. During the experimental period, no crops were grown inside the greenhouse. The weather parameters, air temperature, solar radiation, and relative outdoor humidity were monitored by mounting several sensors outside the greenhouse. The annual mean temperature and solar radiation measured outside the greenhouse are given in Figures 3 and 4, respectively. In addition, wind speed, wind direction, and ambient pressure data were obtained from the Korean Meteorological Administration (KMA). Wind speeds

were recorded at a height of 10 m, but taking the height of our greenhouse into account, the wind speed data were modified to the height of its eaves using the following power law Equation (1) [27]:

$$W = W_d \left(\frac{h}{H} \right)^\alpha \quad (1)$$

where W is the wind speed in ms^{-1} at the required height h (in m), W_d is the wind speed at the given height H (in ms^{-1}), and α is an empirically derived coefficient (2/9).

Table 1. Characteristics of the weather data used in the simulations.

Weather Parameter	Unit	Time Interval	Sensor	Data Recorded
Temperature	°C	10 min	TR-76Ui-H, TECPEL	Field recorded
Relative humidity	%	10 min	TR-76Ui-H, TECPEL	Field recorded
Solar radiation	kW	10 min	CMP3, Kipp & Zonen	Field recorded
Wind speed	ms^{-1}	1 h	JY-WS161B, Jingang	KMA
Wind direction	degree	1 h	JY-WS161B, Jingang	KMA
Ambient pressure	hPa	1 h	PTB-220TS, VAISALA	KMA

KMA: Korean Meteorological Administration.



Figure 1. Experimental greenhouse at Daegu (latitude 35.53° N, longitude 128.36° E).

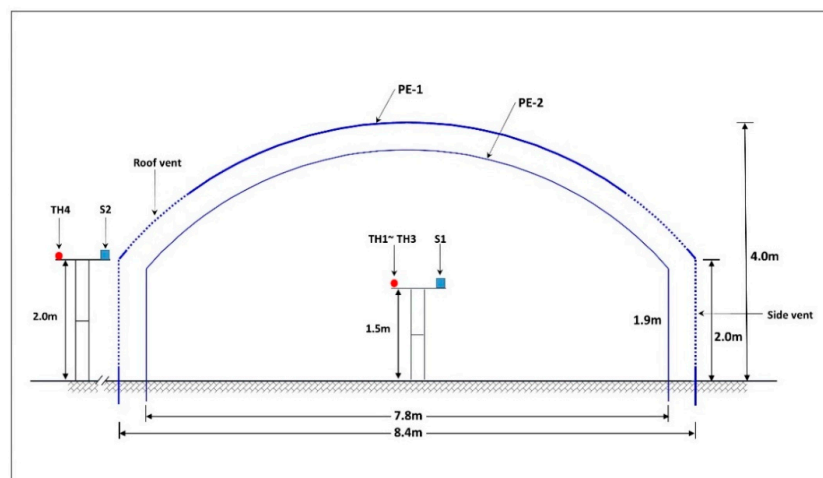


Figure 2. Dimensions and positions of sensors (S (solar radiation), TH (temperature & humidity)) in the experimental greenhouse. PE: Polyethylene.

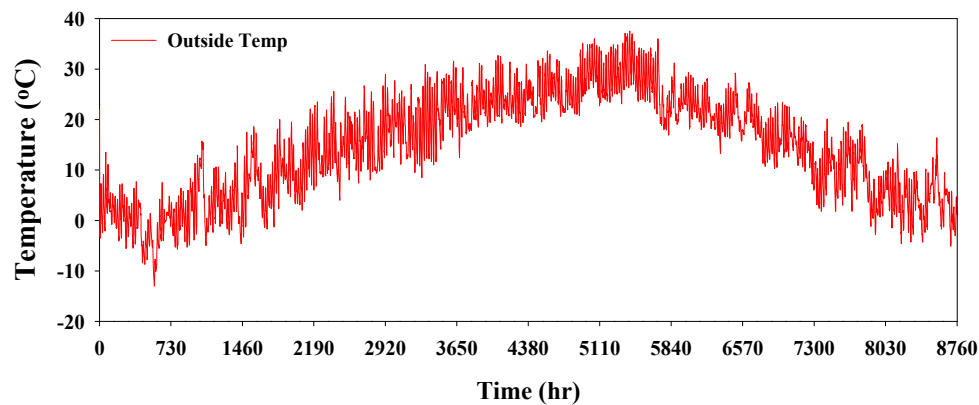


Figure 3. Hourly mean temperature outside the greenhouse.

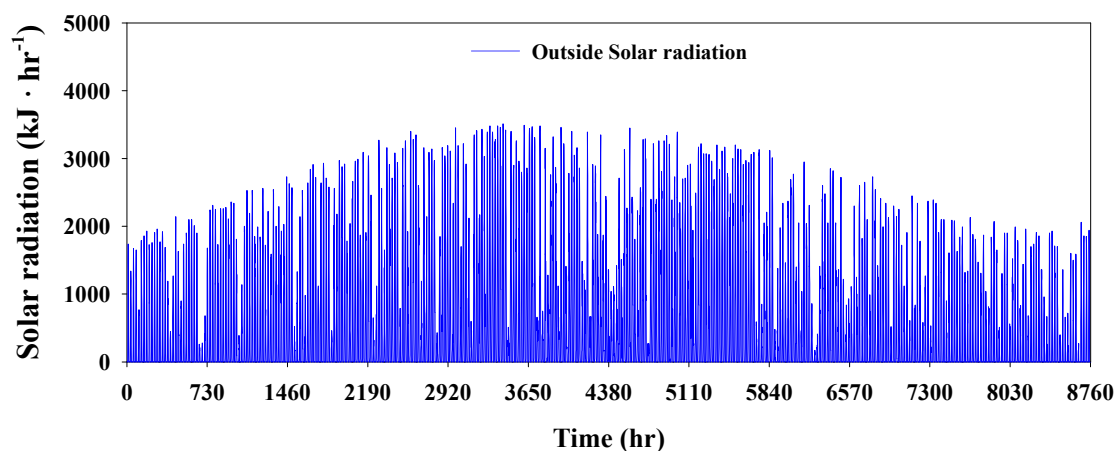


Figure 4. Hourly solar radiation outside the greenhouse.

2.2. Building Energy Simulation (BES)

2.2.1. Modeling

A BES model was designed, using the TRNSYS 17 program, to evaluate the effects of various greenhouse design parameters on its internal thermal environment. A sensitivity analysis was conducted by evaluating the impact of each parameter on the energy conservation capacity of the greenhouse. The details of each greenhouse design parameter, studied using BES modeling, are given in Table 2. For this study, we used the following TRNSYS 17 software modules: Simulation studio, TRNBuild, Google SketchUp™, Trnsys3d, TRNFlow, the SoilNoding program, and Berkeley Lab Window 7.4 software. These modules were run on a desktop personal computer with an Intel core i7-5820k processor (3.30 Ghz), DDR3-RAM (32 GB), and NVIDIA GeForce GTX 960 graphics card, using 64-bit Windows 7. The elements of the modeling process are detailed in the flow diagram presented in Figure 5. TRNSYS simulation studio (the main interface of the program) connects all the components of the model. All the simulations were carried out by inputting the 2016 weather data for Daegu into the weather data module (Type-9) in the simulation studio. Three commonly used single-span greenhouse shapes: Gothic, round, and even-roof, were evaluated to assess the structure of the greenhouse. Utilizing the same specifications as the experimental greenhouse, three dimensional (3D) models of these greenhouses were designed in Trnsys3d, which is a plugin for the Google SketchUp™ software. These 3D models were then imported into TRNBuild, and the basic project data were created. TRNSYS simulation studio TYPE-56 (multizone building module) was used, in conjunction with TRNBuild to input the basic description of the project. We used

Berkley Lab Window 7.4 software to create a DOE-2 file (which is readable by TRNBuild) of the covering materials, using the following known properties of materials: Solar transmittance and reflectance, thermal radiation transmittance and emission, visible radiation transmittance and reflectance, conductivity ($\text{W m}^{-1} \text{K}^{-1}$), and thickness (mm).

Table 2. Details of studied parameters.

Parameter		Test Condition											
Roof shape		Gothic				Round				Even roof			
Orientation		0 (E-W)		30	45	60	75	90 (N-S)					
Glazing		Single						Double					
Natural ventilation	Side vent opening (m)	0.0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	
	Roof vent opening (m)	0.0	0.2		0.4		0.6		0.8				
Covering material		PE		PVC		HG		PMMA		PC			
Thickness of PMMA (mm)		4	6	8	10	16	20	30	40	50			

Note: PE: Polyethylene; PVC: Polyvinyl chloride; HG: Horticulture glass; PMMA: Polymethylmethacrylate; PC: Polycarbonate.

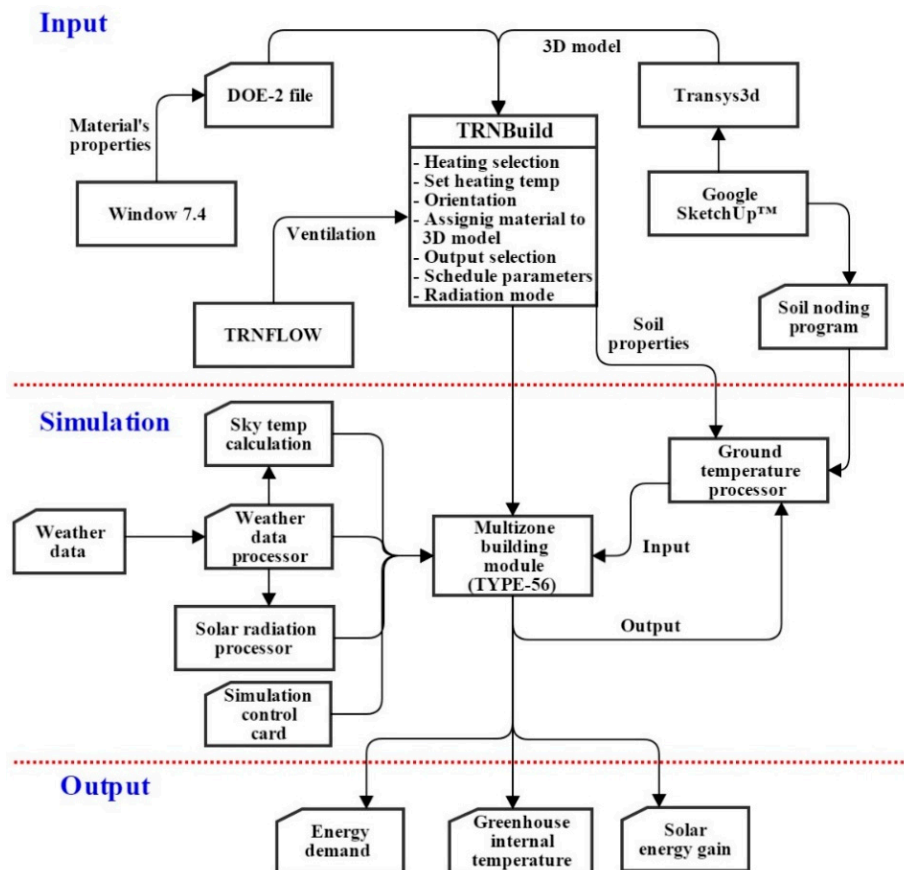


Figure 5. Flow chart of the modeling process.

Moreover, Figure 6 shows a sample of the DOE-2 file for PMMA material. The ground energy exchange is also important to consider, as solar energy captured during daytime is retained in the surface layers of the ground and contributes to an increased night-time air temperature in the greenhouse. To account for this, we used the Multizone slab model (Type 49) offered by TRNSYS, which requires a greenhouse floor input file created using the SoilNoding program, a plugin for

Google SketchUp™. The input file was imported into Type 49, where it was connected with Type 56 to obtain an input for the energy transferred to the floor and with TRNBuild to provide inputs for soil properties. The calculated ground surface temperature (output of Type 49) was applied to the greenhouse model to simulate the internal greenhouse environment. Natural ventilation was simulated using TRNFLOW, a ventilation module of the TRNSYS 17 program. TRNFLOW coupled the internal and surrounding greenhouse environments with a consideration of wind speed, wind direction, wind pressure, and internal and external temperatures. The airflow network in the model was defined by linking the external node (ambient environment) to the thermal node (internal greenhouse) through the open windows using the TRNFLOW interface within TRNBuild. In addition, the weather data were connected with Type 56 in the simulation studio to make them available for the TRNFLOW interface. To perform these evaluations, the annual energy demand for both heating and cooling was obtained by setting the internal temperature of the greenhouse at a constant of 18 °C for heating and 27 °C for cooling; these are the target temperatures for the tomato crop in South Korea. The length, width, and height were kept the same as those of the experimental greenhouse used for the validation.

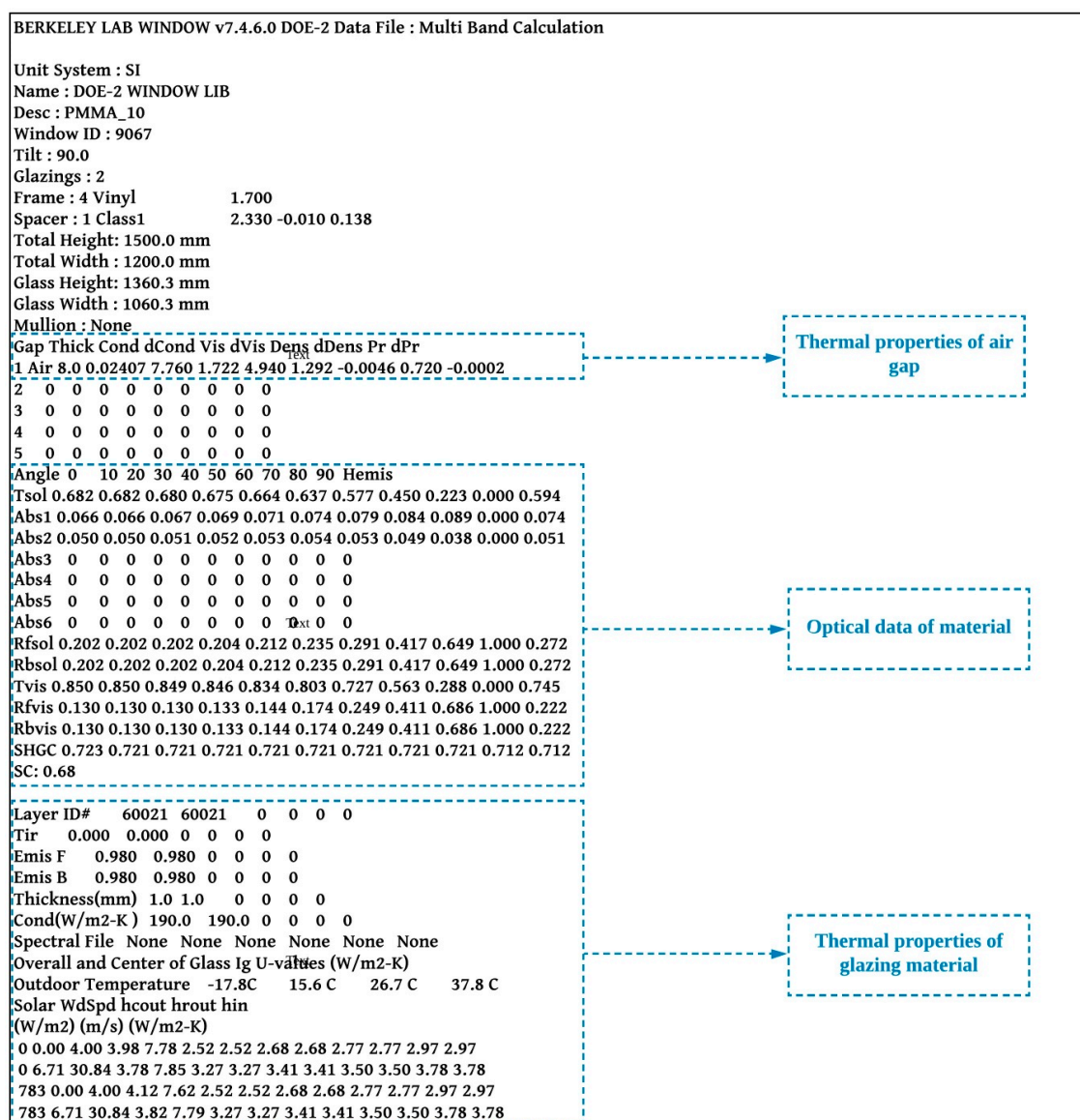


Figure 6. Sample of the DOE-2 file for PMMA (Polymethylmethacrylate).

2.2.2. Statistical Analysis of the BES Model

Statistical analyses were performed to analyze the predictive power of the BES model using the Nash–Sutcliffe efficiency coefficient (NSE) to compare the experimentally observed data with the output of the BES. This coefficient quantitatively describes the accuracy of the model results; its value ranges from $-\infty$ to 1, and values closer to 1 indicate a better predictive power of the model. The NSE value can be calculated by using Equation (2):

$$\text{NSE} = 1 - \left[\frac{\sum_{i=0}^n \left(T_{\text{ai}}^{\text{experimental}} - T_{\text{ai}}^{\text{simulated}} \right)^2}{\sum_{i=0}^n \left(T_{\text{ai}}^{\text{experimental}} - T_{\text{ai}}^{\text{mean}} \right)^2} \right] \quad (2)$$

where $T_{\text{i}}^{\text{experimental}}$ is the experimentally obtained internal air temperature of the greenhouse, $T_{\text{i}}^{\text{simulated}}$ is the simulated internal air temperature of the greenhouse, $T_{\text{i}}^{\text{mean}}$ is the mean of the experimental air temperature, and n is the total number of observations.

2.2.3. Calibration

The BES model was calibrated to reduce the uncertainties that occurred as a result of variations in the input parameters. Firstly, we needed to define the thermal and optical properties of the construction materials of the modeled greenhouse, as TRNSYS does not contain data on materials that are typically used as greenhouse covers. Table 3 shows the characteristics properties of the greenhouse covers necessary to conduct the simulation [28]. In addition, TRNSYS used constant values for the internal and external convective heat transfer coefficients (h_{i} and h_{e} , respectively). These needed to be adjusted as they are weather dependent. One [29] of our previous studies examined different h_{i} and h_{e} values recommended by different researchers, and found the best fit for the BES as shown in Equations (3) and (4) below:

$$h_{\text{i}} = 1.247(T_{\text{ai}} - T_{\text{si}})^{1/3} \quad (3)$$

$$h_{\text{e}} = 7.2 + 3.8W \quad (4)$$

where h_{i} and h_{e} ($\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$) are the internal and external convective heat transfer coefficients, respectively. W is the wind speed, T_{ai} the internal air temperature, and T_{si} the internal surface temperature.

Table 3. Characteristics of the greenhouse cover materials.

Cover Characteristics	Greenhouse Covers				
	PE	PVC	HG	PMMA	PC
Solar transmittance	0.86	0.91	0.89	0.82	0.78
Solar reflectance	0.10	0.07	0.08	0.12	0.14
Visible radiation transmittance	0.89	0.92	0.91	0.92	0.75
Visible radiation reflectance	0.08	0.14	0.08	0.07	0.15
Thermal radiation transmittance	0.18	0.06	0.00	0.00	0.02
Thermal radiation emission	0.79	0.62	0.90	0.98	0.89
Conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	0.33	0.13	0.76	0.19	0.19
Thickness (mm)	0.10	0.10	4.00	10	10

Moreover, the greenhouse energy demand during both heating and cooling periods is particularly sensitive to the solar energy gain of the greenhouse, in a simulation, this is dependent upon correct processing and estimation of the solar radiation received inside the greenhouse. The input parameters of the solar radiation processor of TRNSYS affect the model results directly. Therefore, the model needs to be calibrated using a selection of input parameters by evaluating their effects on the results. The ambient weather data input for the solar radiation processor were the external total horizontal

radiation, temperature, and relative humidity. The outputs were estimated as beam (I_{bT}), diffuse (I_{dT}), and reflected (I_{gT}) radiation on the tilted surface.

The radiation processor calculated the total solar radiation on the tilted surface by adding these measurements of radiations. The beam radiation on the tilt surface is calculated by a geometric factor, that can be defined as shown in Equation (5) [30]:

$$I_{bT} = I_b \cdot R_b \quad (5)$$

where I_b is the beam radiation on the horizontal surface, and R_b is a geometric factor (the ratio of tilted to horizontal beam radiation) that can be defined as shown in Equation (6) [30]:

$$R_b = \frac{\cos \theta_i}{\cos \theta_z} \quad (6)$$

$$\cos \theta = \cos \theta_z \cos \beta + \sin \theta_z \cos(\gamma_{sol} - \gamma_s) \sin \beta \quad (7)$$

In the Equations (6) and (7) above, θ_i is the angle of incidence of beam radiation on the tilt surface, θ_z is the solar zenith angle, β is the slope of the surface, γ_s is the azimuth angle of the surface, and γ_{sol} is the solar azimuth respectively. Figure 7 shows the hourly value of solar zenith and azimuth angles calculated using the solar radiation processor over different periods of time during the year.

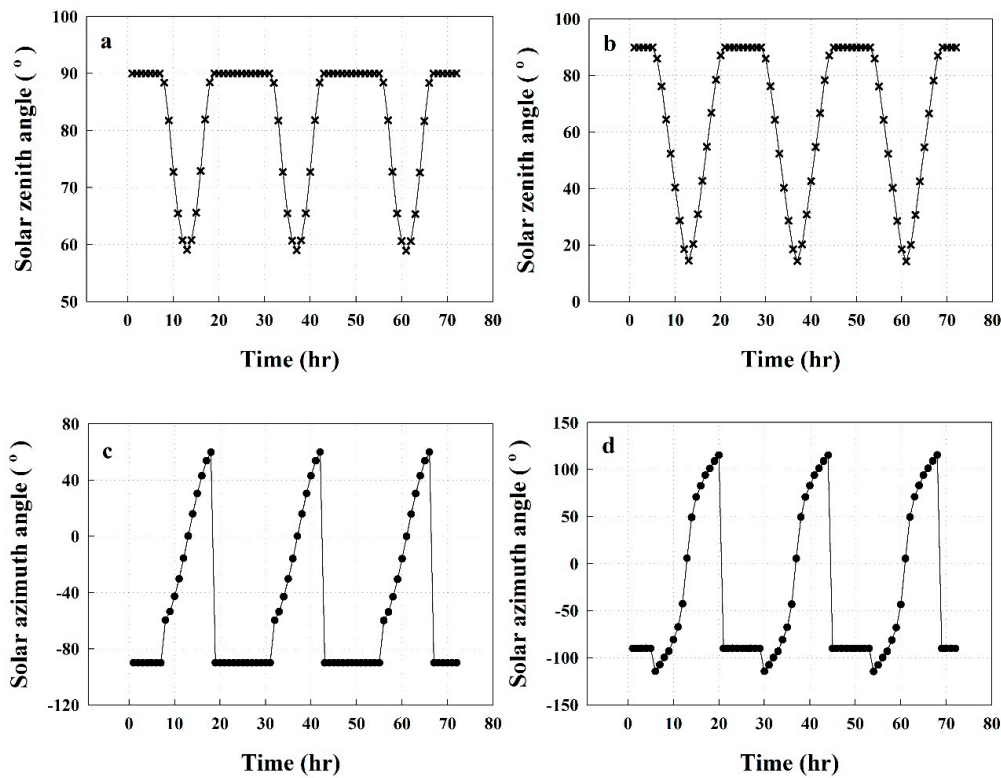


Figure 7. Solar azimuth in (a) January, (b) June, and zenith angles in (c) January, (d) June.

The reflected radiation on the tilted surface is estimated by assuming that the ground acts as an isotropic reflector using Equation (8) [30]:

$$I_{gT} = I_g \cdot 0.5(1 - \cos \beta) \rho_g \quad (8)$$

where ρ_g is reflectance of the ground surface:

The radiation processor of TRNSYS 17 uses five different “tilted surface radiation” modes to estimate the diffuse solar radiation, based on the different relationships prescribed by different researchers. All these modes use the same techniques to estimate the beam and reflected radiations but differ regarding how diffuse radiation is estimated on an inclined surface. Mode 1 uses an isotropic sky model that assumes that the diffuse radiation is distributed uniformly across the sky and is given by Equation (9) [30,31]:

$$I_{dT} = I_d [0.5(1 + \cos \beta)] \quad (9)$$

where I_{dT} is the diffuse radiation on the tilted surface, and I_d is diffuse radiation on a horizontal surface.

The Mode 2 model, developed by Hay and Davies [30,32], accounts for the anisotropy index by defining a portion of the diffused radiation as circumsolar, while another portion is considered to be isotropic. The empirical equation of the model is expressed in Equation (10):

$$I_{dT} = I_d [0.5 (1 - A_I)(1 + \cos \beta) + A_I R_b] \quad (10)$$

where A_I is the anisotropy index, and the third tilted surface mode is modelled based on Reindl model. In this model, a term for the horizon brightening factor is added to the Hay and Davies model equation, resulting in Equation (11) [30,33]:

$$I_{dT} = I_d [0.5 (1 - A_I)(1 + \cos \beta) \{1 + (f) \sin^3(0.5 \times \beta)\} + A_I R_b] \quad (11)$$

where f is the modulating factor, that can be calculated using Equation (12):

$$f = (I_b/I)^{0.5} \quad (12)$$

where I is the total radiation on the horizontal surface.

The model used in Mode 4 was developed by Perez et al. [34]. This model accounts for circumsolar radiation, horizon brightening, and isotropic diffuse radiation by using an empirically calculated “reduced brightness coefficient” which is a function of sky clearness and sky brightness factors. This model can be defined as shown in Equation (13) [30]:

$$I_{dT} = I_d [0.5 (1 - F_1)(1 + \cos \beta) + F_1 (\theta_{ac}) + F_2 \sin \beta] \quad (13)$$

where F_1 and F_2 are the reduced brightness coefficients and θ_{ac} is the angular location of circumsolar region.

The tilted surface radiation model used in Mode 5 was also developed by Perez et al. in 1988. This model is identical to the one used in Mode 4, except for reduced brightness coefficients.

The variations in greenhouse temperatures resulting from the use of the different modes are presented in Figure 8. The NSE values for Mode 1, Mode 2, Mode 3, Mode 4, and Mode 5 are 0.761, 0.972, 0.878, 0.793, and 0.812, respectively. Mode 2, a model developed by Hay and Davies, was selected as the most appropriate after results of the simulation were compared with experimentally measured internal temperatures; an NSE value of 0.972 also demonstrated that it had greater predictive power than that of the other modes. A study suggested that the Hay and Davies model is straightforward and easy to use when only total horizontal radiations are available as an input [35]. However, this model is simpler to use than the other models, as it does not require any empirical coefficient. The two Perez models used reduced brightness location-dependent coefficients in addition to the Hay and Davies model, that significantly over-predict the total radiation. There are three factors that influence the results of the Reindl model: An increase in the sky diffuse radiation, the lack of incidence angle in the afternoon, and the modulating factor. Moreover, as our greenhouse location is south-facing, i.e., towards the sun in the northern hemisphere, another study [36] also suggested that the Hay and Davies model is best-suited for south facing locations.

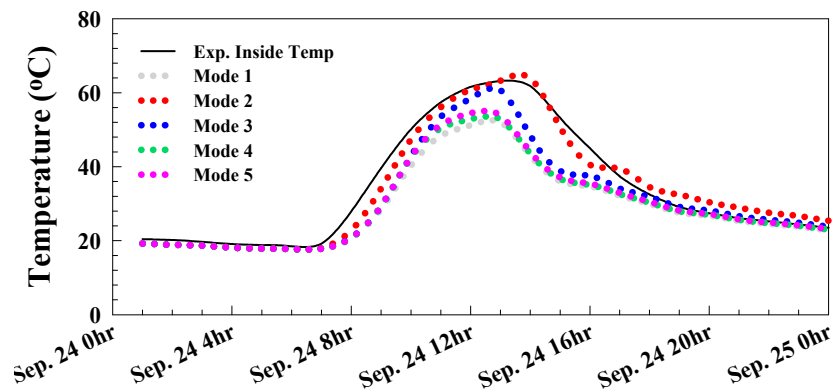


Figure 8. Variation in greenhouse internal temperature for different radiation models.

2.2.4. Validation

To validate our model, the computed results, obtained using the same conditions as those in the experimental greenhouse, were compared to the experimentally obtained results. Figure 9a,b present the computed and experimentally observed internal temperatures of the fully closed and naturally ventilated greenhouses, respectively. In both cases, the experiments were conducted in Daegu over two different periods in 2016, from 23 September to 26 September and from 10 January to 12 January, respectively. The NSE values for both validation results, 0.958 and 0.983, indicate the goodness-of-fit between experimental and simulation results. The agreement between these experimental and computed results under both conditions encourages adoption of the proposed BES model.

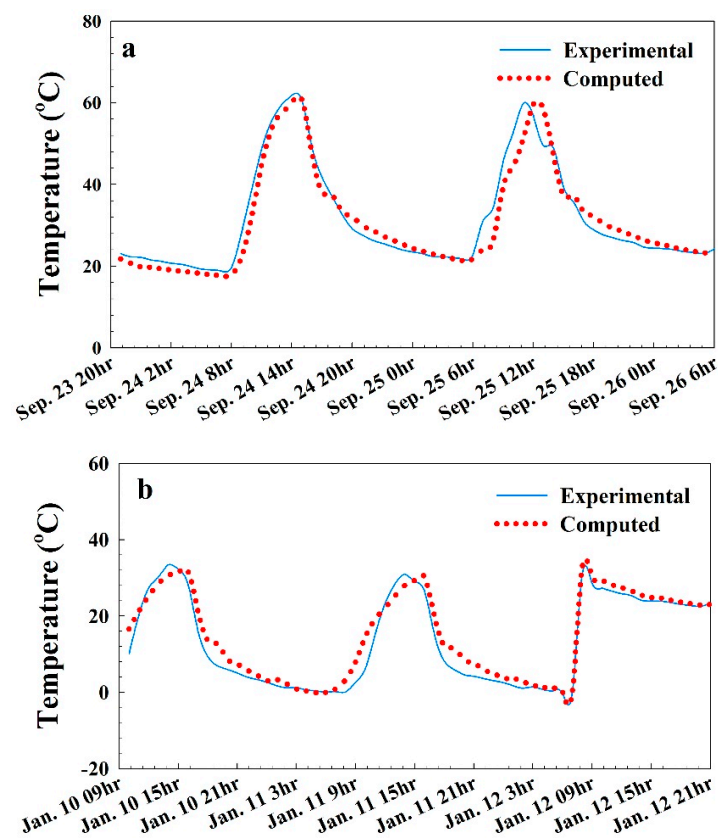


Figure 9. Computed vs. measured internal air temperatures of a (a) fully closed greenhouse, and (b) naturally ventilated greenhouse.

3. Results and Discussion

After the successful creation, calibration, and validation of the BES model, simulations were performed to obtain results for all the parameters presented in Table 2. The first analysis was conducted by running three separate simulations for the three different greenhouse roof shapes of the greenhouse, thereby calculating the annual energy demand required to maintain the desired temperature inside the greenhouse for each, as shown in the Figure 10. The results indicated that the annual energy demand of the gothic-shaped roof greenhouse was 2% and 8% lower than those of the even- and round-shaped roofs, respectively. These results were corroborated by a previous study [24], in which a mathematical model was developed to simulate thermal environment inside the greenhouse; this study compared the internal temperature of the typically used round-, even-, and gothic-shaped greenhouse roofs for 24 h. The greenhouse with the gothic shaped roof had a higher temperature then others under all ambient conditions, which means it required less energy than the others. The reduction in annual energy demand occurs owing to the fact that this greenhouse received more solar radiation during the winter, while receiving less during the summer, compared to the model greenhouses with different shaped roofs.

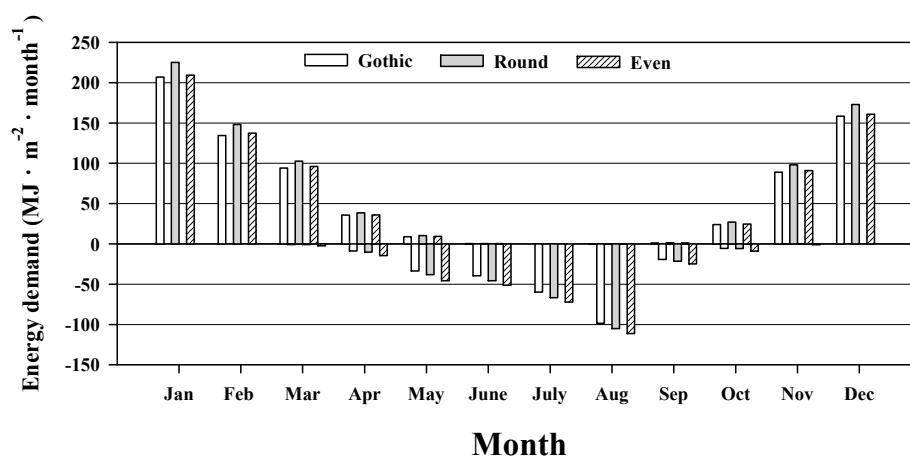


Figure 10. Comparison of the monthly heating and cooling energy demands for selected greenhouse roof shapes.

The effect of greenhouse orientation was studied on otherwise identical gothic-roofed greenhouses. The total solar gain captured at different angles of orientation (described in Table 2) for two typical winter and summer days was modeled to find the best orientation, i.e., the one that received the highest solar radiation in winter and lowest in summer. This difference occurs because the beam and diffuse solar radiation on inclined surfaces depend on the position of the sun and inclined surfaces that face the sun called the geometric factor. This geometric factor takes into account the surface slope, surface azimuth angle, solar zenith angle, and solar azimuth angle, the results of these results are presented in Figure 11. They show that in the northern hemisphere, a greenhouse orientated at 0° (E-W) receives more solar radiation in January and less in June than one orientated at 90° (N-S), which shows the opposite results. Moreover, for all the orientations, the solar energy gain is higher in the summer months than in the winter months because summer has a greater number of daylight hours than winter.

Figure 12 shows the monthly total solar energy gain inside the greenhouse for the both orientations. In addition, the solar gain during the winter months is higher for the E-W oriented greenhouse than for the N-S oriented greenhouse; the opposite trend can be seen during the summer months. To save heat energy in winter, more solar radiation is needed to achieve high internal greenhouse temperatures; it is vice versa in summer. Therefore, an E-W oriented greenhouse is preferred as it receives more solar radiation inside during winter months and less in summer months. In a previous study, Auto-Cad

tool was used to analyze the total solar fraction inside the greenhouse for selected summer and winter days for greenhouses at different orientations. Our results agree with the trend of solar energy gain for different orientations that was reported by Gupta et al. [25].

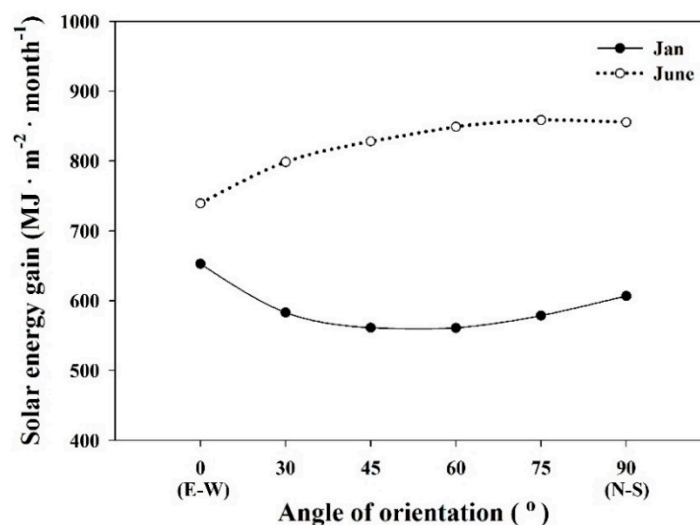


Figure 11. Solar energy gain at different angles of orientations, of a gothic-shaped roof.

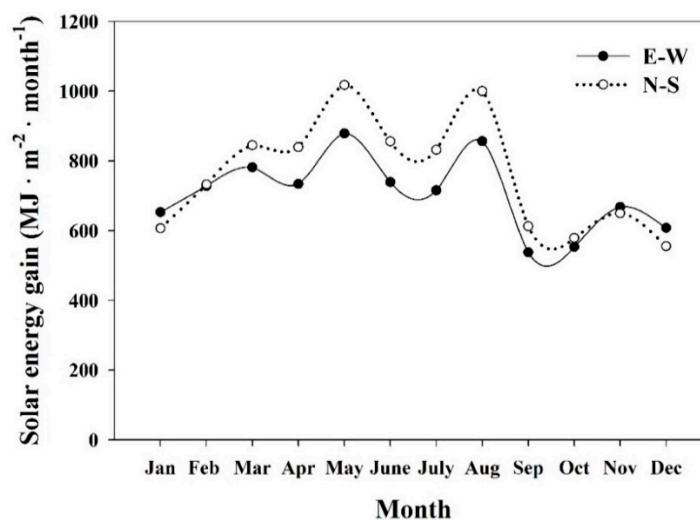


Figure 12. Monthly total solar energy gain for greenhouse oriented (a) E-W and (b) N-S.

Figure 13 shows the effect of double-glazing on internal greenhouse temperatures during heating season (1–5 January 2016). To observe the effect of double-glazing on the internal greenhouse temperature, the single-layered PE material was replaced with a double-layered PE material, for fully closed greenhouse, in the window type manager of TRNBuild. Only the PE material was selected for the assessment, as it is the most commonly used greenhouse-covering material worldwide because of its affordability relative to glass, polycarbonate, polyvinylchloride, and others materials. Double-layered PE materials are used to trap heat inside the greenhouse to reduce heat loss through the coverings. The results show that the internal temperature of the double-layered greenhouse was 2–5 °C higher than that of the single-layered greenhouse.

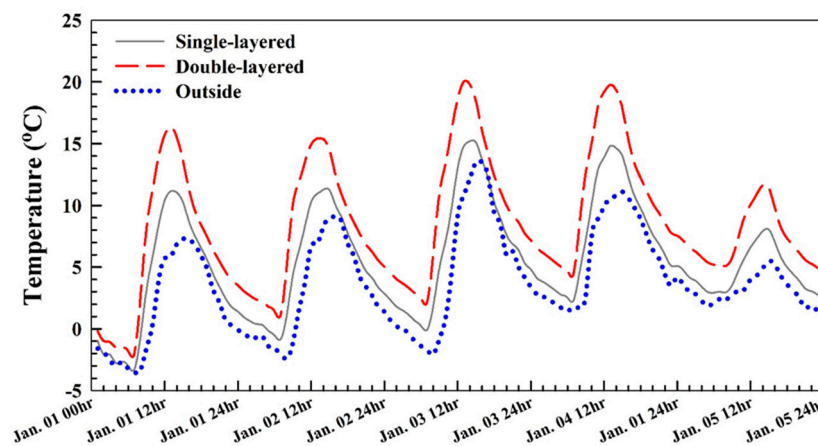


Figure 13. Variation in internal greenhouse air temperatures (from 1–5 January 2016) of greenhouse covered with single and double-layered PE material.

Natural ventilation is widely used to decrease the internal temperature of greenhouses to save cooling energy, especially in the summer. Instead of discussing the natural ventilation rate as a result of different windows being open, herein, we discuss the effect of natural ventilation on the internal temperature of the greenhouse as the focus area of this study is the thermal environment of greenhouses. Analyses were carried out to observe the effect of different side and roof vent openings on the internal temperature of the greenhouse. To observe the effect of natural ventilation on the cooling energy demand in the summer, both side and roof vents of differing opening widths were evaluated. The roof window openings were located in the middle of the greenhouse and the side windows were 50 cm above the ground. Simulations were carried out separately for all cases of side and with roof ventilation described in Table 2, and the results of the effects on the internal temperature of the greenhouse are shown in Figure 14. The outcomes show that there is a slight decrease in greenhouse internal temperature for the different widths in the roof vents; however, when even a small side vent is open, there is a marked drop in the internal temperature of the greenhouse. Furthermore, we can see from the results that the internal temperature dropped significantly with a slight increase in the side openings of the greenhouse, but that the rate of decrease levelled off rapidly. After the opening-length reached 1 m, no significant decrease in temperature was found. The overall result shows that the roof vents are more effective when used in conjunction with side vents than when used alone.

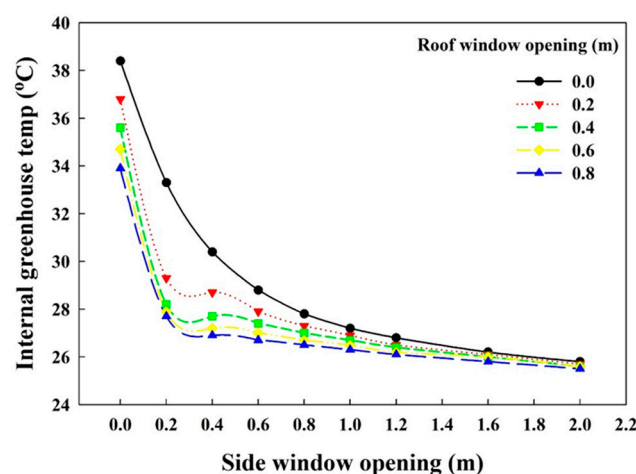


Figure 14. Variations in greenhouse internal temperature with different side and roof openings.

Figure 15 shows the different scenarios (scenario 1: side vents 1 m, scenario 2: roof vents 0.8 m, scenario 3: combined side and roof vents) of side and roof vents openings from 10 to 11 am, used to investigate their effect on the internal temperature of the greenhouse. Scenario 1 shows a reduction of 11 °C in the internal temperature during daylight hours and as time passed, the temperature remained effectively constant even though solar radiation increased. Scenario 2 shows that the temperature decreased rapidly when the roof window was opened, but it started to increase after some time, showing only a 4 °C reduction in internal temperature. These results show that when only roof vents are used, ventilation has less of an effect than solar radiation, so an increase in greenhouse internal temperature occurs. Scenario 3 shows a significant reduction in the temperature when both side and roof windows are open. Furthermore, the temperature dropped rapidly within five minutes in all the scenarios because the single span greenhouse was not very wide, and opening vents along the length of the greenhouse allowed a rapid change in the internal temperature. The Nam [37] evaluated the effect of roof and side vents opening on the internal temperature of a single span greenhouse; the results of these field experiments also confirmed the rapid decrease in the internal temperature of the greenhouse immediately after the vents were opened. Moreover, the results imply that the effect of solar radiation is not significant in the case of side vents.

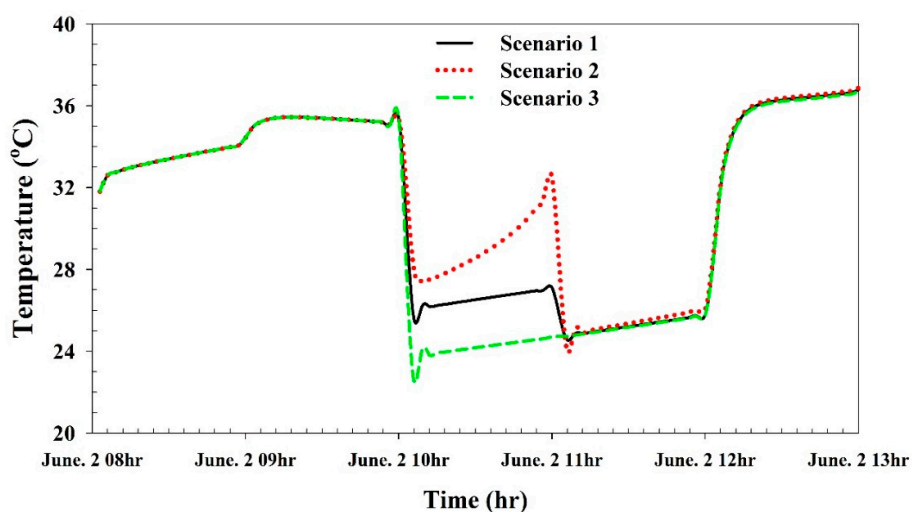


Figure 15. Greenhouse internal temperature for different natural ventilation scenarios.

Greenhouse covering material is another important factor to be considered while conducting thermal analyses of a greenhouse. Many covering materials are commercially available in the market and the choosing of the most appropriate one to meet local requirements can help to minimize operating costs of the greenhouse. In Figure 16, we present the heat energy demand of some of the covering materials used as greenhouse covers. PMMA shows the least demand for heat compared to others including PE, PVC, HG, and PC. We also investigated the effect of different thicknesses, including 4, 6, 8, 10, 16, 20, 30, 40, and 50 mm of double layered PMMA. Each sheet of the material was 0.15 mm thick; hence, the total covering thickness depends on the air-gap between them. The results presented in Figure 17 show the heating demand of the greenhouse after PMMA coverings of different thicknesses were applied. The outcomes of this analysis show that the heating demand decreased significantly when the cover thickness was increased from 4 mm but also that there was no significant decrease in the heating demand after the thickness reached 16 mm. Guohui [38] used Computational fluid dynamics (CFD) to predict the thermal convective heat transfer coefficient, thermal resistance, and thermal transmittance of the double-glazing of greenhouse covering material. One of result from this study regarding overall heat transfer coefficient (U-value) with different air spaces between double-glazing, also confirmed our outcome.

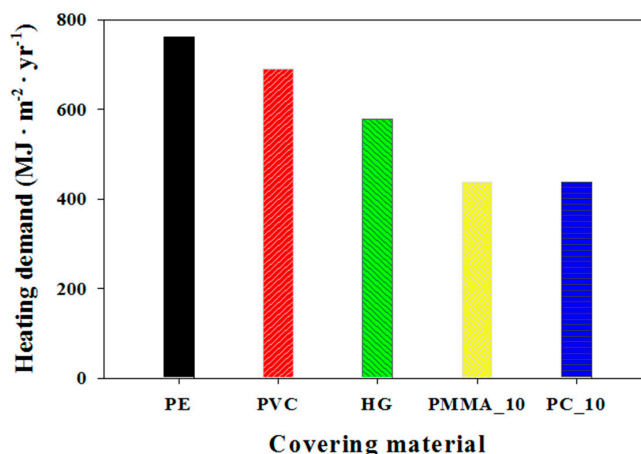


Figure 16. Annual heating demand of gothic-shaped greenhouse by using different coverings. PE: Polyethylene, PVC: Polyvinyl chloride; HG: Horticulture glass; PMMA: Polymethylmethacrylate; PC: Polycarbonate.

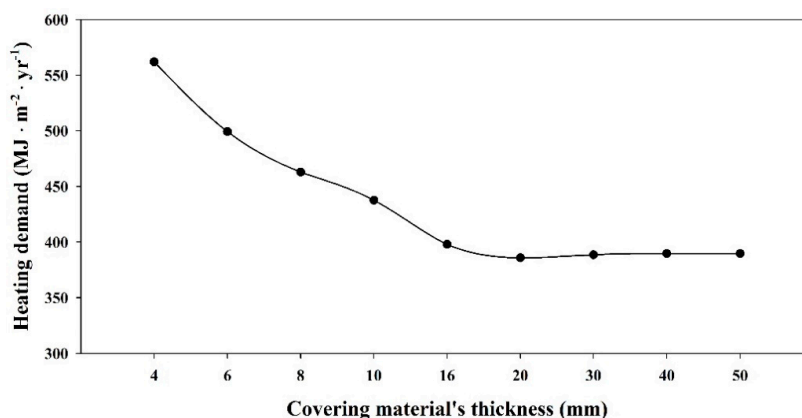


Figure 17. Effect of the thickness of PMMA covering material on the annual heating demand of the greenhouse modeled with gothic-shaped greenhouse.

TRNSYS is a BES software that is not for the greenhouse modeling; in Section 2.2.3, gives the recommended necessary inputs needed to use this software for greenhouse modeling. This study also ignores the crop inside the greenhouse, which is also an important parameter and has influence on the environment inside the greenhouse. Therefore, we plan to include crop modeling and greenhouse vents automatically controlled by the internal environment in future studies.

4. Conclusions

This paper detailed the development, calibration, and validation of a BES model to simulate the thermal environment of a series of greenhouse designs using TRNSYS 17. In the Section 2.2.3 on calibration, we specified the input parameters required to model the thermal environment of greenhouse using BES. The parameters include the internal and external convective heat transfer coefficients, the DOE-2 file, to introduce materials into the TRNSYS using their thermal and optical properties; the properties of the most common greenhouse coverings; and evaluation results for five different calculations of solar radiation on a tilted (roof) surface model. The statistical analyses (NSE values) for these models, known as Mode 1, Mode 2, Mode 3, Mode 4, and Mode 5 are 0.761, 0.972, 0.878, 0.793, and 0.812, respectively. Mode 2, a model developed by Hay and Davies, was found to be most appropriate. It demonstrated a good correlation between measured and simulated results. The NSE values of 0.958 and 0.983 for validation of both type of results indicated that the model can

be a useful tool with which to study the effects of greenhouse design parameters on the total annual heating and cooling load of a greenhouse.

The second part of this paper described the effect of greenhouse design parameters including shape of the roof, orientation, glazing, natural ventilation, covering material, and thickness of the covering material on the energy consumption of a greenhouse. It was discovered that the greenhouses with gothic-shaped roofs required 2% and 8% less energy than those with round- and even-shaped roofs, respectively. In addition, for a greenhouse located in Daegu (latitude 35.53° N, longitude 128.36° E) South Korea, the most suitable orientation is E-W. Furthermore, a 40% reduction in the heat energy requirement was observed when the single-glazed PE covering was replaced with a double-glazed covering. During the summer months, natural ventilation had the potential to decrease the internal greenhouse temperature by approximately 2–11 °C relative to a non-ventilated greenhouse with the same design parameters.

TRNSYS 17 showed a high flexibility in carrying out analyses under local weather conditions by considering all the possible factors that could be modeled to improve the thermal efficiency of a greenhouse. The high correlation between the computational analysis and measured data, as demonstrated by the NSE values, encourages the adoption of the model when investigating energy supplies with an underlying aim to reduce the energy costs of greenhouse agriculture, taking their local environment and specific needs into consideration.

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Nomenclature

Subscripts

ai	Internal air
si	Internal surface

Abbreviations

TRNSYS	Transient Systems Simulation
PE	Polyethylene
PVC	Polyvinyl chloride
HG	Horticulture glass
PMMA	Polymethylmethacrylate
PC	Polycarbonate
BES	Building energy simulation
KMA	Korean Meteorological Administration
NSE	Nash–Sutcliffe efficiency coefficient

Symbols

T	Temperature
H	Humidity
S	Solar radiation
W	wind speed
h_i	Internal convective heat transfer coefficient
h_e	External convective heat transfer coefficient
T_{si}	Internal surface temperature
I_{bt}	Beam radiation on tilted surface
I_{gt}	Reflected radiation tilted surface
I_{dt}	Diffuse radiation tilted surface
I_b	Beam radiation on the horizontal surface

I_d	Diffuse radiation on the horizontal surface
R_b	geometric factor
θ_i	Incidence angle of beam radiation on the tilt surface
θ_z	Solar zenith angle
β	Slope of a surface
γ_s	Surface azimuth angle
γ_{sol}	Solar azimuth angle
ρ_g	Reflectance of the ground surface
A_I	Anisotropy index
f	Modulating factor
I	Total radiation on horizontal surface
θ_{ac}	Angular location of circumsolar region
Y_r	Year

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