TÜBİTAK

Turkish Journal of Agriculture and Forestry

Volume 48 | Number 1 Article 3

2-1-2024

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Recommended Citation

Dölek, Sinan and ARSLAN, Gökhan (2024) "Determination of heating load requirement of greenhouses in Türkiye by dynamic modeling of micro-climate conditions," *Turkish Journal of Agriculture and Forestry*: Vol. 48: No. 1, Article 3. https://doi.org/10.55730/1300-011X.3159
Available at: https://journals.tubitak.gov.tr/agriculture/vol48/iss1/3

Turkish Journal of Agriculture and Forestry

http://journals.tubitak.gov.tr/agriculture/

Research Article

Turk J Agric For
(2024) 48: 15-25
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doi:10.55730/1300-011X.3159

Determination of heating load requirement of greenhouses in Türkiye by dynamic modeling of microclimate conditions

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Received: 29.07.2023 • **Accepted/Published Online:** 29.11.2023 • **Final Version:** 01.02.2024

Abstract: A dynamic model is developed to compute a greenhouse's heating load and microclimatic conditions, such as temperature and humidity. An analysis is carried out for the 4 provinces of Türkiye where greenhouse cultivation is essential and widespread (Adana, Mersin, Antalya, and Muğla). The annual heating load of the greenhouse is determined as 95.52 kWh/m^2, 92.58 kWh/m^2, 74.79 kWh/m^2, and 189.04 kWh/m^2 for Adana, Mersin, Antalya, and Muğla, respectively. The maximum daily heating loads are computed as 1.87 kWh/m^2, 2.06 kWh/m^2, 1.4 kWh/m^2, and 2.91 kWh/m^2 for Adana, Mersin, Antalya, and Muğla, respectively. According to the results of the design day, daytime greenhouse condensation is observed in Adana, Mersin, and Muğla. The ventilation rate must be increased in the daytime to prevent this adverse condition, which leads to an increase in the heating load. The obtained soil temperature profile in the greenhouse is suitable for Adana, Mersin, and Antalya. However, the soil surface temperature is 6–7 °C in Muğla, which is unsuitable for plant growth. Determination of the heating load only by heat transfer through the cover and by ventilation is not sufficient because it ignores factors such as moisture content and soil temperature that affect plant growth. To calculate the accurate heating load, microclimatic conditions must also be determined.

Key words: Solar greenhouse, heating load, dynamic model, energy analysis, solar radiation, Türkiye

1. Introduction

Greenhouse cultivation is essential for Türkiye's agronomics. Türkiye is ranked fourth in the world and second in Europe for greenhouse cultivation area, with a total area of approximately 81088 ha in 2022, according to the Turkish Ministry of Agriculture and Forestry. The greenhouse types break down as 7.35% glass greenhouses, 58.12% plastic greenhouses, 13.62% high tunnel greenhouses, and 20.91% low tunnel greenhouses[1]. A significant percentage of greenhouses in Türkiye are located in the Mediterranean region, with 61.4% of greenhouse cultivation areas in Antalya, 45.2% in Mersin, 25.3% in Adana, and 6.3% in Muğla.

A greenhouse's microclimate conditions (irradiation, temperature, humidity, CO_2 concentration, etc.) directly affect plant growth. Daily global solar radiation should be at least 2.0–2.3 kWh/m^2 for sufficient plant growth (Zabeltitz, 2011). The growth of the plants in the greenhouse is adversely affected when the temperature inside the greenhouse is lower than 12 °C or higher than 30 °C (Castilla and Hernandez, 2007). The average maximum greenhouse temperature for plants should not be above 35–40 °C. Soil temperature should be at least 15 °C. Relative humidity should be within the range of 70%–90% (Zabeltitz, 2011). Under those circumstances, climate control by heating, cooling, and ventilation of the greenhouse is essential for crop quality. For an economical and effective design of air conditioning systems, the heating and cooling loads of greenhouses must be calculated correctly. For this purpose, dynamic (transient) and static (steady state) models are developed. The static model approach neglects the thermal capacity of internal heat sources and overestimates the heating load. Thus, the transient dynamic model approach is more accurate since thermal storage is taken into account.

Studies on dynamic modeling of a greenhouse microclimate date back to the 1970s. A mathematical model was developed to predict greenhouse inside temperatures (Kimball, 1973). Energy equations were derived for the soil layer, plant surface, inside air, and greenhouse cover material. Since measured and computed values agreed closely, the study concluded that the model was successful

1 Republic of Türkiye Ministry of Agriculture and Forestry (2022). BUGEM [online]. Website https://www.tarimorman.gov.tr/BUGEM/kumelenme/Link/12/Tuik-Istatistikleyerri [accessed 03.02.2023].

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to estimate the required heating and cooling loads. In a similar study, an interactive simulator was developed to determine the microclimatic conditions of greenhouses under several climate conditions (Fitz-Rodríguez et al., 2010). A-frame, arch roof, and Quonset-style greenhouse constructions were used in the simulations. It has been reported that plant transpiration decreases the greenhouse inside temperature but increases the humidity ratio, leading to condensation (Fitz-Rodríguez et al., 2010).

In another study, transient energy balance equations for air, plant leaf, and soil inside the greenhouse were developed. Evapotranspiration, mass transfer due to ventilation and condensation inside the greenhouse were also considered. A two-dimensional heat transfer model was included to calculate the thermal storage in the soil layer and heat loss through the ground. The computed air temperature was close to the measured data. On the other hand, the measured data of soil and leaf temperatures were scattered from the computed values. The deviation of the model results with the measured data was explained by the difficulty of measuring average surface temperatures (Takakura et al., 1971). The energy performances of the greenhouse envelopes used in the cold northern regions of China were studied using thermal dynamic simulations (Deiana et al., 2014). A greenhouse was modeled in the EnergyPlus© program to determine the microclimatic conditions. The obtained results showed that the structure of the greenhouse has an important effect on the periods in which the greenhouse inside temperature stays in the desired temperature range without any heating or cooling systems. A similar dynamic model test was carried out for a greenhouse located in Albenga, Italy (Chahidi et al., 2021). The greenhouse was modeled in the EnergyPlus© program and the effects of internal mass and plants were discussed. The heating load of the greenhouse decreased when internal mass and plants were included in the model since solar energy is stored by internal mass. In a Turkish study (Arslan and Dölek, 2021), the hourly coal consumption rate of a greenhouse in the Mersin province over a design day was determined, and the microclimatic conditions of the greenhouse were calculated using a dynamic model. Approximately 0.5 kg/m^2 of coal was consumed to keep the greenhouse inside temperature at 15 °C during the design day of the typical meteorological year. The effects of greenhouse structure and orientation were discussed for the northern region of India (Gupta and Chandra, 2001). A gothic arch-shaped greenhouse required less heating load when compared with gable and Quonset shapes. Moreover, the heating load of the greenhouse oriented in an east–west direction was 2% lower than the one oriented in a north–south direction. Most of the studies in the literature on the determination of the heating load of greenhouses in Türkiye use the static calculation method. In one study (Canakci et al., 2013), the yearly heat consumption of greenhouses placed in Antalya, Muğla, Mersin, Adana, and Hatay was calculated as 147 kWh/m^2, 291 kWh/m^2, 100 kWh/m^2, 156 kWh/m^2, and 160 kWh/m^2, respectively, by using monthly average meteorological data. The set point temperatures of the greenhouses were taken as 16 °C at night and 21 °C during the day. In a similar study (Kaya and Baytorun, 2017), a heating load calculation was carried out for Mersin province. Hourly meteorological data was used and the set point temperatures of the greenhouse at night and during the day were 16 °C. The required heating load was calculated as 91.9 kWh/m^2 for the greenhouse with a single polyethylene cover. It was determined that that heating load values obtained using hourly climatic data were lower than the values obtained using monthly average meteorological data. In another study (Baytorun et al., 2017), the heating energy requirement of greenhouses located in Antalya, Türkiye were investigated. The temperature increase inside the greenhouse due to thermal storage and ventilation was taken into account, and a 29% difference was observed compared to the methodology which is calculating heating load of the greenhouse only heat transfer through the cover due to the temperature difference between the inside set point and the surrounding. The set point temperature of the greenhouse was taken as 16 °C and the required heating energy was calculated as 20.6 kWh/m^2, 18.4 kWh/m^2, 10.5 kWh/m^2, 3.9 kWh/m^2, and 14.4 kWh/m^2 for January, February, March, November, and December, respectively. The annual required heating energy was 67.8 kWh/m^2. The yearly heat consumption of a greenhouse placed in Antalya was calculated as 56.1 kWh/m^2 (Zabeltitz, 2011). The study reported that only approximate results were obtained because the heating load of the greenhouse depends on the greenhouse structure, soil storage capacity, and climatic conditions inside and outside of the greenhouse. A further study (Baytorun et al., 2018) compared the calculated fuel consumption rate results obtained by using conventional methods with measured fuel consumption rate data in a modern greenhouse located in Adana. Hourly meteorological data were used to perform steady-state heat transfer calculations. Only heat transfer between the inside air of the greenhouse and the outside air was taken into account. The results obtained with the applied method failed to predict daily data. The calculated daily fuel consumption rate values differed from the actual consumption values. However, the calculated annual fuel consumption differed by only 3% from the measured annual fuel consumption rate. The monthly heat consumption calculated per unit area to keep the temperature of the greenhouse over 16 °C were 24.43 kWh/m^2, 16.37 kWh/m^2, 9.08 kWh/m^2, 10.56 kWh/m^2, and 17.36 kWh/m^2 for January, February, March, November, and December, respectively. The annual required heating energy was 77.8 kWh/m^2.

The heating and cooling loads of greenhouses depend on various factors such as greenhouse structure, covering material, heating system, meteorological conditions, and soil storage capacity. Besides that, the applied method for the calculation is also important. In this study, a dynamic heat and mass transfer model has been developed to compute the heating load of the greenhouse as well as the humidity ratio, air, and soil surface temperatures. To formulate an accurate heat and mass transfer model, the computation of incident solar radiation on greenhouse surfaces, heat transfer via conduction and convection through the cover, evapotranspiration rate, and soil temperature are important.

2. Materials and methods

The heat and mass transfer equations were developed to compute the hourly heating load, humidity ratio, air temperatures, and soil surface temperatures of the greenhouse. Hourly meteorological data was used and a transient model was developed. The required meteorological data (hourly global horizontal irradiance (GHI), dry and wet bulb temperatures, humidity ratio, wind speed, and monthly average soil temperatures at depths of 5, 10, 20, 50, and 100 cm) was obtained from the Turkish State Meteorological Service.

In this study, a single-span greenuse installed on an area of 1000 m^2 was analyzed. It is assumed that there is no shading effect around the greenhouse. To maximize the solar radiation, the greenhouse was placed so that the largest surface area faced in a southern direction. A schematic representation of the greenhouse with dimensions is given in Figure 1. Double-layer polyethylene, the properties of which are given in Table 1, was selected as the greenhouse cover material. For the calculations, it was assumed that there are plants with a total leaf surface area of 250 m^2 in the greenhouse.

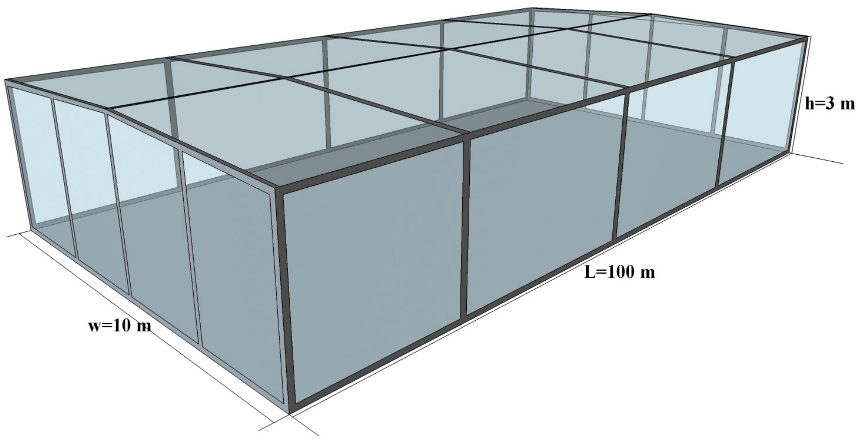

Figure 1. Simple schematic view of the greenhouse.

Table 1. Properties of the cover material.

Density*	1150 kg/m^3
Thickness	0.2 mm
Specific heat	2302 J/kgK
Thermal absorptivity and emissivity	90%
Thermal conductivity**	0.33 W/mK
Cover material reflectance	6%
Cover material transmittance	76%
* (Reyes-Rosas et al., 2017) ** (Rasheed et al., 2017)	

2.1. Solar radiation on the greenhouse surfaces

Solar radiation is one of the most important parameters for the determination of heating load. Besides GHI, the diffuse and direct components of the radiation must be determined to calculate the amount of solar radiation on the vertical surfaces of the greenhouse. The diffuse solar radiation on a horizontal surface is determined by using the correlation given in Equation 1 (Erbs et al., 1982). Calculations for extraterrestrial solar radiation and the clearness index used in this model are given in Equations 2 and 3, respectively. The solution for beam solar radiation on a horizontal surface is given in Equation 4.

$$\frac{I_d}{I} = \begin{cases} 1 - 0.09k_t & k_t \le 0.22 \\ 0.9511 - 0.1604k_t + 4.388k_t^2 - 16.638k_t^3 + 12.336k_t^4 & 0.22 < k_t \le 0.8 \\ 0.165 & k_t > 0.8 \end{cases} \quad (1)$$

$$I_e = 1367\left(1 + 0.034\cos\left[\frac{360n}{365}\right]\right) \quad (\frac{W}{m^2}) \quad (2)$$

$$k_t = \frac{I}{I_e} \quad (3)$$

$$I_b = I - I_d \quad (4)$$

To calculate the beam radiation on a tilted surface, the geometric factor (R) which is a function of solar incidence and zenith angles is used.

$$R = \frac{I_{b,t}}{I_b} = \frac{\cos(\theta)}{\cos(\theta_z)} \quad (5)$$

$$\cos(\theta) = \sin(\delta)\sin(\varphi)\cos(s) - \cos(\gamma_{surface})\sin(\delta)\cos(\varphi)\sin(s)$$
$$+ \cos(\delta)\cos(\varphi)\cos(\omega)\cos(s) + \cos(\delta)\sin(\varphi)\sin(s)\cos(\omega)\cos(\gamma_{surface}) \quad (6)$$
$$+\sin(\gamma_{surface})\cos(\delta)\sin(\omega)\sin(s)$$

$$\cos(\varphi)\cos(\delta)\cos(\omega) + \sin(\varphi)\sin(\delta) \quad (7)$$

To determine the solar radiation on tilted surfaces of the greenhouse beam, sky-diffuse, and ground-reflected solar radiation must be calculated. The ground-reflected solar radiation is part of the total solar radiation incident on a horizontal surface obtained by multiplying by the ground reflectance η_{gr} (Duffie and Beckman, 2013).

$$I_t = I_{b,t} + I_d\left(\frac{1 + \cos(s)}{2}\right) + I\eta_{gr}\left(\frac{1 - \cos(s)}{2}\right) \quad (8)$$

2.2. Heat transfer through the cover

Since heat transfer through the outside surface of the greenhouse cover material is a function of wind speed and radiation, a correlation including surface roughness and wind speed is used (ASHRAE 1989). This is valid for smooth surfaces and the effect of radiation is included.

$$h_{out} = 8.23 + 3.33V_w - 0.036V_w^2 \quad (9)$$

There are many different types of correlations available for inside convection heat transfer coefficients. In this study, air change per hour (ACH) heat transfer correlations for surfaces are used and the overall heat transfer coefficient is calculated according to Equation 14 (Fisher and Pedersen, 1997).

$$h_{in} = 3.873 + 0.082ACH^{0.98} \quad \text{(floor)} \quad (10)$$

$$h_{in} = 2.234 + 4.099ACH^{0.503} \quad \text{(ceiling)} \quad (11)$$

$$h_{in} = 1.208 + 1.012ACH^{0.604} \quad \text{(wall)} \quad (12)$$

$$\frac{1}{UA} = \frac{1}{h_{in}A} + \frac{L_{cv}}{k_{cv}A} + \frac{1}{h_{out}A} \quad (13)$$

2.3. Psychrometrics

Humidity ratio and relative humidity are required for the determination of microclimate conditions inside a greenhouse. The saturation pressure over liquid water is a function of dry bulb temperature, and is given in Equation 15. The constants of this equation are $c_1 = -5.8002206 \times 10^3$, $c_2 = -5.5162560$, $c_3 = -4.8640239 \times 10^{-2}$, $c_4 = 4.1764768 \times 10^{-5}$, $c_5 = -1.4452093 \times 10^{-8}$, and $c_6 = 6.5459673$. Relative humidity and humidity ratio are determined by using Equations 16 and 17, respectively.

$$\ln P_{ws} = \frac{c_1}{T} + c_2 + c_3T + c_4T^2 + c_5T^3 + c_6\ln T \quad (14)$$

$$\phi = \frac{P_w}{P_{ws}} \quad (15)$$

$$W = 0.621945\frac{P_w}{P - P_w} \quad (16)$$

2.4. Evapotranspiration

Evapotranspiration is an important parameter to determine the humidity ratio inside the greenhouse, and it occurs mainly by transpiration through the plant leaf, a complex physiological process in which water vapor in plants is transferred to the air through the leaf stomata. This process also depends on solar radiation at the plant surface. The correlation in Equation 18 for plant transpiration rate as a function of solar radiation was used (Fitz-Rodríguez et al., 2010).

$$\dot{E}_{tr} = \begin{cases} 0.0003\tau_{cv}\dot{Q}_r + 0.0021 & , \quad \text{large crop} \\ 0.00006\tau_{cv}\dot{Q}_r + 0.0004 & , \quad \text{small crop} \end{cases} \quad (17)$$

2.5. Undisturbed ground temperature

Heat storage in the soil and heat loss through the ground can be predicted by the determination of the temperature distribution throughout the soil depth. Values for soil thermal conductivity and heat diffusion coefficient are required to determine the temperature distribution. For this purpose, monthly average soil temperatures at 5, 10, 20, 50, and 100 cm depths were used. Moreover, the analytical model was modified to predict the soil's thermal properties (Xing, 2014). The thermal diffusivity of the soil is determined by fitting the model equation data to the measured data. This model is also used to determine the depth where the temperature gradient is zero since heat transfer through the soil occurs down to that level.

$$T(z,t) = T_{s,avg} - \Delta T_s e^{-z\sqrt{\frac{\pi}{\alpha_s \tau}}} \cos\left(\frac{2\pi}{t_p}(t - P_{lag}) - z\sqrt{\frac{n}{\alpha_s t_p}}\right) \quad (18)$$

Sesveren (2007) investigated the thermal properties of soil in greenhouses located in the Mediterranean region of Türkiye. The average value of the thermal conductivity of the clay soil obtained in that research was used in the current study. Finally, volumetric heat capacity was obtained by using the relation between thermal conductivity and thermal diffusivity. For all provinces, the thermal diffusivity, thermal conductivity, and volumetric heat capacity of the soil were taken to be 3.85 × 10^{-7} m^2/s, 1.5 W/mK, and 3.9 × 10^6 J/m^3K, respectively.

2.6. Energy balance of the inside air temperature

To determine the air temperature, the heat exchanges between the inside air, the environment ($\dot{Q}_l$), and the ground ($\dot{Q}_{a,s}$) were modeled. As solar radiation from the atmosphere enters the greenhouse through the covering material, a certain part of it is absorbed by the air ($\dot{Q}_{r,i}$). Another factor causing heat exchange with the environment is natural ventilation and infiltration (($\dot{Q}_v$). Plant evapotranspiration also leads to heat transfer inside the greenhouse ($\dot{Q}_e$). The required amount of heat transferred inside the greenhouse to maintain air temperature at 15 °C ($\dot{Q}_h$) is introduced to the algorithm.

$$\rho_a c_{pa} \forall_a \frac{dT_a}{dt} = \dot{Q}_{r,i} - \dot{Q}_l - \dot{Q}_v - \dot{Q}_{a,s} - \dot{Q}_e + \dot{Q}_h \quad (19)$$

$$\dot{Q}_{r,i} = \tau_{cv}(1 - \kappa_s)(A_v I_t + A_h I) \quad (20)$$

κ_s is the solar radiation reflectance on the soil surface and its value is 0.5 (Fitz-Rodríguez et al., 2010).

$$\dot{Q}_l = [\,(UA)_{wall} + (UA)_{ceil}](T_a - T_{out}) \quad (21)$$

$$\dot{Q}_{a,s} = A_s h_{gr}(T_a - T_s) \quad (22)$$

$$\dot{Q}_v = \rho_a c_{pa} \frac{ACH \times \forall}{3600}(T_a - T_{out}) + h_{fg} \frac{ACH \times \forall}{3600}(W_a - W_{out}) \quad (23)$$

$$\dot{Q}_e = h_{fg} \dot{E}_{tr} A_c \quad (24)$$

2.7. Greenhouse mass balance

The humidity level inside the greenhouse is another climatic parameter that directly affects crop quality. Condensation, evapotranspiration, infiltration, and ventilation are the factors affecting air humidity. The mass balance generated in the model is given in Equation 26.

$$\rho_a \forall_a \frac{dW_a}{dt} = \dot{E}_{tr} A_c - \rho_a \frac{ACH \times \forall}{3600}(W_a - W_{out}) \quad (25)$$

Infiltration of the greenhouse is assumed to be 1 ACH, and ventilation is not done when the inside temperature is below 20 °C. To prevent overheating inside the greenhouse, the ventilation rate is assumed to be 2 ACH when the greenhouse inside temperature is over 20 °C during the heating season.

2.8. Soil energy balance

Soil temperature is another important climatic parameter for greenhouse cultivation. The heat transfer between the soil surface and the inside air of the greenhouse occurs by convection ($\dot{Q}_{a,s}$). Some amount of solar radiation that penetrates the greenhouse is absorbed by the soil layer ($\alpha_g \dot{Q}_{r,i}$). Temperature distribution throughout a depth of 1 m in the soil is assumed to be linear. The developed energy balance equation is given in Equation 27.

$$\rho_s c_{ps} \forall_s \frac{dT_s}{dt} = \alpha_g \dot{Q}_{r,i} + \dot{Q}_{s,c} + \dot{Q}_{a,s} \quad (26)$$

$$\dot{Q}_{s,c} = -k_s A_s \frac{T_{z=1m} - T_s}{L_s} \quad (27)$$

2.9. Solution algorithm

An iterative solution algorithm was used to solve the coupled transient energy and mass balance equations. The finite difference discretization method was applied and a 1 s time step was chosen for convergence.

3. Results and discussion

The microclimatic conditions of greenhouses in the provinces where greenhouse cultivation is widespread in Türkiye (Adana, Mersin, Antalya, and Muğla) were determined. A dynamic model was formed and greenhouse inside temperature, humidity ratio, and soil surface temperature were computed. The monthly and annual heating loads of the greenhouse was determined for each region (Table 2). The heating loads of the greenhouses in Adana and Mersin were similar since the climatic conditions are similar in those provinces. The highest and lowest heating loads were obtained in Muğla and Antalya, respectively.

For Muğla, the regular heating requirement in the greenhouse started on 1 November and ended on 9 April (159 days), according to the average long-term meteorological data. This period was determined as 28 November to 4 April (127 days) for Antalya and 1 November to 4 April (154 days) for both Mersin and Adana. The highest monthly heating load was calculated in January for Antalya and Muğla. The monthly heating loads for Adana and Mersin were highest in December. For heating system design, the daily peak heating load must be determined. The maximum daily heating loads were

Table 2. Heating loads of the provinces (kWh/m^2).

	Adana	Mersin	Antalya	Muğla
January	22.45	21.38	21.90	59.53
February	22.64	19.84	16.23	41.50
March	14.99	14.83	12.61	38.17
April	1.10	0.78	0.81	2.44
May	0	0	0	0
June	0	0	0	0
July	0	0	0	0
August	0	0	0	0
September	0	0	0	0
October	0	0	0	0
November	7.01	9.70	5.13	14.29
December	27.33	26.07	18.12	33.11
Annual	**95.52**	**92.60**	**74.80**	**189.04**

computed as 1.87 kWh/m2-day, 2.06 kWh/m^2-day, 1.4 kWh/m^2-day, and 2.91 kWh/m^2-day for Adana, Mersin, Antalya, and Muğla, respectively.

The coldest day of the typical meteorological year was selected as the design day and the calculated relative humidity, air, and soil surface temperatures for the greenhouse during the design day in each province are shown in Figures 2–5. Data for the days before and after the design day are included to indicate the effect of dynamic analysis. According to the long-term average meteorology data, 12 January was the design day for Adana. On that day, there was no heating requirement for 9 h due to the solar radiation heat gain in the daytime. There is always a risk of freezing due to the temperature falling below 0 °C at night, so a 1.87 kWh/m^2 heating load was required to keep the inside temperature at 15 °C. The soil surface temperature was nearly 15 °C due to energy storage in the soil as a result of regular heating of the greenhouse and solar radiation heat gain. High solar radiation inside the greenhouse increased the evapotranspiration rate, which led to the greenhouse inside air being saturated. In the daytime, the relative humidity inside the greenhouse reached the saturation level and condensation was observed inside the greenhouse. This is not a desired situation for plant growth, so the ventilation rate must be increased. However, this leads to an increase in the heating load.

14 February was the design day for Mersin, and similar results were obtained as for Adana. The only observed difference was in the relative humidity of the greenhouse in the daytime. In Mersin, the greenhouse inside air was saturated for a longer time due to the low moisture content capacity of the air at a low inside temperature.

12 January was the design day for Antalya. When compared with the other provinces, the outside dry bulb temperature was higher, so the heating load was lower. The microclimatic conditions of the greenhouse in this location are convenient for plant growth.

22 January was the design day for Muğla, and the lowest outside dry bulb temperature was observed in this province. Compared to the other provinces, the soil surface temperature was lower, at approximately 6–7 °C. Adding to this adverse condition, it was observed that the greenhouse inside air was saturated during the daytime.

The results obtained for all provinces in this study show that there is no need for heating during daytime hours due to sufficient solar radiation. The most suitable microclimate conditions for plant growth were obtained in Antalya province.

The dominant factors in the determination of the heating load were the heat transfer through the walls and ceiling of the greenhouse and the solar radiation. The overall heat transfer coefficient defined for the greenhouse varied between 3.0 and 5.3 W/m^{2}K in the proposed model. In this model, beam and diffuse radiation components are determined to compute the solar irradiation for the surfaces of the greenhouse. For simplicity, the shading effect is ignored and the highest surface area of the greenhouse is designed to be in the south direction. In Figure 6, the solar radiation intensity in each direction for all provinces is given for the design day. All provinces are

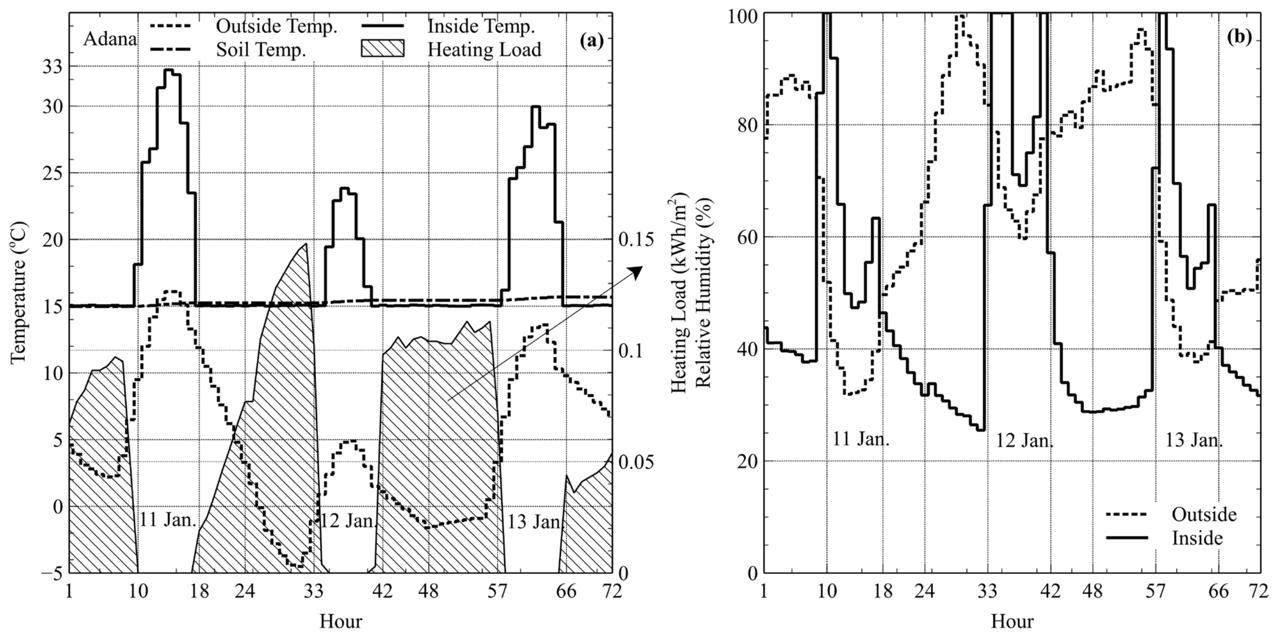

Figure 2. Hourly temperature, heating load (a), and relative humidity (b) profiles of the greenhouse over the design day (Adana).

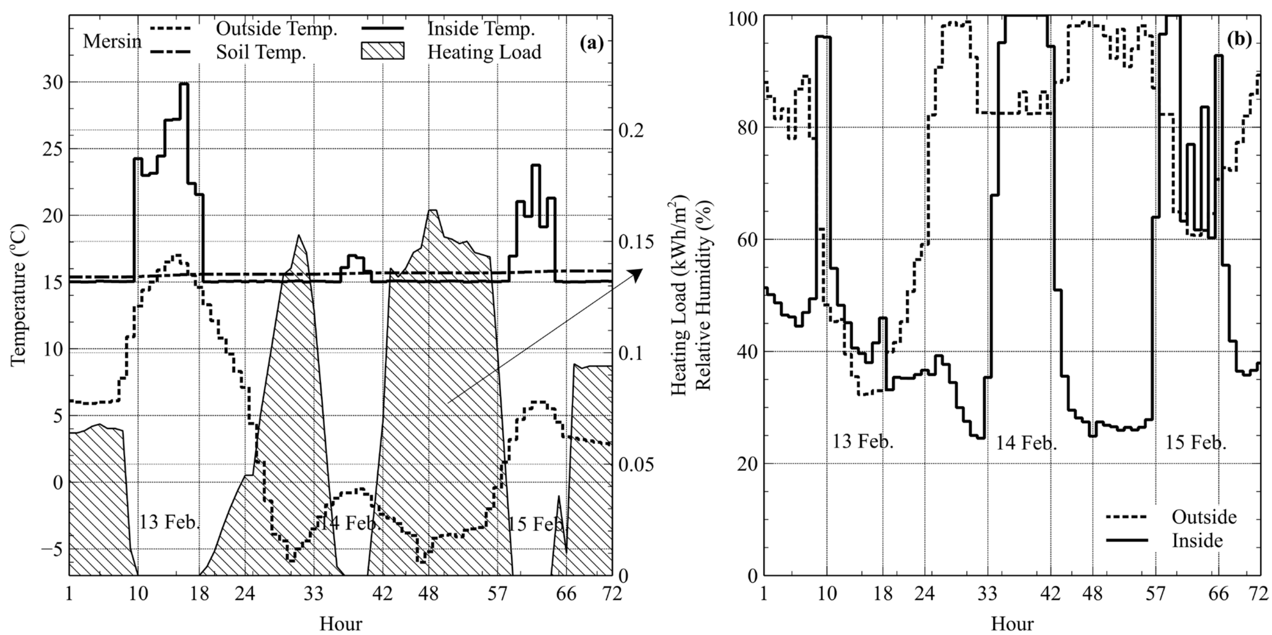

Figure 3. Hourly temperature, heating load (a), and relative humidity (b) profiles of the greenhouse over the design day (Mersin).

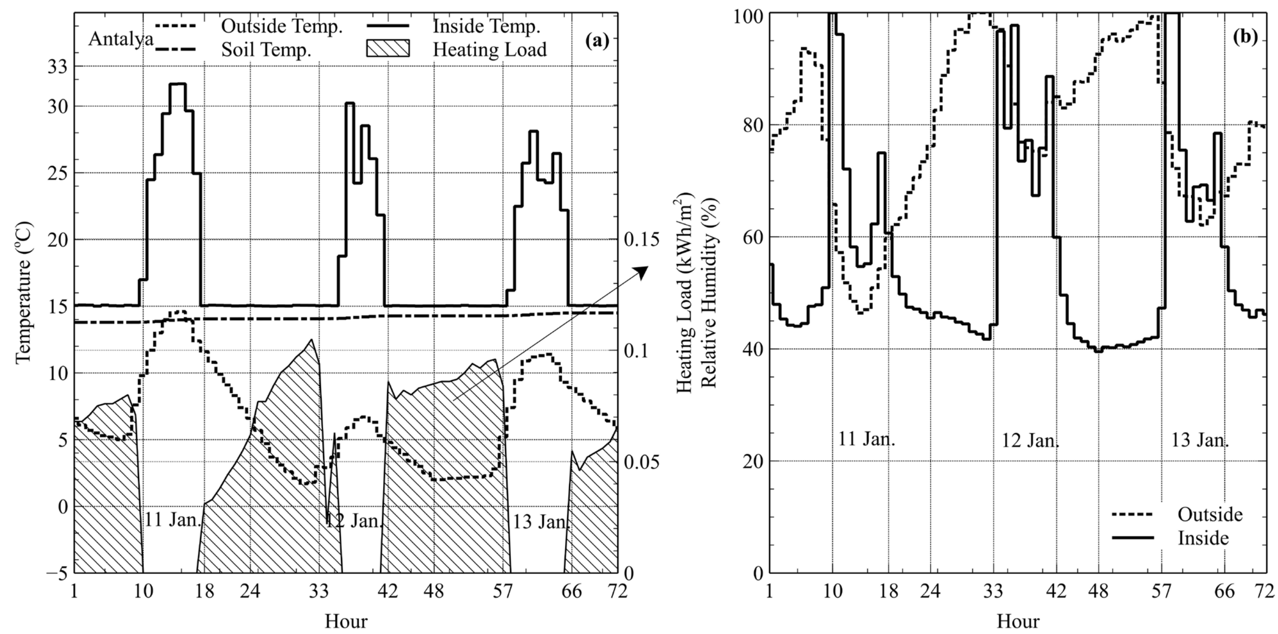

Figure 4. Hourly temperature, heating load (a), and relative humidity (b) profiles of the greenhouse over the design day (Antalya).

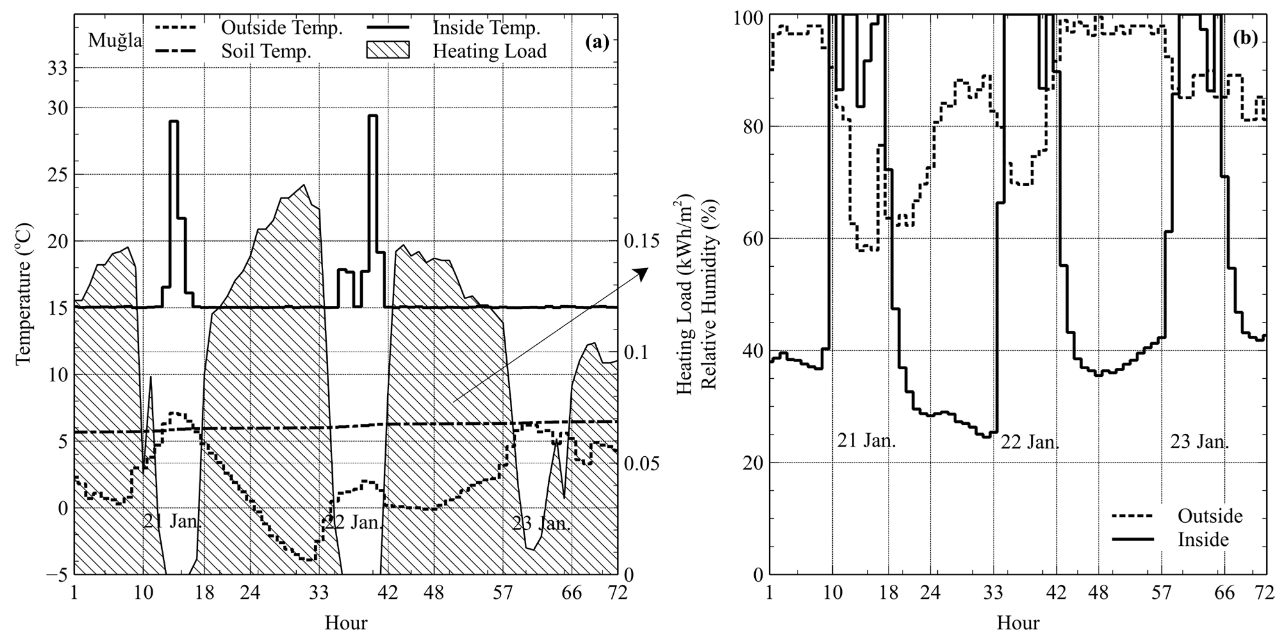

Figure 5. Hourly temperature, heating load (a), and relative humidity (b) profiles of the greenhouse over the design day (Muğla).

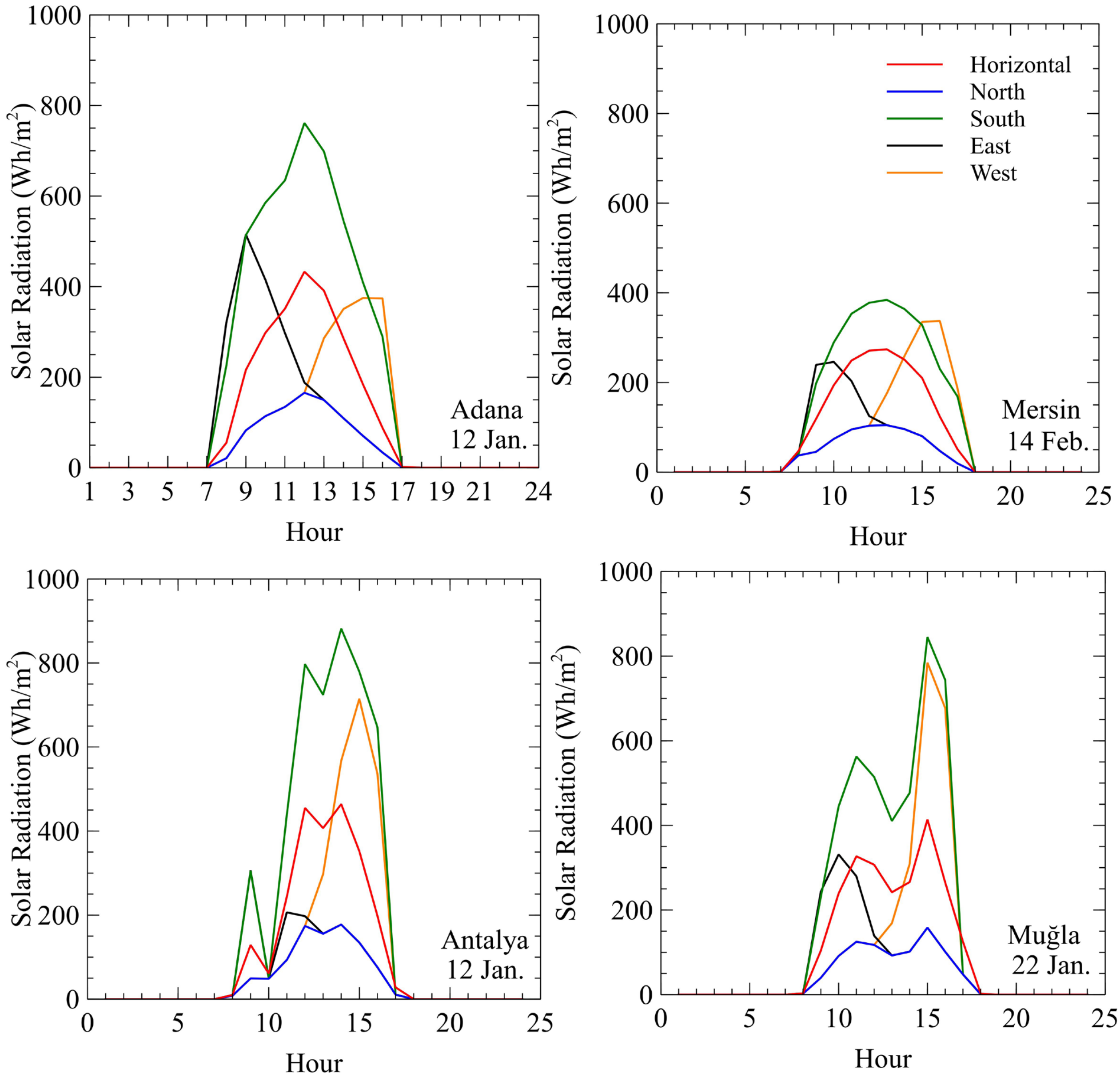

Figure 6. Solar radiation intensity on the walls and ceiling of the greenhouse.

in the Mediterranean region of Türkiye and the highest radiation intensity is computed on the south wall during the heating season. For the design day, also the coldest day, the area-weighted average solar radiation intensities were 2.11 kWh/m^2, 1.56 kWh/m^2, 2.24 kWh/m^2, and 2.15 kWh/m^2 for Adana, Mersin, Antalya, and Muğla, respectively.

4. Conclusion

The practical static approaches in the literature use only solar radiation intensity on a horizontal surface and heat transfer through the cover material to calculate the heating load, and that is not adequate for heating system design. In this study, a dynamic model has been developed to determine the greenhouse heating load for the provinces of Türkiye where greenhouse cultivation is common. In addition to the air temperature of the greenhouse, soil surface temperature and relative humidity must be considered in the desired conditions for plant growth. Thus, microclimatic conditions were determined for the design day in the provinces. The lowest heating load requirement was obtained in Antalya. Furthermore, the most suitable microclimatic conditions were also found in this province. The highest heating load was obtained in Muğla. In contrast to the other provinces, the computed soil surface temperature was 6–7 °C for the design day in Muğla, which is not a desirable condition for plant growth. Therefore, it can be understood that determining the heating load only according to the inside temperature is not sufficient for crop cultivation. To also increase the soil temperature up to the necessary level, extra heating load must be provided.

The obtained model results for Adana, Mersin, and Muğla showed that condensation in the greenhouse occurs in the daytime. To prevent this undesirable condition, the basic method was to increase the ventilation rate, which also leads to an increase in heating load.

Another important point that must be taken into account is that the heating load depends on the greenhouse construction type and location. It is not sufficient to design a greenhouse heating system based only on the heating load data published in the literature, because the type of the greenhouse, the shading, and the location of solar radiation surfaces affect the heating load.

Nomenclature

A: area (m^2)
ACH: air change per hour (1/h)
C: volumetric heat capacity (J/m^3K)
c_p: specific heat (J/kgK)
E_{tr}: evapotranspiration rate (gr/m^2s)
h: heat transfer coefficient (W/m^2K)
h_{fg}: water latent heat (j/kg)
I: incident solar radiation on a horizontal surface (W/m^2)
$I_{b,t}$: beam solar radiation on a tilted surface (W/m^2)
I_o: solar constant (1355 W/m^2)
k: heat conductivity (W/mK)
k_t: clearness index
L: depth or thickness (m)
m: excess air coefficient
n: number of days
P: pressure
P_{lag}: phase angle (in days)
Pr: Prandtl number
P_w: partial pressure of vapor
P_{ws}: saturation pressure of air
$Q_{a,s}$: heat transfer between air and the ground
Q_e: heat transfer by plant evapotranspiration
Q_h: heating load
Q_l: heat transfer between the greenhouse inside air and the environment
Q_r: solar radiation on the cover surface (W)
$Q_{r,i}$: net solar radiation transferred inside the greenhouse (W)
$Q_{s,c}$: conduction heat transfer rate through soil (W)
Q_v: heat transfer due to infiltration or ventilation
R: geometric factor for tilted surface
s: surface tilt angle (°)
t: time
t_p: soil temperature cycle period
T: temperature (°C)
$T_{s,avg}$: annual average soil temperature (°C)
UA: overall heat transfer coefficient (W/K)
V: velocity (m/s)
W: humidity ratio (kg/kg dry air)
z: soil depth (m)
α_a: solar radiation absorption of air (0.36)
α_g: solar radiation absorption of soil (0.5)
α_s: soil diffusivity (m^2/s)
$\gamma_{surface}$: surface azimuth angle (°)
δ: declination angle (°)
ΔTs: amplitude of average soil temperature (°C)
η_{gr}: ground solar reflectivity (0.6)
θ: solar incidence angle (°)
θ_z: Zenith angle (°)
κ_s: Reflectance of the solar radiation on the soil surface, 0.5.
ρ: Density (kg/m^3)
σ: Stefan-Boltzmann constant
τ: Solar transmittance, 0.76
ϕ: Relative humidity
ω: Hour angle (°)
$\forall_a$: Greenhouse volume (m^3)
$\forall_s$: Soil volume (m^3)
φ: Latitude (°)

Subscripts

a: ambient air
b: beam
c: crop
cv: cover material
d: diffuse
e: extraterrestrial
gr: ground
h: horizontal
in: inside
out: outside
s: soil
t: tilt
v: vertical
w: wind

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