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EVALUATING REQUIRED HEAT FLOW BY SOFTWARE ANALYSES IN GREENHOUSES: CASE STUDY OF IRAN

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The greenhouse sector is responsible for the largest proportion of total final energy consumption in agriculture. One effective method to reduce overall energy consumption in greenhouses is through an economical and efficient control strategy. In this study, a computer program was developed using the Visual Basic programming language to calculate the required heat flow for the growth and cultivation of greenhouse crops in most cities of Iran. The results indicated that the plastic covering material with double artificial plates was superior to other materials in maintaining internal heat. In the cities of Shiraz and Yazd, it was possible to cultivate pepper, tomato, cucumber, rose, lettuce, and strawberry with heat flow within the range of 0–24 kW and 0–30 kW, respectively. For colder cities such as Tabriz and Arak, the investigated parameter was calculated to be within the ranges of 24–70 kW and 17–63 kW, respectively. When comparing two other greenhouse covering materials, the minimum and maximum heat flow required for lettuce (glass with steel frame – Yazd and Shiraz) and rose cultivation (glass single plate – Tabriz) were observed to be 0 kW and 156.75 kW, respectively.

Keywords: energy; covering material; heating requirement; Visual Basic program; crops

It is predicted that the global population will reach at least 10 billion individuals by 2040. However, the availability of oil resources is rapidly declining, necessitating the rational use of energy by humanity (Fazilati et al., 2017). The production and supply systems of food are crucial for meeting societal needs, but agricultural activities can have detrimental effects on the environment (Pata, 2021). The Food and Agriculture Organisation (FAO) stated in 2016 that a fundamental transformation of the food and agriculture system, considering climate change, is necessary to achieve the goals set for 2030 (FAO, 2016).

In most countries, the greenhouse sector contributes significantly to the overall final energy consumption (Zhang et al., 2020). The greenhouse production sector in most countries is considered crucial in raising the standard of living in the countryside; it is even a source of agricultural support for the Iraqi national economy (Khessro et al., 2022). Greenhouses operate with energy consumption throughout all seasons of the year. Energy consumption in agriculture is highly intensive, and having precise knowledge of its quantity can reduce production costs and enhance profitability (De et al., 2001; Nourani and Bencheikh, 2020). Energy consumption in agricultural greenhouses can be categorised into direct and indirect modes. The direct utilisation of energy encompasses lighting, heating, cooling, and mechanical ventilation, among others, resulting in elevated costs and carbon emissions. Additionally, the energy required for the production of greenhouse

materials (e.g., plastics, metals, etc.), which is associated with indirect energy consumption, surpasses direct energy consumption (Aguilera et al., 2015). The materials employed for greenhouse coverings, such as glass, polyethylene, semi-hard plastic, and plastic film, exhibit inadequate thermal insulation properties, leading to a loss of 20–40% of energy in conventional greenhouses through the coverings (Hee et al., 2015). Conversely, high shading coefficients in these materials contribute significantly to the absorption of solar heat during summer, thereby playing a crucial role in the cooling requirements of greenhouses (Ghoshal and Neogi, 2014).

Agricultural greenhouses enable the harvesting of higher quality agricultural crops even during the off-season by controlling air temperature and humidity (Sethi and Sharma, 2008). In modern greenhouses, renewable and sustainable technologies such as photovoltaic modules, solar thermal collectors, hybrid PV/T collectors and systems, phase change materials (PCM), and underground thermal storage are utilised for energy saving and climate control (Cuce et al., 2016). In Iran, the use of subsidised energy by farmers leads to higher energy consumption compared to other regions, and the low cost of energy discourages farmers from implementing energy-saving measures (Solaymani, 2021). However, a significant portion of the costs is allocated to heating and cooling the greenhouse. Therefore, by understanding the energy consumption and implementing solutions to reduce it, higher crop yields can

be achieved (Hülsbergen et al., 2001). Official statistics indicate that there are 22,477 greenhouses in Iran, covering an area of 9856 hectares. The provinces of Tehran, Kerman, Isfahan, Yazd, and East Azarbaijan have the highest agricultural production, accounting for 30%, 17%, 15%, 14%, and 5%, respectively. Additionally, vegetables constitute 59.3% of greenhouse crops in Iran, followed by flowers (39.81%), fruits (0.54%), and mushrooms (0.35%) (Nakhaei et al., 2022).

Heidari and Omid (2011) conducted a study on the energy consumption patterns and energy input analysis of major greenhouse vegetable productions in Iran. The total energy consumption in cucumber and tomato production was found to be $141,493.51 \text{ MJ}\cdot\text{ha}^{-1}$ and $131,634.19 \text{ MJ}\cdot\text{ha}^{-1}$, respectively. The energy ratio for cucumber and tomato productions was calculated as 0.69 and 1.48, respectively, indicating the inefficiency of energy consumption

in cucumber production. In another study, the operational energy and energy resources required for greenhouse vegetable production in Antalya province were found to be between $23,883.5\text{--}28,034.7$ and $45,763.3\text{--}49,978.8 \text{ MJ}\cdot 10^{-3}\cdot\text{m}^{-2}$, respectively. The energy ratio for cucumber and tomato in this study was calculated as 0.32 and 0.31, respectively (Canakci and Akinci, 2006). These results indicate high energy consumption in both direct and indirect modes for vegetables, which are the most cultivated crops in Iran's greenhouses. Furthermore, the map of solar resources in Iran shows that the average annual solar radiation in the southern cities is higher than in the northern cities (Solargis, 2020; Fig. 1). However, due to the presence of cold weather in some seasons and the monsoon winds blowing from the deserts around the southern cities, it is more common to build greenhouses in these areas.

It is evident that the development of greenhouses in Iran requires farmers and artisans to have a comprehensive understanding of the total energy consumption in the production process. The efficiency of energy consumption (output energy to input energy ratio) and specific energy, which is the input energy to yield ratio ($\text{MJ}\cdot\text{kg}^{-1}$), are important indices that define the efficiency and performance of farms in crop production systems. Additionally, estimating the amount of heat requirements and heat losses is crucial for analysing the condition of each greenhouse (Ren et al., 2021). In recent years, studies have been conducted on estimating energy consumption patterns using data envelopment analysis (Omid et al., 2011), economic analysis (Mohammadi and Omid, 2010), and evaluating the heating and cooling demands of greenhouses (Banakar et al., 2021) in Iran. However, there is currently no research available on the efficient and precise calculation of the energy input in greenhouses. In this study, a computer program was developed using the Visual Basic programming language to calculate the required heat flow for the growth and cultivation of greenhouse crops in most cities of Iran. The objective of this article is to present an efficient method for determining the necessary heat flow within a greenhouse at various times and locations, while minimising both time and cost.

Material and methods

Greenhouses in Iran are primarily designed and constructed in Quonset and Arched gable types. In this specific study, the dimensions of a Quonset greenhouse located in Tabriz, Iran (38.0792° N , 46.2887° E) were utilised (Fig. 2). The subsequent step involved calculating the greenhouse's area, considering its tunnel shape (Quonset), using the following equations:

$$A = A_c + A_w \quad (1)$$

$$A_c = A \times C \quad (2)$$

$$A_w = \pi \times B \times D \quad (3)$$

where: A – the total area of the greenhouse (m^2); A_c – the curved area of the roof

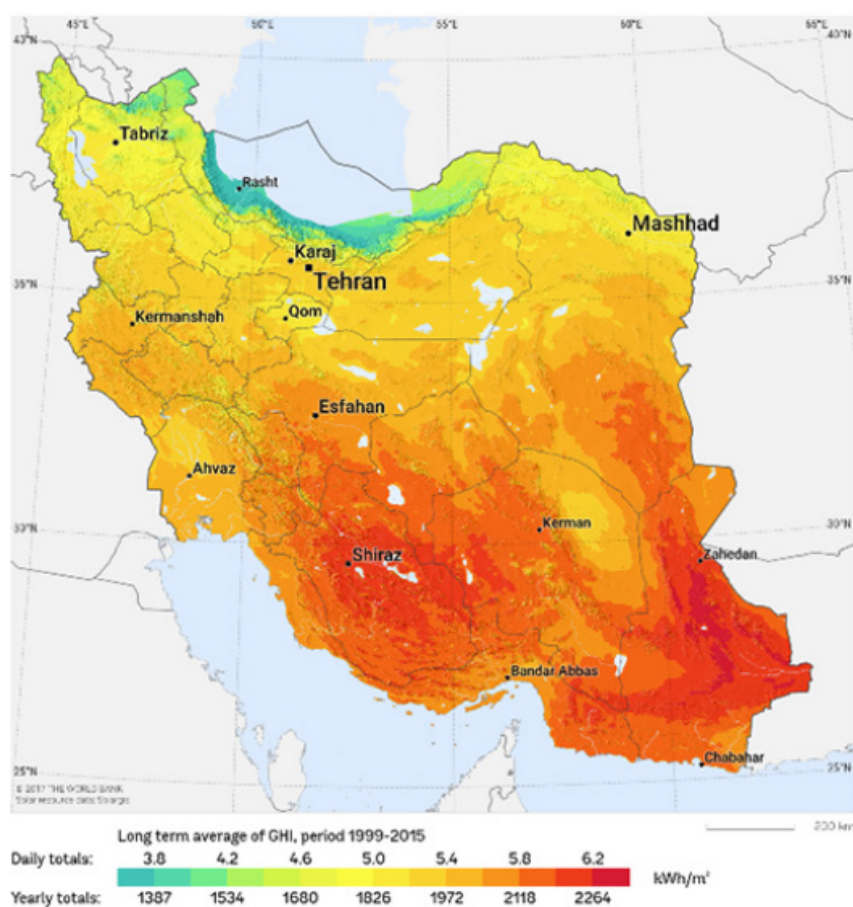


Fig. 1 The map of solar resources in Iran (Global horizontal irradiation)
Source: Solargis, 2020

and wall (m^2); A_w – the area of the end walls (the formula for the area of an ellipse, m^2)

The objective of determining the heating requirement of the greenhouse is to calculate the necessary heat flow within the greenhouse, as stated by ASABE in FAO sources (Canakci and Akinci, 2006). The required heat flow within the greenhouse was calculated using Eq. (4):

$$Q = Q_1 - Q_2 \quad (4)$$

where: Q – the amount of required heat flow within the greenhouse (W); Q_1 – the amount of heat loss (W); Q_2 – the amount of incoming solar radiation (W)

The amount of incoming solar radiation can be determined using Eq. (5), as shown below:

$$Q_2 = I_0 \times A_r \times \eta_s \quad (5)$$

where: I_0 – the average daily solar radiation intensity ($W \cdot m^{-2}$); A_r – the roof area (m^2); η_s – solar energy efficiency, which is accepted as 0.5 (Mobtaker et al., 2016)

The average daily solar radiation intensity values for greenhouses, which typically operate from October to May, are presented in Table 1.

To calculate the heat loss from the greenhouse, Eq. 6 can be used (Garzoli and Blackwell, 1981).

$$Q_1 = A \times K \times (T_i - T_d) \quad (6)$$

where: K – the total heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$); T_i and T_d – the inside and outside temperatures of the greenhouse (K), respectively

The average values of these parameters can be found in Tables 1 and 2. In order to determine the outside temperatures, climatic data were obtained from the nearest meteorological station to the city centres. The outside temperature is determined by considering the climatic conditions of the region where the greenhouse is located, taking into account the average minimum temperature during the coldest time of the year (Çakır and Şahin, 2015). Maintaining the optimal temperature is essential for crop

growth. The optimal temperature values for the growth of various crops are given in Table 2 (Esmaili and Roshandel, 2020; Gürdil et al., 2009).

The total heat transfer coefficient (K) is calculated by adding the heat transfer coefficient from the greenhouse to the atmosphere (K_1) and the heat transfer coefficient for heat gain by ventilation (K_2), as shown in Eqs (7), (8), and (9).

$$K = K_1 + K_2 \quad (7)$$

$$K_1 = \frac{1}{\frac{1}{\alpha_i} + \frac{d}{\lambda} + \frac{1}{\alpha_0}} \quad (8)$$

$$K_2 = 0.19 \times v \quad (9)$$

where: α_i – the convection heat transfer coefficient of the greenhouse ($W \cdot m^{-2} \cdot K^{-1}$); d – the thickness of the covering material (m); λ – the thermal conductivity of the material ($W \cdot m^{-1} \cdot K^{-1}$); α_0 – the heat transfer coefficient from the covering materials to the atmosphere ($W \cdot m^{-2} \cdot K^{-1}$); v – the wind velocity ($m \cdot s^{-1}$)

The average wind velocity values for various cities are presented in Table 1. Additionally, Table 3 (Al-Mahdouri et al., 2013) provides the thermal conductivity values relative to the thickness of certain covering materials utilised in greenhouses.

In the air heating system, the convection heat transfer coefficient of the greenhouse was calculated using the following equations:

$$\alpha_i = \alpha_a + \alpha_{sc} \quad (10)$$

$$\alpha_{sc} = \frac{Q_{sc}}{A_{sc}(T_i - T_d)} \quad (11)$$

$$Q_{nc} = C_s \times A_s \left[\left(\frac{T_s}{100} \right)^4 - \left(\frac{T_{ci}}{100} \right)^4 \right] \quad (12)$$

where: α_a – the heat transfer coefficient from hot air to the greenhouse ($W \cdot m^{-2} \cdot K^{-1}$); α_{sc} – the heat transfer coefficient from soil to the covering material ($W \cdot m^{-2} \cdot K^{-1}$); Q_{sc} – the heat flow from soil to the covering material (W); A_{sc} – the projection area of the covering material (m^2); C_s – the heat radiation coefficient of the soil in the greenhouse ($W \cdot m^{-2} \cdot K^{-4}$); A_s – the area of the soil surface (m^2); T_s – the soil surface temperature (K); T_{ci} – the covering material temperature (K)

The temperature of the covering material can be calculated using Eq. (13):

$$T_{ci} = 0.43 (T_i - T_d) + T_d \quad (13)$$

In order to calculate the required heat flow in the greenhouse, a computer program was developed using the MS Visual Basic 6.0 programming language. The flowchart of the developed program for calculating the heating capacity in greenhouses is shown in Fig. 3.

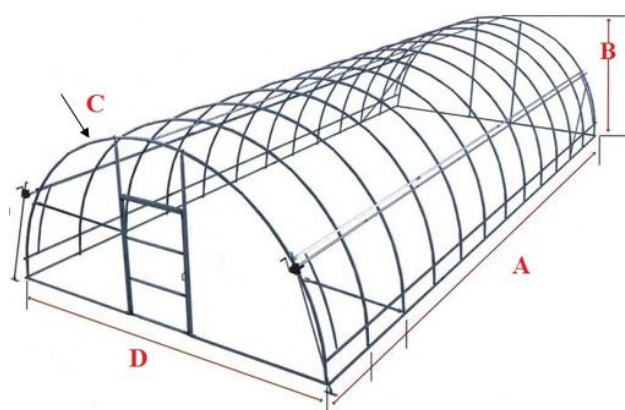


Fig. 2 Schematic of a Quonset greenhouse

Table 1 Average values of absolute outdoor temperature, daily solar radiation intensity, and wind velocity in various cities of Iran

City	T_d (K)	I_0 (MJ·m ⁻² ·day ⁻¹)	v (m.s ⁻¹)
Tehran	279.25	5.217	2.35
Tabriz	274.35	4.721	4.06
Kerman	278.45	6.824	3.40
Isfahan	277.04	6.447	3.20
Yazd	281.93	6.074	3.35
Arak	275.38	5.302	3.95
Mashhad	277.6	4.950	3.30
Shiraz	280.93	7.742	2.98
Karaj	276.49	5.153	2.58

Source: Solargis, 2020; Weather Spark, 2023

The initial data, including location, the type of covering material, the type of heat flow, the floor area, and the type of crop, were inputted into the software. Upon processing the data, the required heat flow was presented in kilowatts.

Table 2 Optimal temperature for various greenhouse crops

Crop	Temperature range (°C)
Pepper	15.5–21
Tomato	16–19
Cucumber	18–30
Rose	24–26
Lettuce	12–15
Strawberry	15–22

Source: Esmaeli and Roshandel, 2020; Gürdil et al., 2009

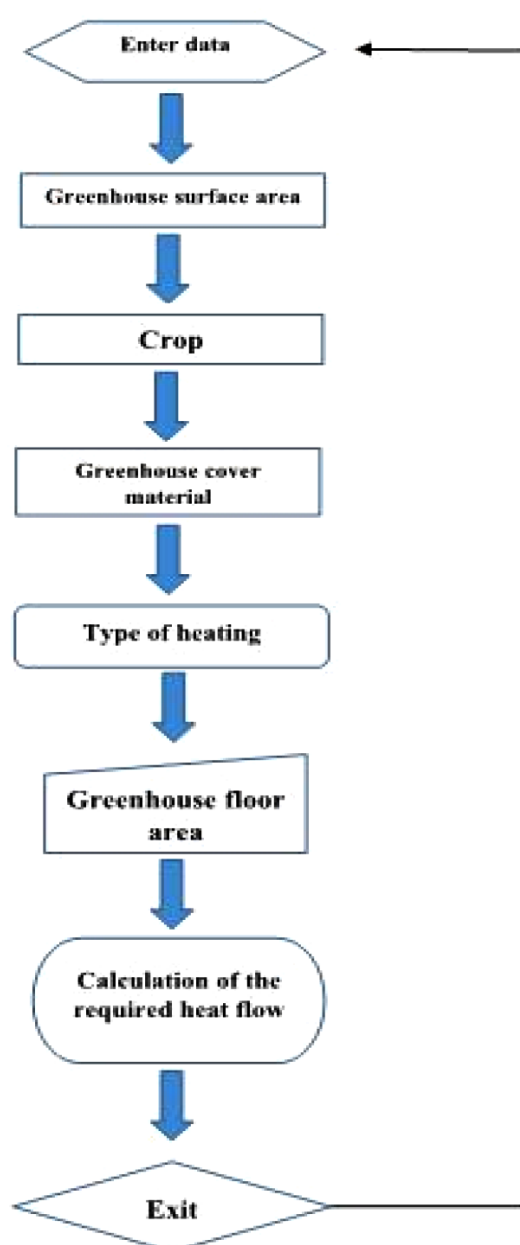
Table 3 Thickness-to-thermal conductivity ratio of materials utilised in greenhouses

Material	d/λ (W·m ⁻² ·K ⁻¹)
Glass (single plate)	0.008
Double glass with steel frame (12 mm space)	0.111
Plastic material with double artificial plate (16 mm thickness)	0.234

Source: Al-Mahdouri et al., 2013

Results and discussion

The average temperature outside the greenhouse is considered during the operational seasons of the year (Canakci and Akinci, 2006). This study considered the absolute temperature outside the greenhouse for each city from November to May (Fig. 4). The dimensions of the greenhouse were used to calculate the floor and roof areas, which were determined to be 750 m² and 870 m², respectively.

**Fig. 3** Algorithm for calculating the required heat flow

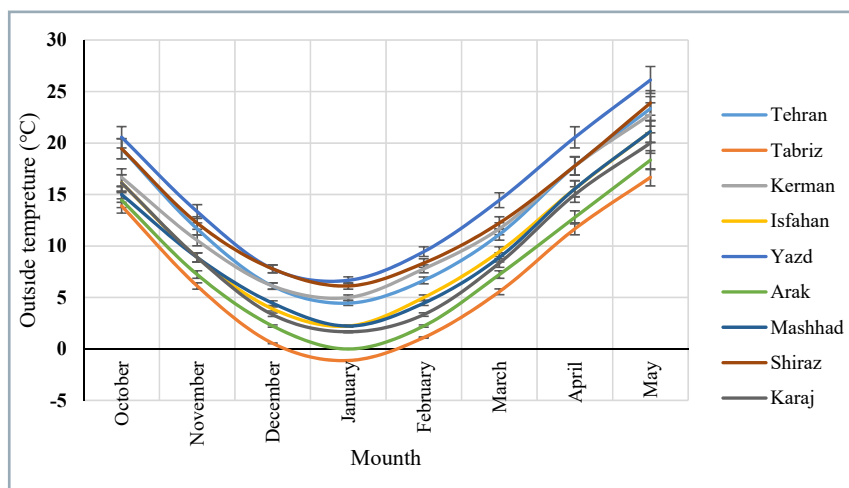


Fig. 4 Average temperature values for the selected cities

The required heat flow values for selected crops and cities, based on the type of covering material, are presented in Tables 4 to 6. The minimum and maximum heat flow values for glass covering in the cities of Shiraz and Tabriz were calculated as 05.19 kW and 156.75 kW, respectively (Table 4). Among the cultivated crops, lettuce requires the least amount of heat

flow when using this type of covering material. It can be concluded that the production of lettuce and tomatoes in the cities of Yazd and Shiraz is very cost-effective during the greenhouse's operational seasons. On the other hand, the cultivation of cucumber and rose crops in the cities of Tabriz and Arak requires a higher heat flow, which may not be economically viable.

The selection of a suitable botanical species based on the specific climatic conditions prevailing in a given locality can yield substantial reductions in energy consumption (Mostafavi and Rezaei, 2019).

The data obtained from the software used to calculate the required amount of heat flow inside the greenhouse with a glass cover for tomato production in Tabriz and Shiraz cities is presented in Fig. 5a. The software takes into account basic information such as city, product, greenhouse cover, and heating type, and provides the required amount of heat flow in kilowatts based on the greenhouse's surface area. Furthermore, the output data obtained from the software was found to be consistent with the calculated data. Taki et al. (2016) utilised various mathematical models to forecast the indoor temperature of a greenhouse in Iran. Through the implementation of a thermal screen during the night (specifically, for 12 hours during the autumn season), they successfully achieved a 58% reduction in fossil fuel consumption.

Table 4 Heat flow requirements in glass cover (single plate) for various cities and crops (kW)

City	Pepper	Tomato	Cucumber	Rose	Lettuce	Strawberry
Tehran	54.60	49.53	93.84	100.72	22.66	56.30
Tabriz	104.31	98.50	148.92	156.75	68.01	106.24
Kerman	59.07	53.56	101.66	109.14	24.40	60.90
Isfahan	69.61	64.18	111.66	119.04	35.40	71.43
Yazd	37.63	32.16	79.95	87.3912	07.58	39.46
Arak	92.91	87.18	137.17	144.95	56.88	94.81
Mashhad	73.90	68.43	116.22	123.65	39.45	75.72
Shiraz	34.41	29.02	75.64	82.88	05.19	36.19
Karaj	75.095	69.91	115.19	122.23	42.45	76.82

Table 5 Heat flow requirements in double glass with steel frame (12 mm space) cover for various cities and crops (kW)

City	Pepper	Tomato	Cucumber	Rose	Lettuce	Strawberry
Tehran	29.45	25.97	56.23	60.92	07.52	30.61
Tabriz	64.53	60.60	94.90	100.21	39.68	65.85
Kerman	29.94	26.17	58.95	64.03	06.19	31.19
Isfahan	37.80	34.09	66.44	71.45	14.30	39.04
Yazd	16.33	12.58	45.19	50.24	0.00	17.58
Arak	55.72	51.82	85.87	91.14	31.05	57.03
Mashhad	43.10	39.36	71.92	76.97	19.50	44.34
Shiraz	11.50	07.85	39.62	44.54	0.00	12.72
Karaj	43.66	40.11	70.99	75.77	21.29	44.84

The utilisation of a more precise technique, such as software-based calculation, to determine internal parameters such as internal temperature, crop temperature, and soil temperature in the aforementioned study could have influenced the modelling outcomes. In another study, a model was modified and validated to calculate the heating requirements of greenhouses in ten climate zones in Iran. Experimental data was used to fit the model. The results indicated that cold mountainous regions and dry coastal climates have the maximum and minimum annual heating demands, with values of 1380 and 210 GJ respectively at a temperature of 25 °C. The study also introduced the strategy of night curtain system (NCS) as the most suitable energy-saving approaches for the majority of climate zones (Nasrollahi et al., 2021).

The minimum and maximum heat flow required for lettuce production was determined in the cities of Yazd and Shiraz using double glass covering with steel frame

(Table 5). In both cities, the heat flow required for lettuce production was found to be 0 kW. Other crops such as pepper, tomatoes, and strawberries can also be cultivated in greenhouses using this type of covering material with the minimal heat flow. Generally, greenhouse crop cultivation in the cities of Tehran, Kerman, and Yazd appears to be relatively cost-effective. Additionally, in the cold city of Tabriz, it is more economical to plant tomatoes and lettuce compared to other crops, with heat flow requirements of 60.60 kW and 39.68 kW, respectively. The heating requirement of a plastic model greenhouse with a gothic roof was calculated in five provinces of Turkey, covering an area of 1 ha. The greenhouse was equipped with a central heating system that utilised hot water. Due to the relatively expensive fuel prices in Turkey compared to Iran, coal was chosen as the primary fuel source. The annual heating requirement in all provinces ranged from 3,592,848 to 10,459,688 MJ·ha⁻¹ (Canakci et al., 2013). Finding the most

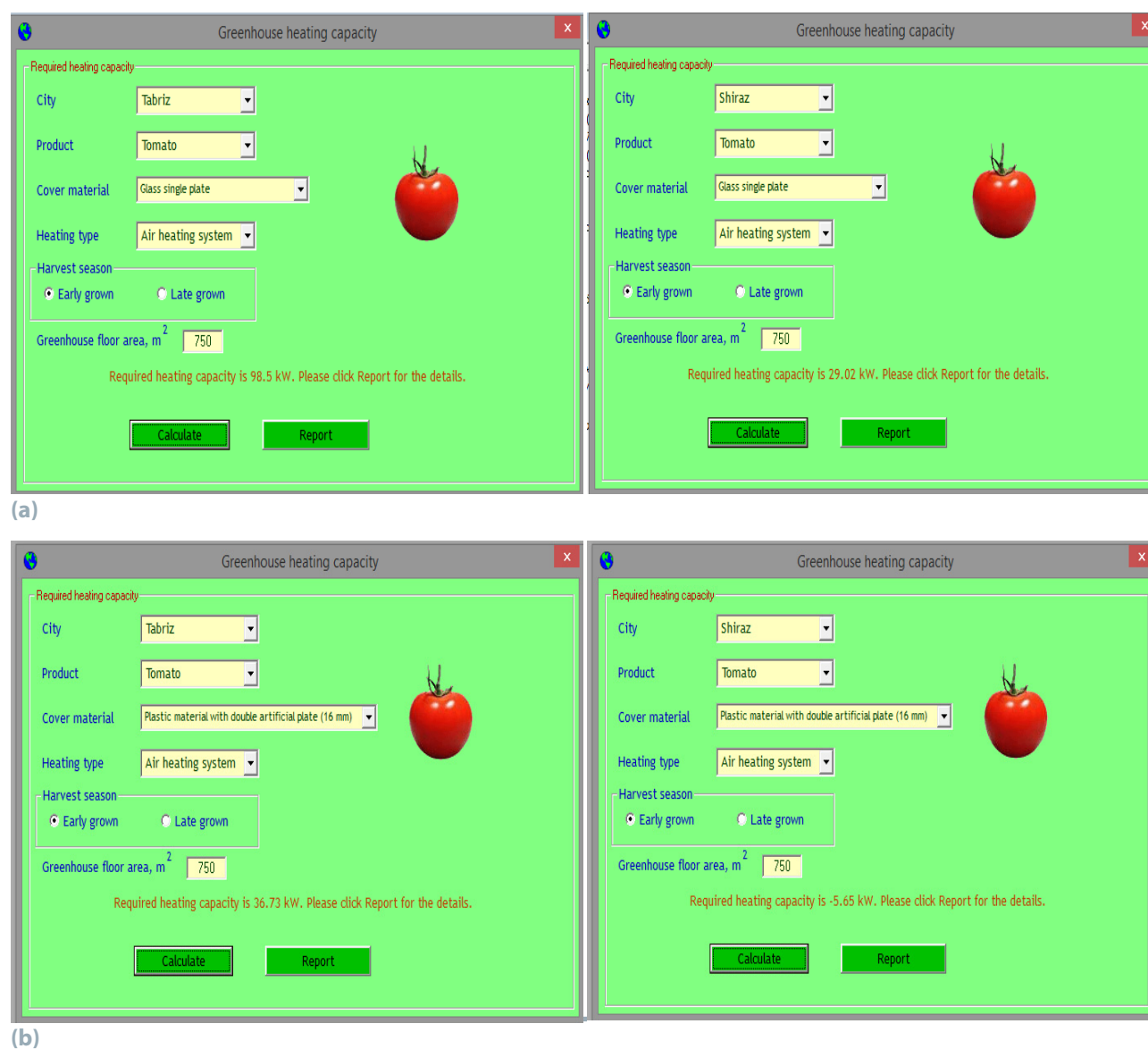


Fig. 5 Heat flow requirements for tomato greenhouses in the cities of Tabriz and Shiraz with (a) glass (single plate) cover and (b) plastic cover

Table 6 Heat flow requirements in plastic material with double artificial plate (16 mm thickness) cover for various cities and crops (kW)

City	Pepper	Tomato	Cucumber	Rose	Lettuce	Strawberry
Tehran	15.31	12.73	35.20	38.67	03.01	16.17
Tabriz	43.03	36.73	65.85	69.84	24.30	44.02
Kerman	14.00	11.18	35.71	39.50	03.81	14.94
Isfahan	20.32	17.54	41.70	45.43	06.76	21.24
Yazd	04.67	01.87	26.27	30.00	0.00	05.61
Arak	35.59	32.65	58.23	62.18	17.01	36.57
Mashhad	26.20	23.40	47.75	51.51	08.51	27.14
Shiraz	0.00	0.00	19.83	23.50	0.00	0.00
Karaj	26.10	23.46	46.41	49.96	09.42	26.98

suitable heating method and utilising various covering materials based on the climatic conditions in these areas appears necessary due to the elevated heating expenses. Furthermore, the calculations pertaining to the required heat in this study have been done using the conventional approach, although the authors had the option to employ a tailored computer program for the calculations.

The results of study conducted on industrial greenhouses located in different cities, using plastic with double artificial plate as the covering material, indicate that the environmental conditions are superior compared to other types of covering materials (Table 6). In most greenhouse covering materials, an increase in the thickness to thermal conductivity ratio leads to a decrease in the amount of heat flow required to maintain favourable conditions (Tantau, 2013). According to Mostafavi and Rezaei (2019), it was observed that a decrease in the heat transfer coefficient of the material used for covering results in a reduction in heat loss. In the case of plastic covering material similar to double glass, the heat flow required for greenhouses in Yazd and Shiraz cities for lettuce crop was found to be 0 kW. Following these cities, Kerman and Tehran had the lowest values with 3.81 kW and 3.01 kW, respectively. The required heat flow calculated by the software for the tomato product in the cities of Tabriz and Shiraz is 36.73 and -5.65 (0) kW, respectively (Fig. 5b). A negative value for the calculated heat flow indicates that the heat gained in the greenhouse exceeds the heat loss. Therefore, in such a situation, there is no requirement to provide additional heating within the greenhouse. Natural ventilation is also essential in these instances. It appears that the use of this type of covering material is suitable and recommended for greenhouses in various cities. This allows farmers to conserve the necessary heat during the cold seasons of the year by utilising plastic material with a double artificial plate in greenhouse construction.

Conclusion

The required heat flow for greenhouse crops was estimated in nine major cities in Iran. To expedite the calculations, a computer program was developed using the MS Visual Basic programming language. Greenhouses with plastic cover material (16 mm thickness) required less heat flow

for planting and growing all selected crops in the cities. Specifically, the required heat flow for cultivating lettuce in the cities of Yazd and Shiraz was calculated as 0 kW. For other crops in all cities, the required heat flow was estimated to be in the range of 0–70 kW. In colder cities such as Tabriz and Arak, the required heat flow for glass covering materials was in the range of 68–157 kW and 56–145 kW, respectively. The minimum required heat flow for greenhouses with glass cover material (steel frame) was observed in the cities of Yazd and Shiraz, at 0 kW. The results of this study demonstrate that the computer program developed to calculate the required heat flow for industrial greenhouses in selected crops and cities achieved the maximum efficiency within a short timeframe.

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