INFRASTRUKTURA I EKOLOGIA TERENÓW WIEJSKICH
INFRASTRUCTURE AND ECOLOGY OF RURAL AREAS

2024, Vol. 19(1), 77-92
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DOI: https://doi.org/10.14597/infraeco.2024.006

DETERMINATION OF HEAT REQUIREMENT IN GREENHOUSES AND EVALUATION OF PRECAUTIONS TO BE TAKEN FOR ENERGY EFFICIENCY

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ABSTRACT

The thermal energy demand during the production period in greenhouses is important for determining the production economics and feasibility studies to be carried out. This is because evaluating future investments in the greenhouse sector requires accurate estimates of energy demand and costs. For this purpose, the heat energy required in the greenhouse and the heating costs were calculated, taking into account the meteorological conditions of the region, the optimum temperature demand of the plants and the technical specifications of the greenhouse. Two different cover materials were used to determine the heat energy requirement: polyethylene sidewalls and roof (PE) and polycarbonate sidewalls + polyethylene roof (PC+PE). In addition, calculations were made for 8 different greenhouse combinations, including different insulation statuses (poor, medium and good insulation) of these greenhouses without thermal screen and with thermal screens. As a result of the study, it was calculated that the amount of energy consumed was reduced by 4.5% when PC covering material was used instead of PE covering material as covering material for the greenhouse side walls. In greenhouses covered with PE and PC+PE covers, if well-insulated thermal screens are used, the amount of energy consumed will decrease by 23.1%-22.4%, respectively, compared to PE and PC+PE greenhouses without thermal screens. Heating energy and fuel costs that can be saved with low heat transfer coefficient cover materials and well-insulated thermal screens could be reduced by 25.8%. The results of the study will guide greenhouse producers in regions with similar climates in determining the energy consumed, greenhouse design, investment evaluation and also greenhouse sector policies.

Keywords: *greenhouse, cover material, thermal screen, energy requirement*

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INTRODUCTION

Greenhouses are agricultural structures that allow indoor conditions to be controlled and are one of the most important income-generating branches of agriculture (Saltuk 2019; Saltuk and Mikail, 2019). These structures are attracting global attention in agriculture due to their capacity to provide high quality product production throughout the year and to ensure efficient and continuous use of available resources (Samaranayake *et al.,* 2020). Due to climate change and increasing population, greenhouses will become increasingly important in the coming years (Saltuk 2019; Saltuk and Mikail, 2019). Growing in greenhouses permits the correct management of the environmental conditions. This helps to increase the yield and improve the quality of the product (Cola *et al.,* 2020). By controlling growth factors such as temperature, light and humidity, the greenhouse environment can be precisely controlled. Among these factors, indoor temperature is the most important and affects optimum plant growth and efficient production (Canakci *et al.,* 2013 Boyacı *et al.,* 2023a). While there are significant advantages to growing in a greenhouse over growing in the open, there are also a number of challenges that need to be addressed. The large amount of energy required to maintain a stable growing environment continues to be a major issue in greenhouse production. Modern greenhouse agriculture is among the areas that require the most energy in the agricultural industry (Rasheed *et al.,* 2018; Samaranayake *et al.,* 2020). The vast majority of that energy is consumed for heating (Ahamed *et al.,* 2019a). Therefore, energy saving in greenhouse cultivation has become one of the most important challenges (Rasheed *et al.,* 2017). Significantly reducing energy costs is therefore one of the main objectives of modern greenhouse applications (Tataraki *et al.,* 2020). Greenhouses are seasonal production structures that consume large amounts of energy. In previous studies, researchers have reported that heating costs account for 20-60% of total production costs, depending on outdoor climatic conditions (Baytorun *et al.,* 2016; Shen *et al.,* 2018; Tataraki *et al.,* 2020).

These high energy costs have become an major factor negatively affecting the improving of greenhouses. Therefore, in order to increase the energy efficiency of greenhouses, it is very important to estimate the energy consumption (Shen *et al.,* 2018). An accurate estimate of greenhouse energy costs is needed to evaluate future investments in the greenhouse sector. The development and use of thermal modelling is an approach that provides an approximate and cost-effective way of improving greenhouse management and helping to conclude on the feasibility of potential investments (Ahamed *et al.,* 2019b). By using thermal models it is possible to increase the accuracy of the predictions. These models take into account three basic factors: the meteorological conditions of the region (ambient temperature and solar radiation), the growing requirements of the plants (various optimum temperature requirements for different products) and the technical features of the greenhouse (covering material, thermal screen, etc.) (Tataraki *et al.,* 2020; Dimitropoulou *et al.,* 2023). Nowadays, various studies have been carried out aimed at estimating heating requirements during vegetable cultivation in greenhouses. Among these, Canakci et al. (2013) determined the heating needs of greenhouses in five different provinces in southern Turkey, taking into account local climate data. As a result of the study, the heating needs of the greenhouse in the provinces were determined and recommendations were made on the necessary measures to reduce the energy demand. Baytorun et al.

(2018) developed the specialised ISIGER-SERA system to determine the heat requirements in greenhouses and calculate the parameters required for the design of heating systems. The ISIGER-SERA system, taking into account the temperature increases due to the actual temperature in the greenhouse and the type of greenhouse, calculates the heat requirements in greenhouses. In the comparison with the ISIGER-SERA system according to annual fuel consumption amounts, it was found that the calculated fuel consumption differed from the actual consumption by 3%. Ahamed et al. (2019b) used the GREENHEAT model to calculate the annual heating requirements of plants commonly grown in greenhouses, considering greenhouses located in Saskatoon, Canada. Mariani *et al.* (2016) studied the determination of energy requirements for tomato production in greenhouses in 56 locations with different latitudes. Dimitropoulou *et al.* (2023) developed a model to estimate the thermal energy demand of greenhouses in Europe. The common aspect of the studies carried out by the researchers is that the determination of regional greenhouse energy demand will guide producers in greenhouse design, investment evaluation and greenhouse sector policy.

Plant cultivation in greenhouses is an increasingly developing agricultural sector worldwide. Because it provides increased productivity by protecting the products grown against climate risks compared to open field cultivation. The fact that the greenhouse sector has spread to all continents and is increasing day by day in terms of area reveals its importance. This highlights the importance of assessing the impact of climate variability and change on greenhouse activities and the changes in energy consumption, primarily for heating and cooling, on a regional scale (Mariani *et al.*, 2016).

The objectives of this study were to (i) calculate the heat energy requirements considering the meteorological conditions of the region, the optimum temperature needs of the plants and the technical specifications of the greenhouse; (ii) determine the effect of thermal screens without thermal screens and with different insulation values on the heat energy requirements in greenhouses; and (iii) compare the fuel consumption, fuel cost, heating cost per unit tomato yield and the amount of CO_2 released into the atmosphere as a function of the amount of energy required in greenhouses. The results of this study are expected to guide feasibility studies and greenhouse sector policies for greenhouse enterprises to be established in regions with similar climatic characteristics.

MATERIAL AND METHOD

General Characteristics of the Study Area

To determine the heat energy demand in greenhouses, calculations were made for the province of Kırşehir, which is located in the Central Anatolian region of Turkey and has a continental climate. The geographical location of Kırşehir province is between latitude and longitude 39°08'02"N and 34°07'08"E. The altitude of the province above sea level is 1082 m.

Long-year meteorological data regarding the climate characteristics of Kırşehir province are given in Table 1 (MGM, 2024).

Table 1. Long-term (1930 - 2023) meteorological data of Kırşehir province

Measurement	Months												Annual
	Jan.	Feb.	Mar.	Apr.	May	Jun.	July	Aug.	Sep.	Oct.	Nov.	Dec.	
Avg. temperature [°C]	-0.2	1.4	5.3	10.8	15.5	19.7	23.1	23.1	18.6	12.8	6.6	2.2	11.6
Avg. highest temperature [°C]	4.6	6.7	11.3	17.2	22.1	26.3	29.9	30.1	26.1	20.1	13.1	7.0	17.9
Avg. lowest temperature [°C]	-4.2	-3.1	-0.2	4.4	8.6	12.4	15.7	15.7	11.1	6.1	1.2	-1.8	5.5
Relative humidity [%]	78.2	74.3	67.6	62.4	60.2	54.2	47.6	47.6	52	61.8	71.9	78.7	63
Wind speed, [m/s]	1.8	2.1	2.3	2.3	2.1	2.5	3.3	3.1	2.5	1.9	1.7	1.7	2.3
Radiation, [kWh/m^2]	1.78	2.38	3.89	4.83	6.09	6.47	6.42	5.85	4.84	3.43	2.08	1.58	4.14

Technical specifications of greenhouses

In the study, greenhouse features of the same size were used in order to eliminate the effect of greenhouse dimensions on the calculations. The greenhouse dimensions used to calculate the heat requirement are shown in Table 2.

Table 2. Greenhouse dimensions used to calculate heat requirements

Greenhouse specifications	Dimensions	Greenhouse specifications	Dimensions
Number of compartments	25	Side wall area	700.00 m^2
Compartment width	8.00 m	Frontline area	1981.53 m^2
greenhouse length	100.00 m	Roof area	23324.04 m^2
Roof slope angle	27.70 °	Greenhouse volume	98000.00 m^3
Sidewall height	3.50 m	Cover area	26005.57 m^2
Column spacing	2.50 m	Floor area	20000.00 m^2
Roof height	2.10 m	Roof length	9.33 m
Greenhouse perimeter	500.00 m	Ridge height	5.60 m

In the study, water inlet temperature of 60°C and water outlet temperature of 40°C were used in the calculations for heating the greenhouses. The diameter of the steel pipes through which water circulates in the greenhouse is 51 mm, and the pipes are planned to be hung on the side walls.

In order to determine the heat requirement in the greenhouse and to compare different energy sources for heating, 2 different cover materials (PE and PC+PE) and 3 different insulation conditions of thermal screens for energy saving were considered in the calculations. In insulation, the conditions of the greenhouse being closed and the thermal screen being poorly insulated, moderately insulated and well insulated were taken into consideration. Accordingly, the structural features of greenhouses are given in Table 3.

Table 3. Structural features of greenhouses

Greenhouses	Cover material	Thermal screen uses	Insulation of thermal screen
G-1	PE	No	-
G-2	PE	Yes	Bad
G-3	PE	Yes	Medium
G-4	PE	Yes	Good
G-5	PC+PE	No	-
G-6	PC+PE	Yes	Bad
G-7	PC+PE	Yes	Medium
G-8	PC+PE	Yes	Good

Determination of climate parameters outside and inside the greenhouse

Measuring indoor climate parameters in the greenhouse on an hourly basis instead of daily averages is important in determining the heat requirement more accurately (Baytorun *et al.,* 2016). Accordingly, the long-year hourly mean temperature values of Kırşehir province were used as the outdoor temperature values in the calculations to determine the heat requirements in the study.

Optimum temperature values needed for growing tomato plants were used as the greenhouse indoor temperature. In the calculations, greenhouse indoor temperatures were determined as 16/21°C night/day throughout the year, in line with the recommendations of the researchers (Heuvelink, 1995; Peet *et al.,* 1998; Sato *et al.,* 2000; Adams *et al.,* 2001; Pressman *et al.,* 2002). Additionally Nisen *et al.* (1988) reported that the temperature difference between day and night of 5-8°C in greenhouse production did not have a negative effect on quality and yield.

Determining the Heat Requirement in the Greenhouse

In greenhouses, heat energy requirement, fuel amount, fuel cost and amount of carbon dioxide emission released into the atmosphere were calculated with the help of ISIGER-SERA expert system developed by Baytorun et al. (2016). In ISIGER-SERA expert system, the annual heat energy required in the greenhouse as a function of the hours of the year was calculated using (Equation 1) (Rath, 1992).

$$Q = \sum_{n=1}^{8760}(((\vartheta_{in} - \vartheta_{ioHn} - \Delta\vartheta_{spn}) \times k'_a * A_H \times (1 - EE_{ES})) \times t_{si} \quad (1)$$

where; Q is the heat energy requirement of the greenhouse (Wh), ϑ_{in} is the desired internal temperature in the greenhouse (°C), ϑ_{ioHn} is the actual temperature in the unheated greenhouse (°C), $\Delta\vartheta_{spn}$ is the temperature increase depending on the characteristics of the greenhouse (°C), k'_a is the overall heat transfer coefficient of the cover material (W/m^2°C), A_H is the cover surface area of the greenhouse (m^2), EE_{ES} is the heat savings provided by the thermal screen (-), n is the hours of the year, t_{si} is the time period (1 h)

The overall heat transfer coefficient of the cover material was calculated using Equation 2 of Rath (1992) as a function of the cover material and wind speed.

$$k_a' = k_a' + \frac{k_a'}{x_1} \times (x_2 \times \upsilon_w) + x_3 \quad (2)$$

where; υ_w is the wind speed (m/s), x_1=7.56 (-), x_2: 0.35 (m/s), x_3: −1.4 (-)

When considering the thermal screen effect, the heat increase due to the thermal screen used is calculated using Equation 3 in the case of ka'≤10 and EEES≤0.6 (Rath, 1992).

$$\mathrm{EE_{ES}} = \frac{\mathrm{EE_{ES}}}{\mathrm{KF_{ES}}} * \mathrm{k_a'} \quad (3)$$

where; the correction factor depending on the impermeability of the thermal screen is taken as 0 W/m^2°C in the case of no thermal screen, in the case of poorly insulated and closed thermal screen is taken as 23.43 W/m^2°C, in the case of moderately insulated and closed thermal screen is taken as 11.05 W/m^2°C, in the case of well insulated and tightly closed thermal screen is taken as 6.8 W/m^2°C.

The theoretical temperature value was calculated according to Equation 4 to find the actual temperatures in the greenhouse (Rath, 1992).

$$\vartheta_{\mathrm{ith}} = \frac{\mathrm{q_{GS}} \times \mathrm{D_G} \times \eta \times \mathrm{A_G}}{\mathrm{k_a'} \times (1 - \mathrm{EE_{ES}}) \times \mathrm{A_H}} + \vartheta_\mathrm{a} \quad (4)$$

In the equation; ϑ_{ith} is the theoretical temperature (°C), q_{GS} is the solar radiation (W/m^2), D_G is the permeability of the cover material used (%), η is the solar energy conversion factor into heat energy, A_G is the greenhouse floor area (m^2), ϑ_a is the outdoor temperature (°C)

The amount of fuel required for annual heat energy in greenhouses is calculated using Equation 5, and the amount of CO_2 released to the atmosphere by fuels used to heat greenhouses is calculated using Equation 6 (Baytorun *et al.*, 2016).

$$\mathrm{B_y} = \frac{\mathrm{q_h}}{\mathrm{H_u} \,.\, \eta\mathrm{ges}} \quad (5)$$

$$\mathrm{SEGMy} = \mathrm{B_y} \,.\, \mathrm{H_u} \,.\, \mathrm{FSEG} \quad (6)$$

Where; By is the fuel amount corresponding to unit area (kg/m^2), qh is the heat energy required in the greenhouse (W/m^2), Hu is the lower heating value of the fuel (kWh/kg), ηges is the combustion efficiency (%), SEGMy is the annual CO_2 emission amount (kg eq. CO_2), FSEG is the CO_2 emission equivalence according to fuel type (kg eq. CO_2/kWh)

The lower heating values, combustion efficiency and unit prices per kWh in 2024 of the fuels considered in the study are given in Table 4 (Bursagaz, 2024).

Table 4. Lower heating values, combustion efficiency and 2024 unit prices of fuels

Fuel type	Lower heating value of fuel [kWh]	Combustion efficiency [%]	Price [$/kWh]	FSEG (CO_2) conversion coefficient [kg Eq. CO_2/kWh]
Imported Siberian coal [kg]	7.00	0.65	1.76	0.448
Fuel-oil No: 6 [kg]	9.56	0.80	3.92	0.313
Natural gas [m^3]	8.25	0.93	1.57	0.239

RESULT AND DISCUSSION

Plants grown in greenhouses, where agriculture is carried out out of season, are adversely affected by extreme weather events in the outdoor environment. Thermal screens are important for improving indoor climate conditions, for more economical greenhouse management and for reducing CO_2 emissions into the atmosphere due to fuel consumption, by reducing these negative effects and the amount of energy used. (Boyacı *et al.*, 2023b).

In the study, the monthly change in heat energy requirement in greenhouses with different equipment features, if the temperature is kept at 16/21°C night/day, is given in Table 5.

Table 5. Heat energy requirement in greenhouses with different equipment features

Season	Month	G-1	G-2	G-3	G-4	G-5	G-6	G-7	G-8	Ratio [%]
Winter	December	76.3	72.3	65.7	59.1	72.8	69.1	62.9	56.8	19.4
	January	89.5	84.8	77	69.2	85.3	81	73.8	66.5	22.8
	February	67.1	63.6	57.7	51.9	64.1	60.9	55.5	50.1	17.1
	Total, kWh/m²	**232.9**	**220.7**	**200.4**	**180.2**	**222.2**	**211**	**192.2**	**173.4**	**59.2**
	Ratio [%]	**-**	**5.2**	**14.0**	**22.6**	**-**	**5.0**	**13.5**	**22.0**	
Spring	March	48.5	45.7	41.1	36.5	46.5	43.9	39.7	35.4	12.3
	April	24.2	22.8	20.4	17.9	23.2	21.9	19.6	17.4	6.2
	May	10.3	9.7	8.6	7.6	9.8	9.3	8.3	7.4	2.6
	Total, kWh/m²	**83**	**78.2**	**70.1**	**62**	**79.5**	**75.1**	**67.6**	**60.2**	**21.1**
	Ratio [%]	**-**	**5.8**	**15.5**	**25.3**	**-**	**5.5**	**15.0**	**24.3**	
Summer	June	2.5	2.5	2.4	2.2	2.4	2.4	2.3	2.1	0.6
	July	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.2
	August	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.2
	Total, kWh/m²	**3.8**	**3.8**	**3.7**	**3.5**	**3.6**	**3.6**	**3.5**	**3.3**	**1.0**
	Ratio [%]	**-**	**0.0**	**2.6**	**7.9**	**-**	**0.0**	**2.8**	**8.3**	
Autumn	September	4.5	4.4	4.1	3.9	4.3	4.2	3.9	3.7	1.1
	October	20.7	19.6	17.9	16.1	19.8	18.8	17.2	15.6	5.3
	November	48.4	45.7	41.2	36.7	46.4	43.9	39.7	35.5	12.3
	Total, kWh/m²	**73.6**	**69.7**	**63.2**	**56.7**	**70.5**	**66.9**	**60.8**	**54.8**	**18.7**
	Ratio [%]	**-**	**5.3**	**14.1**	**23.0**	**-**	**5.1**	**13.8**	**22.3**	
Annual	**Total, kWh/m²/year**	**393.3**	**372.4**	**337.4**	**302.4**	**375.8**	**356.6**	**324.1**	**291.7**	**100**
	Ratio [%]	**-**	**5.3**	**14.2**	**23.1**	**-**	**5.1**	**13.8**	**22.4**	

From table 5 it can be seen that most of the greenhouse heating energy is consumed in December, January and February. It is also seen that 59.2% of the total energy is consumed in the winter months, followed by the spring period with 21.2%. When the total energy amount in greenhouses with side walls and roofs constructed as PE is taken into account, it is calculated that

5.3% of energy can be saved in G-2, 14.2% in G-3 and 23.1% in G-4 compared to G-1 greenhouse. Considering the total energy in greenhouses constructed with PC sidewalls and PE roofs, it was calculated that 5.1% energy could be saved in G-6, 13.8% in G7 and 22.2% in G-8 compared to G-5. Accordingly, it has been determined that the insulation and sealing conditions of thermal screens are very important in terms of energy saving. In addition, when comparing G-1 and G-5 greenhouses, the amount of energy saved by using PC material on the side walls was calculated to be 4.4%. In the case of using PC cover material and well insulated thermal screens on the side walls instead of PE material in the greenhouses, the energy saving in the G-8 greenhouse is 25.8% compared to G-1.

Today, the most widely used method of conserving thermal energy in greenhouses is the use of thermal screens. Their use is very important because the high heating costs in greenhouses can be reduced in the production costs by saving energy. Since the sealing conditions of the covering materials and thermal screens used in greenhouses significantly affect the heat consumption, their installation must be done in the best possible way (Baytorun and Gügercin, 2015). Researchers carried out experiments with different types of thermal screens in greenhouses have reported savings of 17-70% depending on the type of thermal screen and its sealing status (Arinze *et al.*, 1986; Critten and Bailey, 2002; Le Quillec *et al.*, 2005; Baytorun *et al.*, 2016). The values obtained in the study are similar to the researchers' savings rates. It was found that in order to achieve these values, it is important to use PC cladding instead of single-layer PE cladding on the greenhouse sidewalls. Another important point was that the installation of thermal screens was found to be very important in increasing the amount of energy saved.

The amount of fuel used per unit area in greenhouses with different equipment features in the study is given in Table 6.

Table 6. Required fuel amount in greenhouses with different equipment features

Features	**Covering material**							
Side wall cover (PE)	**PE**				**PC+PE**			
Thermal screen/insulation	**G-1**	**G-2**	**G-3**	**G-4**	**G-5**	**G-6**	**G-7**	**G-8**
Imported coal [kg/m^2]	89.0	84.3	76.4	68.5	85.1	80.7	73.4	66.0
Fuel-oil [kg/m^2]	53.0	50.2	45.4	40.7	50.6	48.0	43.6	39.3
Natural gas [m^3/m^2]	52.8	50.0	45.3	40.6	50.4	47.9	43.5	39.2

When examined in Table 6, the amount of fuel required for the per unit floor area of the greenhouse varies between 39.16-89.03 depending on different fuels. Increased energy conservation measures in greenhouses have reduced fuel amounts due to reduced heat energy requirements. Accordingly, in case of using imported coal, the fuel requirement, which was 89.03 kg/m^2 in G-1, decreased to 68.46 kg/m^2 in G-4. In this case, if the insulation of the thermal screens is good, the coal requirement per unit area is reduced by 20.58 kg. Similarly, the fuel amount, which was 85.07 kg/m^2 in G-5, decreased to 66.03 kg/m^2 for G-8. In this case, the fuel requirement decreased by 19.04 kg per unit area. The amount of fuel used in greenhouses varies depending on the outside temperature, the growing environment temperature and the heat transfer coefficient of the cover material used in the greenhouse. For this reason, the amount of fuel used in greenhouses varies depending on the regions, the equipment features in the greenhouse and the internal temperature value that the plant wants in the growing environment. For this reason, determining the operating expenses for the investments to be made before the greenhouse establishment is established is very important in terms of sustainability.

The cost of fuel per unit area in greenhouses with different equipment features in the study are shown in Table 7.

Table 7. Cost of fuel in greenhouses with different characteristics of the equipment ($\$/m^2$ per year)

Features	**Covering material**							
Side wall cover (PE)		**PE**				**PC+PE**		
Thermal screen/insulation	**G-1**	**G-2**	**G-3**	**G-4**	**G-5**	**G-6**	**G-7**	**G-8**
Imported coal [kg/m^2]	22.3	21.1	19.1	17.1	21.3	20.2	18.4	16.5
Fuel-oil [kg/m^2]	49.6	47.0	42.6	38.2	47.4	45.0	40.9	36.8
Natural gas [m^3/m^2]	19.9	18.8	17.1	15.3	19.0	18.0	16.4	14.7

When Table 7 is examined, in case of using imported coal for heating, it will be 22.3 $\$/m^2$ for G-1, 49.6 $\$/m^2$ for heating oil and 19.9 $\$/m^2$ for natural gas. These values are calculated as 16.5 $\$/m^2$, 36.8 $\$/m^2$ and 14.7 $\$/m^2$ in the G-8 greenhouse, respectively. The high calorific value and efficiency of natural gas as well as its low unit prices compared to other fuels have reduced heating costs per unit area. Accordingly, if imported coal is used in heating, the fuel cost will increase by 1.12 times compared to natural gas, while if fuel oil is used, the fuel cost will be 2.50 times compared to natural gas. Accordingly, it has been determined that increasing insulation values in greenhouses will reduce fuel costs depending on the amount of fuel. Rising energy costs in heated greenhouses are causing growers to discuss the cost effectiveness of heating. In terms of profitability and energy efficiency, saving energy in heated greenhouses is just as important as heating greenhouses. (Baytorun and Gügercin, 2015). Tezcan and Büyüktaş (2013) reported in their study examining greenhouse cover materials and fuel types that fuel oil is 1.90 times more expensive than solid fuel and 2.48 times more expensive than natural gas, while solid fuel is 1.31 times more expensive than natural gas. Today, high and variable energy costs also affect fuel costs. In addition, the use of natural gas, which is less expensive than other fuels, is important for businesses to reduce fuel costs. However, since the use of natural gas is limited in agricultural areas, it is extremely important for businesses to use cheap and renewable energy sources for heating in terms of economic cultivation.

It is important to construct greenhouse structures in accordance with the climatic conditions of the production area and to take the necessary heat conservation measures in order to reduce production costs arising from heating expenses (Boyacı *et al.*, 2016; Boyacı, 2018). In the study, heating costs for tomato yield per unit area in greenhouses are shown in Table 8.

Table 8. Heating cost per unit tomato yield in greenhouses with different equipment features ($/kg per year)

Features	**Covering material**							
Side wall cover (PE)	**PE**				**PC+PE**			
Thermal screen/insulation	**G-1**	**G-2**	**G-3**	**G-4**	**G-5**	**G-6**	**G-7**	**G-8**
Imported coal [kg/m^2]	0.45	0.42	0.38	0.34	0.43	0.40	0.37	0.33
Fuel-oil [kg/m^2]	0.99	0.94	0.85	0.76	0.95	0.90	0.82	0.74
Natural gas [m^3/m^2]	0.40	0.38	0.34	0.31	0.38	0.36	0.33	0.29

In order to compare the fuel costs that arise depending on the fuel consumption required in greenhouses, the amount of product to be obtained should also be taken into account in the evaluations to be made. In regions where production can be done all year round, 50 kg of tomato yield is obtained from a unit greenhouse area depending on the length of the production period, while in regions where production is done between September and June, it is between 30-34 kg (von Zabeltitz 2011; Baytorun *et al.*, 2016). If the tomato yield is assumed to be 50 kg/m^2 during the production period in greenhouses with regular heating, the heating cost for producing one kilogram of tomatoes will be 0.45 $/kg if imported coal is used for PE covered G-1. In case of heating with natural gas, it will be 0.40 $/kg. In PC+PE covered G-8, it will decrease to 0.33 $/kg if imported coal is used and to 0.29 $/kg if natural gas is used.

It is very important to use heat preservation methods to reduce heating costs, which have a large share in production costs in greenhouses (Boyacı, 2018). Boyacı *et al.* (2023b) reported that the heating cost of 1 kg of tomatoes is $0.11 more in a greenhouse without a thermal screen than in a greenhouse with a thermal screen. Accordingly, increasing insulation values will also reduce fuel costs. In addition, when Table 9 is examined, it is seen that natural gas is the most suitable fuel to be used in heating greenhouses in terms of price.

Similarly, Tezcan and Büyüktaş, (2013) stated that modern greenhouses covered with different materials and with the same area could be heated with natural gas at the cheapest cost. However, since natural gas infrastructure has not been established in the areas where greenhouses are established in Turkey, its use is not possible yet. In this case, it is important to establish natural gas infrastructure or use alternative and renewable energy sources for the high energy costs that occur in regions with continental climate characteristics. In addition, in regions of Turkey with continental climate and high energy demand, there is a possibility of using existing geothermal energy resources in greenhouse farming. In this case, enterprises have the opportunity to produce more profitably by significantly reduced the proportion of heating in production.

As the population grows, so does the demand for energy. Providing energy from renewable, non-polluting sources rather than fossil fuels is important for economic and environmental reasons (Ertop *et al.*, 2023). CO_2 emissions depending on the fuel used for heating per unit area in greenhouses are shown in Table 9.

Table 9. CO_2 emissions as a function of the fuel used for heating in greenhouses with different equipment features (CO_2 equivalent kg/m^{2}year)

Features	**Covering material**							
Side wall cover (PE)	**PE**				**PC+PE**			
Thermal screen/insulation	**G-1**	**G-2**	**G-3**	**G-4**	**G-5**	**G-6**	**G-7**	**G-8**
Imported coal [kg/m^2]	324.7	307.4	278.5	249.6	310.2	294.4	267.6	240.8
Fuel-oil [kg/m^2]	184.4	174.6	158.2	141.7	176.2	167.2	151.9	136.7
Natural gas [m^3/m^2]	121.0	114.6	103.8	93.0	115.6	109.7	99.7	89.8

The costs and CO_2 emissions into the atmosphere are different for fossil energy sources (imported coal, fuel oil, natural gas, etc.) used in greenhouses. As seen in Table 10, the amount of CO_2 released into the atmosphere is the highest in heating with imported coal, while natural gas is the lowest. Accordingly, if imported coal is used for heating in G-1, CO_2 emissions will be 1.76 times more than fuel oil and 2.68 times more than natural gas. In addition, the amount of CO_2 that fuels will release into the atmosphere in G-1 will be 1.35 times more than in G-8. Boyacı *et al.* (2023b) reported that in case of using thermal screens, CO_2 emissions released into the atmosphere decreased by 29.5 kg/night compared to greenhouses without thermal screens. Accordingly, it was determined that carbon dioxide emissions released into the atmosphere would also decrease with the energy conservation measures taken in greenhouses. Baytorun and Gügercin (2015) reported that the reduction of heating energy requirements in greenhouses can lead to an increase in energy efficiency and environmentally friendly production, due to a reduction in the use of fossil energy resources. In addition, Giuliano *et al.* (2010) reported that one of the objectives of sustainable greenhouse systems should be an environmentally friendly system that does not produce as much waste as possible. Mitigating climate change requires reducing greenhouse gas emissions into the atmosphere and increasing the use of renewable energy to replace fossil fuels. Greenhouses are energy-intensive agricultural systems, mainly fossil fuel-based. The use of renewable energy sources in the operation of greenhouses is limited (Vourdoubas, 2020). The use of natural gas for heating in greenhouse operations in the study area will also be important in terms of reducing CO_2 released into the atmosphere. In addition, if renewable energy sources are used for heating, less CO_2 will be released compared to fossil fuels, and thus the negative environmental effects will be minimized.

CONCLUSION

In the study evaluating the heat requirement in greenhouses and the measures to be taken for energy efficiency, according to the present results, the following concluding remarks were obtained:

1. The heat energy requirement in the greenhouse (G-1) covered with PE and without thermal screen 393.3 kWh/m^{2}year, while it is calculated as 291.7 kWh/m^{2}year in the greenhouse (G-8) covered with PC+PE and with well-insulated thermal screen. The heat energy that can be saved with heat conservation will be 25.8%. Especially in greenhouses to be established in

cold climate regions, the use of high heat tranfer resistance covering material and good insulation of thermal screens will provide significant energy savings and increase energy efficiency.

2. If coal is used as fuel in greenhouses, 89 kg/m^2 of coal will be consumed in the G-1 greenhouse and 66.0 kg/m^2 in the G-8 greenhouse.The amount of fuel that can be saved will be 23 kg/m^2. Considerable fuel savings could be achieved by taking heat conservation measures today, when energy prices are high.
3. In the case of using coal for heating purposes in the G-1 greenhouse, the fuel cost was calculated as 22.3 \$/m^2, 49.6 \$/m^2 for fuel oil and 19.9 \$/m^2 for natural gas. These values were detemined as 16.5 \$/m^2, 36.8 \$/m^2 and 14.7 \$/m^2 in the G-8 greenhouse, respectively. Using low-cost fuels with high calorific value and efficiency for heating purposes in enterprises will reduce fuel costs.
4. The heating cost of producing one kilogram of tomatoes will be 0.45 $/kg in case of coal heating in G-1, while it will be 0.40 $/kg in case of natural gas heating. In case of PC+PE coated G-8, it will be 0.33 $/kg in case of coal heating, while it will be 0.29 $/kg in case of natural gas heating. The decrease in fuel costs will reduce the share of heating in production costs.
5. If imported coal is used for heating in G-1, CO_2 emissions will be 1.76 times higher than fuel oil and 2.68 times higher than natural gas. In addition, the amount of CO_2 that fuels will release into the atmosphere in G-1 will be 1.35 times higher than in G-8. Reducing the emissions released into the atmosphere by fuels in heated greenhouses will be as important as heating greenhouses for sustainable greenhouse farming.

As a result, especially in greenhouses to be established in cold climate regions, using PC cover material with low heat transfer coefficient instead of PE cover material on side walls will provide significant energy savings. Additionally, using well-insulated thermal screens at night will increase energy efficiency. The results are expected to guide greenhouse enterprises in regions with similar climate and cultivation conditions to take the necessary precautions and determine greenhouse sector policies.

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Received: August 26, 2024
Revised: October 08, 2024
Accepted: October 09, 2024