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Energy Efficiency in Greenhouses and Comparison of Energy Sources Used for Heating

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Abstract: Sustainability in greenhouse farming, one of the areas where the most energy is needed in the agricultural sector, can be achieved by increasing energy efficiency. Due to increasing energy costs in Türkiye and worldwide, increasing energy efficiency in greenhouses is seen as possible using renewable energy sources that do not produce waste instead of fossil energy sources. This study determined the heat-energy demand in the provinces of Türkiye with continental (Kırşehir and Kütahya) and Mediterranean (Antalya and Mersin) climates. For this purpose, the heat-energy requirement was calculated for greenhouse types with three different insulation properties (S-1: roof and side walls polyethylene, S-2: roof polyethylene, side walls polycarbonate, and S-3: roof polyethylene, side walls polycarbonate, and thermal curtain). Then, the amount and cost of fossil (coal, fuel oil, and natural gas) and renewable energy sources (geothermal and biogas) to be used in obtaining this energy, the heating cost for unit tomato yield, and the amount of carbon dioxide (CO_2) released into the atmosphere were compared. According to the results obtained, the highest heat-energy requirement was 356.5 kWh m^{-2} $year^{-1}$ in the S-1 greenhouse in the Kütahya province, and the lowest was 46.3 kWh m^{-2} $year^{-1}$ in the S-3 greenhouse in the Mersin province. Depending on energy conservation, 6% of energy savings can be achieved in S-2 and 29% in S-3 compared to S-1. The highest heating cost for producing one kilogram of tomatoes was 0.70 USD kg^{-1} in fuel oil and Kütahya province (S-1). The lowest was calculated as 0.06 USD kg^{-1} in geothermally heated greenhouses in Kırşehir and Kütahya provinces (S-3). The highest CO_2 to be released into the atmosphere with fuels was equal to 253.1 kg m^{-2} $year^{-1}$ in coal fuel in Kütahya province (S-1). The lowest was calculated as 1.1 kg m^{-2} $year^{-1}$ in geothermally heated greenhouses in Kırşehir and Kütahya provinces (S-3). The results of this research can be used to develop feasibility studies for greenhouse companies, greenhouse sector policies, policymakers, environmental protection, and taking precautions against the climate crisis.

Keywords: heat requirement; greenhouse heating; fossil energy; geothermal energy; CO_2 emissions

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1. Introduction

With the increasing demand for food worldwide, controlled environment agriculture is a crucial strategy for growing crops throughout the year. One important type of controlled environment agriculture is greenhouses [1]. Greenhouses are agricultural structures that extend plant production season by providing controlled indoor microclimate conditions [2]. Greenhouses attract global agricultural interest because they can meet the demand for producing high-quality products throughout the year and ensure the efficient and sustainable use of available resources (water, energy, and others) [3]. Although greenhouse cultivation offers significant benefits compared to open-field cultivation, it also brings some challenges that must be considered. The high energy required to maintain a stable growing environment remains one of the most important issues in greenhouse production. From an energy perspective, greenhouse cultivation requires high energy use, making it one of the most energy-consuming sectors in the agricultural industry [3–5]. One of the reasons for the high energy demand for the environmental control of greenhouses is the technology of the covering material, which maximizes light transmission but does not guarantee as good thermal insulation as in civil buildings [6]. A large part of this energy demand is consumed for heating purposes [7]. Heating applications in greenhouses are not only to prevent low temperatures at night but also to balance the temperature inside the greenhouse. Thus, during the winter season, when product prices reach their highest values in the market, the adverse effects on plant growth that affect the quality and quantity of production are prevented [8]. Although the energy price in agriculture varies in countries and the energy power load of a greenhouse depends on local climatic conditions, heating costs account for approximately 30–50% of the overall operating cost of a greenhouse [9–11]. Therefore, reducing greenhouse heating costs can make greenhouse production more economical and sustainable [7]. Increasing energy demand has become an important issue for greenhouse sectors to achieve sustainable development [12]. Sustainability in greenhouses can be reached by increasing energy efficiency [13]. In order to increase energy efficiency, the required heat-energy value must be reduced [14]. Reducing heating costs is a major challenge for greenhouse growers, especially in cold regions [7]. Technical measures to be taken in greenhouses allow for significant energy savings and increased energy efficiency [15]. At the same time, the chance of competition can be increased in regions that are disadvantaged in terms of heating costs (cold regions) [16]. These high energy costs have become a significant factor that negatively affects greenhouse improvements. Therefore, it is very important to estimate energy consumption to increase the energy efficiency of greenhouses [10]. In order to evaluate future investments in the greenhouse sector, an accurate estimation of greenhouse energy costs is required. The development and use of thermal modeling is an approach that provides an approximate and cost-effective way to improve greenhouse management and helps to conclude the feasibility of potential investments [17].

Energy saving has become urgent due to the scarcity of energy reserves, rapid increases in energy prices, and increasingly serious environmental problems such as global warming, ozone depletion, and climate change. The use of renewable energy sources and the adoption of energy-saving measures are of great importance for all sectors, such as industries, transportation, and agriculture [18]. Recent reports have revealed that building construction contributes to approximately 40% of the energy consumed and 25% of greenhouse gas emissions globally [19]. Due to lightweight construction and inefficient operation, greenhouses consume more fossil fuel energy in mechanical systems and have larger carbon footprints than other buildings of similar size [1]. Agricultural production in greenhouses is evolving towards industrialization and scale with the modernization of facility agriculture. The greenhouse industry heavily depends on fossil fuels, contributing to significant greenhouse gas (GHG) emissions [20]. The relatively high cost and uncertain availability of fossil fuels restrict producers' use of heating practices and cause adverse effects on yields such as quality, quantity, and cultivation period of plant products [21,22]. Since many plants require frequent supplementary heating for healthy growth and energy costs are high, using alternative, renewable, and low-cost heating systems will be of primary importance both to provide optimum indoor conditions for crops and achieve significant energy savings [23].

The greenhouse sector is Türkiye's fastest-growing agricultural sector, mainly due to favorable climatic conditions. However, plants often require auxiliary heating for healthy growth, especially during winter nights. Greenhouse heating is one of the most energy-consuming activities during winter periods in Türkiye. Due to the high relative cost of energy, only a few greenhouse owners can afford to use auxiliary heating systems. Therefore, using a low-cost and alternative or renewable heating system is of primary importance for a greenhouse to provide optimum indoor conditions during winter [24]. For this purpose, researchers have been conducting research on biogas, photovoltaics, and geothermal heating systems for a long time to meet the high heating demands of greenhouses and to reduce the environmental impacts of fossil fuels using renewable energy sources [25–29].

Using geothermal heat for greenhouse heating is a well-known and widespread practice worldwide. Türkiye, Russia, Hungary, China, and Italy are leading countries in annual geothermal energy use for greenhouse heating [30]. As of 2002, Türkiye's geothermal and biomass installed power is 1686 MW and 2172 MW, respectively, and their ratio in the total installed power is 1.66% and 2.14%, respectively. Türkiye ranks seventh globally and 1st in Europe regarding geothermal heat potential. However, the level of use is approximately 3% of the resources, which is relatively low compared to the country's capacity. The size of greenhouse areas heated with geothermal energy in Türkiye is approximately 434.4 hectares, approximately 1% of the greenhouse assets. The average operating size in geothermal heated greenhouses is approximately 2.1 hectares [31]. Ertop et al. (2023) [32] determined that there are many advantages to using animal waste as biogas and that the potential energy that can be obtained by converting biogas into electrical energy is 8,105,058 MWh in Türkiye at the end of 10 years. This value is equivalent to 3,902,020 MWh of potential electricity in Poland. If Türkiye uses this great potential, it will significantly reduce carbon dioxide released into the atmosphere by fossil fuels and the cheap energy potential in sustainable greenhouse activities. Considering the negative effects of climate variability and change experienced in recent years on open-field plant production, plant cultivation in greenhouses protects products against climate risks and increases yield. However, although the spread of the greenhouse sector worldwide and the fact that it increases in terms of area daily reveal its importance, the energy required for cultivation is quite high. For this reason, studies on energy conservation, efficient use, and reduction of adverse environmental effects to ensure sustainability in the greenhouse sector are gaining more and more importance every day. At the same time, these studies contribute to the "Affordable and Clean Energy" and "Good Health and Well-Being" titles, which are among the sustainable development goals of the United Nations (UN) to protect the environment and take precautions against the climate crisis [33].

The aims of this study are (i) to calculate the heat-energy requirements of greenhouses by taking into account their technical characteristics, (ii) to determine the effect of the cover material and thermal curtain on the heat-energy requirements of greenhouses, and (iii) to reveal the amount of fuel, its cost, the heating cost per unit production, and the amount of CO_2 released into the atmosphere by fuels. The study results are expected to guide feasibility studies for greenhouse enterprises to be established in regions with similar climate characteristics, greenhouse sector policies, and decision-makers in protecting the environment and taking precautions against the climate crisis.

2. Materials and Methods

2.1. Study Area

The four regions of Türkiye where the greenhouses were located were used for the study. These regions were: Kırşehir, Kütahya, Antalya and Mersin. Details of their locations are shown in Table 1 and Figure 1.

Table 1. Some geographical information about the provinces.

Province	Altitude (m)	Latitude (°)	Longitude (°)
Kırşehir	985	39° 09′ N	34° 10′ E
Kütahya	970	39° 25′ N	29° 59′ E
Antalya	39	36° 54′ N	30° 42′ E
Mersin	5	36° 48′ N	34° 38′ E

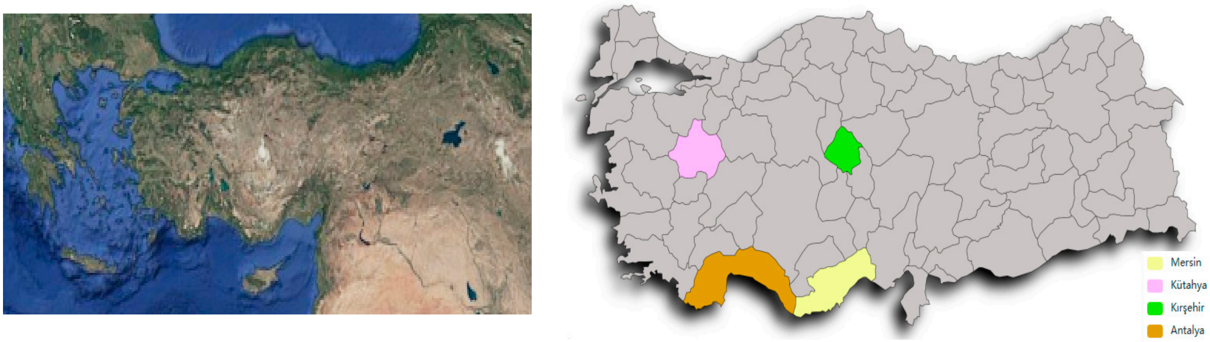

Figure 1. Geographic location of the study area.

Cities in different regions of Türkiye were selected for the study. One of the reasons for choosing Kırşehir and Kütahya, which are located in a continental climate, is that the hot geothermal water resources found there have started to be used in greenhouse agriculture in recent years. In addition, due to their favorable geographical location and Mediterranean climate, Antalya and Mersin provinces rank 1st and 2nd in terms of area and production in greenhouse agriculture in Türkiye, which conditioned their selection for the study. Furthermore, greenhouse activities in all selected provinces play an important role in the socio-economic development of the provinces by providing employment opportunities.

2.2. Greenhouse Cultivation Area and Production in Türkiye and Provinces

Information on Türkiye's total greenhouse area, tomato growing area, and production quantities are given in Table 2 [34].

In Türkiye, 48.1% of the total greenhouse area is in Antalya, 25.9% in Mersin, 0.3% in Kırşehir, which has a continental climate, and 0.1% in Kütahya. Tomatoes are the most commonly grown crops in greenhouses in this country. A total of 62.5% of the greenhouse tomato areas in Türkiye are in Antalya, 9.8% in Mersin, 0.1% in Kırşehir, and 0.2% in Kütahya. In Türkiye, 62.3% of greenhouse tomato production is in Antalya, 9.4% in Mersin, 0.1% in Kırşehir, and 0.4% in Kütahya (Table 2). Tomato cultivation in Antalya and Mersin begins in August or September and continues for approximately ten months until the end of June. In Kırşehir and Kütahya provinces, production can be carried out yearly in greenhouses thanks to their geothermal resources. Accordingly, in regularly heated greenhouses, the average tomato yield during the production period was accepted as 50 kg·m^{-2} in Kırşehir and Kütahya provinces and 32 kg·m^{-2} in Antalya and Mersin provinces [35].

Table 2. Greenhouse agricultural areas and production values of Türkiye and its provinces.

Location	Greenhouse Area and Production	High Tunnels	Plastic Greenhouse	Glass Greenhouse	Total
Türkiye	Total area, ha	11,774.3	44,851.0	5531.2	62,156.5
	Tomato planted area, ha	1378.5	20,689.7	2691.5	24,759.7
	Production, tons	166,568.0	3,444,325.0	448,103.0	4,058,996.0
Antalya	Total area, ha	1710.6	23,876.4	4318.8	29,905.8
	Tomato planted area, ha	619.4	12,628.9	2216.2	15,464.5
	Production, tons	66,253.0	2,096,828.0	365,210	2,528,291.0
Mersin	Total area, ha	4819	10,688.4	587.3	16,094.7
	Tomato planted area, ha	-	2432.4	3.5	2435.9
	Production, tons	-	379,188.0	450.0	379,638.0
Kırşehir	Total area, ha	16.4	158.4	-	174.8
	Tomato planted area, ha	14.2	9.5	-	23.7
	Production, tons	2030.0	2090.0	-	4120.0
Kütahya	Total area, ha	16.8	59.7	0.5	77.0
	Tomato planted area, ha	5.0	56.3	0.5	61.8
	Production, tons	423.0	16,669.0	150.0	17,242.0

2.3. Some Meteorological Data of the Research Area

Today, alternative areas for greenhouses are regions with renewable energy sources (geothermal). When the climate values of Antalya and Mersin provinces are examined, they show typical Mediterranean climate characteristics. On the other hand, Kırşehir and Kütahya provinces, where geothermal resources are widespread, have a continental climate. Annual average temperature and solar radiation values between 1930 and 2023, provided by the General Directorate of Meteorology for provinces in different climate zones, are shown in Table 3 [36].

Table 3. Temperature and solar radiation data of the selected provinces.

Province	Mean Temperature, (°C)	Mean High Temperature (°C)	Mean Low Temperature (°C)	Highest Temperature (°C)	Lowest Temperature (°C)	Solar Intensity (kWh·m^{-2} Year)
Antalya	18.8	24.2	13.8	45.0	−4.6	1646
Mersin	19.3	23.4	15.0	41.5	−6.6	1614
Kırşehir	11.6	17.9	5.5	40.5	−28.0	1321
Kütahya	10.8	17.1	4.9	41.4	−28.1	1490

As seen in Table 3, temperature and radiation values are considerably higher in Antalya and Mersin provinces with Mediterranean climates compared to Kırşehir and Kütahya provinces. According to the long-term values measured in the outdoor environment, it is clear that the amount of energy required for heating in greenhouses established in Kırşehir and Kütahya provinces will be high. The production of this energy with fossil fuels will be necessary in terms of energy costs and the adverse effects of fossil fuels on the atmosphere.

2.4. Dimensions and Technical Specifications of Greenhouses

In the study, greenhouse dimensions were taken similarly to eliminate errors that may occur in the calculations. Furthermore, greenhouse dimensions were taken the same way to eliminate errors in the calculations. Moreover, calculations were made by accounting for polyethylene (PE) and polycarbonate cover material combinations, greenhouse type, and dimensions, which have been widely used in Türkiye in recent years [15,37]. In addition, well-insulated thermal curtains, which have become widespread in these greenhouses for energy-saving purposes, were considered in the calculations [15,38].

Table 4 provides the greenhouse dimensions used in the calculations to determine the heat requirement needed in greenhouses for the selected provinces, and Table 5 provides their structural features.

Table 4. Greenhouse dimensions and heat transfer coefficients used in calculations.

Greenhouse Specifications	Dimensions	Greenhouse Specifications	Dimensions
Number of span	45 unit	Cover area (Ac)	29,176.7 m^2
Compartment width	8.0 m	Ground area (Ag)	21,600.0 m^2
Compartment length	60.0 m	Ac/Ag	1.35–
Sidewall height	3.5 m	Single-layer PE	6.5 W m^{-2} °C
Roof height	2.1 m	Polycarbonate	3.3 W m^{-2} °C

Table 5. Structural features of greenhouses.

Scenarios	Abbreviations	Cover Material		Thermal Screen Uses
		Sidewall	Roof	
Scenario 1	S-1	PE	PE	No
Scenario 2	S-2	PC	PE	No
Scenario 3	S-3	PC	PE	Yes

PE: Polyethylene, PC: Polycarbonate.

2.5. Determination of Heat Requirements and Fuel Amounts for Greenhouses

In the study, the heat-energy requirement is calculated from hourly values, taking into account the actual temperature in a greenhouse that is not ventilated and heated up to a certain temperature value and the temperature increases that occur depending on the characteristics of the greenhouse [39]. In calculating the heat requirement, greenhouse temperature was used as 15/21 °C day and night. These values were selected as the temperature values commonly used in greenhouses in the provinces [15,38,40]. In addition, these values are also compatible with the values recommended by researchers for tomato cultivation [41–43]. In order to reduce the high energy demand that occurs at night due to high energy costs, the high energy costs play an important role in selecting the optimum lower limit of indoor temperature, which is 15 °C in the provinces [15,37]. Moreover, temperature differences between 5 and 8 °C during the day and night in greenhouse production do not harm quality and yield [35,44]. Accordingly, the heat-energy required in the greenhouse was calculated with Equation (1).

$$Q = \sum_{n=1}^{8760}\left(\left(\left(\vartheta_{i_n} - \vartheta_{i,oH_n} - \Delta\vartheta_{Sp_n}\right) * k'_a * A_H * (1 - EE_{ES})\right) * t_{Si}\right) \quad (1)$$

where Q is the heat-energy requirement of the greenhouse (Wh), ϑ_{in} is the desired internal temperature in the greenhouse (°C), $\vartheta_{i,oHn}$ 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 total heat transfer coefficient of the cover material (W m^{-2} °C), A_H is the total area of the cover (m^2), EE_{ES} is the heat savings provided by the thermal curtain (-), n is the hours of the year, t_{si} is the period (1 h).

The overall heat transfer coefficient of the cover material was calculated using Equation (2) of Rath [39] as a function of the cover material and wind speed.

$$k'_a = k'_a + \frac{k'_a}{x_1} \times (x_2 \times v_w) + x_3 \tag{2}$$

where v_w is the wind speed (m s^{-1}), x_1 = 7.56 (-), x_2: 0.35 (m s^{-1}), 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 $k'_a \leq 10$ and $EE_{ES} \leq 0.6$ [39].

$$EE_{ES} = \frac{EE_{ES}}{KF_{ES}} * k'_a \tag{3}$$

where the correction factor depending on the impermeability of the thermal screen is taken as 0 W m^{-2} °C^{-1} in the case of no thermal screen, and in the case of the well-insulated and tightly closed thermal screen, is equal to 6.8 W m^{-2} °C^{-1}.

The theoretical temperature value was calculated according to Equation (4) to find the actual temperatures in the greenhouse [39].

$$\vartheta_{ith} = \frac{q_{GS} \times D_G \times \eta \times A_G}{k'_a \times (1 - EE_{ES}) \times A_H} + \vartheta_a \tag{4}$$

where 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 fuel consumption required in greenhouses based on the annual heat energy was calculated with the help of Equation (5), and the CO_2 emissions to the atmosphere of the fuels used in greenhouse heating were calculated with the help of Equation (6) [35].

$$By = \frac{Q}{Hu \times \eta ges} \tag{5}$$

$$SEGMy = By \times Hu \times FSEG \tag{6}$$

where By is the fuel amount for the unit ground area (kg m^{-2}), Hu is the heating value of fuel (kWh kg^{-1}), ηges is combustion efficiency (%), $SEGMy$ is yearly CO_2 emission amount (kg eq. CO_2), $FSEG$ is CO_2 emission equivalence by fuel type (kg eq. CO_2 kWh^{-1}).

The calorific values, average combustion efficiencies, prices, and CO_2 emission conversion coefficients of the fuels to be used in heating the greenhouse are given in Table 6 [45].

Table 6. Values for different fuels used in calculations.

Fuel Types	Heating Value of Fuel (kWh)	Mean Combustion Efficiency %	Price USD (kWh^{-1})	FSEG (CO_2) Conversion Coefficient (kg Eşd. CO_2 kWh^{-1})
Coal	8.14	65	0.043	0.448
Fuel oil	11.12	80	0.095	0.313
Natural gas	9.59	93	0.029	0.239
Geothermal	1	95	0.022	0.100
Biogas	10	85	0.133	0.026

3. Results and Discussion

3.1. Determining the Air Conditioning Needs in Greenhouses Depending on the Climate of the Provinces

One of the most important factors affecting growth in greenhouses is temperature. If the daily average temperature is below 7 °C, heating is required all day; if it is between 7 and 12 °C, heating is only needed at night. If the temperature is between 12 and 22 °C, natural ventilation should be used; if it is between 22 and 27 °C, ventilation/cooling should be used. If the temperature is above 27 °C, greenhouse production should not be done [44,46]. Plants have adapted to average temperatures between 17 and 27 °C in greenhouse cultivation [47]. Long-term average temperature and daily radiation values of the provinces selected in the study are given in Figure 2.

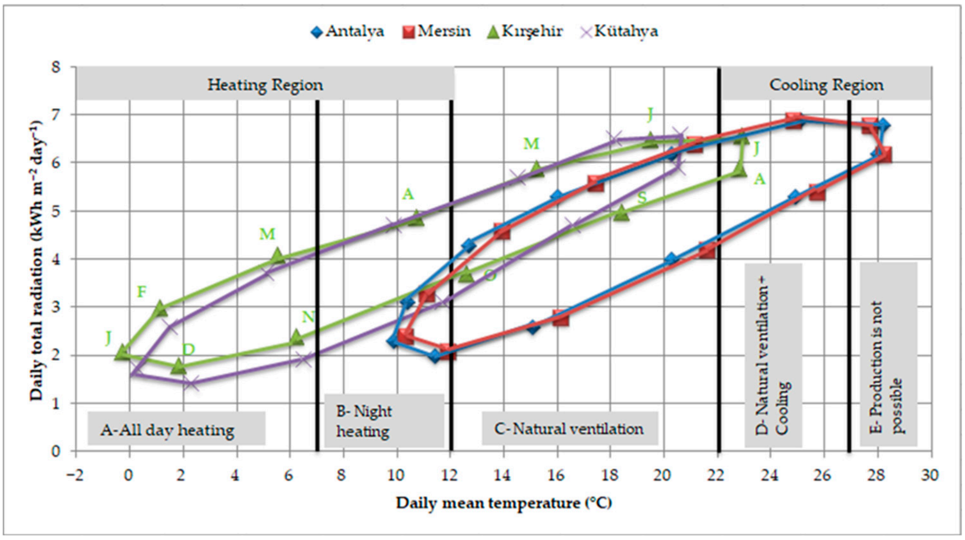

Figure 2. Long-term average temperature and daily radiation values of the provinces.

When Figure 2 is examined, in Antalya and Mersin, which have a Mediterranean climate, the need for heating arises during the night hours for three months due to temperatures below 12 °C. In Kırşehir and Kütahya provinces, which have a continental climate, the need for heating arises during the six months between October and April. Greenhouses in Antalya and Mersin provinces are left empty after June because the temperatures exceed 27 °C. In this case, producers can find the opportunity to produce in greenhouses for 10 months of the year (Figure 2). In Kırşehir and Kütahya provinces, there is the opportunity to produce in greenhouses for 12 months because the temperatures in July and August can be reduced with natural ventilation. This situation, which restricts the production period, is an important factor in decreased yield per unit area in Antalya province. In addition, since vegetable cultivation is carried out in the open between June and September in Türkiye and energy costs for mechanical cooling are high, it is more suitable in terms of production costs to leave greenhouses empty in Antalya and Mersin provinces.

3.2. Comparison of Heat-Energy Requirement Depending on Energy Conservation Measures in Greenhouses

The limited availability of energy resources and the increasing prices of these resources increase the heating costs of greenhouses, and this situation is reflected in the prices of the products grown. In recent years, researchers have accelerated their work on using new and renewable energy resources and the development of systems to reduce heat loss and heating and energy costs in greenhouses [48]. In this study, the required heat energy, depending on the energy conservation measures in greenhouses with different equipment features when the temperature is kept at 15/21 °C during the production period, is given in Figure 3.

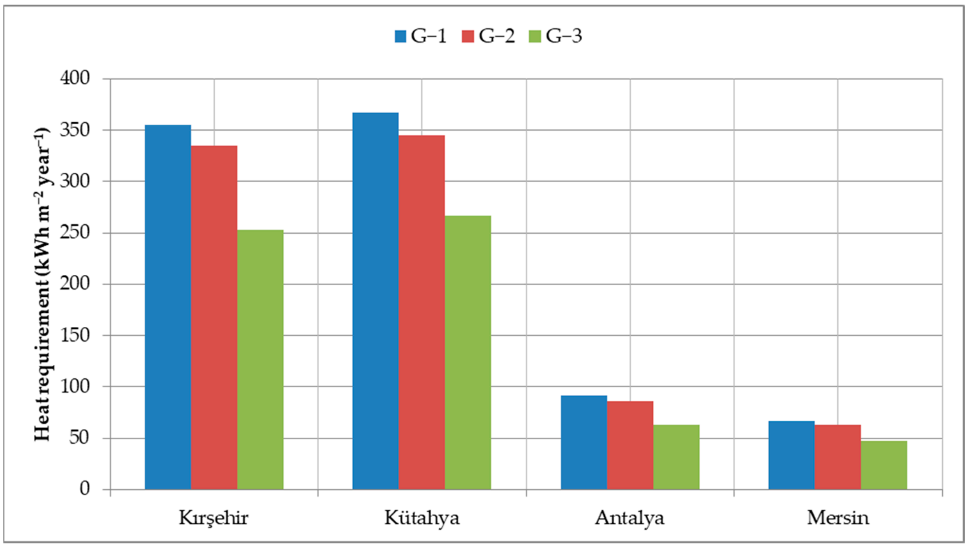

Figure 3. Change in heat-energy requirement for greenhouses.

It is possible to increase the prediction accuracy when thermal models are used. These models take into account three main factors: meteorological conditions of the region (ambient temperature and solar radiation), plant growing requirements (optimum temperature demand varies for different crops), and technical characteristics of the greenhouse (covering material, thermal curtain, etc.) [11,49]. When Figure 3 is examined in the calculations made according to these features in order to increase the accuracy in the heat-energy requirement in the study, the highest heat-energy requirement in the greenhouse covered with PE was calculated as 367.2 kWh m^{-2} year in Kütahya province for the greenhouse covered with S-1. The lowest heat-energy requirement was 47.7 kWh m^{-2} year in Mersin province for the greenhouse covered with S-3 with side walls made of PC and thermal curtain. It is seen that the energy requirement for the same greenhouse features in Kırşehir and Kütahya provinces with continental climates is approximately four times higher than in Antalya and Mersin provinces. Trépanier et al. [50] reported that the calculation of energy consumption is based on 30 years of "Typical Meteorological Year" data, and this approach does not include recent climate variability or extreme weather events that are becoming increasingly important due to climate change. This study's heat-energy requirements are calculated according to long-term hourly climate values because the uncertainties in climate change and variability in the coming years will limit the applicability of the study results. However, using automation systems in greenhouse heating will also save energy by setting the indoor temperatures to the set values [14]. Canakci et al. [40] determined the heat requirement in a PE-covered greenhouse to be 147 kWh m^{-2} year in Antalya province and 99.8 kWh m^{-2} year in Mersin province. Baytorun et al. [35] determined it as 130.4 kWh m^{-2} year in a PE-covered greenhouse in Antalya province, while it was determined as 85.5 kWh m^{-2} year in the case of using double-layer PE and thermal curtain. It was found to be 432.8 kWh m^{-2} year and 307.7 kWh m^{-2} year for Kütahya province. Boyacı et al. [51] determined the heat requirement in a PE-covered greenhouse as 393.3 kWh m^{-2} year for Kırşehir province and 302.4 kWh m^{-2} year for using PE and thermal curtain. When the results obtained were examined in the studies conducted by the researchers for the provinces, they were found to be approximately similar. However, they varied depending on the type and size of the greenhouses. This will increase the accuracy rate in the calculations for feasibility studies. At the same time, as seen in Figure 3, using

PE material (S-1) on side walls requires more energy for the same size greenhouse. The standard method to reduce energy demand in buildings is to decrease heat losses from covering materials. Applying insulation improves the energy efficiency of a building and the quality of the indoor environment [52]. Fabrizio [6] found that the energy demand for greenhouses in Italy can be reduced by 30% using better-insulated transparent materials. In the case of using PC material with a low heat transfer coefficient on side walls and placing thermal curtains in the indoor environment, the energy requirement is lower due to energy conservation measures. When energy requirements are compared, it is higher in Kırşehir and Kütahya provinces with continental climates than in Antalya and Mersin provinces, even if energy conservation measures are taken.

3.3. Determination of Saving Rates Due to Energy Conservation Measures in Greenhouses

Table 7 gives the savings rates that can be achieved with the energy conservation measures in greenhouses in the provinces.

Table 7. Saving rates in greenhouses depending on energy conservation measures.

Provinces	Heat-Energy Requirement (kWh m^{-2} $year^{-1}$)			Saving Rates (%)	
	S-1	S-2	S-3	S-2	S-3
Kırşehir	355.0	334.5	253.2	5.8	28.7
Kütahya	367.2	345.2	266.9	6.0	27.3
Antalya	88.6	83.6	61.0	5.6	31.2
Mersin	66.5	62.8	47.7	5.6	28.3

As seen in Table 7, compared with S-1, the energy saved is approximately 6.0% if PC material is used instead of PE in the side walls (S-2). In the case of using PCs and thermal curtains in greenhouses (S-3), the amount of energy that can be saved will be approximately 29.0%. As seen from Table 7, even if energy conservation measures are taken in Kırşehir and Kütahya provinces, the energy needed cannot compete with Antalya and Mersin due to external climate conditions. Conservation of energy in heated greenhouses is as essential as heating greenhouses. The method is widely used worldwide, including in Türkiye, for preserving heat energy in greenhouses by covering materials with low heat transfer coefficients and thermal curtains [14]. Trépanier et al. [50] stated that regional differences significantly affect energy demand and the applicability of various energy measures. As seen in the study, it was observed that regionally changing climate conditions affect energy requirements. However, the study investigating the effect of decreasing heat transfer coefficients on energy-saving rates observed that the energy values that can be saved with energy-saving measures will give similar results in regions with similar characteristics. Furthermore, Baytorun and Gügercin [14] reported that the measures to reach these rates must be correctly projected and operated. In the studies conducted by the researchers, Kim et al. [53] reported that the energy-saving effect of greenhouses was mainly represented by the decrease in the overall heat transfer coefficient, and a 1 W m^{-2} °C decrease in the coefficient reduced the energy consumed by 70.8 kWh. Baytorun and Gügercin [14] found that if the side walls of the greenhouse are covered with double-layer PE plastic, the amount of heat energy that can be saved is 6% compared to the greenhouse covered with a single layer of plastic. However, the measures to reach these rates must be correctly projected and operated. Boyacı et al. [38] reported that approximately 21% heat-energy saving can be achieved due to decreased heat conduction coefficient when using thermal curtains in the greenhouse. Trépanier et al. [50] found that thermal screens reduce energy consumption by 17.7% to 26.5%. Teitel et al. [54] determined that approximately 40% energy saving can be achieved using aluminum curtains due to lower heating demand at night. The values obtained in the study are consistent with the researchers' savings rates. However, it has been shown that using PC and thermal curtains instead of single-layer PE as a covering material on the side walls of the greenhouse is essential in increasing the amount of energy saved. Its use is essential because it can reduce the share of high heating and production costs by saving energy in greenhouses. In this case, it is crucial to determine the amount of fuel required for energy and its costs.

3.4. Comparison of Fuel Amounts Depending on Energy Conservation Measures in Greenhouses

The fuel used in greenhouses varies according to the external temperature, the internal temperature value desired by the plant in the growing environment, the heat transfer coefficient of the cover material used in the greenhouse, and the equipment features in the greenhouse. In terms of investments to be made before the establishment of greenhouse enterprises, enterprises need to determine the operating expenses accurately. In the study, the amount of fuel required in greenhouses with different equipment features in case the temperature is kept at 15/21 °C is given in Figure 4.

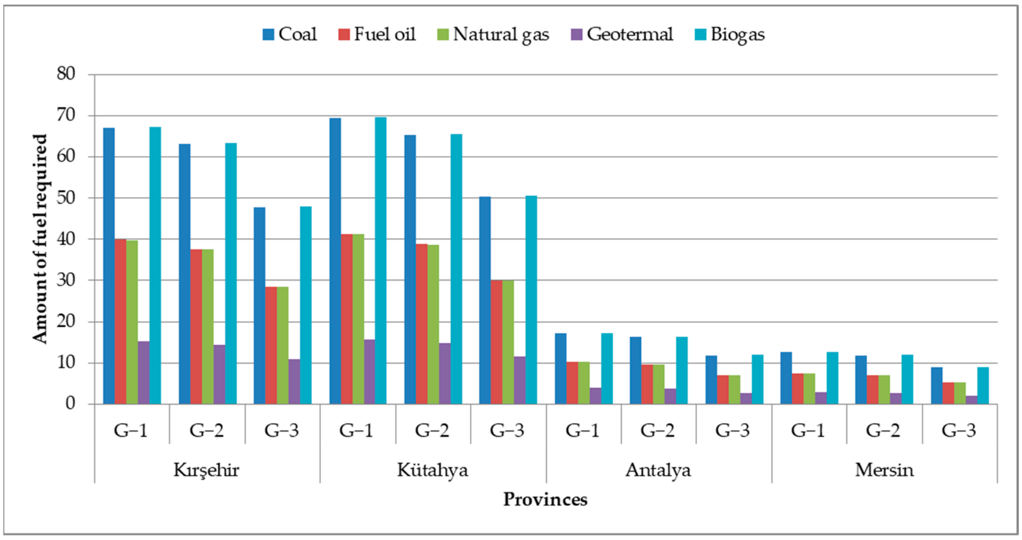

Figure 4. Fuel amount depending on energy conservation measures in greenhouses.

When Figure 4 is examined, it is seen that the fuel amounts to be used in the provinces of Kırşehir and Kütahya, which have a continental climate, are higher than those in the provinces of Antalya and Mersin, which have a Mediterranean climate. Accordingly, the highest fuel amount among the provinces was Kütahya, which had 69.4 kg m^{-2}, while the lowest fuel amount was calculated as 9 kg m^{-2} for Mersin. The fuel used has decreased depending on the climate conditions and increased energy conservation measures. Accordingly, the fuel amount of the greenhouse covered with PE plastic (S-1) decreased by 6% when the side walls were covered with PC cover material (S-2). In the case of using a PC and a well-insulated thermal curtain (S-3), it decreased by approximately 29%. In the studies conducted by researchers on determining the amount of fuel, Boyacı et al. [38] the fuel consumption in the greenhouse heated with natural gas and using thermal curtains was 59.14 m^3 $night^{-1}$. In contrast, the fuel consumption in the greenhouse using thermal curtains was 74.11 m^3 $night^{-1}$. It was also determined that 21% of the fuel savings could be achieved if the thermal curtain were closed at night in the greenhouse. Baytorun et al. [55] found that 15.95 kg m^{-2} of coal was used per unit greenhouse area in a greenhouse heated with coal and using thermal curtains in the Adana province of Türkiye, which has a Mediterranean climate. Baytorun et al. [15] determined the amount of fuel consumed in a greenhouse using a central heating system and compressed natural gas (CNG) as

0.016 m^3 m^{-2} day^{-1} in December, 0.064 m^3 m^{-2} day^{-1} in January, 0.059 m^3 m^{-2} day^{-1} in February and 0.047 m^3 m^{-2} day^{-1} in March. Üstün [56] and Önder [57] determined that in the case of a greenhouse temperature of 16 °C in the provinces of Adana and Hatay with a Mediterranean climate, approximately 10 L m^{-2} of fuel oil is consumed. When the results obtained in the study are examined, it is found that the calorific value of different fuels in greenhouses varies depending on the combustion efficiency and energy conservation measures taken in the greenhouse. Therefore, determining the cost of the consumed fuel is as important as the consumption of the fuel in terms of operating expenses.

3.5. Comparison of Fuel Costs Depending on Energy Conservation Measures in Greenhouses

Increasing energy efficiency in greenhouses can achieve sustainability. This is possible using renewable energy sources that do not produce waste instead of fossil energy sources [38]. The study gives the fuel costs in greenhouses with different equipment features if the temperature is kept at 15/21 °C in Figure 5.

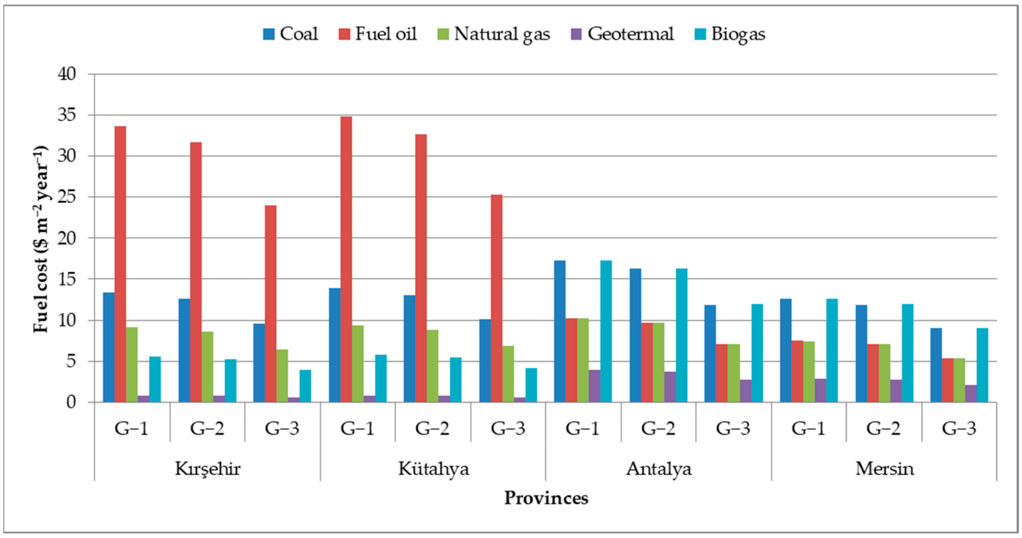

Figure 5. Fuel costs depending on energy conservation measures in greenhouses.

When the fuel costs of the provinces are compared in Figure 5, the decrease in fuel due to energy conservation measures contributed to the decrease in fuel costs. Among fossil fuels, the costliest fuel is fuel oil. Furthermore, the most suitable fuel is natural gas. However, since its use in agriculture is not widespread, cost comparisons were made with coal, widely used in greenhouses. In the study, if coal is used for greenhouse heating, fuel cost in greenhouse S-1 will be 19.2 USD m^{-2} $year^{-1}$ in Kırşehir, 19.8 USD m^{-2} $year^{-1}$ in Kütahya, 4.9 USD m^{-2} $year^{-1}$ USD kg^{-1} in Antalya and 3.6 USD m^{-2} $year^{-1}$ in Mersin. These values will decrease by approximately 6% for greenhouse S-2 to 18.1 USD m^{-2} $year^{-1}$, 18.6 USD m^{-2} $year^{-1}$, 4.6 USD m^{-2} $year^{-1}$ USD kg^{-1} and 3.4 USD m^{-2} $year^{-1}$, respectively. The S-3 greenhouse will decrease by approximately 29% to 13.7 USD m^{-2} $year^{-1}$, 14.4 USD m^{-2} $year^{-1}$, 3.4 USD m^{-2} $year^{-1,}$ and 2.6 USD m^{-2} $year^{-1}$, respectively. Increasing energy-saving measures in greenhouses has reduced fuel costs. However, for the same greenhouse characteristics and fuel type, the fuel cost in Kırşehir and Kütahya provinces will be approximately 4 times higher than in Antalya and Mersin. As can be seen from the calculations, the production in Kırşehir and Kütahya provinces cannot compete with the fuel cost in Antalya and Mersin provinces if fossil fuels (coal, fuel oil, and natural gas) are used to heat greenhouses. In Türkiye, natural gas is preferred for heating due to the high unit price of coal and fuel oil. As can be seen from Figure 5, natural gas is the cheapest fuel per unit area among fossil fuels. However, due to the lack of natural gas infrastructure in agricultural areas, its use in greenhouses is limited. In this case, cheap and renewable energy sources are needed in these regions for greenhouses in Kırşehir and Kütahya provinces to compete with Antalya and Mersin provinces. As a result of using geothermal resources for heating, the fuel cost will be between 2.9 and 4.2 USD m^{-2} $year^{-1}$ for Kırşehir and Kütahya provinces. Fuel costs range from 33.7 to 48.8 USD m^{-2} $year^{-1}$ for heating with biogas. In Türkiye, the state provides incentives for producing biogas, a renewable energy source. For this reason, its price has become higher than geothermal energy. Accordingly, geothermal heating in the continental climate provinces of Kırşehir and Kütahya will be more profitable than in the provinces of Antalya and Mersin. In this case, the amount of product obtained should also be considered in the evaluations to compare the fuel consumption and costs of the enterprises in greenhouses.

3.6. Comparison of Heating Costs for Tomato Yield per Unit Area Depending on the Fuel Used in Greenhouses

Determining the heating costs for the tomato yield to be obtained from the unit area depending on the fuel consumed and costs per unit area in greenhouses will play an important role in the feasibility studies of the enterprises. In the study, the heating costs per unit tomato yield depend on the fuel used in the greenhouses. If the temperature in the greenhouses is kept at 15/21 °C, they are given in Figure 6.

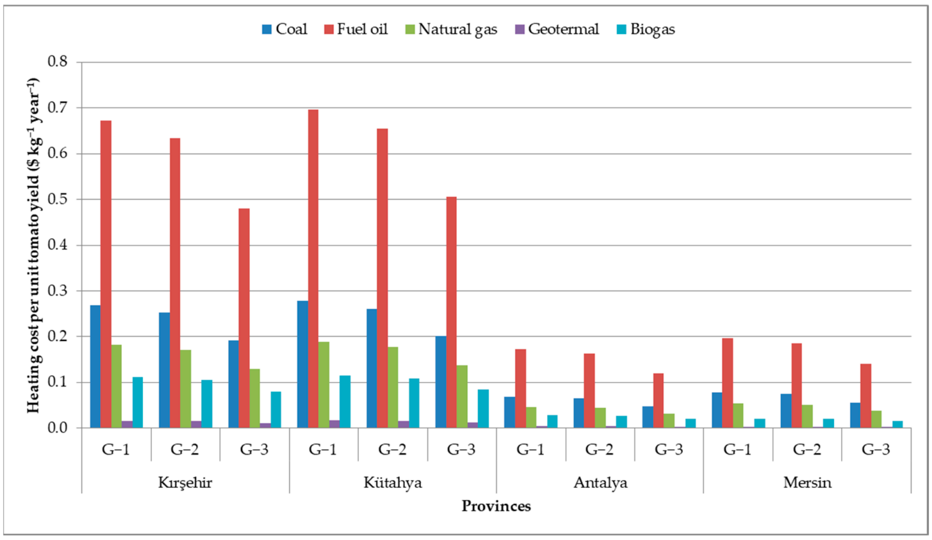

Figure 6. Heating costs per unit tomato yield depending on fuel used in greenhouses.

Looking at Figure 6, if coal is used for greenhouse heating, the heating cost for the production of one kilogram of tomatoes in greenhouse S-1 will be 0.38 USD kg^{-1} in Kırşehir, 0.40 USD kg^{-1} in Kütahya, 0.10 USD kg^{-1} in Antalya and 0.11 USD kg^{-1} in Mersin. These values will decrease by approximately 6% for greenhouse S-2 to 0.36 USD kg^{-1}, 0.37 USD kg^{-1}, 0.09 USD kg^{-1}, and 0.11 USD kg^{-1}, respectively. The S-3 greenhouse will decrease by approximately 29% to 0.27 USD kg^{-1}, 0.29 USD kg^{-1}, 0.07 USD kg^{-1}, and 0.08 USD kg^{-1}, respectively. Increasing energy-saving measures in greenhouses has reduced heating costs. However, for the same greenhouse characteristics and fuel type, the heating cost for 1 kg of tomatoes in Kırşehir and Kütahya provinces will be approximately 4 times higher than in Antalya and Mersin. As can be seen from the calculations, the production in Kırşehir and Kütahya provinces cannot compete with the production in Antalya and Mersin provinces if fossil fuels (coal, fuel oil, and natural gas) are used to heat greenhouses. Competition between these provinces is only possible if the same energy costs are provided for producing one kilogram of tomatoes.

As a result of using geothermal resources for heating, the heating cost for producing one kilogram of tomatoes will be 0.06–0.08 \$USD kg^{-1} for Kırşehir and Kütahya provinces. In the case of heating with biogas in these provinces, it will be between 0.71–0.0.98 USD kg^{-1}. Accordingly, Kırşehir and Kütahya provinces will have advantages in terms of the length of the production period and heating costs in case of using their geothermal resources for greenhouse heating. Boyacı et al. [38] reported that the heating cost of 1 kg of tomatoes in a greenhouse heated with natural gas and without a thermal curtain is 0.11 USD more than in a greenhouse with a thermal curtain. Increasing energy costs cause producers to discuss the profitability of heating [14]. In previous research, it has been reported that heating costs constitute 20–60% of total production costs depending on external climate conditions [10,11,14]. When the results obtained in the study are examined, it is seen that the heating costs per unit area have decreased with increasing energy conservation measures. In this case, using geothermal energy sources instead of fossil fuels in Kırşehir and Kütahya provinces and increasing energy conservation measures in greenhouses will contribute to reducing the share of heating in production costs. In addition, there will be a chance to compete in greenhouse cultivation with provinces such as Antalya and Mersin in terms of cost. It will also increase greenhouse activities and employment in regions with continental climates. According to the results obtained, energy conservation measures should be increased to compete with greenhouses in Mediterranean climates in cultivation in climates with continental climates. Covering the costs required for heat conservation measures with government incentives will also ensure that producers are more interested in energy conservation measures.

3.7. Comparison of CO_2 Emissions Released into the Atmosphere Due to Fuel Used in Heating Greenhouses

The biggest problem caused by fossil energy sources used in greenhouse heating is the CO_2 emission they give to the atmosphere. CO_2 increases the greenhouse effect, which causes global warming. In addition, the continuous use of fossil fuels contributes to severe environmental pollution and the formation of an abnormal climate [58]. In the study, the CO_2 emissions due to the fuel used in greenhouses with different equipment features in case the temperature is kept at 15/21 °C is given in Figure 7.

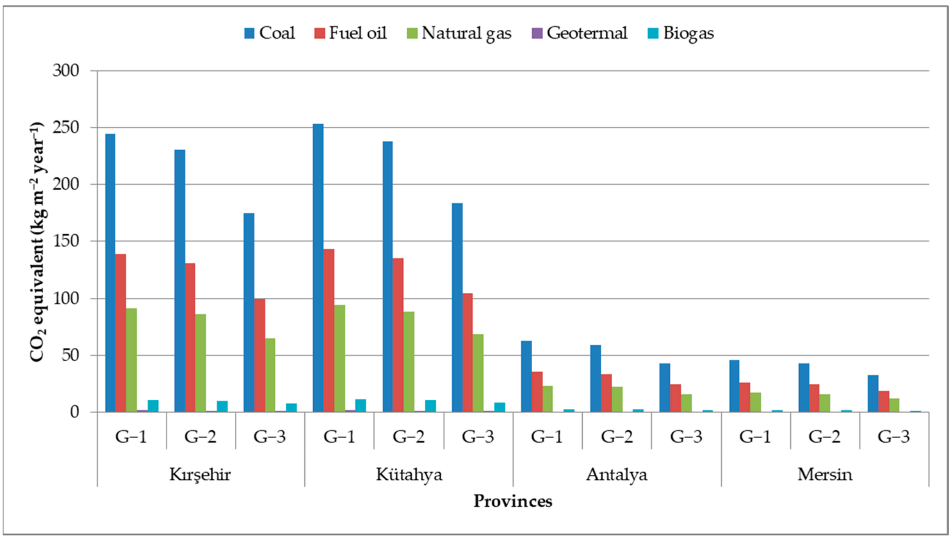

Figure 7. CO_2 emissions depending on fuel type in greenhouses.

Looking at Figure 7, in the case of using coal for greenhouse heating, the amount of carbon dioxide to be released into the atmosphere from S-1 greenhouse will be

244.7 kg m^{-2} year^{-1} in Kırşehir, 253.1 kg m^{-2} year^{-1} in Kütahya, 62.9 kg m^{-2} year^{-1} in Antalya and 45.9 kg m^{-2} year^{-1} in Mersin. Accordingly, when comparing the S-1 greenhouse, if coal is used, there will be approximately 4 times more CO_2 emissions in the provinces of Kırşehir and Kütahya than in Antalya and Mersin. As a result of using geothermal resources for heating, the CO_2 release per unit area will be 1.5 kg m^{-2} year^{-1} in Kırşehir and 1.6 kg m^{-2} year^{-1} in Kütahya for greenhouse S-1. In the case of heating with biogas, it will be 6.7 kg m^{-2} year^{-1} in Kırşehir and 7.0 kg m^{-2} year^{-1} in Kütahya province. The amount of CO_2 released into the atmosphere by coal used in greenhouses will be 160 and 36 times more than geothermal and biogas. No geothermal resource has been used for greenhouse heating in the Antalya and Mersin provinces yet. However, it is seen that the amount of CO_2 released into the atmosphere can be reduced significantly with the biogas facilities established in these provinces (Figure 7). Evans et al. [59] reported in their study, where renewable energy technologies were evaluated based on critical sustainability indicators, that wind energy was the most sustainable, followed by hydroelectric, photovoltaic, and then geothermal. Holm et al. [60] reported that the carbon dioxide released from coal, natural gas, and geothermal sources is approximately 1012–510–81 g kWh^{-1}, respectively. Accordingly, they stated that the CO_2 emissions released from geothermal power plants are lower than those from coal and natural gas. Ertop et al. [32] found that in addition to the economic advantages of biogas, as an environmental gain, 5,543,857 tons of year^{-1} CO_2 emissions could be prevented in Türkiye and 3,004,552 tons of year^{-1} CO_2 emissions in Poland. When the results obtained in the study are examined, increasing energy conservation measures have reduced the amount of fuel in regions with Continental and Mediterranean climates and reduced the amount of CO_2 released into the atmosphere. These results will be similar in all greenhouses where energy conservation measures are taken.

Giuliano et al. [61] reported that one of the goals of sustainable greenhouse systems should be a system that is environmentally friendly and does not produce as much waste as possible. Mitigating climate change requires reducing greenhouse gas emissions into the atmosphere and increasing renewable energies instead of fossil fuels. Agricultural greenhouses are energy-intensive farming systems that use fossil fuels predominantly. The use of renewable energies during their operation has so far been limited [62]. In Kırşehir and Kütahya provinces, biogas facilities' number and installed capacity have been increasing in recent years due to the high potential for animal husbandry and geothermal resources. In this respect, Kırşehir and Kütahya provinces have a significant advantage in renewable energy resources. The use of fossil energy resources in greenhouse heating negatively affects the profitability of production. Moreover, the CO_2 emission given to the atmosphere by fossil energy resources increases the carbon footprint. If geothermal and biogas energy are used in greenhouse heating, the CO_2 emission to the atmosphere will be quite low compared to fossil fuels. Therefore, in this study, Kırşehir and Kütahya provinces will be more advantageous in sustainable, clean environment and production than Antalya and Mersin provinces. In addition, it is crucial to provide government incentives to increase the technical measures to reduce the heat transfer coefficient in greenhouses in regions where these opportunities are not available. The high cost of installing geothermal and biogas facilities prevents small and medium-sized enterprises from benefiting from these energy sources. However, establishing organized greenhouse zones in geothermal regions in Türkiye in recent years will increase the chance of competition with greenhouses established in regions with Mediterranean climates, especially in regions with continental climates. Greenhouses are one of the most energy-intensive sectors in agriculture. Today, increasing and continuing energy costs in greenhouse production are restricted. However, the energy conservation measures to be taken in greenhouses will help to reduce the share of heating in production costs. At the same time, increasing energy conservation measures have become more important, especially in regions with cold climates. However, to achieve the savings that can be achieved, developing greenhouse technologies for sustainable greenhouse systems is necessary. This will be as important around the world as it is in Türkiye.

4. Conclusions

In the study where the amount of CO_2 released into the atmosphere depending on the energy requirement, cost, and fuel used for heating in greenhouses located in the provinces of Türkiye with different climate characteristics (Mediterranean and Continental) was investigated,

- While the heating need will arise for approximately six months in Kırşehir and Kütahya provinces, the heating period will be approximately three months in Antalya and Mersin provinces.
- With the use of geothermal resources in greenhouse farming, it is possible to produce all year round in Kırşehir and Kütahya provinces, while in Antalya and Mersin provinces, this period is 10 months due to the high temperatures that occur in June–September. This situation, which restricts the production period, is an essential factor in the decrease in yield obtained from the unit area in Antalya and Mersin provinces. This situation reveals that geothermal heated cultivation to be carried out in greenhouses all year round in Kırşehir and Kütahya provinces is more advantageous than greenhouses in Antalya and Mersin provinces.
- While the energy requirement in S-1, S-2, and S-3 greenhouses in Antalya and Mersin provinces varies between 47.7 and 91.2 kWh m^{-2} $year^{-1}$, this value varies between 253.2 and 355.0 kWh m^{-2} $year^{-1}$ in Kırşehir and Kütahya provinces. In this case, 4 times more energy requirements will occur in Kırşehir and Kütahya provinces.
- If PC material is used instead of PE on greenhouse side walls, the amount of energy that can be saved will be approximately 6%. If thermal curtains are used, the amount of energy that can be saved will be approximately 29.0%.
- In Antalya and Mersin provinces, the fuel cost for imported coal in S-1, S-2, and S-3 greenhouses varies between 2.6 and 4.9 USD m^{-2} $year^{-1}$. In Kırşehir and Kütahya provinces, it is between 13.7 and 19.8 USD m^{-2} $year^{-1}$. In the case of using geothermal energy sources in Kırşehir and Kütahya provinces, it will be 3.0–4.1 USD m^{-2} $year^{-1}$. The competition between provinces will only be possible if the same energy cost is provided for producing one kilogram of tomatoes.
- In the case of coal used in S-1, S-2, and S-3 greenhouses in Antalya and Mersin provinces, the heating cost for producing one kilogram of tomatoes varies between 0.07 and 0.10 US kg^{-1}. Kırşehir and Kütahya provinces vary between 0.27 and 0.40 USD kg^{-1}. Accordingly, in the case of using coal, fuel oil, and natural gas in greenhouse heating in Kırşehir and Kütahya provinces, the production to be made will not be competitive with the production to be made in Antalya and Mersin provinces.
- In Kırşehir and Kütahya provinces, the heating cost for producing one kilogram of tomatoes will be between 0.06 and 0.08 USD kg−1 due to the use of geothermal resources for heating. In the case of biogas, it varies between 0.71 and 0.94 USD kg^{-1}. Accordingly, if geothermal energy is used, there will be a chance of competing with provinces such as Antalya and Mersin in greenhouse cultivation.
- In the case of coal used in S-1, S-2, and S-3 greenhouses in Antalya and Mersin provinces, the CO_2 released into the atmosphere is 32.9–62.9 kg m^{-2} $year^{-1}$. In Kışehir and Kütahya provinces, it is between 174.5 and 244.7 kg m^{-2} $year^{-1}$. In Kırşehir and Kütahya provinces, if geothermal resources are used for heating, it is

between 1.1 and 1.6 USD kg m^{-2} year^{-1}, and in the case of using biogas, it is between 5.1 and 7.0 kg m^{-2} year^{-1}. Among the fuels, the highest CO_2 will be in the case of using coal, and the lowest will be in the case of geothermal energy.

It is essential to use energy conservation methods to reduce heating costs, which have a large share in production costs in greenhouses. However, even if heat conservation measures are taken in greenhouses to be established in Kırşehir and Kütahya provinces, they cannot compete with Antalya and Mersin provinces, where greenhouse farming is intensively carried out. Therefore, using geothermal energy sources, which are cheap and renewable in the provinces and suitable for greenhouse enterprises, will increase the province's competitiveness in greenhouse farming. In addition, another advantage of geothermal energy enterprises in these provinces is that by reducing the consumption of fossil fuels used for heating greenhouses, CO_2 gas emissions, which are one of the most important gases that cause the greenhouse effect in the atmosphere and contribute to the protection of the environment.

The results obtained due to reducing heat requirement with energy conservation measures will apply to different climate zones. However, the savings rates that can be achieved will be possible with the correct projecting of the technical measures to be taken. In addition, establishing greenhouse systems suitable for developing greenhouse technologies and controlling the internal environment with computer systems are important in terms of savings. New studies are needed on a regional scale to determine the effects of the savings rates obtained from these systems on recycling periods and profitability. At the same time, the measures to be taken in greenhouses will contribute to the sustainable development goals of the United Nations (UN) (Affordable and Clean Energy and Good Health and Well-Being). In addition, providing state incentives to contribute to these goals will contribute to developing sustainable and environmentally friendly greenhouse technologies and reduce energy costs in enterprises.

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