International Journal of Science and Research Archive

eISSN: 2582-8185

Cross Ref DOI: 10.30574/ijsra

Journal homepage: https://ijsra.net/

(Research Article)

Modeling of solar and heat pump energy supply systems for autonomous greenhouses

Alisher Safarov * and Obid Rakhmatov

Department of Alternative Energy Sources, Faculty of Energy, Karshi State Technical University, 180019, Khonobod st., 19, Karshi, Uzbekistan.

International Journal of Science and Research Archive, 2025, 15(02), 559-567

Publication history: Received on 03 April 2025; revised on 10 May 2025; accepted on 12 May 2025

Article DOI: https://doi.org/10.30574/ijsra.2025.15.2.1411

Abstract

The article presents the results of determining the heat load of a even-span greenhouse with a usable area of 50 m² in variable climatic conditions, modeling the heating system of an autonomous greenhouse based on solar and heat pump devices. The modeling was performed taking into account the ambient temperature, solar radiation and heat losses in the greenhouse for the period from November 15, 2023 to March 15, 2024. According to the results, it was studied that the greenhouse consumed 14720 kWh of heat energy during this season. Of this, 11135 kWh of heat energy was provided by a heat pump, 2225 kWh by a solar thermal collector, 100 kWh by a heat boiler, and the rest by solar radiation.

Keywords: Even-Span Greenhouse; Solar Heating Collector; Heat Pump; Solar Radiation; Heat Load; Modeling

1. Introduction

In the world, great importance is attached to the use of renewable energy sources to improve the energy efficiency of greenhouses, save natural fuel resources and stabilize environmental problems. In particular, an action strategy has been developed to develop new greenhouse designs based on the climatic conditions of the region, determine the optimal size and orientation of greenhouses depending on external factors, increase the possibilities of using renewable energy sources instead of traditional energy sources and minimize environmental pollution. The global market for smart greenhouses, valued at US$1.7 billion in 2022, is expected to reach US$3.6 billion by 2030, and the annual growth rate (Compound Annual Growth Rate, CAGR) is expected to increase by 9.5% during the analysis period 2022-2030. One of the segments analyzed in the report, hardware, is expected to register a CAGR of 9% and reach US$2.9 billion by the end of the analysis period. The software and services segment is expected to grow at a CAGR of 12% over the next 8 years. The smart greenhouse market in the US was valued at $403.6 million in 2022, while China, the world's second largest economy, is expected to grow to $363 million by 2030. Other notable geographic markets include Japan and Canada, each expected to grow by 8.4% and 9.7%, respectively, between 2022 and 2030, and Germany at around 9.3% [1].

The State of Qatar has adopted trends for the development of energy-efficient smart greenhouses in 2024-2025. Growing crops in greenhouses located in Qatar requires a large amount of energy and water resources. In countries with a climate similar to Qatar, a large part of this energy is required for cooling and ventilation, and agriculture is the first major consumer of water, using 92% of groundwater. Due to the large share of natural fuel sources in the energy supply of greenhouses in Qatar, there are environmental problems in these regions. In Qatar, trends for the development of greenhouses have been adopted to increase food security, stabilize environmental problems and achieve energy efficiency, including: developing innovative greenhouse designs adapted to the Qatari climate, which is characterized by high temperatures, humidity and solar radiation; developing innovative cooling systems that allow year-round crop production, especially in the summer months, for example, requiring less water than evaporative cooling systems;

* Corresponding author: Alisher Safarov

developing advanced technological solutions such as the Internet of Things (IoT), measurement and communication infrastructure, artificial intelligence, advanced monitoring and control methods, and smart greenhouses to optimize resource use, maximize agricultural productivity, and mitigate climate change impacts; using solar, wind, geothermal, and other alternative energy sources to meet irrigation, cooling, and desalination needs, while reducing carbon emissions associated with fossil fuel use [2]. A program has been developed to reduce energy costs by up to 40% through the efficient use of solar energy in greenhouses located in East African countries. In this program, solar energy is used to meet the energy needs of the greenhouse, in particular, solar panels are installed to generate electricity, and solar thermal collectors generate heat. Some sections of the greenhouse are also illuminated with artificial lighting. Part of the energy generated by the solar panels is directly supplied to the water pumps and electrical appliances in the greenhouse. Excess energy is stored in batteries. Solar collectors are installed for heating three greenhouses with a total area of 4,000 m^2. As a result, a greenhouse energy supply system has been established that is independent of centralized energy supply; energy costs have been reduced by 40%; it has become possible to increase the volume and quality of production; technical maintenance has been facilitated; problems such as power outages and poor-quality power supply have been eliminated; environmental problems around the greenhouses have been stabilized [3]. Growing plants in solar greenhouses in the Italian regions today plays a leading role in modern agriculture, both in terms of the value of the product produced and in terms of the development of highly innovative technologies and production techniques. Intensive research in the field of energy production from renewable energy sources is leading to the development of greenhouses partially covered with solar elements. This study presents the potential of an innovative solar greenhouse with variable shading to optimize energy production through solar panels [4]. A study by Pakistani scientists presents results on improving the quality of products grown in smart greenhouses, achieving energy efficiency and automation by using Internet of Things (IoT) technologies in solar greenhouses. Currently, devices based on IoT technology are widely used in monitoring and control systems in several sectors. IoT-based technologies consist of various types of actuators, sensors, drones, cloud computing, analytical systems and navigation, which work effectively to increase productivity with less human intervention. Using this system, it is possible to control the irrigation of plants grown in the greenhouse, as well as greenhouse temperature, humidity, cooling, and lighting in real time [5].

Despite the positive results achieved, there has been insufficient scientific research on determining the maximum total solar radiation depending on the trajectory of the sun, the optimal structural dimensions and orientation of greenhouses, and the development and study of an autonomous energy supply system with a heat pump for greenhouses in sharply changing continental climate conditions. Therefore, the development and improvement of the efficiency of an energy-efficient autonomous energy supply system for greenhouses based on solar and heat pump devices is an urgent scientific and technical task.

The purpose of the study is to substantiate the development and efficiency of an autonomous energy supply system for greenhouses with a even-span structure based on solar and heat pump devices in changing climate conditions.

2. Material and methods

The object of study is an autonomous greenhouse with a useful area of 50 m^2, located at the alternative energy sources polygon under the Karshi Institute of Engineering and Economics. Tomatoes and cucumbers are grown in the autonomous greenhouse, which require a temperature in the range of 15-22 ^oC during the growing season. The growth period of such crops is several months. However, due to the problem of maintaining the set temperature, the most critical period for heating the greenhouse is the four-month period from mid-November to mid-March. Therefore, the study of the operation of the heating and electrical system is carried out at an estimated air temperature inside the greenhouse of 15 ^oC in the evening and 22 ^oC in the daytime, and it covers the above-mentioned months.

The walls of the autonomous greenhouse are made of 4 mm thick glass sheets, separated from each other by a 1 cm thick air layer, the roof part is made of 1 cm thick glass sheets, and the base foundation is made of 30 cm thick concrete blocks. For natural ventilation, the greenhouse ceiling has windows with a size of 0.8x10 m that can be opened and closed. Figure 1 shows the geometric dimensions of a greenhouse with a double-slope structure.

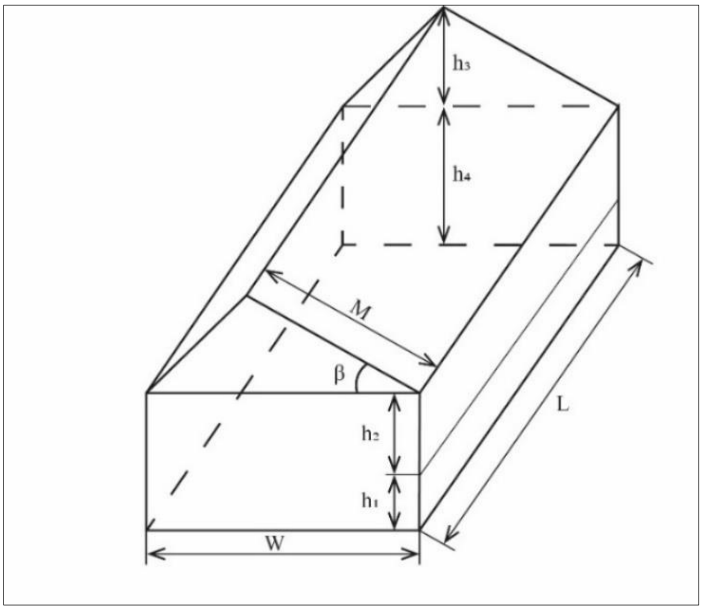


Figure 1 Scheme of geometric dimensions of the greenhouse

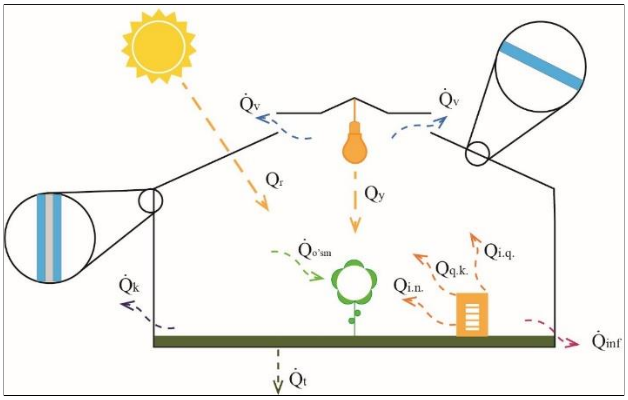
The dimensions and parameters of the greenhouse are presented in Table 1. It lists the greenhouse covering material, the greenhouse structural dimensions, and the internal and external characteristic parameters.

Table 1 Greenhouse dimensions and parameters

Greenhouse structural parameters	Designation and unity	Amount
Greenhouse dimensions	L, [m]	10
	W, [m]	5
	h_1, [m]	0.7
	h_2, [m]	2
	h_3, [m]	1.5
	h_4, [m]	2.7
	M, [m]	3
	β, [angel.]	50
	F_d, [m^2]	60
	F_a, [m^2]	21
	F_{sh}, [m^2]	60
	V, [m^3]	172.5
Concrete layer (base)	δ_1, [m]	0.3
	λ_1, [W/m·°C]	1.5
Glass layer (wall)	δ_2, [m]	0.004
	λ_2, [W/m·°C]	0.76
Air layer	δ_3, [m]	0.01
	λ_3, [W/m·°C]	0.022
Glass layer (ceiling)	δ_4, [m]	0.01

	λ_4, [W/m·°C]	0.76
Cropland (soil)	A_t, [m^2]	50
	λ_t, [W/m·°C]	0.73

The internal air temperature of an autonomous greenhouse varies depending on several external and internal factors. These factors depend on the amount of solar radiation penetrating the walls and ceiling of the greenhouse, the heat source operating on natural fuel and electricity, lighting, the amount of natural ventilation and air infiltration, the amount of constructive heat loss, the amount of heat lost through the soil, and the amount of heat consumed by plants. All of the above values were taken into account when compiling the heat balance of an autonomous greenhouse in Figure 2.



Q_r - heat amount of solar radiation; Q_{in} - heat amount of heat pump; Q_y - heat amount of lighting lamps; Q_{qk} - solar thermal collector; Q_{iq}- heat boiler; Q_v - heat amount lost through natural ventilation; Q_{inf} - heat amount lost through air infiltration; Q_{sh} - heat amount lost through the greenhouse ceiling; Q_d - heat amount lost through the greenhouse walls; Q_a - heat amount lost through the greenhouse base Q_t - heat amount lost through the soil; $Q_{o'sm}$ - heat amount lost through plants

Figure 2 Calculation scheme of the heat balance of an autonomous greenhouse

The mathematical model of the heat balance of the autonomous greenhouse under study is expressed by the following equations:

$$Q_r + Q_{i.n} + Q_{q.k} + Q_{i.q} = \dot{Q}_v + \dot{Q}_{inf} + \dot{Q}_k + \dot{Q}_t + \dot{Q}_{o'sm} \quad \text{........} \quad (1)$$

We determine the amount of heat absorbed by a vacuum solar water heater collector using the following formula:

$$Q_{q.k} = \sum I \cdot \alpha_{yut} \cdot S \cdot N \cdot \tau \quad \text{..........} \quad (2)$$

where: $\sum I$ - total solar radiation; α_{yut} - light absorption coefficient of glass; S - light absorption surface of one vacuum tube; N- number of vacuum tubes in one solar water heating collector; τ- heating time.

The mathematical expression that allows obtaining thermal energy in a solar water heating collector is as follows:

$$Q_{ak.b} = \rho \cdot V \cdot (t_1 - t_2) \quad \text{............} \quad (3)$$

where: ρ- water density; V- water volume of the solar collector; t_1 - average temperature of the solar thermal collector; t_2 - ambient temperature.

The constructive limit of a greenhouse is the amount of heat lost through the greenhouse ceiling, walls and base as follows:

$$\dot{Q}_k = \dot{Q}_d + \dot{Q}_{sh} + \dot{Q}_a \quad \text{...............} \quad (4)$$

The amount of heat lost through the side walls of a greenhouse depends on the thermal conductivity coefficient, the surface area of the side walls, and the difference between the internal and external temperatures, and is determined by the mathematical expression below [6]:

$$\dot{Q}_d = k_d \cdot \sum F_d \cdot (t_1 - t_2) \quad \text{.....................} \quad (5)$$

$$k_d = \left(\frac{1}{\alpha_1} + 2 \cdot \frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \frac{1}{\alpha_2}\right)^{-1} \quad \text{.....................} \quad (6)$$

$$\sum F_d = 2 \cdot h_2 \cdot L + 2 \cdot h_4 \cdot W + h_3 \cdot W \quad \text{.....................} \quad (7)$$

where: k_d - heat transfer coefficient of the wall; F_d - total surface area of the greenhouse walls; t_1 -internal temperature of the greenhouse; t_2- ambient temperature; α_1 and α_2 heat transfer coefficients.

We can determine the amount of heat lost through the greenhouse base using the following mathematical expression:

$$\dot{Q}_a = k_a \cdot \sum F_a \cdot (t_1 - t_2) \quad \text{.....................} \quad (8)$$

$$k_a = \left(\frac{1}{\alpha_1} + \frac{\delta_3}{\lambda_3} + \frac{1}{\alpha_2}\right)^{-1} \quad \text{.....................} \quad (9)$$

$$\sum F_a = 2 \cdot h_1 \cdot L \quad \text{.....................} \quad (10)$$

where: k_a - heat transfer coefficient of the greenhouse base; F_d - total surface area of the greenhouse base.

We determine the amount of heat lost through the greenhouse ceiling using the following mathematical expression:

$$\dot{Q}_{sh} = k_{sh} \cdot \sum F_{sh} \cdot (t_1 - t_2) \quad \text{.....................} \quad (11)$$

$$k_{sh} = \left(\frac{1}{\alpha_1} + \frac{\delta_4}{\lambda_4} + \frac{1}{\alpha_2}\right)^{-1} \quad \text{.....................} \quad (12)$$

$$\sum F_{sh} = 2 \cdot M \cdot L \quad \text{.....................} \quad (13)$$

where: k_{sh} - heat transfer coefficient of the greenhouse ceiling; F_{sh} - total surface area of the greenhouse ceiling.

The expression for determining the convective heat transfer coefficient from the inner surfaces of the greenhouse is as follows (for turbulent flows) [7]:

$$\alpha_1 = 0{,}1 \cdot \frac{\lambda_h}{L_p} \cdot (Gr \cdot Pr)^{0{,}33} \qquad 10^9 \leq Gr \cdot Pr \leq 10^{13} \quad \text{.....................} \quad (14)$$

where: L_p - the perimeter length of the selected side, [m]; λ_h - the thermal conductivity coefficient of air.

Grasgofa kriteriyasi [8]:

$$Gr = \frac{g \cdot \beta_h \cdot (T_1 - T_c) \cdot L_p^3}{(\frac{\mu_h}{\rho_h})^2} \quad \text{.....................} \quad (15)$$

Prandil criterion:

$$Pr = \frac{\mu_h \cdot C_h}{\lambda_h} \quad \text{.....................} \quad (16)$$

Kinematic viscosity is equal to the ratio of dynamic viscosity to air flow density and is determined by the formula below:

$$v_{in} = \frac{\mu_h}{\rho_h} \quad \text{.....................} \quad (16)$$

Greenhouse construction coating temperature [9]:

$$T_c = \frac{T_1 + 2 \cdot T_2}{3} \quad \text{………….. (17)}$$

Airflow volumetric expansion coefficient [10]:

$$\beta_h = \frac{2}{T_1 + T_c} \quad \text{………… (18)}$$

The convective heat transfer coefficient between the outside air and the greenhouse cover can be calculated for turbulent flows using the following equation [11]:

$$\alpha_2 = 0{,}037 \cdot \frac{\lambda_h}{L_p} \cdot (Re)^{0,8} \cdot Pr^{0,33} \qquad Re \geq 5 \cdot 10^5 \quad \text{…………… (19)}$$

Reynolds criterion:

$$Re = \frac{\rho_h \cdot v_{sh} \cdot L_p}{\mu_h} \quad \text{…………… (20)}$$

Infiltration reduction in greenhouses refers to the amount of air entering or leaving the greenhouse, which affects the heating load and energy efficiency. Reducing infiltration flow can save an average of 3 to 10% on greenhouse heating costs. The amount of heat lost through infiltration is determined by the following mathematical expression [12]:

$$\dot{Q}_{inf} = \rho_h \cdot C_h \cdot N \cdot V \cdot (T_1 - T_2) \quad \text{………………….. (21)}$$

The amount of heat lost through ventilation through windows installed in the greenhouse ceiling is determined by the following relationship [13].

$$\dot{Q}_V = \rho_h \cdot C_h \cdot V_v \cdot (t_1 - t_2) \quad \text{………………….. (22)}$$

The amount of heat lost through heat exchange with the soil and plants of the greenhouse crop area is determined by the mathematical expression below [14]:

$$\dot{Q}_{tup} = \frac{\lambda_{tup}}{H_t} \cdot A_t \cdot (T_1 - T_t) \quad \text{………………….. (23)}$$

$$\dot{Q}_{o'sm} = k_{o'sm} \cdot F_{o'sm} \cdot (T_{o'sm} - T_1) \quad \text{………………….. (24)}$$

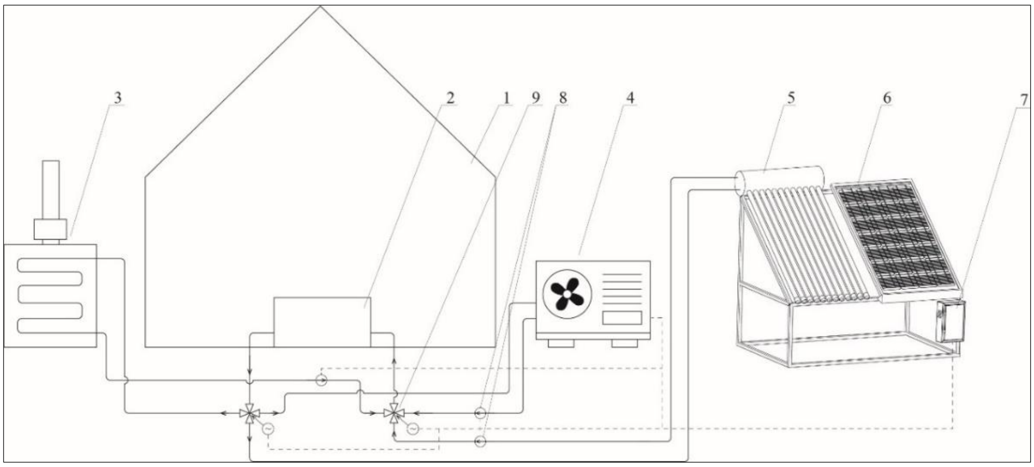
The amount of heat gained by artificial lighting in a greenhouse is determined by the following equation [15]:

$$Q_y = W \cdot F_{hc} \cdot F_a \cdot A_{is.m} \quad \text{………………….. (25)}$$

where: W - is the nominal power of the heat-generating lamps; F_{hc} - is the heat conversion coefficient, equal to 0.6; F_a - is the light supply coefficient, equal to 0.9; $A_{is.m}$ - is the greenhouse area.

3. Result and Discussion

Figure 3 shows a diagram of the energy supply system of an autonomous greenhouse. In this case, solar radiation, solar thermal devices, heat pumps, and heat boilers are used as heat sources to increase the reliability of heat supply in case of abnormal cold. Heat pumps are powered by integrated power grids with solar photovoltaic devices.



1-greenhouse; 2-heat exchanger; 3-heat boiler; 4-heat pump; 5-solar heat collector; 6-solar photovoltaic panels; 7-electrical equipment box; 8-circulating water pumps; 9-controlled water heaters.

Figure 3 Scheme of the energy supply system of an autonomous greenhouse

Figure 4 shows the dynamics of the greenhouse heat load change in the absence of changes in ambient temperature and solar radiation. The average temperature inside the greenhouse is assumed to be 20 °C. It was found that in January, due to the maximum temperature drop, the heat load increases to 12 kWh. At such times, natural fuel boilers are started in parallel at short wattage to heat the greenhouse.

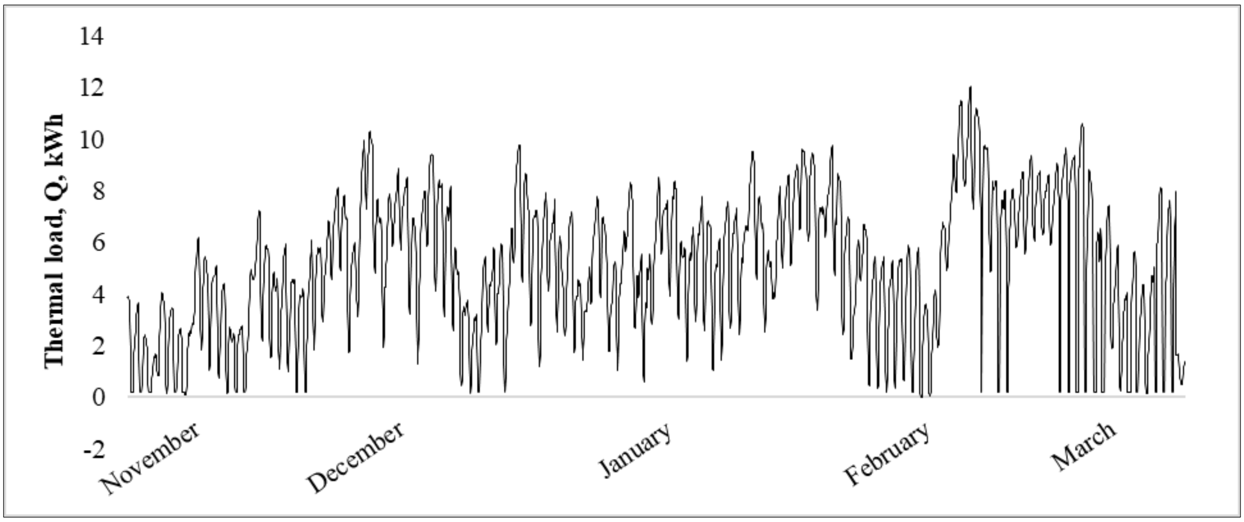


Figure 4 Dynamics of greenhouse heat load change

Calculations were carried out from November 15 to March 15, 2023 at 1-hour intervals (Figure 5). In this case, the average internal temperature of a greenhouse with a glass-covered useful surface of 50 m^2 was assumed to be 20 °C. Taking into account the ambient temperature changes and heat losses in the greenhouse, it was calculated that the greenhouse would consume 14.720 kWh of thermal energy during this season. It was determined that the heat pump produced 11.135 kWh of thermal energy when heating the greenhouse during the dark hours, and the solar water heating collectors (6x200 l) produced 2.225 kWh of thermal energy during the sunny hours. It was assumed that the heat pump would consume 2.710 kWh of electricity in this case.

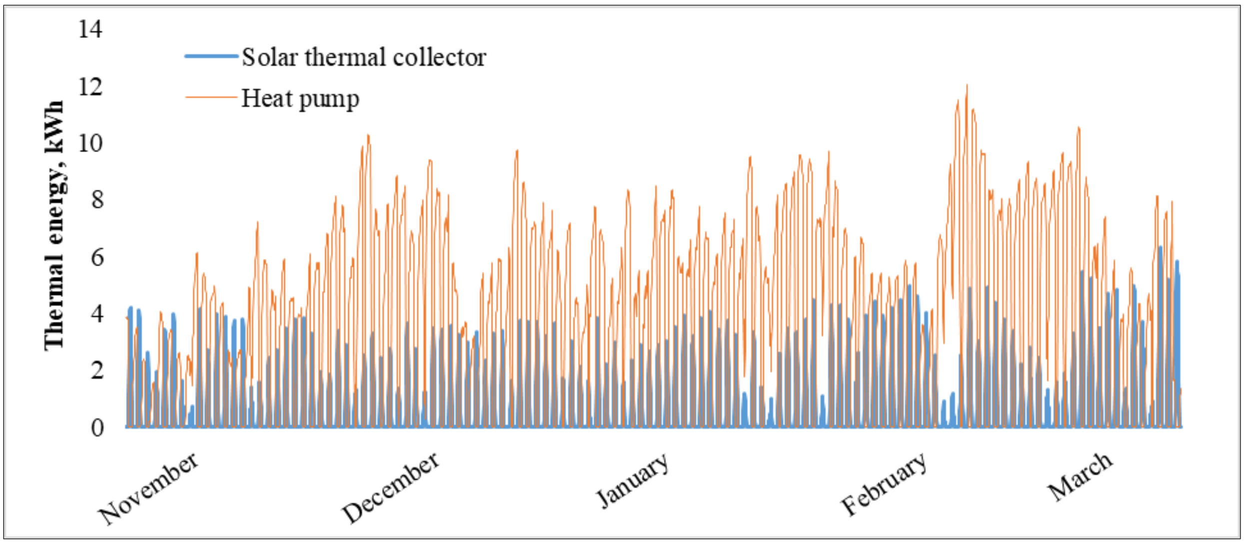


Figure 5 Graph of greenhouse heat supply

4. Conclusion

The heat load of a two-slope greenhouse with a useful area of 50 m^2 located in the city of Karshi for the period from November 15, 2023 to March 15, 2024 is determined taking into account the ambient temperature, solar radiation and heat losses in the greenhouse. According to the results, it was studied that the greenhouse will consume 14720 kWh of heat energy during this season. Of this, 11135 kWh of heat energy was provided by a heat pump, 2225 kWh by a solar thermal collector, 100 kWh by a heat boiler, and the rest by solar radiation.

During the greenhouse heating season, 1835 m^3 of natural gas and 2.26 ton of conventional fuel of conventional fuel were saved, and 3395 kg of CO_2 was reduced when this natural gas was burned. The economic efficiency indicators of the greenhouse energy supply system were assessed using the discount method. According to this, it was determined that the net present value is 10600 $, the internal rate of return is 10%, the profit index is 2.03, and the payback period is 6.4 years.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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