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Carbon Footprint of a Flower Geothermal Heating System Based on Life Cycle Assessment

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ABSTRACT

Geothermal energy is a kind of green and low-carbon renewable energy. The application of geothermal energy to agricultural greenhouse heating can effectively solve the problems of high energy consumption and large carbon emission in traditional greenhouse heating system. In this work, a carbon footprint analysis model of geothermal greenhouse heating system is built based on life cycle assessment. This model can analyze the whole carbon footprint process including the extraction of geothermal energy in the middle and deep layer, compression and lifting, greenhouse end and plant absorption of carbon dioxide. Based on the experimental data collected during the heating period of XinSheng flower geothermal heating system in Xianyang area, the carbon emission per unit greenhouse heating area is calculated under different power generation technology (coal-burning power generation, gas-fired power generation) and different heat source. The results show that: 1) During the 2021-2022 heating period, the carbon footprint of heating unit area and unit time of an 80000m^2 connected greenhouse in Xianyang area is 107.8 and 23.1 (m^2·d), respectively, under coal-fired power generation and gas-fired power generation. 2) The carbon emission of gas-fired power generation as the driven power to the heat pumps is only 21.4% of that of coal-fired power generation. 3) During the heating period, the contribution rate of R134a leakage from the heat pump unit is 2.4% and 11.4% of the total carbon emissions under CFPP and GFPP, respectively. The development of new environmentally friendly refrigerants can reduce the carbon footprint of system heating. 4) Compared with oil-fired boiler heating system, the carbon footprint of middle-deep geothermal heating is 49.08% of its under coal-fired power generation; If gas fired power generation is used, the former is only 13.28% of the latter. In this paper, the carbon footprint of greenhouse per unit area per unit time calculated by coal-fired power generation and gas power generation is 84.2% and 30.6% of the carbon footprint calculated by Lilong C for solar greenhouse shallow ground source heat pump heating system, respectively.

1. INTRODUCTION

Greenhouse is a kind of modern agricultural production mode in which people control environmental factors by using various facilities to make crops in the most suitable growing environment [1]. Compared with the traditional agricultural production mode characterized by low input, low output and low income, greenhouse agriculture is not subject to environmental restrictions such as temperature and season, which can obtain better economic and social benefits. Affected by the energy crisis and global warming, Van and Faisal et al. believed that the cost of developing facility agriculture was constantly increasing and the production competitiveness was declining[2][3]. As a result, the core of facility agriculture had shifted to energy conservation, focusing on the development of new energy sources such as wind, solar and geothermal energy[4]. As a kind of clean energy that can be recycled, geothermal energy has the advantages of stable heating, large reserves and wide distribution. Therefore, the research on the application of geothermal energy in facility agriculture is of great significance for reducing energy consumption and carbon dioxide emission.

In recent years, shallow ground source heat pump technology has been widely used in many countries, Ozgener et al. [5] analyzed the application economy of GSHPs in greenhouse in Turkey, and concluded that compared with traditional energy heating, GSHPs heating had better economy in Turkey. Giuseppe Emmi et al. [6] used the Transient System (TRNSYS) simulation tool to simulate the operating conditions of the solar-assisted ground source heat pump system in six cold locations. The application of shallow ground source heat pump in agricultural production heating research had also made great progress in China. Hui Fang[7] studied the Venlo-type greenhouse heated by buried tubular GSHPs in Beijing. The COP of the system was 2.62, compared with the traditional coal-fired system, which saved 29.6% energy. Junling Liu et al. [8] designed a heating system using shallow geothermal energy as a heat source according to the distribution characteristics of geothermal energy in Qitzhuang Village, Panzhuang Town, Ninghe County, Tianjin. The results showed that the COP of the experimental greenhouse heating system reached 3.79, which saved 47.4% energy compared with the greenhouse using coal-fired heating system. Lilong C., et al. [9] analyzed the carbon footprint of a GSHP heating system in a solar greenhouse in Beijing, and found that the carbon footprint of GSHP heating system driven by gas power generation in a solar greenhouse was only 41% of that of Venlo greenhouse heating. Scholars such as Zhenyong Qiao [10]had demonstrated that different climatic zones in the southwest and northwest regions of China provide great opportunities for geothermal energy application. It is worth noting that, compared with shallow geothermal, middle-deep geothermal can give full play to the characteristics of geothermal energy, such as energy saving and emission reduction, stable heating and low annual operating cost. In addition, there have been many studies on the technical performance (COP) and economic performance of greenhouse heating systems, but the research on the environmental performance (carbon emission) of greenhouse is not in-depth enough. In this work, the transient system simulation tool (TRNSYS) was used to calculate the heating load of a flower greenhouse in Xianyang City during the heating period, and the carbon footprint of the whole process from the extraction of geothermal energy from the middle and deep layers to the capture of carbon dioxide by plants at the end of the greenhouse was analyzed. At the same time, this work also compares the impact of coal and gas generation on the carbon footprint of the whole heating system in China.

2. MODEL AND METHOD

2.1 THE GREENHOUSE

The reference in this work is a Venlo-type greenhouse with an area of about 80,000m^2 located in Xixian New District, Xianyang City, Shaanxi Province (108.8° E, 34.2° N), which is used for peony planting. It is 179.2m long from east to west, 44m wide from north to south, and 4.8m high eaves. Based on the basic principles of thermodynamics and heat transfer, we can establish a balance equation between the internal and external environment of the greenhouse:

$$Q + Q_r + Q_b + Q_c = Q_w + Q_s + Q_c + Q_p \tag{1}$$

where Q, Q_r, Q_b, Q_e, Q_w, Q_s, Q_c and Q_p are the heat consumption of greenhouse heating, solar radiation, the heat of plant respiration, the heat dissipation of equipment, the heat loss of envelope, the heat lost by the soil, the heat lost by cold air penetration and the heat of photosynthesis.

In the actual production, the heat released by respiration and the heat consumed by photosynthesis of crops are very small, and the heat emitted by equipment motor and lighting is also small and unstable, which is usually ignored[11]. Therefore, the above equation can be simplified as follows:

$$Q + Q_r = Q_w + Q_s + Q_c \tag{2}$$

The following is the greenhouse each part of the heat dissipation area and maintenance structure form of statistical table and greenhouse structure diagram.

Table 1 Maintain structural form statistics

order	Parts		material	area (m^2)	Thermal Conductivity (W/(m^2·K))
1	top		PC board(8mm)	8350	3.3
2	Around	upper part	PC board(8mm)	1562	3.3
		bottom	brick(360mm)	223	2.02

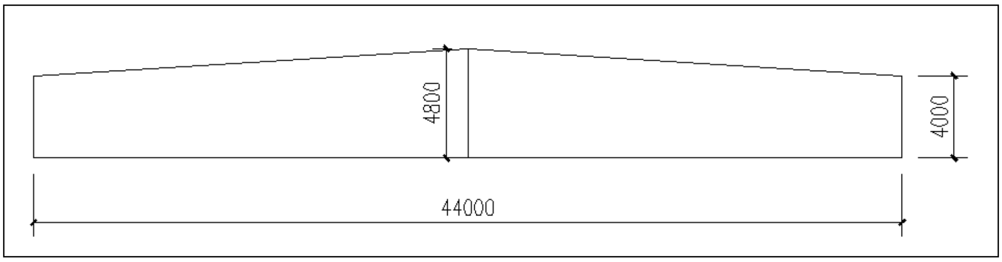

Figure 1 Schematic diagram of greenhouse structure

2.2 BUILDING HEAT LOAD

2.2.1 HEAT LOAD CALCULATION MODEL

Combined with JB/T 10297-2014, NY/T 2970-2016 and other specifications and actual use requirements, the indoor design temperature of the greenhouse is 18℃, and the water supply and return temperature is 65/50℃, respectively. The heating time is from September 15th to May 15th of the next year, and the heating cycle is 8 months. The heating period is affected by sunshine and outdoor temperature every day. The basic heating period is 5:00 p.m.~ 10:00a.m. (17 hours).

Firstly, we set the orientation, structural data, ventilation, heating temperature and other parameters of the greenhouse in TRNSYS sub-module TRNBUILD. Secondly, the weather data found in Meteonorm is imported into the weather module. Finally, by controlling the time through Type 14h, the hourly load of the greenhouse in the heating period can be obtained. The Figure 2 is greenhouse heat load calculation model.

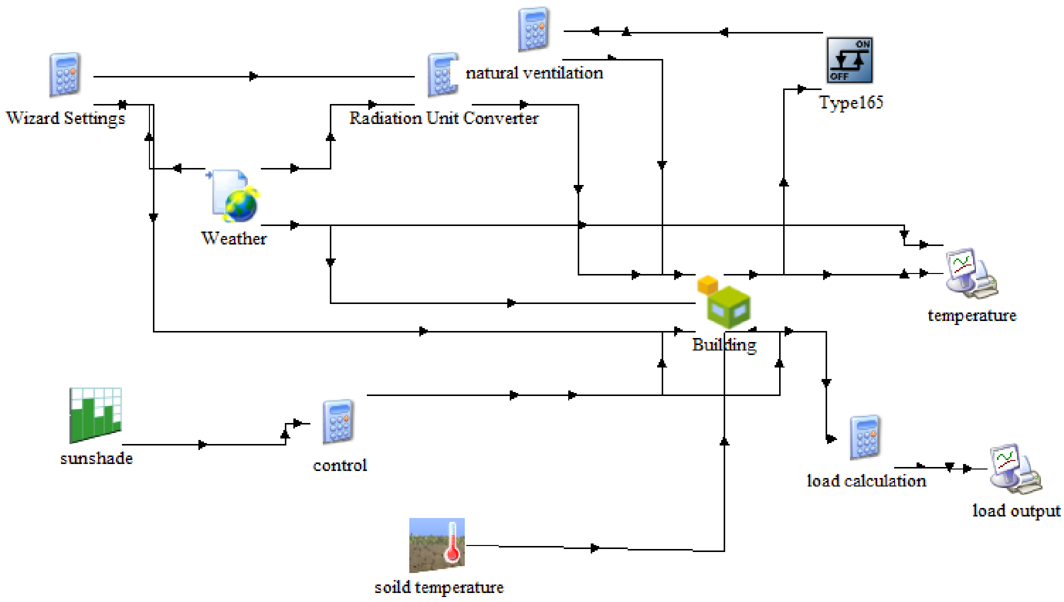

Figure 2 Building heat load calculation model

2.2.2 THE RESULTS OF SIMULATION

By running the heat load model, we can get the ambient temperature and monthly load of the connected greenhouse in Xianyang area. According to Figure 3 and Figure 4, the monthly heat load of the flower greenhouse decreases with the increase of the temperature of the environment. The maximum heat consumed by the greenhouse is 2234553.02KWh in January, and the maximum heat load is9653.40kW. According to the maximum load, the heat load per square meter of the greenhouse is about 120W /m^2, which conforms to the design specification. Therefore, the running result is reliable.

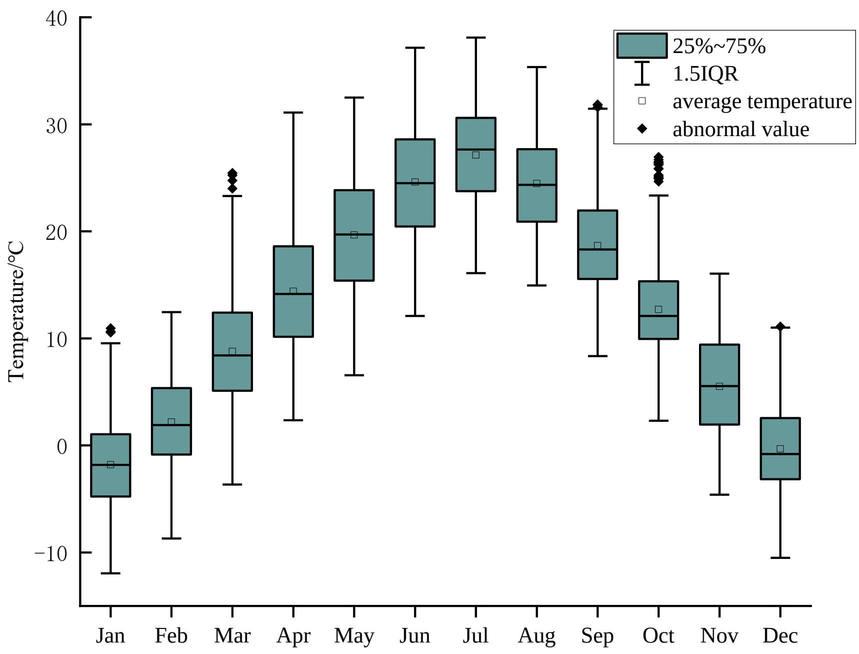

Figure 3 The monthly environment temperature

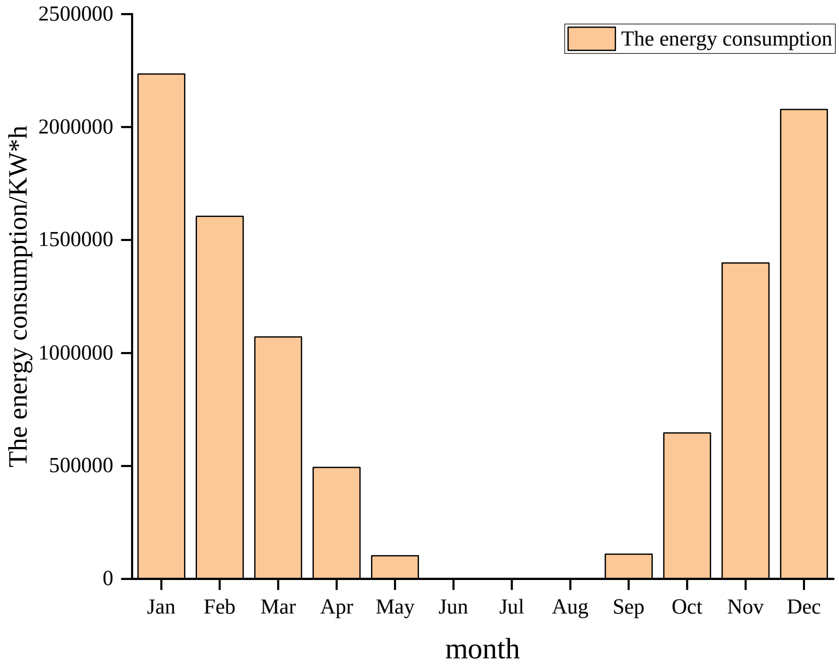

Figure 4 The monthly load of the greenhouse

2.3 MIDDLE AND DEEP GEOTHERMAL HEATING SYSTEM MODEL

The water supply and return temperatures at the flower greenhouse are 65℃/50℃. The heating system is mainly composed of three plate heat exchangers, two heat pump units and some circulating pumps. The specific parameters of heat pump can be found in Figure 2. It adopts the principle of direct geothermal water heating and stepwise utilization of heat pump. The oil-fired boiler is used as the backup heat source to provide winter heating load for the greenhouse. The system diagram in TRNSYS is shown in Figure 5.

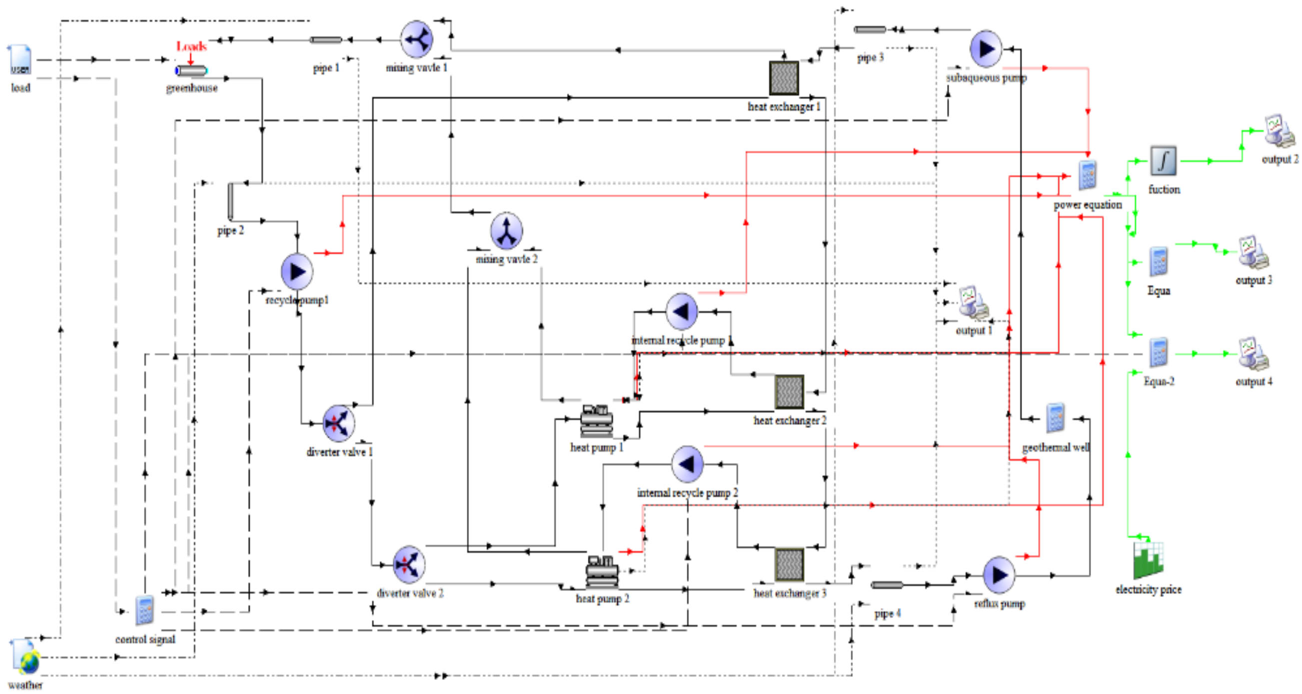

Figure 5 System diagram of greenhouse heating

Table 2 Parameters of heat pump

name	unit	heating pump 1	heating pump 2
Nominal heat production	kW	2955	2197
Heating COP		4.7	3
Heating input power	kW	628	990
Evaporator side inlet	℃	47	37
Evaporator side outlet	℃	55	45
Inlet of condenser	℃	50	50
Outlet of condenser	℃	65	60

The heating system has four main operation modes，

Mode 1: Direct heating with primary heat exchange of geothermal water only;

Mode 2: Operate a heat pump to improve the heat, when the heat exchange load of the primary board cannot meet the demand of the greenhouse;

Mode 3: The two heat pumps are both turned on at the same time to meet the heating load, when operating mode 2 still cannot maintain the temperature of normal plant growth;

Mode 4: Use oil boiler heating, when the geothermal well failure.

The modes 1 to 3 can be controlled in the figure 5. Since the heat load calculated by TRNSYS software is generally negative, the logic function is chosen as LT (*a*, *b*), and the control signal can switch the operation mode by controlling the start and stop of the pump.

$$Control = LT(load, 0) \tag{3}$$

$$Control_1 = LT(load, Q_{e1}) \tag{4}$$

$$Control_2 = LT(load, Q_{e1} + Q_1 + Q_{e2}) \tag{5}$$

$$LT(a,b) = \begin{cases} 1, a < b \\ 0, a \geq b \end{cases} \tag{6}$$

Where Q is hourly load of greenhouse heating period, KW; Q_{e1} is the heating load of the first stage plate straightening, KW; Q_1 is the maximum load that the heat pump can provide, KW; Q_{e2} is a direct load supply for the two-stage heat exchange plate, KW.

When the geothermal well fails to provide heat, the backup heat source oil-fired boiler will be used to provide all the required heat load. According to the previous simulation, the temperature of peony normal growth can be met when 9739430KW·h is provided during the whole heating period. In order to better compare the carbon footprint of geothermal energy heating and oil-fired boiler heating, we assume that the oil-fired boiler provides the heat to maintain the greenhouse at 18℃ during the whole heating period, and the required diesel quality B_{bo} can be calculated by equation[12].

$$B_{bo} = \frac{Q}{41840\eta_{1c} \times \eta_{2c}} \tag{7}$$

Where Q is heating quantity, kJ/d; B_{bo} is the diesel consumption of oil-fired boiler, kg/d; η_{1c} is the efficiency of oil-fired heating boiler, 0.9; η_{2c} is the heat network efficiency, 0.9.

In addition to diesel fuel consumption, boiler heating system energy consumption and boiler auxiliary power consumption, primary network and secondary network water pump power consumption. The total power consumption can be calculated by Equation 8.

$$E_b = k_b Q \tag{8}$$

Where E_b is the power consumption of boiler heating system, kJ /d; K_b is the proportional coefficient. For oil-fired boilers, it is 0. 04.

2.4 CARBON FOOTPRINT ANALYSIS METHODS

In this study, the carbon emission footprint of the system was analyzed using a Life Cycle Assessment (LCA) approach by simulating the study of mid-deep geothermal heating during the 2021-2022 heating period. LCA is a technology and method used to assess the environmental impact of a product in its entire life cycle, from the acquisition of raw materials, production of the product to the disposal of the product after use. The system definition based on LCA can be represented by the figure 6.

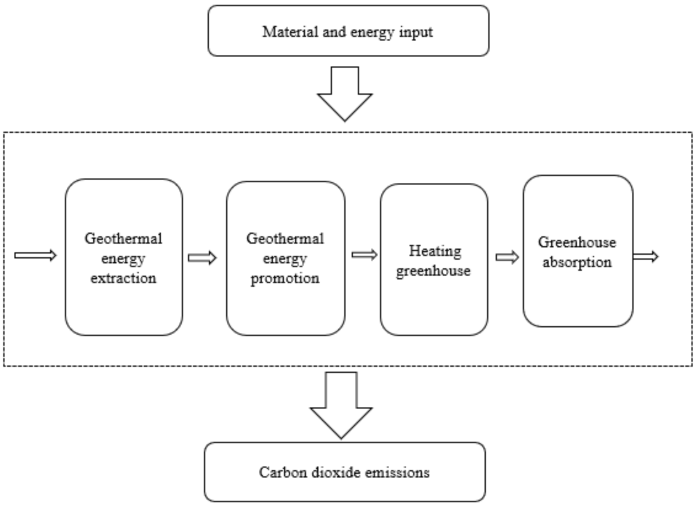

Figure 6 Boundary of the system

In this paper, the middle and deep geothermal energy is studied, and the research scope includes the extraction of geothermal energy, the improvement of heat pump units, the heating of greenhouse and the absorption of carbon dioxide by flowers. The energy consumption is all electric energy, but the amount of carbon dioxide produced is different due to the different power generation methods. According to the BP, coal-fired power accounted for 63.2% of electricity generation in China, gas-fired power accounted for 3.17%, and other energy sources such as hydropower and wind power accounted for 33.63% in 2020[13]. From these data in Table 3, it can be seen that thermal power generation is still in the dominant position in China, and the proportion of coal-fired power generation is decreasing year by year, and gas-fired power generation technology is receiving more and more attention in China. Therefore, this study takes coal-fired and gas-fired thermal power generation as the reference to analyze the amount of greenhouse gases in the power generation process of the energy consumed in the geothermal heating system.

Table 3 Power generation of various energy sources in China (TW·h) 同上

year	CFPP	GFPP	Other	Total generating capacity	CFPP	GFPP
2020	4917.7	247	2614.4	7779.1	63.21682%	3.175175%
2019	4853.7	236.5	2413.2	7503.4	64.68668%	3.151904%
2018	4765	215.5	2185.6	7166.1	66.49363%	3.007215%
2017	4445.5	202.8	1956.2	6604.5	67.31017%	3.070634%
2016	4163.6	188.3	1781.3	6133.2	67.88626%	3.070175%

Carbon emissions from burning coal and gas can follow the formula[14].

$$E_{pp\chi} = \frac{3600E_e}{CV_\chi R_\chi} \tag{9}$$

$$EC_{k,d,s} = \frac{E_k \gamma_k}{AD} \tag{10}$$

Where $E_{pp\chi}$ is the quality of energy consumed by the power plant in standard state, kg; E_e is power consumption, kWh; CV_χ is the thermoelectric conversion rate of coal or gas system, 29.3 and 52.6 respectively; R_χ is the thermoelectric efficiency of coal-fired power plant (CFPP) and gas-fired power plants (GFPP), 0.27 and 0.42 respectively. E_k is the energy consumption of system K, kg; γ_χ is the greenhouse gas emission coefficient, which is 3.67 for CFPP and 2.75 for GFPP. $EC_{k,\,d,\,s}$ is the mass of greenhouse gases emitted by building per unit area supplied by system K per unit time, kg/(m^2·d); A is the area of greenhouse, m^2; D is the number of days with heating, d.

Global warming potential (GWP), or carbon dioxide equivalent emissions (CO_2 eq.), is an important indicator to measure the contribution level of greenhouse gas emissions to global warming[15]. According to the greenhouse gas equivalent factor published by the Intergovernmental Panel for Climate Change (IPCC) [16].

$$EM = \sum_{x=1}^{4}\sum_{y=1}^{6} E_{xy} GWP_y \tag{11}$$

Where *EM* is the total GWP contribution in the greenhouse heating process in this study, measured in CO_2, kg; *X* is the four stages going through; Y is the six GHG equivalent factors published by IPCC; E_{xy} is the amount of Y factor that the shallow ground can emit in the X stage, kg; GWP_y is the greenhouse gas emission equivalent of factor Y, kg/kg.

Table 4 Greenhouse gas equivalent factor

Pollutants	Global warming potential/(kg/kg) GWP		
	20a	100a	500a
CO_2	1	1	1
CH_4	72	25	7.6
N_2O	289	298	153
HFCs(HFC-134a)	3830	1430	435
PFCs(PFC-116)	8630	22800	32600
SF6	16300	22800	32600

As the main research object of this paper is the carbon footprint of geothermal energy system heating, without considering the equipment manufacturing and building materials, only CO_2 and a small amount of refrigerant R134a leaked from the heat pump unit are greenhouse gases in this process. According to Refrigerant Numbering Method and Safety Classification (GB7778-2008), it is recommended that the annual refrigerant leakage rate is 2% of the charged amount (500Kg). In this paper, according to the calculation of R134a and CO_2 equivalent factor when the age is 20a, the leakage of refrigerant R134a from each heat pump is equivalent to the emission of 38300Kg/a CO_2. Because the actual heating time of the heating period is 242d, the actual R134a equivalent greenhouse gas emissions of the two heat pumps during the heating period are about 50786.85kg.

3. RESULTS AND ANALYSIS

3.1 ENERGY CONSUMPTION OF MEDIUM AND DEEP GEOTHERMAL HEATING SYSTEM

The simulation results of the middle and deep geothermal heating system are shown in the figure 7.

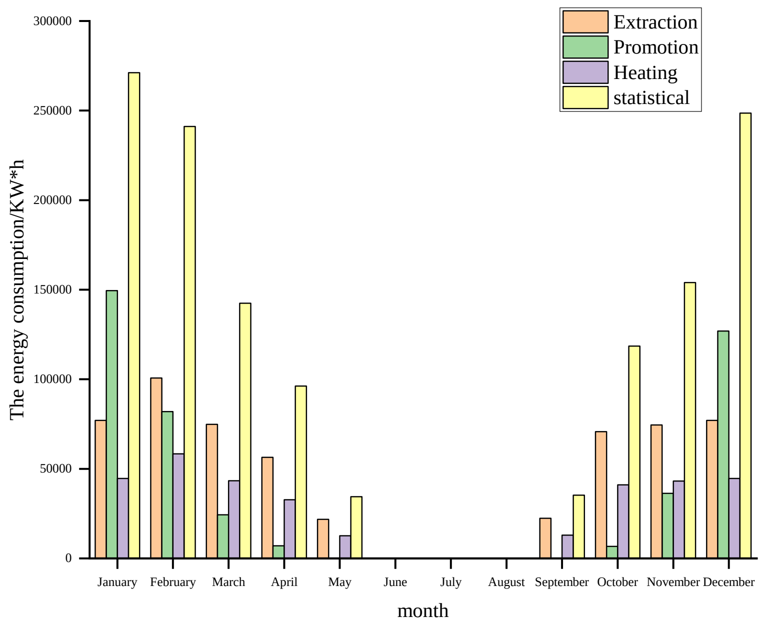

Figure 7 Electricity consumption in different months

As seen from the figure7, the amount of electricity consumed is closely related to climate. When the temperature exceeds low, the system will run the third operation mode to start the two heat pumps, because the power of the heat pump is very large, resulting in a sharp increase in power consumption. The amount of electricity consumed in January with low temperature is the largest among several months, reaching 271131.42kW·h. However, in months with high temperature, such as May and September, the primary heat exchange of geothermal water can fully meet the demand of plants for temperature, so there is no need to start the heat pump and the power consumption is very low. If the energy consumption of each month is accumulated, we can get the Figure 8**.** The result showed that the main power consumption stage of the whole heating period is the stage of geothermal energy extraction.

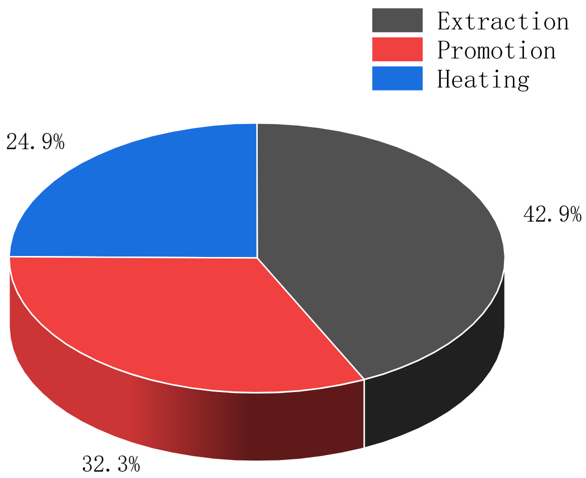

Figure 9 The proportion of energy consumption at different stages

3.2 CARBON FOOTPRINT OF MEDIUM AND DEEP GEOTHERMAL HEATING SYSTEM

In the case of coal and gas power generation, the calculation results of energy consumption, resource consumption(Table 5) and carbon emissions in the whole heating period of the connected greenhouse(Figure 9) are as follows. In the whole heating process, if the electricity consumed is generated by CFPP, the carbon dioxide generated by this part of electricity is 2241.03t. If gas power generation is used, Then the carbon dioxide emission is 601.33t. The whole connected greenhouse covers an area of 80,000 m^2, and the heating period is 242 days long. The average daily carbon dioxide emissions per unit area of the greenhouse are 115.8 g/ (m^2•d) and 31.1 g/ (m^2•d), respectively.

Table 5 Consumptions of electricity, resource and CO_2 emission of medium and deep geothermal heating system

Energy flows	power consumption KW·h	Coal fired power producing（CFPP)		Gas fired power producing (GFPP)	
		Coal consumption Kg	co_2 emissions Kg	Coal consumption Kg	co_2 emissions Kg
Extraction	575459.9574	261870.2878	961063.9562	93774.02891	257878.5795
Promotion	432813.4148	196957.1854	722832.8702	70529.07357	193954.9523
Heating	333600	151808.8737	557138.5666	54361.75991	149494.8398
Inventory	1341873.372	610636.3469	2241035.393	218664.8624	601328.3716

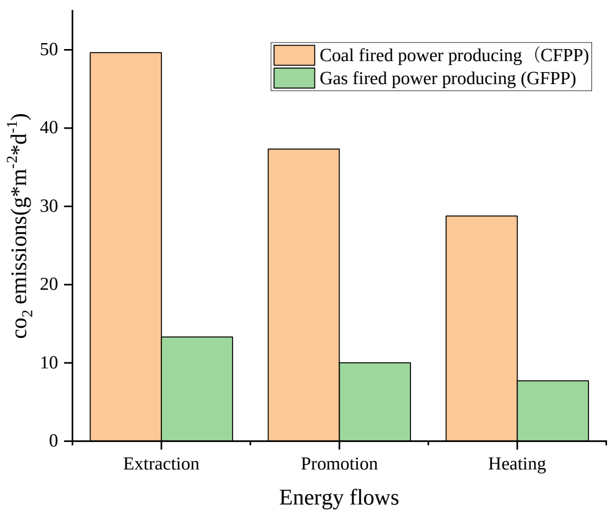

Figure 10 CO_2 equivalent emission from medium and deep geothermal heating system

When coal-fired power generation is used in this connected greenhouse, the CO_2 emissions during geothermal energy extraction and heating are 49.6 g/ (m^2·d) and 28.8 g/ (m^2·d), respectively, which are similar to the carbon footprint results of the ground source heat pump heating system in the solar greenhouse of 57.4 g/ (m^2·d) and 29.4 g/ (m^2·d) studied by Lilong C[17]. However, in the stage of geothermal energy enhancement, the calculation result of this paper is 37.3 g/ (m^2·d), which is far less than his calculation result of 167.7 g/ (m^2·d). This law also appears when using gas power generation. This is because the middle and deep geothermal can provide more and more stable heat sources and reduce the use of heat pumps. The results fully prove that the middle and deep geothermal has the advantage of being cleaner than the shallow geothermal.

Considering the leakage of heat pump and the absorption of carbon dioxide by crops in the greenhouse, the heating carbon footprint of the system based on CFPP and GFPP power is calculated as follows: the heating carbon footprint per unit area per unit time of the connected greenhouse is 107.8 and 23.1 g/ (m^2·d), respectively. The carbon footprint contribution rate of refrigerant R134a in CFPP and GFPP is 2.4% and 11.4%, respectively.

Table 6 Carbon footprint of medium and deep geothermal heating system based on life cycle assessment method（CO_2 eq.）

Energy flows	CO_2 emissions（CFPP） g/ (m^2·d)	CO_2 emissions (GFPP) g/ (m^2·d)
Extraction	49.64173	13.32017
Promotion	39.9597	12.64162
Heating	28.77782	7.721841
Absorption	-10.58	-10.58
Total carbon footprint	107.7992	23.10364

3.3 CARBON FOOTPRINT OF OIL-FIRED BOILER HEATING SYSTEM

If the oil-fired boiler system is used as the heating source during the whole heating period, it can be calculated that the total diesel oil consumption is 1034.57t, and the electric energy consumed by the auxiliary equipment is 3895777.2KW ·h. Diesel oil is mainly hydrocarbon, the ratio of carbon to hydrogen is about 1:2, 1Kg diesel contains about 0.857 Kg carbon, and generates about 3.14Kg carbon dioxide. The electric energy consumption of the heating equipment at the end of the greenhouse and the amount of carbon dioxide absorbed by crops did not change. The carbon footprint of the available oil-fired boiler heating system is calculated as follows.

Table 7 Carbon footprint of oil-fired boiler heating system based on life cycle assessment method（CO_2 eq.）

Study index	co_2 emissions（CFPP） g/ (m^2·d)	co_2 emissions (GFPP) g/ (m^2·d)
oil-firing boiler	167.7968	167.7968
auxiliary equipment	33.60666	9.017545
Heating	28.77782	7.721841
Absorption	-10.58	-10.58
Total carbon footprint	219.6013	173.9562

The carbon footprint per unit area per unit time of the greenhouse is 219.60 g/ (m^2·d)and 173.96 g/ (m^2·d), respectively, when the heating system of oil-fired boiler is powered by coal and gas. By comparing the geothermal energy heating system with the oil-fired boiler heating system, the CO_2 emission of the geothermal energy heating system is 49.08% of that of the oil-fired boiler heating system when the coal-fired power generation is adopted. If gas fired power generation is used, the former is only 13.28% of the latter. Compared with traditional heating system, geothermal heating system has significant advantages in environmental protection.

4. CONCLUSIONS AND SUGGESTIONS

1) During the 2021-2022 heating period, the carbon footprint of heating unit area and unit time of an 80000m^2 connected greenhouse in Xianyang area is 107.8 and 23.1 (m^2·d), respectively, under coal-fired power generation and gas-fired power generation.

2) During the heating period, the contribution rate of R134a leakage from the heat pump unit is 2.4% and 11.4% of the total carbon emissions under CFPP and GFPP, respectively. The development of new environmentally friendly refrigerants can reduce the carbon footprint of system heating.

3) Compared with oil-fired boiler heating system, the carbon footprint of middle-deep geothermal heating is 49.08% of its under coal-fired power generation; If gas fired power generation is used, the former is only 13.28% of the latter. In this paper, the carbon footprint of greenhouse per unit area per unit time calculated by coal-fired power generation and gas power generation is 84.2% and 30.6% of the carbon footprint calculated by Lilong C for solar greenhouse shallow ground source heat pump heating system, respectively. It shows that deep geothermal energy has significant advantages in environmental protection and has important application value in agricultural production.

4) According to the calculation, The carbon emission of gas-fired power generation as the driven power to the heat pumps is only 21.4% of that of coal-fired power generation, gas-fired power generation has a smaller carbon emission than coal-fired power generation.

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