Chapter 10

Mitigating Greenhouse Gas Emissions from Winter Production of Agricultural Greenhouses

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Additional information is available at the end of the chapter

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Abstract

Consuming conventional fossil fuel, such as coal, natural gas, and oil, to heat agricultural greenhouses has contributed to the climate change and air pollutions regionally and globally, so the clean energy sources have been increasingly applied to replace fossil energies in heating agricultural greenhouses, especially in urban area. To assess the environment performance (e.g., greenhouse gas (GHG) emissions) of the ground source heat pump system (GSHPs) for heating agricultural greenhouses in urban area, a GSHPs using the shallow geothermal energy (SGE) in groundwater was applied to heat a Chinese solar greenhouse (G1) and a multispan greenhouse (G2) in Beijing (latitude 39°40′ N), the capital city of China. Emission rates of the GSHPs for heating the G1 and G2 were quantified to be 0.257–0.879 g CO_2 eq. m^{-2} day^{-1}. The total GHG emissions from heating greenhouses in Beijing with the GSHPs were quantified as 1.7–2.9 Gt CO_2 eq. $year^{-1}$ based on the electricity from the coal-fired power plant (CFPP) and the gas-fired power plant (GFPP). Among different stages of the SGE flow, the SGE promotion contributed most GHG emissions (66%) in total due to the higher consumption of electricity in compressors. The total GHG emissions from greenhouses heating with the coal-fired heating system (CFHs) and gas-fired heating system (GFHs) were quantified as 2.3–5.2 Gt CO_2 eq. $year^{-1}$ in Beijing. Heating the G1 and G2 with the GSHPs powered by the electricity from the CFPP, the equivalent CO_2 emissions were 43% and 44% lower than directly burning coal with the CFHs but were 46% and 44% higher than the GFHs that burn natural gas. However, when using the GFPP-generated electricity to run the GSHPs, the equivalent CO_2 emissions would be 84% and 47% lower than the CFHs and the GFHs, respectively.

Keywords: urban agriculture, greenhouse heating, greenhouse gases, fossil energy, shallow geothermal energy

1. Introduction

Agricultural buildings, such as horticultural greenhouse, usually require additional heating during winter and cold days in high latitude regions of the Northern Hemisphere [1, 2]. In northern China and many European countries, coal-fired heating system (CFHs) and the natural gas-fired heating system (GFHs) are dominant heating methods in greenhouses [3, 4]. However, conventional fossil fuels, such as coal, natural gas, and oil, which are nonrenewable and are the major greenhouse gas (GHG) contributors, may lead to the global climate change, air pollution, and energy crisis [5-7].

Renewable and clean energy, such as solar, geothermal, and shallow geothermal energy (SGE), has been increasingly applied to replace fossil energy systems in heating agricultural buildings (especially in urban area) across the world [8-11]. The SGE is mainly the stored solar energy in groundwater and soil layers less than 200 m deep from the earth soil surface [12, 13]. It can be used as heat source or sink for air conditioning in residential, industrial, and agricultural buildings with the ground source heat pump system (GSHPs), also known as geothermal heat pumps (GHPs) [4, 14].

The GSHPs has been applied to heat agricultural greenhouse in many countries [15-18]. The GSHPs could be considered with zero GHG emissions if the electricity was the only energy source that could be consumed by the system. However, producing electricity in coal-fired power plant (CFPP) or gas-fired power plant (GFPP) would emit a large quantity of GHG (e.g., CO_2). Besides, the refrigerant (e.g., R22 and R134a) used by the heat pump unit has been reported with the high risk of leaking in the year-round operation [19]. Therefore, assessing GHG emissions of the GSHPs should consider both direct and indirect sources.

In northern China (the area with altitude higher than 30° in the Northern Hemisphere) [20], there was mainly two kinds of horticultural greenhouses: the Chinese solar greenhouse (denoted as G1), which may or may not require assisted heating depending on the building design and the plants be cultivated, and the multispan greenhouses (denoted as G2), which require 100% assisted heating systems (primarily in the form of coal burning or gas burning) during winter time [21, 22]. The Chinese solar greenhouse, characterized with east-west orientation, transparent camber south roof, and solid north roof and east and west walls, usually has higher heat-preserving capacity than multispan greenhouse and requires less heating [23, 24]. However, the healthy growth of thermophilic vegetables, such as cucumber and tomato, and most flowers in Chinese solar greenhouse still requires assisted heating especially during cold winter nights or consecutive days of snowing or cloudy [3].

By the end of 2007, about 19,300 ha of greenhouses and tunnels had been constructed and used in Beijing, the capital city of China [25, 26], primarily for producing vegetables, flowers, and fruits. About 6000 ha Chinese solar greenhouses (the structure similar to G1) and 1000 ha multispan greenhouses (the structure similar to G2) may require assisted heating in winter with the systems of the CFHs and GFHs [27]. Therefore, quantifying the heating rate and GHG emission rate for the primary types of agricultural greenhouses with different heating systems and energy sources is important for developing the national or regional GHG emissions inventory of the greenhouse heating and mitigation strategies.

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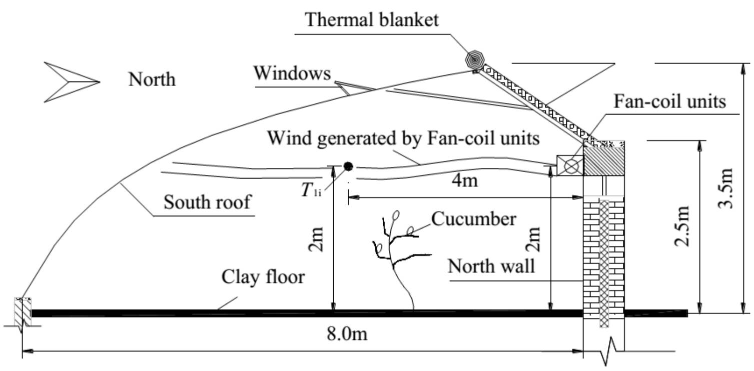
The objectives of this chapter are to (1) address the environmental concern on agricultural production over winter; (2) quantify the heating loads and the GHG emission rates for the two primary agricultural greenhouses (the G1-Chinese solar greenhouse and the G2-multispan greenhouses) in northern China; (3) assess the annual GHG emissions inventory of the greenhouse heating with different energy sources in Beijing, the capital city of the China; and (4) identify the difference between the shallow geothermal energy and the conventional fossil energy systems in GHG emissions of agricultural greenhouses heating.

2. Materials and Methods

2.1. Selected/tested greenhouses and the GSHPs

A Chinese solar greenhouse (G1, Figure 1 and Table 1) and a multispan greenhouse (G2, Figure 2 and Table 1), two important types of greenhouse in Northern China, were equipped with the groundwater-type GSHPs (Figure 3 and Table 2) in Beijing (latitude 39°40′N) and tested for developing heating rate and GHG emission rate. Performances of GHSPs were compared to CFHs and GFHs. In addition, different electricity generation methods (e.g., coal and gas power plant) were considered for assessing the GHG emissions of the GSHPs.

(a) Cucumbers in the G1



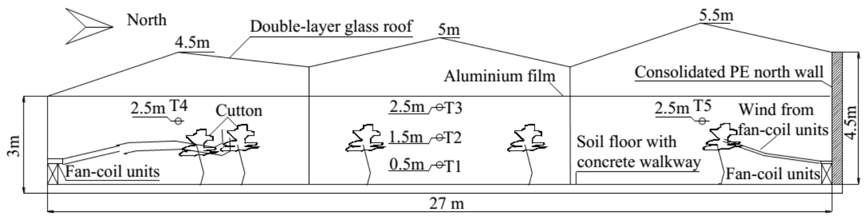
(b) The profile of the G1

Figure 1. The Chinese solar greenhouse (G1)

Section	Construction and coverage material	Surface area, m^2
Chinese solar greenhouse (G1)		
(1) North wall	240 mm clay brick+100 mm polystyrene heat preservation layer+240 mm clay brick	150
(2) East and west end walls	240 mm clay brick+100 mm polystyrene heat preservation foam board+240 mm clay brick	36
(3) South roof	0.15 mm single layer transparent polyethylene (south roof was covered with 10 mm needled felt heat blanket at winter nights)	510
(4) North roof	50 mm steel plate+100 polystyrene heat preservation layer+50 mm steel plate	108
(5) Floor	Bare soil (clay)	480
Multispan greenhouses (G2)		
(1) North wall	5 mm coated steel sheet+100 mm polystyrene heat preservation layer+5 mm coated steel sheet	126
(2) East and west wall	20 mm double-layer glass	110
(3) South wall	20 mm double-layer glass	98
(4) North roof	20 mm double-layer glass	108
(5) Floor	Bare soil for planting with concrete walkway (floor area was covered with aluminum film at horizontal height of 3.5 m at winter nights)	756

Table 1. Characteristics of the testing greenhouses.

(a) Cottons in the G2



(b) The profile of the G2

Figure 2. The multispan greenhouse.

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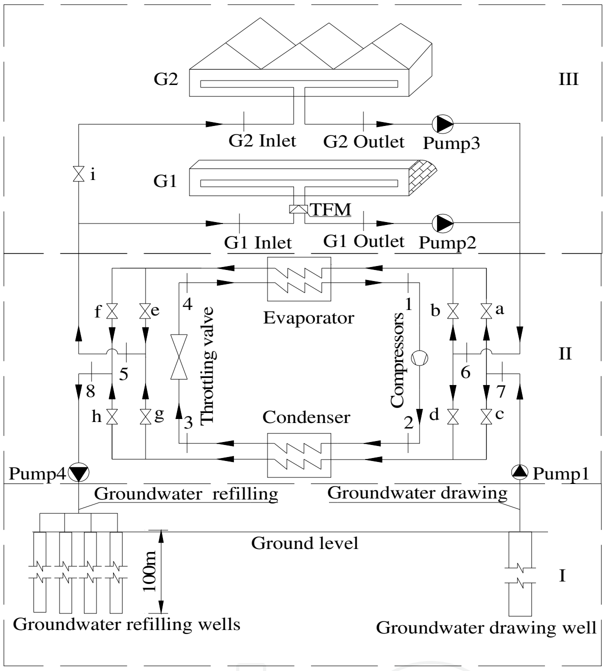
(a) The heat pump and water circulating system



(b) Diagram of the GSHPs greenhouse heating system

Figure 3. The groundwater type of GSHPs. (I is the stage of SGE extraction, II is the stage of SGE promotion, and III is the stage of greenhouse heating. **a–i** are valves installed in different water pipes. Pump 1 is groundwater drawing pump; pumps 2 and 3 are circulating water pumps; and pump 4 represent the groundwater backfilling pump. TFM is the thermal flow meter installed position. 1–8 represent the thermodynamic points in each section of GSHPs [18].

The GSHPs started to heat greenhouses on October 15, 2007 and ended on February 4, 2008. Cucumbers and strawberries were grown in G1 and cotton was grown in G2 during heating tests. The fan coil units in two greenhouses were controlled by the T-type thermocouple controllers automatically. For G1, the indoor air temperature was controlled in the range of 18°C–20°C, and for G2, the indoor air temperature was controlled in the range of 18°C–22°C, considering the poor thermal stability caused by the larger volume in G2.

Elements	Performance parameters
(1) Compressor	Manufacturer: four Danfoss hermetic scroll compressor; rated power of electric motor driving: 16.08×4 kW; refrigerant: 58 kg R22. Rate of refrigeration capacity: 380 kW; rate of heating capacity: 450 kW.
(2) Condenser	Horizontal shell–tube model
(3) Evaporator	Dry evaporator model
(4) Throttle	Copper capillary tube
(5) Fan-coil	In G1: FP-136; rated input power: 56 W; number: 6. In G2: 42VM006; rated input power: 87 W; number: 45
(6) Pumps	Flux: 33.2 $m^3 h^{-1}$; rated input power: 11 kW; number: 4
(7) Control system	PLC touching screen controller

Table 2. Characteristics of the GSHPs.

2.2. Power inputs and heating rate quantification

The heat provided by the GSHPs for heating greenhouses was quantified with the thermal flow meter (TFM) (Model DN35 and DN100, Beijing Jingyuan Liquid Apparatus Company, Beijing, China). A weather station (Qingsheng Electronic Science and Technology Co. Ltd., Handan, China) installed in the agriculture station was used to monitor outdoor environmental factors. Total electricity consumption of the GSHPs was recorded with watt-hour meter (Shanghai Huaxia Ammeters Manufactory, Shanghai, China).

2.3. Quantifying the GHG emissions

There are six kinds of gases (Table 3) highlighted as the GHG in Intergovernmental Panel on Climate Change (IPCC 2006) [5]. For the greenhouse heating with the CFHs and GFHs, carbon dioxide (CO_2) is the only GHG to be considered. But for the GSHPs greenhouse heating, most electricity consumed (in Beijing area) was generated in the CFPP or the GFPP, and the process of the power generation could emit large amount of CO_2 [25]. Besides, it has been reported that the leaking fraction of the refrigerant (i.e., R22(HFC-22) in this study) used in the GSHPs is around 0.02 kg^{-1} (2%) per year [19]. The R22 was not listed as one of the six primary GHG in the IPCC (2006), but it was reported with 1.28 times of the global warming potential (GWP) of the R134a (HFC-134a) [28]. Therefore, the GWP of R22 was estimated to be 4902, 1830, and 557 based on 20a, 100a, and 500a, respectively, based on the relationship of the GWP with the R134a.

The GHG emissions from heating G1 and G2 with the GSHPs can be quantified with Eq. 1.

$$\mathrm{EM}_{\mathrm{GSHPs-Gi-j}} = M_{\mathrm{GSHPs-G}i-j} * f_{j-\mathrm{co}_2} + \frac{HE_{\mathrm{GSHPs,G}i}}{HE_{\mathrm{GSHPs,G}}} M_{\mathrm{R22,Gi}} * f_{\mathrm{R22-leak}} * f_{\mathrm{R22-co}_2} \quad (1)$$

where $\mathrm{HE}_{\mathrm{GSHPs,G}}$, total energy provided by the GSHPs for heating G1 and G2 during whole winter (monitored with TFM), MJ; $\mathrm{HE}_{\mathrm{GSHPs,G}i}$, total energy provided by the GSHPs for heating

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GHG	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	22,800	32,600
SF6	16,300	22,800	32,600

Note: Data were cited from IPCC 2006[5], expressed in CO_2 eq.

Table 3. GWP of different greenhouse gases

the greenhouse of type *i* (G1 or G2) during whole winter (monitored with TFM), MJ; $EM_{GSHPs-Gi-j}$, equivalent CO_2 emissions from the GSHPs for heating greenhouse *i* (G1 or G2) be driven by electricity generated in power plant *j* (CFPP or GFPP), kg CO_2 eq.; $M_{GSHPS\text{-}Gi-j}$, the coal or natural gas consumed in power plant *j* (CFPP or GFPP) for generating the electricity that the GSHPs had used for heating greenhouse *i* (G1 or G2), kg C or kg CH_4; $M_{R22,Gi}$, the amount of the refrigerant R22 in the GSHPs be allotted for heating greenhouse *i* (G1 or G2), kg; f_{j-} $co_{2\,2,}$ the CO_2 emissions coefficient of fossil energy (coal or natural gas) in power plant *j* (CFPP or GFPP), kg CO_2 eq. (kg C)$^{-1}$ or kg CO_2 eq. (kg CH_4)$^{-1}$; f_{R22-} $co_{2,}$ the equivalent CO_2 emissions coefficient of R22, kg CO_2 eq. kg^{-1} R22; and $f_{R22-leak}$, the leaking fraction of total R22, %.

The carbon (C) or natural gas (assumed to be 100% as CH_4 in calculating CO_2 emissions) consumed to produce the electricity consumed by the GSHPs was estimated for the CFPP and GFPP based on Eq. 2.

$$M_{\text{GSHPs}-\text{G}i-j} = \frac{3600\ \text{ELE}_{\text{GSHPs,G}i}}{\text{CV}_j} \tag{2}$$

where $ELE_{GSHPs,Gi}$, total electricity consumed by the GSHPs in heating greenhouse *i* (G1 or G2) during winter production, kWh; and CV_j, conversion factor between heat and electricity in CFPP or GFPP, 0.27 was used for CFPP, and 0.42 was applied to GFPP in this study [29].

The GHG emissions from the GSHPs were compared with two primary greenhouse heating systems used in northern China: the CFHs and the CFHs. The equivalent quantity of CO_2 emissions from the GSHPs, CFHs, and GFHs was quantified based on the same heat energy provided by the GSHPs during whole winter for the G1 and G2 (Eqs. 3–6). In northern China, the heating efficiencies of CFHs and GFHs were considered as 0.6 and 0.8, respectively [27, 29].

$$M_{\text{carbon}-\text{G}i} = \frac{\text{HE}_{\text{GSHPs,G}i}}{F_{\text{carbon}-\text{heat}} * f_{C-\text{HE}}} \tag{3}$$

$$M_{\text{Gas}-\text{G}i} = \frac{HE_{\text{GSHPs,G}i}}{F_{\text{gas}-\text{heat}} * f_{\text{G}-\text{HE}}} \tag{4}$$

$$\text{EM}_{\text{CFHs,G}i} = M_{\text{Carbon}-\text{G}i} * f_{\text{C}-\text{co}_2} \tag{5}$$

$$\text{EM}_{\text{GFHs,G}i} = M_{\text{Gas}-\text{G}i} * f_{\text{G}-\text{co}_2} \tag{6}$$

where EM_{CFHs}, CO_2 emissions from greenhouse CFHs, kg CO_2; EM_{GFHs}, CO_2 emissions from greenhouse GFHs, kg CO_2; $f_{\text{C–CO2}}$, CO_2 emissions coefficient of the CFHs, kg CO_2 (kg C)$^{-1}$; $f_{\text{G–co2}}$, CO_2 emissions coefficient of the natural GFHs, kg CO_2 (kg CH_4)$^{-1}$; $f_{\text{C–HE}}$, the heating efficiency of the CFHs, dimensionless; $f_{\text{G–HE}}$, the heating efficiency of the GFHs, dimensionless; $F_{\text{carbon–heat}}$, specific calorific value of burning per kg carbon, MJ (kg C)$^{-1}$; $F_{\text{carbon–heat}}$, specific calorific value of burning per kg natural gas, MJ (kg CH_4)$^{-1}$; $M_{\text{carbon–G}i}$, the carbon consumed in heating greenhouse i (G1 or G2) during whole winter, kg C; $M_{\text{gas–G}i}$, the natural gas consumed in heating greenhouse i (G1 or G2) during whole winter, kg CH_4; and $M_{\text{R22–G}i}$, the R22 used in the GSHPs be attributed to greenhouse i (G1 or G2) based on the proportion of heat energy received by G1 and G2, kg.

Under the normal temperature and atmospheric pressure (288 K and 1 atm), burning a kilogram of the standard coal (C) and natural gas (CH_4) in oxygen (O_2) completely has potential to emit 3.67 and 2.75 kg CO_2, respectively, with Eqs. 7 and 8 [30]. Meanwhile, the $F_{\text{carbon–heat}}$ and $F_{\text{gas–heat}}$ were quantified as 29.3 and 52.6 MJ for burning each kilogram of the C and CH_4, respectively.

$$1\,\text{kg C} + 2.67\,\text{kg O}_2 \rightarrow 3.67\,\text{kg CO}_2 + 29.3\,\text{MJ energy} \tag{7}$$

$$1\text{ kg CH}_4 + 4\text{ kg O}_2 \rightarrow 2.75\text{ kg CO}_2 + 2.25\text{ kg H}_2\text{O} + 52.6\text{ MJ energy} \tag{8}$$

Total GHG emissions from greenhouses heating in Beijing can be estimated based on the total area of greenhouses (similar to G1 or G2) and heat rate per square greenhouse floor (Eqs. 9–11):

$$\text{EMG}_{\text{Beijing,GSHPs},j} = \frac{A_{\text{G1, Beijing}} \times f_{\text{G1,heating}} \text{EM}_{\text{GSHPs,G1}-\text{elej}}}{480} + \frac{\text{A}_{\text{G2, Beijing}} \times f_{\text{G2,heating}} \text{EM}_{\text{GSHPs,G2}-\text{elej}}}{756} \tag{9}$$

$$\text{EMG}_{\text{Beijing,Carbon}} = \frac{A_{\text{G1, Beijing}} \times f_{\text{G2,heating}} \text{EM}_{\text{CFHs,G1}}}{480} + \frac{\text{A}_{\text{G2, Beijing}} \times f_{\text{G2,heating}} \text{EM}_{\text{CFHs,G2}}}{756} \tag{10}$$

$$EMG_{Beijing,gas} = \frac{A_{G1,\ Beijing} \times f_{G2,heating} EM_{GFHs,G1}}{480} + \frac{A_{G2,\ Beijing} \times f_{G2,heating} EM_{GFHs,G2}}{756} \quad (11)$$

Where, $EMG_{Beijing,GSHPs,\ j}$, equivalent CO_2 emissions from the GSHPs heating for greenhouses similar to G1 and G2 be driven electricity generated in the power plant *j* (CFPP or GFPP), kg CO_2 eq. in Beijing; $EMG_{Beijing,carbon}$, equivalent CO_2 emissions from the CFHs heating for greenhouses similar to G1 and G2 in Beijing, kg CO_2 eq; and $EMG_{Beijing,gas}$, equivalent CO_2 emissions from the GFHs heating for greenhouses similar to G1 and G2 in Beijing, kg CO_2 eq.

3. Results and Discussion

3.1. Emissions from the GSHPs

Total heat energy provided by the GSHPs for G1 and G2 were 149270.4 and 640659.1 MJ during 2007–2008 winter at the electricity consumptions of 10826.1 and 44372.2 kWh, respectively. The electricity consumed by the GSHPs usually came from the power plants of CFPP and GFPP in northern China. Therefore, the difference between the CFPP and GFPP in producing GHG at different stages of the SGE in the GSHPs was compared (Table 4).

	SGE extraction	SGE promotion	SGE heating	Inventory
Electricity from CFPP				
G1 electricity consumption, kWh	2440.6	7135.5	1250.3	10826.4
G1 standard coal consumption, kg C	1095.5	3202.7	561.2	4859.4
G1 GHG emissions, kg CO_2 eq.	4020.3	11754.0	2059.5	17833.8
G2 electricity consumption, kWh	10003.0	29245.0	5124.2	44372.2
G2 standard coal consumption, kg C	4489.8	13126.4	2300.0	19916.2
G2 GHG emission, kg CO_2 eq.	16477.4	48174.0	8440.9	73092.3
Electricity from GFPP				
G1 electricity consumption, kWh	2440.6	7135.5	1250.3	10826.4
G1 natural gas consumption, kg CH_4	397.7	1162.8	203.7	1764.2
G1 GHG emissions, kg CO_2 eq.	1093.7	3197.6	560.3	4851.6
G2 electricity consumption, kWh	10003.0	29245.0	5124.2	44372.2
G2 natural gas consumption, kg CH_4	1630.0	4765.6	835.0	7230.7
G2 GHG emission, kg CO_2 eq.	4482.6	13105.4	2296.3	19884.3

Note: (1) G1=480m^2, heated with GSHPs for 146 days; G2=756 m^2, heated with GSHPs for 111 days. (2) In calculating the CO_2 emissions, the CH_4 was assumed to be 100% chemical component of the natural gas.

Table 4. GHG emission from G1 and G2 heating with GSHPs.

In producing the amount of the electricity consumed by the GSHPs for G1 and G2, about 4.9 and 20 t of coal (C) were consumed in CFPP. If use the GFPP produced electricity, the total natural gas burned could be 1.8 and 7.2 t (CH_4). During 2007–2008 winter heating, the GWP of the GHG emissions from G1 and G2 (Figure 4) was estimated to be 18.3 and 74.9 t CO_2 eq. with the CFPP and 5.3 and 21.7 t CO_2 eq. with the GFPP, respectively, over a 20-year time horizon. The GWP of 100a was 1.5%–1.6% lower than 20a for G1 and 5.3%–5.4 % lower than 20a for G2 due to the reduced GWP on R22. Similar to HCFC-22, R22 has shorter atmospheric lifetime [5]. Generally, the CO_2 eq. contributed by the leak of R22 accounted for 2.4% and 8.4% in the scenarios of CFPP and GFPP, respectively.

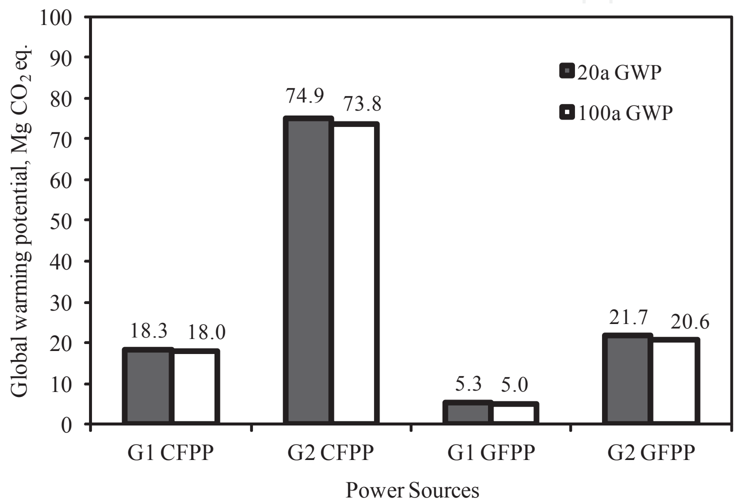


Figure 4. GWP of the GHG emissions derived from the GHSPs heating in G1 and G2.

Among different stages of the SGE flow, most GHG emissions (66%) happened at the stage of SGE promotion due to the higher consumption of electricity in compressors. Therefore, improving the efficiency of the compressors has the potential to reduce the GHG emissions from the GHSPs heating.

3.2. Greenhouse gas emissions from fossil energy systems

Providing G1 and G2 with the same quantity of heat that the GSHPs has provided (i.e., 149270.4 and 640659.1 MJ) requires the CFHs to consume 8.49 and 36.40 t of standard coal and the GFHs to consume 3.55 mg (4964 m^3 at 288 K and 1 atm) and 15.22 t (21,304 m^3 at 288 K and 1 atm) of natural gas (CH_4), respectively. Accordingly, the GHG emissions from heating G1 and G2 (Figure 5) were estimated to be 32.7 and 133.7 t CO_2 eq. for the CFHs system and 9.8 and 41.8 t CO_2 eq. for the GFHs system.

3.3. Standardized GHG emissions from greenhouse heating

The unit electricity consuming rate of the GSHPs was 0.15 and 0.53 kWh m^{-2} d^{-1} for heating G1 and G2 and which can be standardized as 1500 and 5300 kWh ha^{-1} d^{-1} in Beijing during

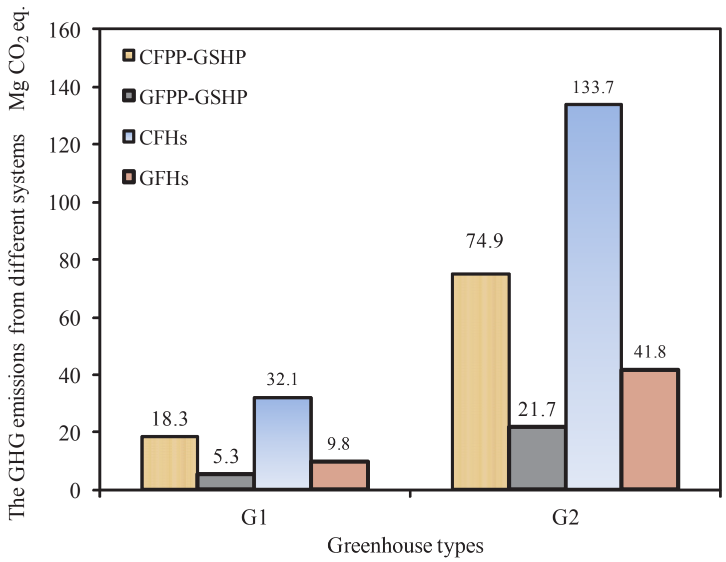
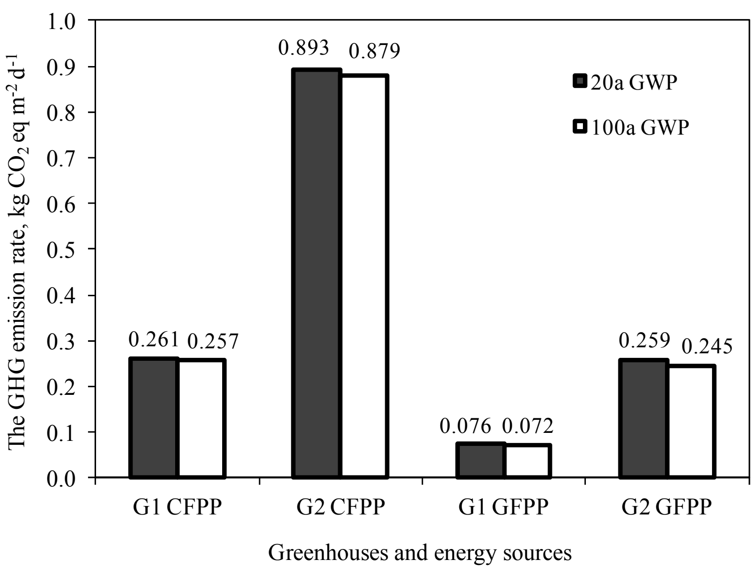


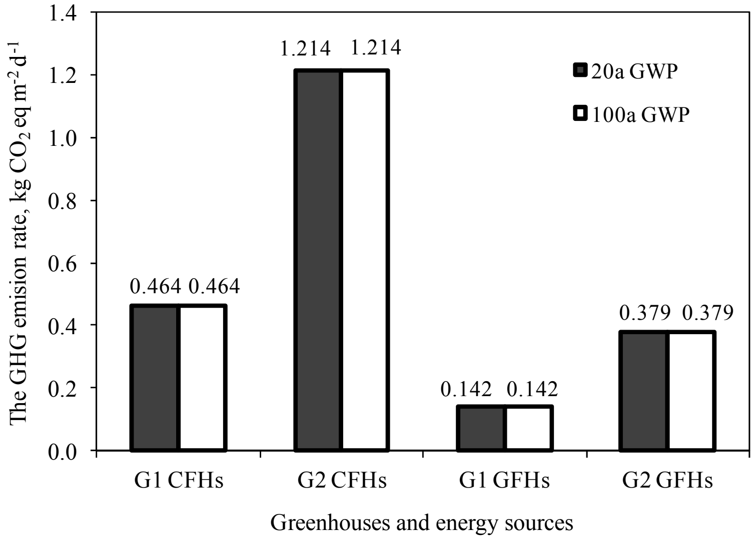
Figure 5. The GHG emissions from the GHSPs and the fossil energy systems.

2007–2008 winter. The 20a and 100a GWPs of the GHG emissions from the GSHPs heating for G1 and G2 (Figure 6a) were 0.076–0.893 and 0.072–0.879 g CO_2 eq. m^{-2} $d^{-1,}$ respectively. The GHG emission rate of G2 is 3.42 times of G1 because Chinese solar greenhouse has better heat-preserving capacity than multispan greenhouses.

Regarding to the CFHs and GFHs, the standardized GWPs of the GHG emissions (Figure 6b) were 0.142–1.214 CO_2 eq. m^{-2} day^{-1}, and there were no difference between 20a and 100a because the GWP of the CO_2 will not change with the time.



(a) The shallow geothermal energy



(b) The fossil energy

Figure 6. Standardized GHG emissions (GWP) for different greenhouse types and energy sources.

3.4. Emissions inventory in Beijing, China

According to the areas of the G1 and G2 in Beijing that require assisted heating (6000 ha Chinese solar greenhouses-G1 and 1000 ha multispan greenhouses-G2), the total GHG emissions from greenhouses heating with the CFHs or GFHs were quantified as 5238 or 2294 Mt CO_2 eq. in Beijing, and there is no difference between 20a and 100a GWP (Figure 7).

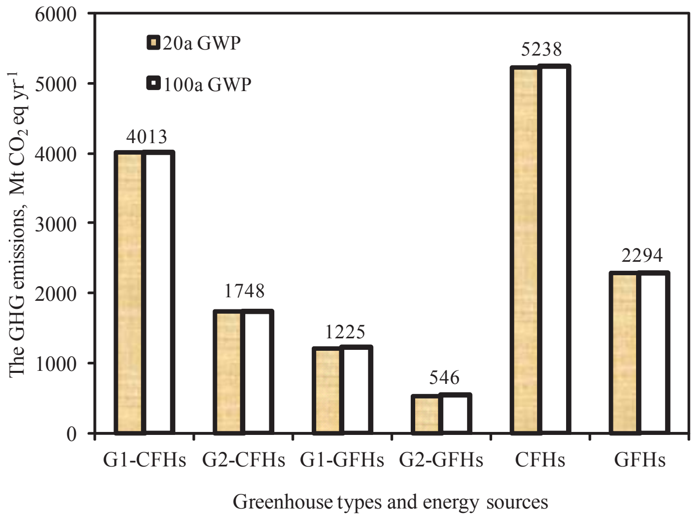


Figure 7. Total GHG emissions from heating greenhouses with fossil energies in Beijing.(G1-CFHs, heating all the G1-type greenhouses in Beijing with CFHs; G2-CFHs, heating all the G2-type greenhouses in Beijing with CFHs; G1-GFHs, heating all the G1-type greenhouses in Beijing with GFHs; G2-GFHs, heating all the G2-type greenhouses in Beijing with GFHs).

The total GHG emissions from heating greenhouses in Beijing with the GSHPs were quantified as 1658 and 2909 Mt CO_2 eq., based on 20a GWP or 1619 and 2839 Mt CO_2 eq. based on 100a GWP (Figure 8). The GHG emissions from heating G1-type greenhouses are higher than heating G2-type of greenhouses due to the large area of the G1 built and used in Beijing during 2007–2008 winter.

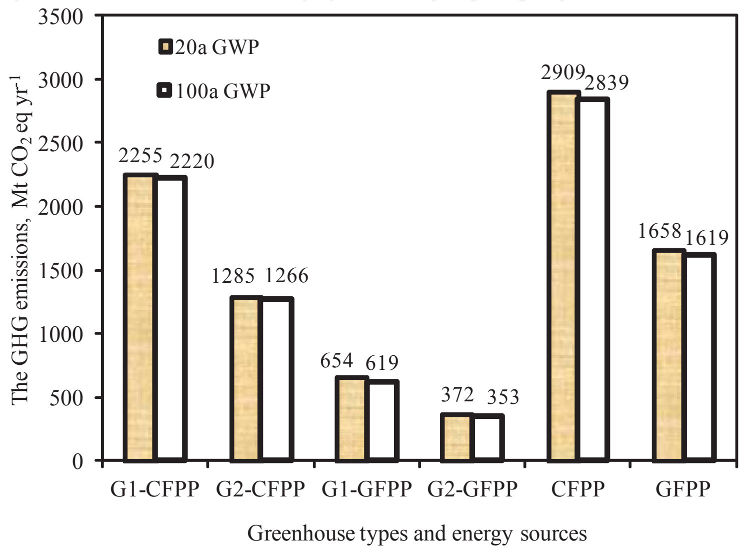


Figure 8. Total GHG emissions from heating greenhouses with the GSHPs in Beijing (G1-CFPP, heating all the G1-type greenhouses in Beijing with the GSHPs be powered with the electricity generated in CFHs; G2-CFPP, heating all the G2-type greenhouses in Beijing with the GSHPs be powered with the electricity generated in CFHs; G1-GFPP, heating all the G1-type greenhouses in Beijing with the GSHPs be powered with the electricity generated in GFHs; G2-GFPP, heating all the G2-type greenhouses in Beijing with the GSHPs be powered with the electricity generated in GFHs).

Applying the GSHPs to heat G1 and G2 with the electricity from the CFPP, the equivalent CO_2 emissions were 43% and 44% lower than directly burning coal with the CFHs but were 46.4% and 44.2% higher than the GFHs that burning natural gas. However, when using the GFPP generated electricity to run the GSHPs, the equivalent CO_2 emissions would be 83.5% and 83.8% lower than directly burning coal with the CFHs and were 45.9% and 48.1% lower than the GFHs that burning natural gas.

3.5. Uncertainty evaluation

It was assumed that all the solar greenhouse and multispan greenhouses with the same heating rate of G1 and G2 in this study, which would lead to errors due to the varying structures and materials in different greenhouses. For the solar greenhouses with improved wall materials and structures, the heat loss and heating rate would be lower [31]. Besides, heat-preserving technologies, such as multilayer aluminum foil heat reflecting materials, would have lower heat loss and heating rate than G2 in this study [3].

The shallow geothermal heat used in the GSHPs came from the groundwater (14°C), which has different GHG emissions from the borehole or U-tube-based HPs [19, 32]. Besides, the leaking factor of R22 was assumed to be 2% per year based on European studies, which may be changing with the change of the pump unit and maintenance of the system.

The GHG emissions calculated in this study are based on the real heating quantity required by G1 and G2 during winter heating, and the cycle of the SGE from extraction, enhance, and greenhouse heating was considered, the analysis can be considered as a partial life cycle assessment (LCA). However, a full LCA analysis could be applied to account the GHG emissions from greenhouse constructing with different materials, the transportation of the coal or natural gas for the location of the greenhouses, and the plants cultivated in the greenhouses [33-35].

In this study, we assumed that all the G1-type Chinese solar greenhouses would need additional heating in calculating the GHG emissions. However, novel structures and materials were applied for building Chinese solar greenhouses in Beijing in recent years [36], which improved the heat-preserving capacity of the greenhouse so that heating was not required in winter time. Therefore, the GHG emissions from heating Chinese solar greenhouse could be lower than the amount calculated in this study.

4. Summary

The unit electricity consuming rate of the GSHPs were 0.15 and 0.53 kWh m^{-2} d^{-1} for heating the Chinese solar greenhouse (G1) and multispan greenhouse (G2) or expressed as 1500 and 5300 kWh ha^{-1} d^{-1} in Beijing. The 20a and 100a GWPs of the GHG emissions from the GSHPs heating for G1 and G2 were 0.076–0.893 and 0.072–0.879 g CO_2 eq. m^{-2} $d^{-1,}$ respectively.

The total GHG emissions from heating greenhouses in Beijing with the GSHPs were quantified as 1658–2909 Mt CO_2 eq. Among different stages of the SGE flow, most GHG emissions (66%) happened at the stage of SGE promotion due to the higher consumption of electricity in compressors.

The total GHG emissions from greenhouses heating with the CFHs or GFHs were quantified as 5238 and 2294 Mt CO_2 eq. in Beijing, respectively. Applying the GSHPs to heat G1 and G2 with the electricity from the CFPP, the equivalent CO_2 emissions were 43% and 44% lower than directly burning coal with the CFHs but were 46.4% and 44.2% higher than the GFHs that burning natural gas. However, when using the GFPP-generated electricity to run the GSHPs, the equivalent CO_2 emissions would be 83.5% and 83.8% lower than directly burning coal with the CFHs and were 45.9% and 48.1% lower than the GFHs that burning natural gas.

The glass-covered G2 consumed more heating energy than G1 during the heating period. This demonstrated that the Chinese solar greenhouse design had better heat preservation than the glass greenhouse. Besides, novel structures and materials applied for building Chinese solar greenhouses in Beijing could further reduce the GHG emissions from heating.

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References

[1] Bot G.P.A. (2001). Developments in indoor sustainable plant production with emphasis on energy saving. Computers and Electronics in Agriculture, 30(1-3), 151-165.

[2] Torrellas M., Assumpcio A., Juan I.M. (2013). An environmental impact calculator for greenhouse production systems. Journal of Environmental Management, 118, 186-195.

[3] Ma C., Miao X. (2005). Agricultural Bio-environment Engineering. China Agriculture Press, Beijing, China.

[4] Dickson M.H., Fanelli M. (2013). Geothermal Energy: Utilization and Technology. Routledge.

[5] Intergovernmental Panel on Climate Change (IPCC). (2006). Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies (IGES) for the IPCC, Kanagawa, Japan.

[6] Bayer P., Saner D., Bolay S., Rybach L., Blum P. (2012). Greenhouse gas emission savings of ground source heat pump systems in Europe: a review. Renewable and Sustainable Energy Reviews, 16(2), 1256-1267.

[7] Self S.J., Reddy B.V., Rosen M.A. (2013). Geothermal heat pump systems: status review and comparison with other heating options. Applied Energy, 101, 341-348.

[8] Omer A.M. (2008). Ground-source heat pumps systems and applications. Renewable and Sustainable Energy Reviews, 12(2), 344-371.

[9] Sonneveld P.J., Swinkels G.L.A.M., Bot G.P.A., Flamand G. (2010). Feasibility study for combining cooling and high grade energy production in a solar greenhouse. Biosystems Engineering, 105(1), 51-58.

[10] Blum P., Campillo G., Kölbel T. (2011). Techno-economic and spatial analysis of vertical ground source heat pump systems in Germany. Energy, 36(5), 3002-3011.

[11] Hähnlein S., Bayer P., Ferguson G., Blum P. (2013). Sustainability and policy for the thermal use of shallow geothermal energy. Energy Policy, 59, 914-925.

[12] Adaro J.A., Galimberti P.D., Lema A.I., Fasulo A., Barral J.R. (1999). Geothermal contribution to greenhouse heating. Applied Energy, 64 (1-4), 241-249.

[13] Ozgener O., Hepbasli A. (2005). Experimental investigation of the performance of a solar-assisted ground-source heat pump system for greenhouse heating. International Journal of Energy Research, 29(3), 217-231.

[14] Underwood C.P., Spitler J.D. (2007). Analysis of vertical ground loop heat exchangers applied to buildings in the UK. Building Services Engineering Research & Technology, 28(2), 133-159.

[15] Ozgener O., Hepbasli A. (2007). A review on the energy and exergy analysis of solar assisted heat pump systems. Renewable & Sustainable Energy Reviews, 11(3), 482-496.

[16] Sethi V.P., Sharma S.K. (2008). Survey and evaluation of heating technologies for worldwide agricultural greenhouse applications. Solar Energy, 82(9), 832-859.

[17] Tong Y., Kozai T., Nishioka N., Ohyama K. (2010). Greenhouse heating using heat pumps with a high coefficient of performance (COP). Biosystems Engineering, 106(4), 405-411.

[18] Chai L., Ma C., Ni J.-Q. (2012). Performance evaluation of ground source heat pump system for greenhouse heating in northern China. Biosystems Engineering, 2012, 111(1), 107-117.

[19] Heikkila K. (2008). Environmental evaluation of an air-conditioning system supplied by cooling energy from a bore-hole based heat pump system. Building and Environment, 43(1): 51-61.

[20] Han R., Li W., Ai W., Song Y., Ye D., Hou W. (2010). The climatic variability and influence of first frost dates in northern China. Acta Geographica Sinica, 65 (5), 525-532.

[21] Luo W., de Zwart H. F., Dai J., Wang X., Stanghellini C., Bu C. (2005). Simulation of greenhouse management in the subtropics. Part I: Model validation and scenario study for the winter season. Biosystems Engineering, 90(3), 307-318.

[22] Tong G., Christopher, D.M., Li, B. (2009). Numerical modelling of temperature variations in a Chinese solar greenhouse. Computers and Electronics in Agriculture, 68(1), 129-139.

[23] Tong G., Wang T., Bai Y., Liu W. (2003). Heat transfer property of the wall in solar greenhouse. Transactions of the CSAE, 19(3), 186-189 (in Chinese with English abstract).

[24] Bartzanas T., Tchamitchian M., Kittas C. (2005). Influence of the heating method on greenhouse microclimate and energy consumption. Biosystems Engineering, 91(4), 487-499.

[25] Beijing Statistical Bureau (2008). Beijing Statistical Yearbook 2008. Chinese Statistical Press, Beijing.

[26] Li Z.M., Shen J., Wang Z., Gao L H., Chen Q.Y., Guo Y.X. (2011). Production efficiency analysis of solar greenhouse and plastic big-arch shelter in Beijing. China Veget, 22, 13-19.

[27] Chai L., Ma C., Zhang Y., Wang M., Ma Y., Ji X. (2010). Energy consumption and economic analysis of ground source heat pump used in greenhouse in Beijing. Transactions of the CSAE, 26(3), 249-254 (in Chinese with English abstract).

[28] Zhang J. (1999). Simplified Handbook for the Air Conditioning Professional. Beijing Industry Press, Beijing, China.

[29] Liu Y., Ma Z., Zou P. (2002). Heating Ventilating and Air Conditioning. China Building Industry Press, Beijing, China.

[30] Jones J C (2008). Atmosphere Pollution. www.bookboon.com

[31] Chai L., Ma C., Ji X., Yang R., Zhou Z., Bu Y. (2007). Performances analysis on the energy-saving materials utilized in building solar greenhouses in Beijing. Journal of Agricultural Mechanization Research, 8, 17-21 (in Chinese with English abstract).

[32] Blum P., Campillo G., Münch W., Kölbel T. (2010). CO_2 savings of ground source heat pump systems–a regional analysis. Renewable Energy, 35(1), 122-127.

[33] Russo G., Scarascia Mugnozza G. (2004). LCA methodology applied to various typology of greenhouses. In International Conference on Sustainable Greenhouse Systems-Greensys 2004, September, 691: 837-844.

[34] Torrellas M., Antón A., Ruijs M., Victoria N. G., Stanghellini C., Montero J.I. (2012). Environmental and economic assessment of protected crops in four European scenarios. Journal of Cleaner Production, 28, 45-55.

[35] Xing S., Xu Z., Jun G. (2008). Inventory analysis of LCA on steel-and concrete-construction office buildings. Energy and Buildings, 40(7), 1188-1193.

[36] Chai L., Wang B., Liu M., Wu Z., Xu Y. (2014). Dual-roof solar greenhouse—a novel design for improving the heat preserving capacity in Northern China. Natural Resources, 5(12), 681.