Economic performance evaluation of an active solar heat storage-release system for heating Chinese Solar Greenhouses

Wei Lu, Yi Zhang, Hui Fang, Bo Zhou, Ruifeng Cheng, Qichang Yang*

Abstract. In this study, the economic and environmental performance of four active solar heat storage-release (AHS) systems compared with four other conventional heating systems (as practical options in northern China) were investigated in an experimental test of their ability to store energy during the daytime and heat a Chinese solar greenhouse (CSG) at night during the cold winter in northern China. The case-4 AHS performed best in terms of economic performance compared with the other three designs and four other conventional heating systems. However, future investigations of the long-term performance and environmental impact of AHS heating in greenhouses are needed and further improvements must be developed.

1. Introduction
Typical Chinese solar greenhouses (CSGs) are mainly located in northern China, with its low carbon footprint and high affordability, the CSG is the dominant protected horticultural facility in northern China [1,2]. The local climate in this region is characterised in winter by a combination of a high ratio of direct-to-global radiation and low outdoor temperatures. The north wall stores surplus heat during the daytime and releases it at night. It also shields the greenhouse from the prevailing north wind [3,4]. With this passive energy storage and release and high insulation at night, CSGs remain frost-free as indoor temperatures decrease to approximately 5-10°C, even during cold nights with outdoor temperatures of -20°C [5].

The large diurnal amplitudes of solar radiation and outdoor air temperature are linked to the problems of overheating during the day and low temperatures at night during the cold months. These problems seriously affect the quality and production of greenhouse fruits, vegetables and flowers [2]. Therefore, the growth and development conditions of these crops must be improved. A low-price, active heat storage-release (AHS) system was developed, and the thermal performance of CSGs utilizing this system was studied [6]. Yang et al. [7] and Liang et al. [8] reported on the performance of a prototype of an improved AHS system that used an aluminium absorption plate. However, despite its improved performance, the cost of this more efficient AHS systems compared with other conventional heating systems are still missing for commercial use. Thus, a study of the economic and environmental performance of AHS is needed to enable improvements in AHS design. In this study, four AHS systems were compared with four conventional heating systems used primarily for greenhouse heating in...
northern China to analyse their economic and environmental performance.

2. Materials and methods

2.1. Experimental setup
All experiments were conducted in 8 identical CSGs in the Shunyi District of Beijing (latitude 40°26′ N, longitude 116°52′ E). The AHS systems were installed in four CSGs, while the other four CSGs were reference greenhouses without an AHS. The AHS system had three components: 1) solar collector/release units differing as characterised; 2) a heat storage tank with 8 m³ capacity; and 3) plumbing with insulated rigid PVC pipes (5 cm diameter) connecting the collector and the storage tank.

2.2. Instrumentation
Temperatures were measured using Type T thermocouples (manufacturer claimed accuracy ±0.2°C). Three radiation-shielded air temperature sensors were placed in the middle of the greenhouse at a height of 1.5 m and at distances of 2 m, 4 m and 6 m from the north wall, as indicated in figure 2. Three antirust-treated thermocouples were mounted in the water tank. Solar irradiation at the north wall was measured with a pyranometer (model CMP3, Kipp & Zonen, Delft, The Netherlands). The pyranometer was installed vertically along the south-north centreline of the north wall surface at a height of 1.5 m. All abovementioned temperatures and solar irradiation were recorded with a CR1000 data logger at intervals of 10 min. A manual read electric power metre (T8, Northmeter Co., Ltd., Shenzhen, China) was used to measure the electricity consumption of the water pump.

2.3. Economic performance evaluation of the AHS system
The power consumption of the water pump is the only energy consumption \( E_{\text{con}} \) of an AHS.

\[
E_{\text{con}} = W_p \tau_p \tag{1}
\]

where \( W_p \) is the electric power of the water pump, \( W \), and \( \tau_p \) is the water pump total run time, s.

The economic performance of the AHS system was analysed and compared with the performance of four conventional heating systems that are commonly used in greenhouse heating in northern China based on the same energy input as the AHS and the local energy prices (electricity, coal, natural gas and...
diesel) obtained during the experimental period. The heating costs of the AHSs and other heating systems were calculated using equations (2)-(4) [9,10]:

\[ E_x = \frac{E_i}{C_{o,x}CV_x} \quad (2) \]

\[ CH_x = E_x P_x \quad (3) \]

\[ CH_{x,d,A} = \frac{CH_x}{A_gD} \quad (4) \]

where \( E_x \) is the equivalent energy consumed by heating system \( x \) to provide the primary energy in the experimental greenhouse in kWh for AHS and EHS, kg for CFH and DFH, and m\(^3\) for GFH; \( C_{o,x} \) is the energy conversion efficiency of heating system \( x \), \%; \( CV_x \) is the specific calorific value of the energy source consumed by heating system \( x \), in kJ kWh\(^{-1}\) for electricity, kJ kg\(^{-1}\) for coal and diesel and kJ m\(^{-3}\) for natural gas; \( P_x \) is the unit cost of the energy source in heating system \( x \), in US$ kWh\(^{-1}\) for electricity, US$ kg\(^{-1}\) for coal and diesel and US$ m\(^{-3}\) for natural gas; \( CH_x \) is the cost of heating in US$; \( CH_{x,d,A} \) is the cost of heating per square metre greenhouse area per day in US$ m\(^{-2}\) d\(^{-1}\); \( A_g \) is the experimental greenhouse area in m\(^2\); and \( D \) is the total heating time, d.

### 2.4. Environmental performance evaluation of AHS

The chemical reactions for coal, natural gas and diesel burning in pure oxygen can be expressed with the following equations [11,12]:

\[
\begin{align*}
1 \text{ kg C} + 2.67 \text{ kg O}_2 & \xrightarrow{\text{combustion}} 3.67 \text{ kg CO}_2 + 1.5 \text{ kg H}_2\text{O} + 29.3 \text{ MJ heat} \\
1 \text{ kg CH}_4 + 4 \text{ kg O}_2 & \xrightarrow{\text{combustion}} 2.75 \text{ kg CO}_2 + 2.25 \text{ kg H}_2\text{O} + 52.6 \text{ MJ heat} \\
1 \text{ kg C}_{16}\text{H}_{34} + 3.47 \text{ kg O}_2 & \xrightarrow{\text{combustion}} 3.12 \text{ kg CO}_2 + 1.35 \text{ kg H}_2\text{O} + 46.2 \text{ MJ heat}
\end{align*}
\]

The equivalent quantities of carbon dioxide (CO\(_2\)) emissions from the heating systems were calculated in this study as follows:

\[ EC_x = E_x\gamma_x \quad (8) \]

\[ EC_{x,d,s} = \frac{EC_x}{A_gD} \quad (9) \]

where \( EC_x \) is equivalent CO\(_2\) emissions from heating system \( x \), kg, and \( \gamma_x \) is the CO\(_2\) emission coefficient of heating system \( x \), which includes CO\(_2\) emissions when burning 1 kg coal, natural gas or diesel, kg (CO\(_2\)) kg (\( E_x \))\(^{-1}\). The \( \gamma_x \) values for coal, natural gas and diesel are 3.67, 2.75, and 3.12 respectively, and \( EC_{x,d,s} \) is the equivalent CO\(_2\) emission rate per square metre in the greenhouse heating area per day with system \( x \), kg m\(^{-2}\) d\(^{-1}\).

### 3. Results and discussion

#### 3.1. Economic performance of the AHS system

In this part, the economic performance of the four AHS systems was investigated using equations (1) to (4), with case 4 as the baseline case. The peak price and valley price of electricity were 0.226 US$ kWh\(^{-1}\) and 0.064 US$ kWh\(^{-1}\), respectively, during the experimental period in Beijing.

Table 1. Comparison of the energy sources and heating costs during the experimental period of case 4.

| Thermo-economic parameters | Case 1 | Case 2 | Case 3 | Case 4 | EHS | CFH | GFH | DFH |
|---------------------------|--------|--------|--------|--------|-----|-----|-----|-----|
| Total energy consumption\(^a\) kWh | 566 | 499 | 707 | 485 | 1788 | 348 kg | 203 m\(^{-3}\) | 156kg |
| Caloric value (C\(_{vk}\)), kJ kWh\(^{-1}\) | 3600 | 3600 | 3600 | 3600 | 3600 | 29306 kg\(^{-1}\) | 37590 m\(^{-3}\) | 46200 kg\(^{-1}\) |
| Energy conversion efficiency (C\(_s\)) %\(^b\) | 3 | 3.4 | 2.4 | 3.5 | 0.95 | 0.6 | 0.8 | 0.85 |
| Energy price (P\(_s\)), US$ kWh\(^{-1}\) | 0.145 | 0.145 | 0.145 | 0.145 | 0.145 | 0.145 | 0.532 kg\(^{-1}\) | 1 kg\(^{-1}\) |
| Unit heating cost, US$ m\(^{-2}\) d\(^{-1}\) | 0.0069 | 0.0060 | 0.0086 | 0.0059 | 0.0217 | 0.0042 | 0.0090 | 0.0130 |
Table 1 also illustrates the economic performance comparison results among AHS (cases 1, 2 and 3), EHS, CFH, GFH and DFH during the test. The heating cost of the AHS in case 4 was lower than that in cases 1, 2 and 3 by 16.7%, 2.9% and 45.8%, respectively, and lower than the EHS, GFH and DFH by 267.8%, 53.6% and 121.8%, respectively, but higher than the CFH by 28.2%. With an expected 15% increase in tomato production in the reference greenhouse [7], the payback period of the AHS system was calculated as approximately 5 years with depreciation cost of approximately 0.00252 US$ m⁻² d⁻¹ and 10 years as the designed life. Taking labour, maintenance, depreciation and other costs into consideration and assuming 15 years as the same designated life for EHS, CFH, GFH and DFH, the total daily costs of the heating systems are shown in Table 1. The total heating cost of the AHS in case 4 was lower than those in cases 1, 2 and 3 by 8.6%, 3.4% and 13.7%, respectively; lower than the EHS, GFH and DFH by 74.8%, 11% and 30.2%, respectively; and higher than the CFH by 12.9%.

3.2. Environmental performance of the AHS
In China, approximately 75% of the electrical energy is generated by coal-fired power plants (CFPP). Using equations (5) to (9), figure 3 compares the equivalent CO₂ emissions in the case 4 experimental period with the different systems. For the greenhouse heating using the case 4 AHS during the entire testing period, the equivalent CO₂ emissions were reduced by 16.7%, 2.9% and 45.8% compared with cases 1, 2 and 3, respectively; reduced by 268.7% and 57.7% compared with the EHS and CFH, respectively; and increased by 50.4% and 39.9% compared with GFH and DFH, respectively. However, if the electricity energy expended by the AHS was generated by burning the gas with a thermoelectric conversion and transmission efficiency of 42% [15,16], the case 4 AHS, in fact, would emit 40.4% and 50.8% less CO₂ than the GFH and DFH in heating the greenhouse.

Figure 3. Comparison of equivalent CO₂ emission rates during the baseline case 4 heating period using different heating systems.

4. Conclusions
Economic and environmental performance of four AHS cases was evaluated in comparison with four widespread conventional heating systems in northern China, the total heating cost of the AHS in case 4 was lower than that in cases 1, 2 and 3 by 8.6%, 3.4% and 13.7%, respectively. The total heating cost of the AHS in case 4 was lower than the EHS, GFH and DFH by 74.8%, 11% and 30.2%, respectively. The total heating cost of the AHS in case 4 was higher than the CFH by 12.9%. Case 4 demonstrated better economic and environmental performances than the other three designs in this study. Future investigations of the long-term performance and environmental impact of AHS heating in greenhouses are needed.
Nomenclature

| Abbreviations   | Chinese Solar Greenhouse |
|-----------------|--------------------------|
| CSG             | Chinese Solar Greenhouse |

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