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A low cost seasonal solar soil heat storage system for greenhouse heating: Design and pilot study

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HIGHLIGHTS

- A low cost seasonal solar soil heat storage system used in greenhouse is invented.
- Establish TRNSYS model of heat collection & storage with calibration of actual data.
- Use EnergyPlus to calculate energy saving compared with conventional solar system.
- Use TRNSYS model to further modify the system by optimizing key system parameters.
- Pilot study is conducted and SSSSHS system proves to be energy efficient in Shanghai.

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ABSTRACT

A low cost Seasonal Solar Soil Heat Storage (SSSHS) system used for greenhouse heating was invented and investigated. With soil heat storage technology, the solar energy stored in soil under greenhouse can be utilized to reduce the energy demand of extreme cold and consecutive overcast weather in winter. Unlike conventional underground heat systems, heat pumps are not needed in this system and so the cost is drastically reduced. After the tests, the system proved that seasonal thermal energy storage (STES) is feasible and can partially solve the solar heat demand and supply imbalance problem between summer and winter. TRNSYS is used to simulate the process and effect of solar energy collection and soil heat storage, and the model is calibrated by operational data in a full season. Energy consumption of the SSSHS system and conventional solar heating system have been compared under the same condition: when the indoor air temperature of the greenhouse is kept above 12 °C throughout the year, the energy saving in Shanghai was 27.8 kW h/(m^2 typical greenhouse area · year). In the end, the paper discusses the system optimization, including the optimized solar collector area and depth of buried U-pipes, and the results of a pilot test.

1. Introduction

Greenhouse heating is becoming one of the most energy consuming activities during winter. Greenhouses can protect plants from freezing in winter and expedite the growth. However, for high yields, short cultivation time, improved quality and quantity of the products, plants usually still need fossil fuel heating, especially during winter nights [1].

Space heating of traditional greenhouses in China is primarily provided by coal stoves, natural gas, combustion of straw, electric heating wires, etc. Because greenhouses are not well insulated, these traditional heating practices consume a large amount of energy, cause severe pollution and increase greenhouse gas emissions to the atmosphere. On the other hand, modern solar energy technologies offer a clean, renewable and domestic energy source, and may offer a technical solution to this problem. In general, solar energy is an essential component of the sustainable energy future in agriculture [2].

Simple solar collection systems can be used for greenhouse heating. However, the traditional solar collection systems used for space heating have a disadvantage. As shown in Fig. 1, indoor air temperatures of green houses are high enough in most time of spring, summer and fall, when no heating is needed. While in winter, especially during nights and overcast days, the greatest demand for space heating occurs when the solar insolation

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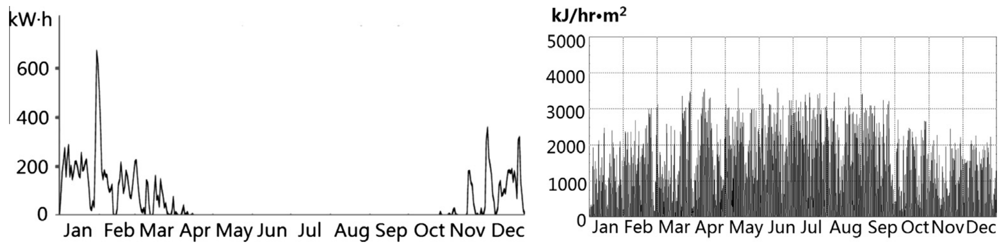

Fig. 1. Annual heating load of a typical greenhouse and horizontal annual solar radiation power in Shanghai.

intensity is at its lowest. The natural imbalance between supply and demand periods precludes the wide use of simple solar heating systems in greenhouses.

In order to overcome this problem, energy storage is an effective solution to use the solar heat collected in the daytime for space heating when is required. However, most agricultural applications are short-term (diurnal) storage [3–5], which can only deal with a small part of heating loads and may not be sufficient in consecutive overcast and rainy days. In contrast, seasonal thermal energy storage (STES), also called long-term storage, which uses excess heat collected in summer to compensate for the heat supply insufficiency in winter can be an attractive option. Fisch et al. [6] compared the cost-benefit-ratio of existing and planned large-scale solar heating systems in Europe, and concluded that seasonal storage was more capable of conserving energy and reducing fossil fuel consumption than short-term storage.

Over recent decades, many researchers have carried out related studies addressing solar applications and storage mechanisms throughout the world [7–10]. There are three different energy storage mechanisms: sensible heat storage, latent heat storage and chemical reaction/thermos-chemical heat storage [11]. The use of water [12], rock [13] and ground [14] as sensible heat storage media has been studied deeply, while the precise simulation of underground conditions should be further investigated in order to improve the storage efficiency. Latent heat storage (LHS) with phase change materials (PCMs) can offer higher energy density and is considered to serve as an efficient energy storage option. However, current LHS projects are mainly used for short-term purposes due to the lack of long-term stability in PCMs [15]. Chemical storage is characterized by its high storage potential with low heat losses. The feasibility of chemical heat storage has been presented in some short-term systems [16,17], while no large-scale seasonal project has been completed because the current related studies are still at the theoretical and testing stage [11].

Compared to the other alternatives, sensible heat storage technologies are considered to be simple, low-cost and relatively mature, among which the UTES (underground thermal energy storage) in aquifers or in soil is more favorable than other technologies from both technical and economic perspectives [18]. Although the BTES (borehole thermal energy storage) in soil has several drawbacks, such as high initial cost [19], complicated underground conditions of water and vapor movement [18,20] and long-time requirement for reaching typical performance [21], it has received considerable attention for its potential in large-scale applications, such as the Drake Landing Solar Community in Okotoks, Alberta, Canada [22]. In addition, the BTES has been introduced into greenhouse heating recently [14,23], which is inspired by previous seasonal BTES applications in residential heating [10,12,21,24].

Simulation tools are usually applied to guide the design of solar thermal system and sizing of components. Building performance simulation (BPS) software can be used to model space heating loads and some BPSs are able to model innovative HVAC systems, like seasonal solar thermal systems [25–28]. As for the UTES simulation, many researchers have studied the underground heat and mass transfer modelling [29–31] in order to analyze the possibility of using soil as a seasonal heat storage option.

To evaluate the performance of heat exchange and storage in soil, some algorithms of heat exchange are investigated. The most widely-used one is DST (Duct Ground Heat Storage) model. DST was developed by Hellström in 1989 [32] and adapted for the first time to be run through TRNSYS [33] in 1996 by Nordell and Hellström [25]. Despite its quite complicated structure, the DST model is efficient from a computational point of view. Besides, DST is often referred as the benchmark method of simulating underground tubes and is conceived for simulating large and compact heat storage.

Most seasonal thermal storage systems use heat pump systems as their heating sources. Researchers have proved that the Ground Source Heat Pump (GSHP) system utilized in greenhouses has advantages over the traditional systems [34]. But the cost of the system is relatively high, especially the heat pump, which prevents the system from being widely used in Chinese agriculture. Although improved systems like GSHP, photovoltaic-GSHP and GSHP–PCM (phase change material) are invented [35], which makes GSHP more environmental-friendly and energy-efficient, their initial costs are too high and they are even harder to be adopted in developing countries like China.

To solve the energy imbalance and high cost problems, we designed and tested an inexpensive and environment-friendly seasonal solar soil heat storage (SSSHS) system that can be used for greenhouse heating. The SSSHS system is easy to install and little training is required for operation. The estimated payback period of SSSHS is 5–6 years for greenhouses in Shanghai, depending on the agriculture products. With soil heat storage technology, the solar heat stored underground during spring, summer and fall can be used for heating in winter without heat pump. TRNSYS has been used to simulate the system performance in order to quantify and calculate the heat exchange and system dynamics. The solar collector area as well as the depth and number of the buried U-pipes have been analyzed and optimized by the model. The results were used to decide whether the SSSHS system is cost effective in Shanghai, and useful in other places.

2. Materials and methods

2.1. SSSHS system description

The SSSHS system applied for greenhouse heating consists of 5 parts (see Figs. 2 and 3). They are solar collector subsystem, soil heat storage subsystem, greenhouse heating subsystem, hydronic subsystem and control subsystem. The soil heat storage subsystem is buried U-pipe heat exchangers underground. The greenhouse heating subsystem is capillary radiators. The hydronic subsystem consists of water pipes, pumps and valves. The hydronic subsystem connects with the solar collector subsystem, the greenhouse capillary radiators and the U-pipe heat exchangers buried in soil. The control subsystem commands hydronic subsystem for ON/OFF

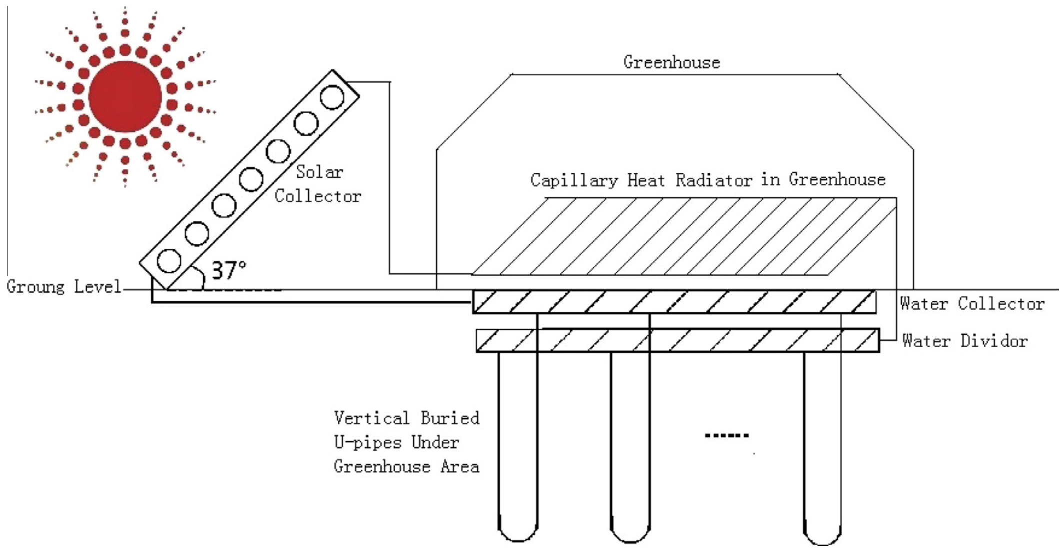

Fig. 2. Simple diagram of the seasonal solar soil heat storage system.

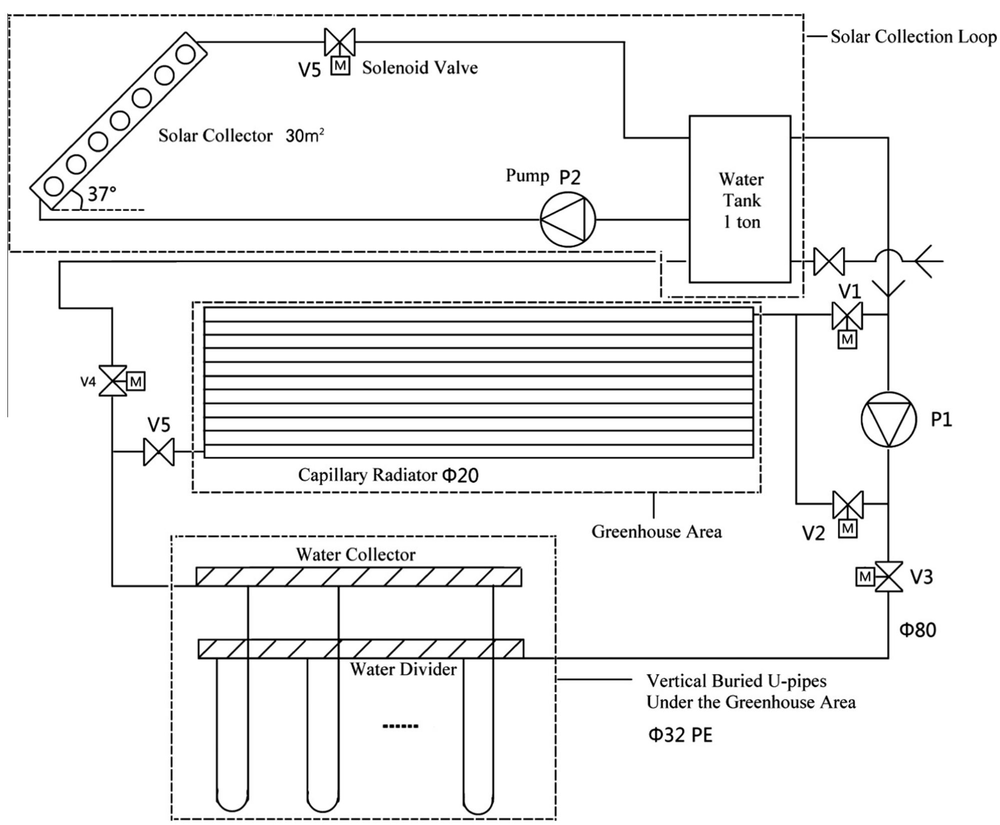

Fig. 3. Detailed diagram of the seasonal solar soil heat storage system.

status. The greenhouse capillary radiators are located inside the greenhouse, on top of the soil. The solar collector subsystem, the hydronic subsystem and the control subsystem are located outside the greenhouse.

Table 1 shows the parameters of a standard size of greenhouse (231 m^2) SSSHS system in Shanghai, including the sizes of solar collectors, capillary radiators, U-pipe heat exchangers and hydronic subsystem. The Standard Greenhouse is a standardized and widely-used one in China, conforming to Chinese national greenhouse standards: GB/T 18622-2002.

It is worth mentioning that the tilt angle of the solar collector (37°) in Shanghai (normal tilt angle in ordinary solar systems in Shanghai is 30°) can ensure the maximum direct solar heat collection during winter and cold spring time, when heating is most needed.

2.2. System operation modes

The SSSHS system has three operation modes to meet the operational requirement of storing solar heat in spring, summer and

Table 1
System parameters.

Standard greenhouse	
Size of greenhouse	38.5 m(L) × 6 m(W) × 3 m(H)
Envelop structure	Metal stand and bilayer plastic membrane
Solar collector subsystem	
Solar collector area	30 m^2
Type	Vacuum-tube
Orientation and tilt angle	South, 37°
Capacity of the water tank	1000 kg
Capillary radiators	
Tube diameter	2 mm
Coverage area	77 m^2
U-pipe heat exchangers	
Tube diameter	32 mm
Well depth	15 m
Number of the wells	25
Distance between wells	3 m
Hydronic subsystem	
Pipe diameter	80 mm
Actual average flow rate	7.1 m^3/h

fall, solar heating in winter, and storage heating in winter. The logic functions of these three modes are stored in DDC (Digital Direct Control) system on site.

Mode 1: Heat storage mode in spring, summer and fall

Hot water provided by the solar collector exchanges heat with soil through the circulation pump. Greenhouses need no space heating but need ventilation in most time during spring, summer and fall. So in this mode, the water in tank 3 is heated by solar collector 5, and then is used to store the heat in soil via circulation pump 4. In such case, electromagnetic valve V1, V2 and V4 are closed, which enables solar collector 5 to heat water and the hot water is then transported to the vertical U-pipes buried in soil, as seen in Fig. 4.

Mode 2: Direct solar heating mode in winter

The hot water provided by the solar collectors is used as working fluid to go directly through the capillary radiators in the greenhouse and to exchange heat with the air. In Shanghai, the outdoor air temperature is about 0–5 °C on clear days in winter, and the air temperature in the agricultural greenhouse is about 10 °C without space heating. Generally speaking, crops need an ambient temperature of above 15 °C to grow and above 5 °C to avoid frost bite. Thus the greenhouse needs space heating in cold clear winter days. In this mode, the hot water heated by solar collector 5 goes not through the vertical buried U-pipes, but through the surface layer capillary in the agricultural greenhouse and heat up the space next to the crops directly. In such case, electromagnetic valve V1, V3 and V5 are closed, which enables hot water from solar collector 5 to be transferred to the capillary radiator inside agricultural greenhouse, as seen in Fig. 4.

Mode 3: Soil heating mode stored heat in winter

Outdoor air temperature is about −5 to 0 °C in winter nights or during daytime under overcast weather conditions. The air temperature in greenhouse is about 5 °C without space heating. The system will change to *Mode 3* to release the stored underground heat for space heating. The circulate water went through underground vertical tubes and be heated first. Then the water goes through the capillary radiators in the greenhouse and releases the heat to the inside space of the greenhouse. In this mode, the solar collector is disconnected from the circulation system and the heat stored in soil is delivered to the surface layer capillary radiators in the greenhouse. In such case, electromagnetic valve V2 and V6 are closed, the heat stored in the soil is delivered to the capillary radiators, as seen in Fig. 4.

2.3. SSSHS models

The heating load is simulated by EnergyPlus [36] and the process of solar collection and soil heat storage were simulated through TRNSYS [33]. TRNSYS is a complete and extensible simulation environment for the transient simulation of systems, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, etc.

The system model consists of solar collection loop and thermal storage loop. Solar collection loop operates according to the control logic described in Subsection 2.2 throughout the year, while the thermal storage loop operates according to the control logic only between April and October when the greenhouse needs no space heating. The TRNSYS model inputs were the actual sizes and parameters of the solar collector, water tank, soil and the buried U-pipes in the experimental platform of the SSSHS system. The structure and layout of the solar collection model and the soil heat storage model are shown in Fig. 5.

2.3.1. Solar collection loop

The weather file used in TRNSYS simulation is CN-Shanghai-583670 (typical meteorological year of 2005). The solar collection loop consists of solar collector model, water tank model, pump model and controller. The solar collector is responsible for collecting heat, which is an important part in the system. The solar collection was modeled in TRNSYS using Type1b corrected in the second-order incidence angle. The control logic Ctrl_1 has the same function as that in the actual control logic. The solar collection loop will start when the temperature difference between the outlet and inlet water of the solar collector is greater than 8 °C, and will stop when such temperature difference is smaller than 4 °C.

The specific parameter setting of tank model in TRNSYS is shown as follows. Type: fluid-filled sensible energy storage tank with stratification; tank volume: 1.0 m^3; tank loss coefficient: 2.5 kJ/h m^2 K; height of temperature sensor: 0.3 m; set point temperature: 60 °C; dead band for heating: 5 °C; environment temperature: read from weather file CN-Shanghai-583670.

Parameter setting of solar collector model is shown as follows. Type: solar collector-quadratic efficiency, 2nd order incidence angle modifiers; collector area: 30 m^2; tested flow rate: 7.1 m^3/h; conversion efficiency: 0.8; orientation and tilt angle: south, 37°.

Parameter setting of Pump_1 model is shown as follows. Type: pump model using variable control function; maximum flow rate: 7100 kg/h; maximum power: 67 W; conversion coefficient: 0.05; power coefficient: 0.5.

2.3.2. Thermal storage loop

The thermal storage loop consists of water tank model, vertical buried U-pipe heat exchanger model, pump model, and control logic. The vertical U-pipe heat exchangers buried in soil are responsible for storing and releasing heat. The multi-tube buried U-pipe heat exchangers were modeled in TRNSYS using Type557 (Vertical Ground Heat Exchanger), which is the DST (Duct Ground Heat Storage) model [37] developed by Hellström in the lab of mathematical physics at Lund University in Sweden. The model adopts the vertical cylinder heat source model symmetrical to its center. The model assumes that the boreholes inside the cylinder heat exchangers of the soil heat storage are well-distributed. The heat exchange pattern is assumed to be

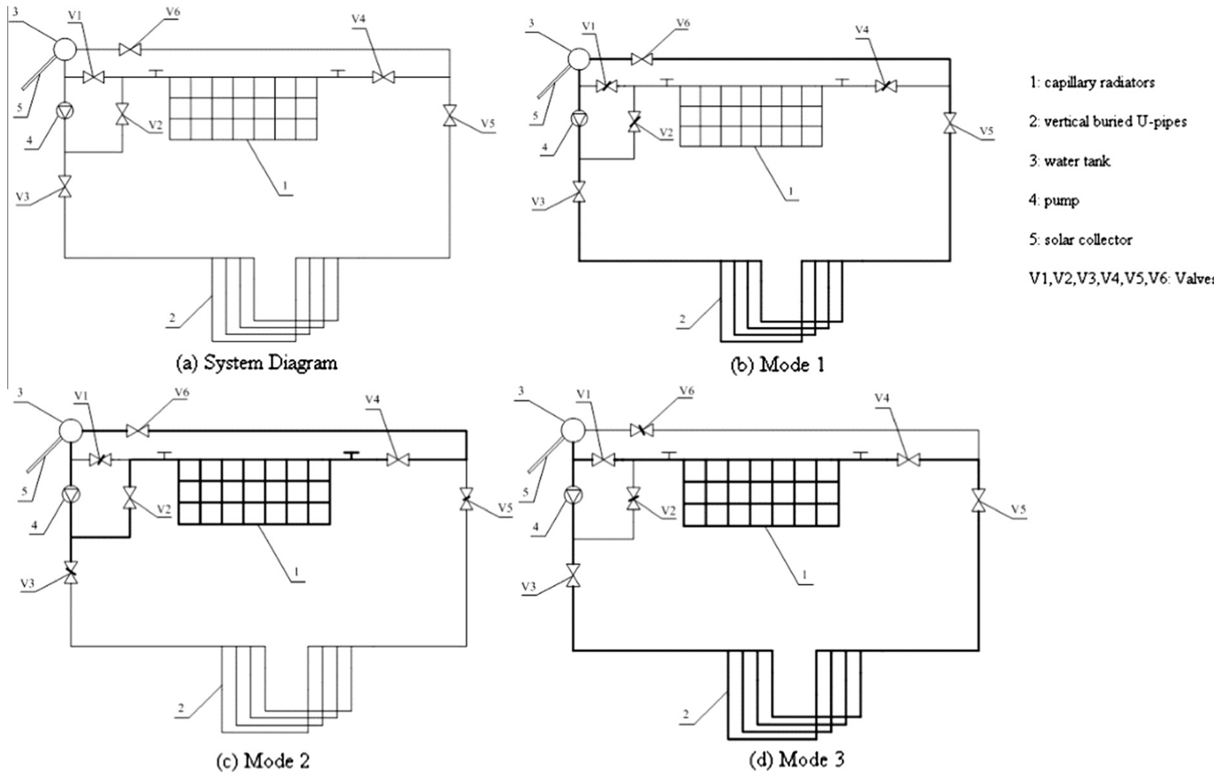

Fig. 4. Greenhouse heating system with seasonal solar heat storage and its three operation modes.

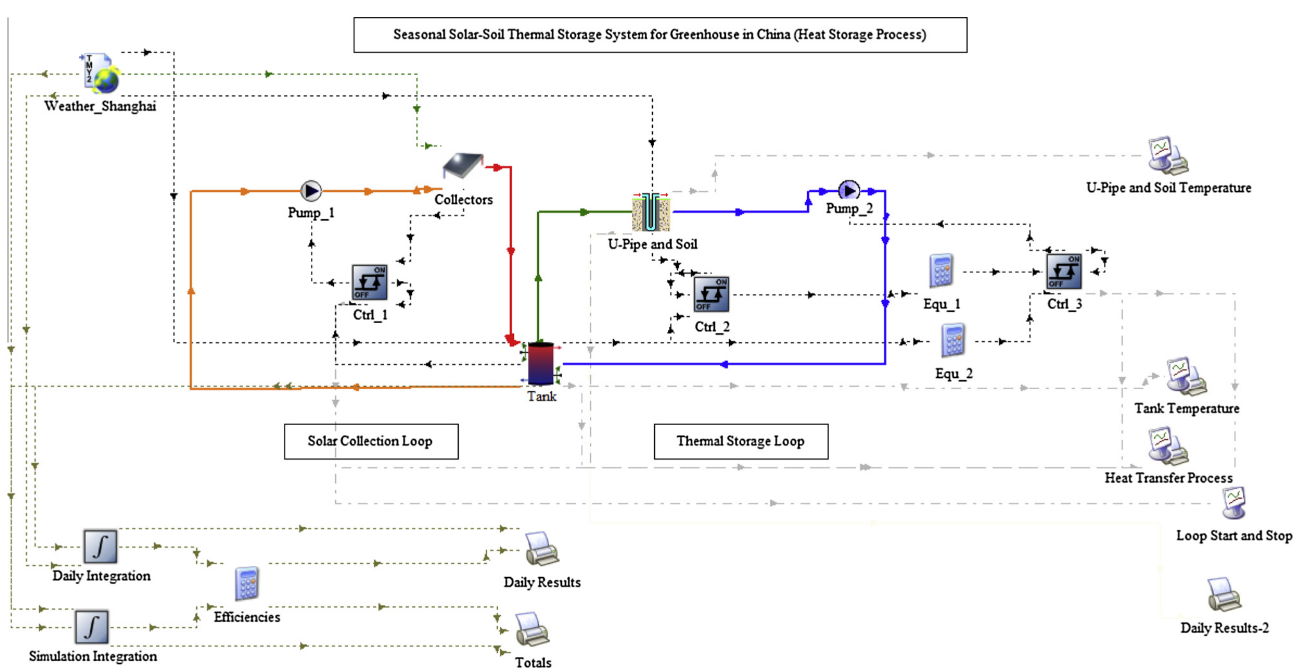

Fig. 5. TRNSYS model of solar energy collection and soil heat storage.

convection inside the boreholes and conduction outside. The model also assumes that many adiabatic boards be assigned outside the heat exchangers. The soil temperatures consist of 3 parts: the total heat exchange temperature, the partial heat exchange temperature and the steady fluid temperature. The calculation model takes into full consideration the influence of factors such as outdoor air and heat distribution at the bottom of boreholes on ground heat exchangers, which makes the calculation results closer to the actual condition. DST takes the heat exchange inside and outside the boreholes as an entirety to calculate.

The specific parameter setting of U-pipe and Soil is shown as follows. Type: heat storage soil and U-pipe model; soil volume for heat storage: 2921 m^3; borehole depth: 15 m^3; header depth: 1.0 m; number of boreholes: 25; borehole radius: 0.1016 m; storage thermal conductivity: 4.68 kJ/(h m K); storage heat capacity: 2016.0 kJ/(m^3 K); outer and inner radius of U-pipe: 0.01664 m, 0.01372 m; center-to-center half distance: 0.0254 m; fill thermal conductivity: 4.68 kJ/(h m K); pipe thermal conductivity: 1.51 kJ/(h m K); gap thermal conductivity: 5.04 kJ/(h m K); reference borehole flow rate: 7100 kg/h; insulation sickness: 0.0254 m; insulation thermal conductivity: 1.0 kJ/(h m K); thermal conductivity of soil: 4.68 kJ/(h m K).

The module Ctrl_2, Ctrl_3, Equ_1 and Equ_2 in Fig. 5 has the following function. The thermal storage loop will start when the water temperature in the tank exceeds 40 °C and the temperature difference between the water in the tank and the outlet water of U-pipe is greater than 10 °C, and the loop will stop when such temperature difference is smaller than 5 °C.

3. Results

3.1. Performance model calibration

The weather file used in TRNSYS simulation, namely CN-Shanghai-583670 (typical meteorological year of 2005), is unable to reflect actual weather conditions of the experiment precisely. To solve the problem, the performance model was calibrated against the measured results of the system. More specifically, the efficiency of solar collector will be calibrated according to the actual heat stored in the soil through U-pipes in one day. Although the heat collection of the solar collector and the water tank are very important in the heat storage process, it is the heat stored in soil through U-pipes that determines the heat storage effect. Thus the actual heat exchanged with soil can be calculated according to the inlet/outlet water temperature and the flow rate of the water through U-pipes recorded by the data logger attached to the system. Such value was compared with the simulation result to modulate the actual efficiency of the solar collector module in TRNSYS in order to make the heat transfer effect of U-pipes in the model the same as the actual one. A day is chosen from the storage period during April and October for the comparison. As seen in Fig. 6, the total heat stored underground of Sep. 20th in 2013 is displayed. The time interval of data recorders is 30 s. 2880 sets of data of flow rate, inlet and outlet water temperature of U-pipe in Sep 20th are obtained, as shown in Fig. 6. The total heat is calculated through the inlet and outlet water temperature difference and the water flow rate: $Q = \sum_{i=1}^{2880} C_p \dot{m}_i (T_{out,i} - T_{in,i}) \Delta t$, $\Delta t = 30$ s. The stored heat on that day was 1.86E5 kJ.

In the simulation weather file, namely Sep. 15th of 2005 in the CN-Shanghai-583670 (typical meteorological year of 2005) has the same average solar radiation (300 W/m^2) and average air temperature (26 °C) as those on Sep. 20th. The TRNSYS simulated heat stored underground with 0.8 efficiency (default value) in the collector model and with no calibration is 2.06E5 kJ. Then, the efficiency of the solar collector module in TRNSYS (“Collectors” in Fig. 5) was adjusted from 0.80 to 0.72 in order to match the testing results.

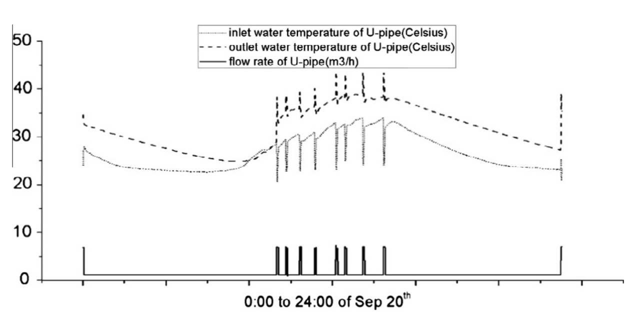

Fig. 6. Inlet/outlet water temperature and water flow rate of the buried U-pipe recorded by data logger on Sep. 20th.

3.2. Simulation results of solar energy collection, soil heat storage, heat loss and center soil temperature

Adding the daily heat flow rates together, the model is able to calculate the accumulative solar radiation of the collector, the heat stored in the water tank, the heat stored in soil and the heat loss via the surrounding soil. The solar energy collection, soil heat storage and heat loss are shown in Table 2.

Results show that 44.2% of solar thermal energy is transferred to the water tank. The tank is used as direct energy storage equipment in hot days and an indirect one in cold days. From April to October, 92.8% of the energy stored in water tank is transferred into soil. The energy loss from the tank to the underground soil in one year is about 12.7%.

Similarly, the result of temperature increase in soil during April and October is used to understand the thermal capacity. The soil temperature is the center soil temperature of Type 557 in the TRNSYS model, which is illustrated in Table 3 and Fig. 7. The initial center soil temperature was 15.01 °C on March 1st. The center soil temperature after the heat storage period during April and October was heated up by 6.3 °C.

3.3. Energy saving estimation

The difference between the SSSHS system and the conventional solar heated greenhouse is that, the SSSHS system has less or even no need for auxiliary heating. This is in particular true under extreme cold and consecutive overcast weather conditions in winter, when conventional solar heated greenhouses require a large use of energy for auxiliary heating. So the energy saving comes mainly from the auxiliary heating. In this study, two identical greenhouses with the same solar collector are modeled and the auxiliary heating consumption is compared with each other. The extra energy used by the SSSHS system on pumps is considered

Table 2
Solar energy collection, soil heat storage and heat loss.

Month	Accumulative solar radiation of the collector (kJ)	Heat stored in the water tank (kJ)	Heat stored in soil (kJ)	Heat loss via the surrounding soil (kJ)
March	1.11E + 07	4.22E + 06	–	9.01E + 05
April	1.24E + 07	5.13E + 06	5.03E + 06	5.28E + 05
May	1.34E + 07	5.66E + 06	5.32E + 06	4.13E + 05
June	1.33E + 07	6.13E + 06	6.00E + 06	2.56E + 05
July	1.64E + 07	8.65E + 06	8.47E + 06	1.18E + 05
August	1.43E + 07	7.46E + 06	7.09E + 06	3.03E + 05
September	1.47E + 07	7.64E + 06	6.62E + 06	8.55E + 05
October	1.14E + 07	5.34E + 06	4.17E + 06	9.03E + 05
November	9.10E + 06	3.37E + 06	–	9.05E + 05
December	1.07E + 07	4.10E + 06	–	1.02E + 06
January	8.21E + 06	2.54E + 06	–	1.12E + 06
February	1.23E + 07	4.90E + 06	–	9.66E + 05

Table 3
Center soil temperature with and without heat storage.

	Soil temperature with heat storage (°C)	Soil temperature without heat storage (°C)
March	15.01	15.01
April	15.96	15.18
May	17.00	15.38
June	18.11	15.59
July	19.58	15.83
August	20.82	16.05
September	21.97	16.24
October	22.70	16.40

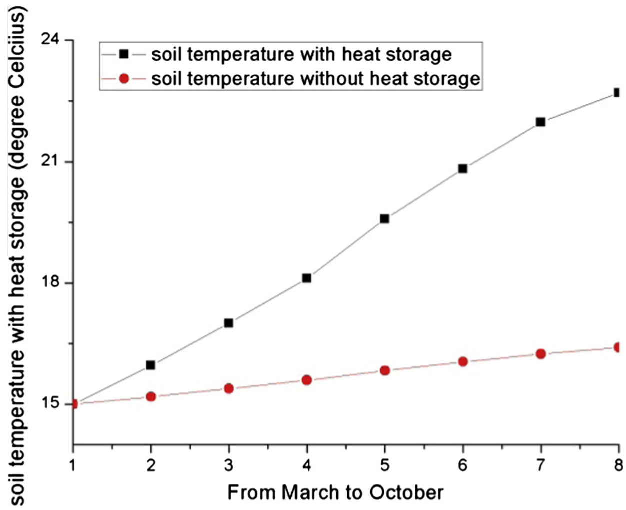

Fig. 7. Comparison of the center soil temperature with and without heat storage.

as well. EnergyPlus was used to calculate the energy consumption of the electrical heating in the ordinary solar heating system when the design temperature was kept at 12 °C in winter. The energy consumption of the two greenhouses was compared to obtain the energy saving with the energy consumption of the pump, the electromagnetic valves and the control box when using the SSSHS system.

In EnergyPlus, a standard greenhouse model was established. The standard greenhouse is conforming to Chinese national greenhouse standards: GB/T 18622-2002, and is exactly the same as the actual greenhouse we built. The parameters of orientation, envelop, temperature control, auxiliary heating arrangement and weather file of the greenhouse are set according to the actual situation, which are shown in Figs. 2, 3 and Table 1.

As shown in Fig. 8, the simulation result illustrates that the heating load of the greenhouse is 4.13E7 kJ. The auxiliary electrical heating energy used in the conventional solar heating system throughout the year is 7668.07 kW h, which equals to 33.2 kW h/(m^2 typical greenhouse area · year). The energy consumption calculated by TRNSYS of auxiliary heating, pump and electromagnetic valves in the SSSHS system throughout the year is 5.4 kW h/(m^2 typical greenhouse area · year). Then the energy saving of SSSHS system over conventional solar heated greenhouses equals to **27.8** kW h/(m^2 typical greenhouse area · year).

3.4. Heat storage efficiency and energy saving effects

From March to October, a total heat of 9.59E7 kJ is collected from the solar collector and 4.60E7 kJ is stored in soil, indicating an energy conversion ratio of 48.0%. Energy loss consists of two parts: system energy loss and heat loss via soil. They, respectively, account for 48.0% and 7.3% of the total energy collected from the solar collector. 7.3% of the underground heat loss is not the storage

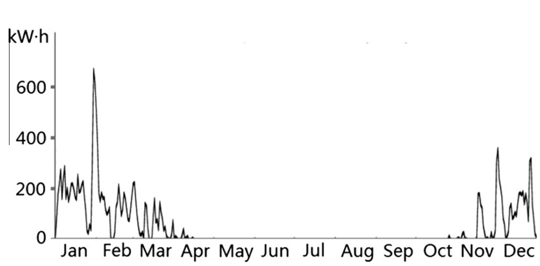

Fig. 8. The annual heating load of the greenhouse simulated by EnergyPlus.

loss over seasons, but the loss during the summer time. The underground soil temperature stays high for a relatively long period. The center soil temperature, 38.4% higher than the control group, also proves the efficiency of soil storage.

According to the calculation in Subsection 3.3, the energy saving equals to 27.8 kW h/(m^2 typical greenhouse area · year), comparing to standard greenhouse using simple solar system. For a standard greenhouse of 231 m^2 in Shanghai, 6,421.8 kW h of electricity will be saved every year. The agriculture electricity rate in China is USD0.083/kW h and so the total saving equals to USD530.32/year.

3.5. System optimization

3.5.1. Optimization of the solar collector area

The solar collector in the SSSHS system is smaller than that without the SSSHS system because the stored thermal energy can cover a part of heating load. Due to heat balance in a year, the heating load must not be smaller than the amount of the heat directly received from the solar collector plus the heat stored in soil and then minus the heat loss via soil. The solar collector area must be compliant with such formula. Similarly, the solar collector area cannot be designed too large; otherwise the initial investment will be too high, making the system less affordable.

The heating load of the greenhouse throughout the year was simulated using EnergyPlus. The greenhouse model was developed and calculated according to the information of the greenhouse, such as the actual area, orientation, envelop structure and temperature control strategy, in EnergyPlus. When the air temperature in the greenhouse is smaller than 12 °C, the space heating will start to automatically control the room air temperature to the scheduled set point. This is because the crop planted in the greenhouse involved in this paper was blueberry, whose normal growth rate can be guaranteed at 12 °C.

The simulation result shows that the heating load of the greenhouse is 4.13E7 kJ. According to the accumulative heat of the system in Table 2, throughout the year the heat directly supplied by solar radiation in winter is 1.91E7 kJ, the heat stored in soil is 4.27E7 kJ, and the heat loss via soil is 8.29E6 kJ. Thus, the total heat gain of the system is: 1.91E7 kJ + 4.27E7 kJ − 8.29E6 kJ =5.41E7 kJ > 4.13E7 kJ, which can meet the formula of heat balance and we are confident that the heating load estimated by EnergyPlus is within a reasonable accuracy range.

According to the simulation result of heat storage in TRNSYS and the simulation result of greenhouse heating load, the sum of the directly supplied heat and the stored heat is greater than the heat needed in winter. Thus, the solar collector area can be reduced properly so that the heat gain can satisfy 120% of the needed heat supply, namely designing the safety coefficient of additional 20%. The solar collector area can be reduced from 30 m^2 to 27.5 m^2, which is the optimized area of the solar collector. In conclusion, as for the SSSHS system involved in this paper, the solar collector area can be designed 1/9 of the greenhouse area in Shanghai.

3.5.2. Optimization of the U-pipe depth and its influence on heat storage effect

The depth and the number of the buried U-pipes in the model and Type 557 were changed. But the total length of the U-pipes was ensured to keep 375 m in order to compare the heat loss throughout the year with the initial temperature under 20 °C. The results are shown in Table 4 and Fig. 9.

The simulation result shows that the deeper the U-pipes, the less the heat loss with the total pipe length unchanged. Thus, when drilling cost remains unchanged with the depth, the U-pipe depth should be maximized, as long as it is within an allowable range of geological conditions.

Table 4
Annual soil heat loss in the system at different depths of the buried U-pipes.

Depth of the buried U-pipes (m)	Number of the buried U-pipes	Annual soil heat loss in the system (E + 06 kJ)
10	38	2.18
15	25	2.06
20	19	1.76
30	13	1.34
50	8	0.94
100	4	0.55

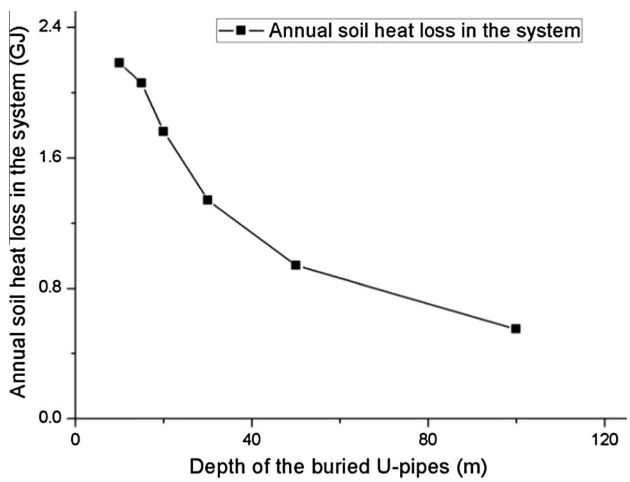

Fig. 9. Annual soil heat loss in the system at different depths of the buried U-pipes.

3.6. Pilot test results and cost benefit analysis

After the detailed analysis, two pilot SSSHS systems with green houses are constructed in Shanghai. One is located at Tongji University and the other is in Blueberry Planting Base in Shanghai rural area. The construction is relatively simple and lasts five months. The size of each farm is 231 m^2 and the solar collector area is 30 m^2 with a one-ton water tank. Inside the greenhouses, insulation board was paved on top of the soil to provide better insulation. The insulation not only can prevent heat loss in winter via the ground, but also can keep heat stored in underground soil from losing in fall. On top of the board, the capillary system used a radiator heat exchanger. We chose 200 potted blueberries as the farming crops. Blueberry is a popular fruit in China and has a high sale price per unit weight, which can be used to justify the additional investment of the SSSHS system. The picture of greenhouse inner space is shown in Fig. 10A.

The result of the first year test is positive. Because the greenhouse is much warmer than other greenhouses with no heating in winter, blueberries were bloomed 2 months earlier (Fig. 10D). The fruits were ready for being picked up in May instead of July. Blueberries are scarce in May, so they can be sold at a high price (retail: USD50–65/1 kg), about 50–100% higher than the price in July. Without SSSHS, farmers have to heat up their greenhouses with fossil fuel or electric heating to realize early harvest. What is more, well temperature-controlled blueberries can increase 20% production compared with the control group. As a result, the economy benefit to use SSSHS in blueberry greenhouses includes 120% higher production and 50–100% higher price.

The blueberry production is weighed by School of Agriculture Science and Technology at Tongji University, and the selling price is strictly recorded. After confirmation of the blueberry production of both two pilots at Tongji University and Xinbang Blueberry Planting Base respectively, knowing the selling price of blueberry in Shanghai and the blueberry loss during the transportation, the sale of the blueberries in SSSHS farm is USD3953.5 in the pilot of Tongji University, with a total blueberry output of 75.4 kg. Considering that there are no professionals for cultivation in the university pilot and no fertilization and appropriate irrigation, the output should be better. The harvest time lasts from May to

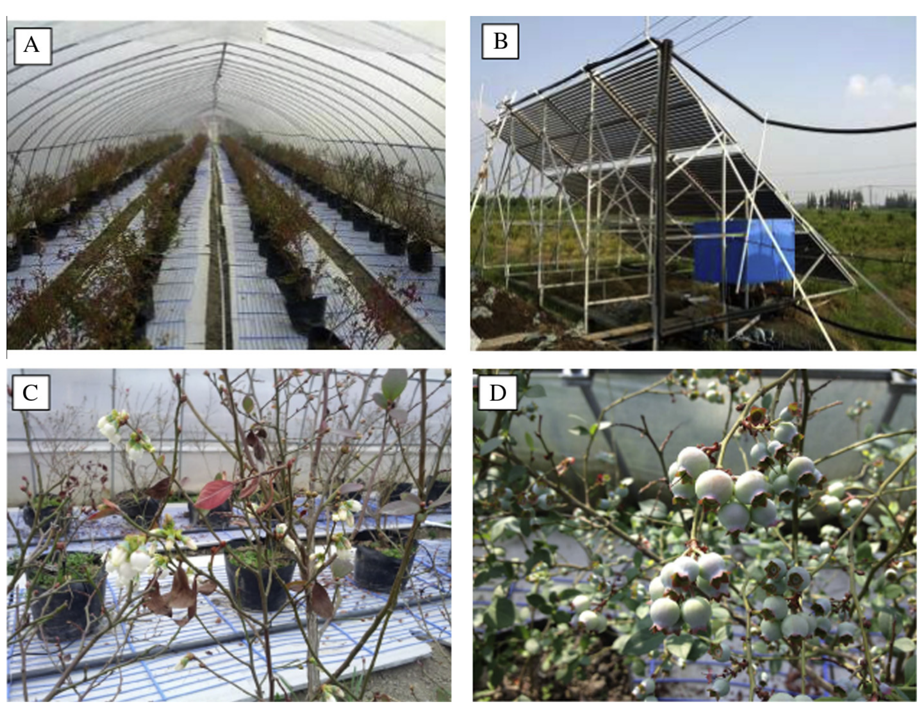

Fig. 10. Pilot greenhouse farms with the SSSHS system. (A) Interior layout; (B) Solar collector; (C) Blue berry early blooming; (D) Blueberry two weeks before harvesting.

Table 5
Cost and benefit analysis.

	University pilot	Xinbang pilot
Plant Form	Pot cultured	Soil planted
Number of plants	198	120
Sales (USD)	3954	3505
Benefits (USD)	10,894	1558
Costs (USD)	7258	7258
Cost of Capital (per yr.)	7%	7%
Dynamic Payback Period (yr.)	5.45	6.15

July and concentrates in mid-May to late-June. It is a very good phenomenon that the blueberry harvest period is prolonged at least one month. Its benefit is clear, by avoiding all the blueberries maturing at the same time when there is a labor shortage for fruit-picking service and rush sale. The characteristics of prolonged harvest period, thanks to the SSSHS system, indirectly increases the value of products.

The costs of two pilots are almost the same, each of them consisting of two parts: a system construction fee of USD5,645.1 and labor costs of USD1,612.9. The total cost is USD7258. Detailed values of the cost, benefit and payback period are summarized in Table 5.

4. Conclusions

A low cost and energy efficient solar and energy storage system, specifically designed for greenhouse heating is presented in this paper. The SSSHS system can store solar heat in spring, summer and fall in order to utilize the stored energy in winter when the weather is cold. The first year operation proves that the system is economically feasible for a wide use in developing countries.

The SSSHS system has 3 operation modes in order to solve the problem of solar energy in summer and use it in winter. They are heat storage mode in spring summer and fall, direct heating mode with solar heating in winter, and stored heat discharge mode in winter.

Compared with conventional solar heated green houses, the main advantage of the SSSHS system reflects in its less or even no need for auxiliary heating for frost prevention when the weather is consecutively cold and overcast in winter. A simulation has been conducted through calibrated TRNSYS models to compare the auxiliary electricity consumption of the SSSHS system and conventional solar heating system under the same condition. If the indoor air temperature of the greenhouse is kept above 12 °C throughout the year, the energy saving of using the SSSHS system in Shanghai is 27.8 kW h/(m^2 typical greenhouse area · year).

Two factors, the solar collector area and the buried U-pipe depth, are important in SSSHS system design. These two factors determine the amount of solar energy collection, the heat storage effect in soil, and the system cost with the given control logic. Analysis of the TRNSYS simulation calibrated by the actual results shows that, as for the SSSHS system in climate area such as Shanghai, the optimized area of the solar collector is about 1/9 of the greenhouse area. If the drilling cost does not change with the U-pipe depth, increasing the U-pipe depth can make the system more effective, as long as the depth is within an allowable range of geological conditions.

The use of SSSHS systems in two pilots in Shanghai is studied. The economy benefit to use SSSHS in blueberry greenhouses includes 120% higher production and 50–100% higher price. The theoretical dynamic payback period of two application, calculated with one-year actual sales data, is 5.45 and 6.15 years respectively.

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