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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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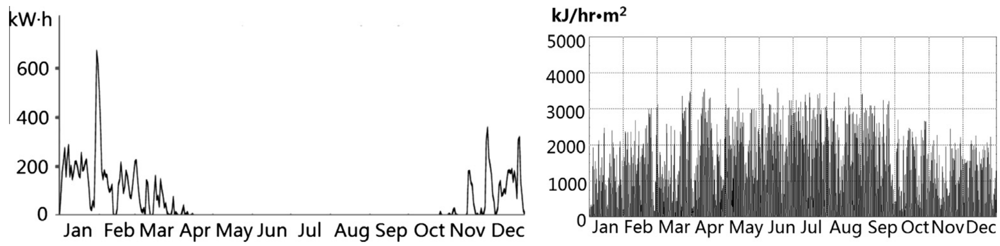

Fig. 1. Annual heating load of a typical greenhouse and horizontal annual solar radiation power in Shanghai.

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