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Seasonal thermal energy storage system for cold climate zones: A review of recent developments

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ABSTRACT

A number of seasonal thermal energy storage (STES) systems have been deployed for heating in cold climate zones due to potential utilisation of solar energy. It overcomes the drawback on intermittency of solar energy and contributes to storing heat from summer to be used in winter. Heat pump and solar collectors with low-temperature storage are the influencing factors to improve the system performance. This paper investigates STES systems integrated with heat pump and solar collectors for heating applications in cold climate zones based on the current available literature. Furthermore, various simulation models and software tools related to STES system were reviewed. This study discusses potential STES systems for space heating system in cold climate zones based on various parameters such as heating demand, climate conditions, and availability of solar resources, storage temperature, energy efficiency, and life cycle cost (LCC). A simple calculation method was applied to demonstrate the potential contribution of different STES options. The double U-tube borehole thermal energy storage (BTES) integrated with ground coupled heat pump (GCHP) and evacuated tube solar collector (ETSC) system was found to be most appropriate for space heating in cold climate zones. The analysis indicated that the system could have higher overall energy efficiency than the traditional space heating systems. Furthermore, a decision support flow chart was presented based on STES options.

1. Introduction

The building sector is a second largest user of energy after the manufacturing sector [1]. According to the International Energy Agency (IEA), 47% of the global energy consumption is for providing heat, out of which more than 50% is utilised in residential and commercial buildings [2] (see Table 1). The space heating contributes to more than 30% of the global residential energy consumption [3]. The building sector is responsible for approximately one-third of black carbon particle emissions and 30% of greenhouse gas (GHG) emissions globally [3]. The current onsite energy generation for heating and cooking is one of the independent contributing factors in increasing the GHG emissions of the residential sector.

Increase in population and number of buildings caused an increase in energy demand for space heating, especially in cold climate zones. The challenge is more intense in developing countries, where the traditional methods, such as direct burning of wood and coal, are still applied to provide the heat. This contributes significantly to the local air pollutions that affect people's health and wellbeing. Therefore, alternative solutions that avoid the fossil based energy supply for space heating could significantly reduce the GHG emissions. While the solar energy technologies are getting mature and more common, the intermittent nature of availability is a limiting factor to provide space heating for building use. This can be addressed by applying thermal energy storage (TES), a type of energy storage different from batteries. Based on the current state of technology, batteries are still expensive for storing the energy for space heating. Compared to batteries, TES is more economical and feasible technique to store the energy for space heating because of batteries cannot store large amounts of energy in a small volume [4].

Solar energy can be stored either short-term (diurnal) or long-term (seasonal) depending on the demand and availability. In the seasonal thermal energy storage (STES) technique, the available solar radiation in summer is harvested by solar thermal collectors and stored in large storage tanks or in the ground to be used during winter. The STES system is one of efficient systems for the heating application in building sector, especially in cold climate zones [5,6]. The STES systems are typically categorised in four types; hot-water thermal storage (HWTS), borehole thermal energy storage (BTES), aquifer thermal energy storage (ATES) and water gravel pit storage (WGPS). Among these types,

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Nomenclature

A	area (m^2)
C_p	specific heat capacity ($J\,kg^{-1}\,K^{-1}$)
D	borehole depth (m)
GT	ground temperature (°C)
L	length of pipe (m)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
q_c	heat produced by a solar collector ($MJ\,m^{-2}$)
q_b	extracted energy from ground (MJ)
$\dot{q}$	heat transfer rate (W)
Q_{hd}	heating demand (MJ)
Q_{loss}	heat loss from the seasonal storage (MJ)
Q_{tank}	stored energy in the tank (MJ)
r	radius (m)
SF	solar fraction (%)
T	temperature (°C)
W_{hp}	work of heat pump (MJ)

Greek letters

η_c	Carnot efficiency (-)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)

Abbreviations

AOC	annual operation cost
ATES	aquifer thermal energy storage
BTES	borehole thermal energy storage
BHE	borehole heat exchanger
COP	coefficient of performance
ETSC	evacuated tube solar collector
FIC	first installation cost
FPSC	flat plate solar collector
GCHP	ground coupled heat pump
GHE	ground heat exchanger
GHG	greenhouse gas
GWHP	ground water heat pump
HTR	heat transfer rate
HP	heat pump
HWTS	hot water thermal storage
IEA	International Energy Agency
LCC	life cycle cost
N	present worth
STES	seasonal thermal energy storage
SC	solar collector
STC	solar thermal collector
SWHP	surface water heat pump
TES	thermal energy storage
WGPS	water gravel pit storage
UGSC	unglazed solar collector

Subscripts

c	collector
h	heating mode
hp	heat pump
in	inlet
ins	insulation
out	outlet
pe	polyethylene
sin	heat sink
sor	heat source

the ATES and BTES are most commonly used due to their cost-effectiveness [7]. More recently, BTES system design has been improved by leveraging the advancement in geological engineering knowledge. In 1956 the first combine borehole heat exchanger with solar collector was proposed by Penrod and Prasanna [8] then extended this idea to store energy in the ground [9]. The performance of BTES depends on its configuration such as single or double U-tube heat exchangers as well as the depth of borehole, heat conduction in the ground and heat convection inside the U-tube. For the optimise configuration within different parameter limits; various analytical, numerical and simulation methods and design tools can be used [10].

This paper provides a detailed investigation of various parameters (options) of a STES system such as thermal storage temperature, heat pump capacity, solar collector area, storage volume, borehole depth, heat exchanger type, heat demand, and life cycle cost to enable a clear understanding of the relationships among these parameters. This would provide designers and researchers with a systematic understanding to select and configure the system based on the local conditions and the predicted heat demand, especially for cold climate regions.

2. Seasonal thermal energy storage (STES) system

The long-term (seasonal) STES system could satisfy 50–100% of annual heat demand, whereas the short-term (diurnal) system could meet approximately 10–20% of annual heat only [11–13]. A thermal storage system is designed based on the heat demand, heat source availability and cost. The operating and design parameters are thermal storage temperature, heat loss, storage interval, and storage medium [14]. The ground storage medium is the most promising technology due to their large time scale and comparatively low cost [15]. There are two common types of storage medium; solid (soil or rock) and liquid (water) [16].

For the HWTS system, the reinforced concrete or steel is usually used to construct the storage tank, and water is used as storage medium to minimise the rate of heat loss and increase the solar fraction (SF). The system cost is generally higher due to ground construction and insulation works [17], and the operating temperature is less than 95 °C [18]. The water and gravel are used as medium of storage in WGPS system. Whereas insulation is required on the side and top position of the storage tank, it becomes a high cost system like HWTS. The ATES system requires a warm well for injecting the heat to the aquifer and extracting the heat from the aquifer. A separate cold well is required to supply the water for injection and to receive the return water. This system usually used for district cooling application [19] where large scale site requirement [20]. Therefore this system is not suitable for small-scale such as a single family house application [21].

For the BTES system, the ground is used as a heat storage medium. In this system, vertical or horizontal pipes are inserted into the field for injecting or extracting the heat. The depth depends on the heat load, ground temperature, thermal conductivities, and groundwater level [22]. The advantage of this system is the availability of ground as the storage medium, which requires less space for storing the heat and storage can be easily extended by drilling more boreholes.

However, depending on the type of seasonal heat store, the systems have operational start-up times (first three to five years), the

Table 1
Global heat consumption by sector [2].

Sector	Industrial	Residential building	Commercial building	Agriculture
Share	44%	42%	9%	5%