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# Seasonal thermal energy storage with heat pumps and low temperatures in building projects—A comparative review

Arefeh Hesaraki [a,*], Sture Holmberg [a], Fariborz Haghighat [b]

[a] Division of Fluid and Climate Technology, School of Architecture and the Built Environment, KTH Royal Institute of Technology, Stockholm, Sweden
[b] Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, QC, Canada

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ABSTRACT

Application of seasonal thermal energy storage with heat pumps for heating and cooling buildings has received much consideration in recent decades, as it can help to cover gaps between energy availability and demand, e.g. from summer to winter. This has the potential to reduce the large proportion of energy consumed by buildings, especially in colder climate countries. The problem with seasonal storage, however, is heat loss. This can be reduced by low-temperature storage but a heat pump is then recommended to adjust temperatures as needed by buildings in use. The aim of this paper was to compare different seasonal thermal energy storage methods using a heat pump in terms of coefficient of performance (COP) of heat pump and solar fraction, and further, to investigate the relationship between those factors and the size of the system, i.e. collector area and storage volume based on past building projects including residences, offices and schools.



**Contents**



## 1. Introduction

Buildings consume a large proportion of worldwide energy sources [1]. Many countries have introduced policies [2,3] to reduce this consumption by making buildings more energy efficient. Heat production accounted for a much greater part of global

* Correspondence to: Brinellvägen 23, 100 44 Stockholm, Sweden. Tel.: +46 8 790 48 84.
*E-mail address:* arefeh.hesaraki@byv.kth.se (A. Hesaraki).

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**Nomenclature**

| | |
|---|---|
| $a$, $b$ | experimentally determined coefficients for solar collector |
| $A_c$ | collector area ($m^2$) |
| ATES | aquifer thermal energy storage |
| COP | coefficient of performance |
| $c_p$ | specific heat of the storage medium ($J\,kg^{-1}\,K^{-1}$) |
| DHW | domestic hot water |
| DTES | duct thermal energy storage |
| $E_c$ | average amount of energy received by 1 $m^2$ of a solar collector ($kW\,h\,m^{-2}$) |
| HP | heat pump |
| HVAC | heating, ventilation and air conditioning |
| HWTS | hot water tank storage |
| $L$ | average monthly value of atmosphere lucidity |
| $m$ | meter |
| PV | photovoltaic |
| PV/T | photovoltaic thermal |
| $q_c$ | average amount of heat produced by a solar collector ($kW\,h\,m^{-2}$) |
| $Q_{hd}$ | heating demand by building (kW h) |
| $Q_{loss}$ | thermal loss from the seasonal storage (kW h) |
| $Q_{max}$ | maximum storage capacity (kW h) |
| $Q_{tank}$ | stored energy in the tank (kW h) |
| SF | solar fraction (%) |
| SPF | seasonal performance factor |
| STES | seasonal thermal energy storage |
| $T_a$ | ambient air temperature (°C) |
| $T_{in}$ | heat carrier inlet temperature into the collector (°C) |
| $T_{sin}$ | temperature of heat sink in heat pump (°C) |
| $T_{sor}$ | heat source temperature of heat pump (°C) |
| $V$ | volume ($m^3$) |
| $W$ | work required for compressor of heat pump, circulation pump or fan (kW h) |
| WGPS | water-gravel pit storage |

*Greek letters*

| | |
|---|---|
| $\eta$ | efficiency of the collector |
| $\eta_c$ | Carnot efficiency |
| $\theta_{max}$ | temperature of fully charged storage (°C) |
| $\theta_{min}$ | temperature of fully discharged storage (°C) |
| $\rho$ | density ($kg\,m^{-3}$) |

energy consumption (47%) than transport (27%), electricity (17%) and non-energy use (9%) [1]. Heating demand in residential buildings for domestic hot water (DHW) and space heating is responsible for almost 80% in northern parts of Europe [4] and Canada [5]. Due to increasing cost of electricity and shortage of fossil fuels together with environmental aspects, renewable energies could be an important alternative solution as energy sources. There are several renewable technologies available in the market that refine renewable energies, e.g. biofuels, wind turbine, photovoltaic (PV), solar thermal collector, or a combination of them, such as photovoltaic/ thermal (PV/T). In a typical house the total amount of solar radiation reaching the roof is more than its annual heating demand even in cold climates [6]. The problem with solar energy, however, is that it is intermittent. The highest production occurs in summer and is not in parallel with the highest demand in winter. Therefore, long term (seasonal) energy storage can help to address this seasonal mismatch between times with highest energy production and largest energy demand.

Energy can be stored both long term (seasonal) and short term (diurnal) [7]. Initially in 1950s Speyer [8] theoretically considered the potential of storing heat during summer and utilizing it during winter. Then, it became practical in Sweden in late 1970s during the energy shortage crisis [9], the so-called energy crises. Seasonal storage is more complex and expensive compared to short term storage. The main difference between these two systems is the size of the system in terms of solar collector area and storage volume. In solar heating systems with seasonal thermal energy storage (STES) the investment cost per square meter of collector area is almost twice that of the system with short term storage [10]. In addition, in short term storage usually the temperature is high, i.e. maximum 95 °C which allows a direct usage in heating distribution network [11]. For long term storage, however, the temperature is usually low and an auxiliary heating system is needed.

Solar heating systems usually consist of an array of solar collectors to collect heat, piping network to transfer heat and storage to preserve this heat for a short or long term. Solar heating systems are mainly evaluated according to their solar fraction (SF). SF is the amount of energy provided by the solar heating system divided by the total energy demand [12], as shown in Eq. (1).

$$SF = \frac{q_c - Q_{loss}}{Q_{hd}} \tag{1}$$

where $SF$ is solar fraction, $q_c$ is average amount of heat produced by a solar collector (kW h), $Q_{loss}$ is the thermal loss from the system (kW h) and $Q_{hd}$ is the heating demand in the building (kW h).

In a solar heating system the aim is to provide a SF of 50–100% for seasonal storage and 10–20% for daily storage [13,14]. However, as shown by Bauer et al. [13] the designed SF is sometimes never reached in reality. This may be due to high heating demand of the building, high return temperature to the storage, and high heat loss from thermal storage.

Thermal energy can be stored in three forms—sensible energy, latent energy and chemical reaction [15]. When adding or removing energy affects the temperature of a material, it would be classified as "sensible". Due to its simplicity, this concept is the most developed and well known technology [16]. The greatest concern in seasonal sensible storage however, is heat loss [17]. In sensible thermal energy storage (TES) the heat loss depends on the storage medium, elapsed time, temperature gradient, and volume of storage [18,19]. Regarding the temperature and the volume of storage, there are different methods to decrease the thermal losses, including optimizing the size of the system or lowering the storage temperature. Designing the system with a low ratio of surface to volume (loss-to-capacity) is one way to keep the heat loss low. Generally the larger sensible TES are more efficient than smaller ones of the same energy density [20]. Another technique for reducing the thermal loss is to have low-temperature storage, i.e. lower than 30 °C. However, this temperature is not appropriate for direct use for heating in conventional heating systems. In addition, even in high temperature storage with a thick insulation layer, the stored temperature is not usually sufficient to be used directly during the whole heating season. Hence, the storage system requires supporting equipment, e.g. a heat pump [21] to increase the temperature to a useful level. Furthermore, low temperature energy storage is a good source of energy to use with a