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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

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* 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

η	efficiency of the collector
η_c	Carnot efficiency
θ_{max}	temperature of fully charged storage (°C)
θ_{min}	temperature of fully discharged storage (°C)
ρ	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

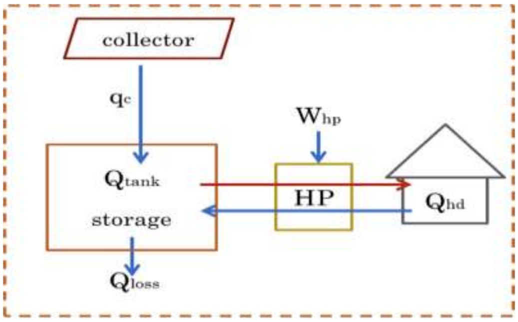

Fig. 1. Energy conservation for seasonal thermal energy storage with heat pump.

heat pump, so as to upgrade the temperature to be suitable for domestic hot water (DHW) or space heating [22].

The two main factors that determine the efficiency of seasonal thermal energy storage with a heat pump are the solar fraction (SF) and coefficient of performance (COP) of the heat pump. These factors change with changing collector area and storage volume. The relation between SF, COP, collector area and storage volume can be calculated considering energy conservation principles, with energy in the storage calculated by Eq. (2). The left side shows total annual energy supplied to the system, i.e. solar energy and heat pump work. The right side indicates heat load in the building, heat loss into the surrounding earth and atmosphere, and the part remaining in the storage. Fig. 1 shows how these terms are applied to the system.

$$q_c + W_{\text{hp}} = Q_{\text{hd}} + Q_{\text{loss}} + Q_{\text{tank}} \tag{2}$$

where q_c is the collector output, W_{hp} is the electricity input to the heat pump, Q_{hd} is the heating demand for space heating and DHW if needed, Q_{loss} is the heat loss from the system, and Q_{tank} is the stored energy in the tank. Units in Eq. (2) are thus kW h.

The purpose of this article was to review the previous studies regarding the combination of heat pump with different seasonal thermal energy storage methods in terms of SF and COP of heat pump and to provide a relation between those factors with collector area and storage volume based on past projects.

2. Seasonal thermal energy storage medium and methods

An appropriate storage medium is expected to have a high specific heat storage capacity, long term stability under the thermal cycling, good compatibility with its containment and low cost. In seasonal storage systems there are mainly two types of storage medium [23], solid, e.g. soil or rock, and liquid, e.g. water. The capacity of the storage medium to absorb or release heat, depending on the thermal conductivity for solids and the convective heat transfer rates for liquids [24] plays an important role in a seasonal storage system. Both mediums have their own advantages and disadvantages. Thermal capacity of liquids is higher than that of solids and it is easier to exchange heat in liquids. However, solids can tolerate a higher range of temperatures since they will not freeze or boil [25] and solids cannot leak from the container. The maximum total storage capacity of a storage medium is calculated using Eq. (3).

$$Q_{\max} = V \times \rho \times c_p \times (\theta_{\max} - \theta_{\min}) \tag{3}$$

where $Q_{\max}$ is the maximum storage capacity, V is the volume (m^3) of the thermal energy storage (TES), ρ is the medium density (kg m^{-3}) and c_p is the specific heat of the storage medium ($\text{J kg}^{-1}\,\text{K}^{-1}$), $\theta_{\max}$ and $\theta_{\min}$ are the temperature (°C) of fully charged and fully discharged storages, respectively.

There are different ways to store heat as seasonal thermal energy storage (STES). The most common storage systems are:

- *Hot water tank storage (HWTS)*: The storage tank, of stainless steel or reinforced concrete, is usually buried underground [26] in order to decrease the heat loss and increase the solar fraction. This system is also called water pit storage. In order to increase stratification and decrease heat loss, a high level of insulation should surround the storage tank [27]. The main problem with this storage system is high cost due to ground works, concrete construction, insulation, and liners to prevent leakage and protect against moisture.
- *Water-gravel pit storage (WGPS)*: In this storage system both water and rock are used as storage mediums. The application of rock and water in such pits can overcome some problems such as high cost of hot water tank storage (HWTS) and the low thermal capacity of rock [17]. This type of storage is also called man-made or artificial aquifer [11]. Using this system the natural aquifers remain untouched. The high cost of this system is due to ground works, sealing of the pit, insulation and moisture protection.
- *Duct thermal energy storage (DTES)*: In this storage method, vertical or horizontal ducts are inserted under the ground to store heat. The optimum depth of the DTES depends on the heat load, ground thermal conductivity, the natural temperature in the ground, the ground water level, and the distance to other similar storage systems [28,29]. For DTES with channels deeper than 3 m the extracted heat from the ground during winter is higher than the natural heat supplied to the ground during summer [30]. Therefore, with borehole systems it is recommended to charge the ground artificially with heat, e.g. by solar collector, or exhaust air from the ventilation system [31]. The temperature of DTES [32] ranges from 2 to 20 °C and from -3 to 6 °C for charged and un-charged storage, respectively. Due to its low stored temperature, this system is usually combined with a heat pump. Hence, in addition to resulting in a higher COP for the heat pump, i.e. up to 4–5 [24,33], the combination of solar collector with DTES also allows for reducing the borehole depth 4.5 to 7.7 m per square meter of solar collector area [34]. However, for a single family house with a single borehole, the economical aspect of recharging should be considered. In addition, where there is a high water table recharging would not be helpful. In DTES the first three to five years of operation is the start-time [35] needed to obtain normal operating conditions, slowly heating the underground surroundings of the storage system and thereby decreasing heat loss. The efficiency of the system is therefore lower in the first years [36].
- *Aquifer thermal energy storage (ATES)*: In this storage system there are at least two wells, one warm and another cold, that are drilled into the aquifer to inject/extract groundwater. This system is equipped with pumps, and extraction and injection pipes. During the charging process in summer, the water is extracted from the cold well, heated by the chosen heat source and injected into the hot well. For the discharging process in the heating season the cycle is reversed, i.e. hot water is extracted from the warm well, cooled by a heat sink and injected into the cold well. Aquifer storage is usually used for cold storage in district cooling applications [37] and is not suitable for small loads such as single family houses [25] due to large site requirements.

Advantages and disadvantages of each storage method are summed up in Table 1 [6,9,38,35,39–41]. In addition to the type of storage, another classification of STES is based on the stored temperature level. Different temperature ranges can be achieved

Table 1
Summary of different types of seasonal storage systems [6,9,38,35,39,40,41,51].

	Hot water tank storage, HWTS	Water-gravel pit storage, WGPS, Artificial aquifer	Duct thermal energy storage, DTES	Aquifer thermal energy storage, ATES
Storage medium	Water	Water and gravel	Soil/rock	Water—sand/gravel
Maximum storage capacity	60–80 kW h m^{-3}	30–50 kW h m^{-3}	15–30 kW h m^{-3}	30–40 kW h m^{-3}
Advantages	– Can be built at almost any location – Most common system – No special geological condition is needed – High stratification – High heat capacity – Easy to install	– Can be built almost everywhere – No special geological condition is needed – More cost effective than the HWTS – Leaving natural aquifer untouched	– Can be used for both heating and cooling – In case of vertical borehole (30–200 m depth with the spacing of about 2–4 m) needs less surface area and it is less sensitive to outdoor climate due to constant ground temperature which is equal to the annual mean temperature – In case of horizontal duct needs less excavation (at depth of 0.8 to 1.5 m) and have lower cost – Feasible for very large and very small application	– Cost effective – Can be used for both heating and cooling – Ability to produce direct cooling without using any supporting device, e.g. heat pump – Low maintenance – Much more efficient heat transfer compared to DTES
Limitations	– High cost in buried water tank – High thermal loss – Corrosion – Leakage	– High cost – Low stratification due to high thermal conductivity – Leakage – Needs 1.3–2 times larger storage volume compared to HWTS	– Needs 3–5 times larger storage volume compared to the HWTS – Not suitable for all locations with ground-water flow – Needs drillable ground – High initial cost – 3–4 years needed to reach typical performance	– Needs special geological conditions, e.g. water saturated sand layers with high permeability without natural groundwater flow – High thermal loss due to no thermal insulation – Needs 2–3 times larger storage volume compared to the HWTS – Clogging effects – Long initial process due to extensive geological investigation

according to types of storage, and solar collectors and size of systems. Higher solar collector area and smaller storage volume allow for higher storage temperature. The temperature range as well as its application is shown in Table 2 [21,42]. In low temperature storage a heat pump is needed, as explained in the following section.

2.1. Low temperature seasonal thermal energy storage

From the energy supply efficiency perspective, low temperature seasonal thermal energy storage has many advantages. In addition to the lower heat loss mentioned earlier, the smaller size of the system [43] in terms of storage volume and collector area, allows cost reduction. Furthermore, as shown by Eq. (4) [44], the heat production by the collector (q_c) depends on the temperature difference between heat carrier inlet temperature (T_{in}) into the collector, and ambient temperature (T_a). The lower outlet temperature from the low temperature storage, which assuming low heat losses from the pipes is approximately equal to inlet temperature to the collector, leads to higher solar collector efficiency [35]. This is due to reducing convective and radiative heat losses from the collectors to the ambient surrounding [9,45].

$$q_c = A_c \times E_c \times \eta \times \left(1 - a \times \left(\frac{T_{\text{in}} - T_a}{L}\right) + b \times \left(\frac{T_{\text{in}} - T_a}{L}\right)^2\right) \quad (4)$$

where q_c is the average amount of heat produced by a solar collector (kW h); A_c is the collector area (m^2); E_c is the average amount of energy received by 1 m^2 of a solar collector (kW h m^{-2}); η is the efficiency of the collector, a, b are the experimentally determined coefficients, T_{in} and T_a are the heat carrier inlet temperature into collector and surrounding air temperature, respectively (°C); L is the average monthly value of atmosphere lucidity.

From the environmental contribution perspective, low temperature seasonal thermal energy storage (STES) is not harmful for environment since high storage temperature may cause geochemical, geotechnical, hydro-chemical and hydro-biological problems [46,47]. As mentioned earlier, although low temperature STES has many advantages, it cannot be used directly to meet heating demand. Therefore, assisting systems such as those utilizing heat pumps are required.

3. Heat pumps

Heat pumps are an energy saving and energy efficient technology for supplying both heating and cooling demand [48,49]. Heat pumps usually deliver more useful energy than the required energy to operate them [50]. In heating mode the heat source of the heat pump normally uses renewable energy stored in ground, groundwater, ambient air, or exhaust air. In heat pumps this low grade energy is converted to high grade by putting in the required amount of work, e.g. by electrical energy. In cooling mode this cycle is reversed and the indoor air acts as an evaporator for the heat pump.

The efficiency of a heat pump in heating mode is determined by the coefficient of performance (COP). The COP of a heat pump indicates the ratio of produced energy to used energy. Presently the average COP of an efficient heat pump can be up to 4. COP depends on many factors, e.g. the temperatures of heat source and heat sink, the efficiency of its compressor, and the type of its working medium. Above all, the temperature of the heat source and heat sink are very important factors influencing the COP value, as indicated by Eq. (5). Lowering the temperature difference between the heat source and the heat sink for a heat pump results in a higher COP value, as shown in Eq. (5). A low temperature heating system and high temperature heat source is therefore beneficial [18]. COP improves by 1–2% [52] for every degree reduction in heat sink temperature. In addition, COP improves by 2–4% [53] for every degree enhancement in heat source temperature. A high COP requires less work by a compressor, as shown by Eq.(6).

$$\mathrm{COP}=\eta_c\left(\frac{T_{\sin}(t)}{T_{\sin}(t)-T_{\mathrm{sor}}(t)}\right) \tag{5}$$

$$W_{\mathrm{compressor}}+\sum_{i=1}^{n} W_{i,\ \mathrm{pump\ \ and\ \ fan}}=\frac{Q_{\mathrm{hd}}}{\mathrm{COP}} \tag{6}$$

where COP is the coefficient of performance of the heat pump, η_c is Carnot efficiency (the relation between the efficiency under real conditions and the theoretically maximum reachable efficiency [54]), $T_{\sin}$ and T_{sor} are the heat sink and heat source temperatures (°C), W is work done by the compressor, pump and fan (kW h), and Q_{hd} is heating demand in the building (kW h).

For a high temperature heat source heat pump, combined with STES, COP can be up to 5–6, as will be shown in Table 4 of this paper. The system in which the solar collector contributes as a heat source of a heat pump is called a solar-assisted heat pump. This system has been investigated both theoretically and experimentally [21,55,56].

The COP of a heat pump fluctuates greatly with varying climate conditions and heating demands. To measure the overall heating efficiency of a heat pump (mean COP) over an entire heating season the seasonal performance factor (SPF) is used.

4. Combination of seasonal thermal energy storage and heat pump (STES-HP)

Combining a heat pump with seasonal thermal energy storage (STES-HP) had many advantages [57] for both large and small applications. In this study, a full range of single to multi-family houses was covered. Using a heat pump causes considerable reduction in the discharging temperature [35]. Due to this reduction, the heat pump helped keep the storage system stratified [58]. Thermal stratification is recommended [45] to reduce thermal losses to the ground, and to increase the collector efficiency as the lower temperature strata return to the solar collector. Experimental and numerical models by Ghaddar [59] showed an increase of 15–20% in storage efficiency with a stratified water tank compared to a mixed tank. This enhancement was also due to lowering the use of an auxiliary heating system [60] since in stratified tanks, the stored temperature is sometimes high enough to be used directly for heating. Mixing cold and hot water in non-stratified storage, however, caused uniformity of temperature through the whole system which decreased the useful quality of energy, exergy [61]. Moreover, the stratified tank caused an increase in COP of the heat pump as the temperature to the evaporator of the heat pump was supplied through the upper part of the stratified tank, with its higher temperature.

In addition, the heat pump in cooling mode can support charging of energy storage by extracting the heat from the building during summer and transferring it to storage. There were different configurations for combining heat pump, solar collector and seasonal storage system. Based on the interaction between solar collector and heat pump there are three main configurations-series, parallel and series-parallel connections. Series and parallel configurations are shown in Figs. 2 and 3, respectively. As can be seen, in the case of series configuration, the collector is a source

Table 2
Temperature range for thermal energy storage [21,42].

Type	Temperature range	Description	Application	Additional information
Cold temperature	Less than 10 °C	Consist of a vertical or horizontal heat exchanger in the ground coupled with heat pump (ground source heat pump)	For low temperature heating system in single family house	– Antifreeze mixture is used to avoid freezing in heat exchanger fluid – No auxiliary conventional heat source is needed – No artificial charging to soil is applied
Low temperature	Between 10 and 30 °C	Consist of unglazed flat plate collector connected to the vertical ground heat exchanger and then to the heat pump	For low temperature heating system in residential apartments, and attached houses	– Artificial charging is required with solar collector
Medium temperature	Between 30 and 50 °C	Consist of evacuated tube solar collector and a heat pump, the heat is transferred either directly to the heating system (if the temperature is high enough) or via a heat pump (if the temperature is not enough)	Group of single family houses or group of apartments, commercial buildings, schools, offices	– Artificial charging is required with solar collector or waste heat – The inner region of the storage can be designed to store the higher temperature and the outer region for keeping lower temperature (benefits: lower heat loss to the ground, gaining heat losses from inner region by outer region, outer region connected to the heat pump and inner region are used directly)
High temperature	More than 50 °C	High temperature evacuated tube collector	District heating, group of apartments or group of commercial buildings, not applicable for small systems due to large heat losses	– No need for heat pump – Auxiliary burner is necessary – Special duct technology is needed – Need a good thermal contact between heat carrier fluid and ground – Small heat loss and good thermal conductivity in the ground

for the heat pump (exclusively or in addition to the other source), and heat pump's functionality depends on the solar collector's operation. The solar collector can directly act as a source for a heat pump, or indirectly via heat storage [57]. This configuration had a better performance in terms of COP of the heat pump compared to the parallel case [62]. In the parallel case, the collector and heat pump worked independently and there was no interaction between heat pump and solar collector. The collector was used mainly for DHW production and also for space heating and heat storage, and the heat pump was used as an auxiliary system for heating. However, in series-parallel configurations, if the temperature produced by the solar collector is high enough for demand, e.g. for space heating or DHW, it goes directly to those requirements, and the heat pump is not in operation. If not, the solar collector or thermal storage acts as heat source for the heat pump. Based on the temperature produced by the solar collector or stored heat in the storage, different operational modes can be introduced in series-parallel configuration, see Table 3.

4.1. Hot water tank storage with heat pump (HWTS-HP)

The structure of HWTS-HP is shown in Fig. 4. Theoretical study by Ucar and Inalli [63] evaluated one, 50, and 500 buildings with HWTS-HP in Turkey. The evaluation was based on finding the optimal area of solar collector and storage volume with the highest possibility of solar fraction and saving. In addition, Yumrutas and Unsal [57] developed an analytical model to predict the HWTS temperature and COP of the heat pump based on the ground properties, year of operation, storage tank volume and collector area. The investigation was for a single family house with 100 m^2 floor area. The results showed that after 5 years of operation for well-buried storage the stored temperature varied between 14 and 40 °C and the mean annual COP of the heat pump was 6. This result was for a system with storage tank volume of 300 m^3 and 20 m^2 of collector area.

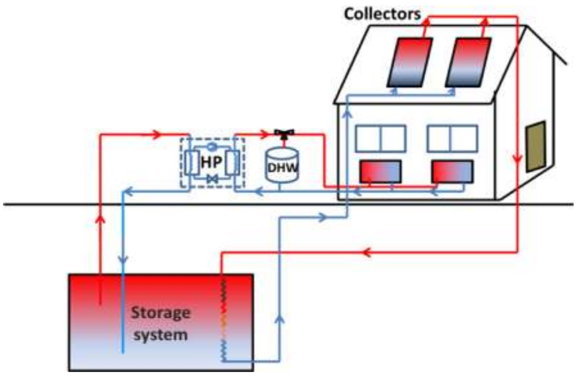

Fig. 2. Series connection of solar collector and heat pump.

The performance of HWTS-HP was also experimentally evaluated for large applications [64–68]. In Sweden [64] the Lambohov HWTS-HP system with 2700 m^2 collector area and 1000 m^3 storage volume was designed to supply 100% of space heating and DHW demand for 55 residential buildings. However, due to high heat loss and high vapour transport through the walls caused by wet thermal insulation the actual solar fraction was only 37% [11]. This result revealed the vital role of storage hot water tank insulation for long term performance. In addition, the first STES in Denmark was built as HWTS-HP in Herlev. It aimed to supply 74% of total heating demand and DHW for 92 houses. However, the real performance showed that only 35% [69] of the total demand was covered by this system. The reason was that a high leakage problem occurred in the first year of operation. Another recent HWTS-HP system was built in Munich [67,68] with 5700 m^3 storage volume and 2900 m^2 solar collector area. The aim was to cover 47% of total heating demand of 300 apartments by solar energy. In this project the construction cost was lower than other systems due to improvement in stratification devices and thermal insulation.

4.2. Water-gravel pit storage with heat pump (WGPS-HP)

Fig. 5 shows the configuration of a typical WGPS-HP system. In Germany the first seasonal large-scale storage was water-gravel pit storage with heat pump [42]. This system consisted of a 211 m^2 solar collector and 1050 m^3 storage volume, and was located on

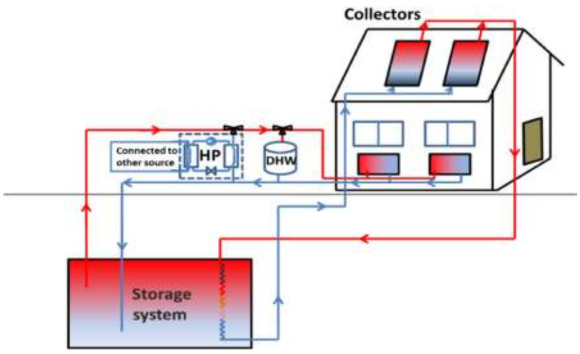

Fig. 3. Parallel connection between solar collector and heat pump.

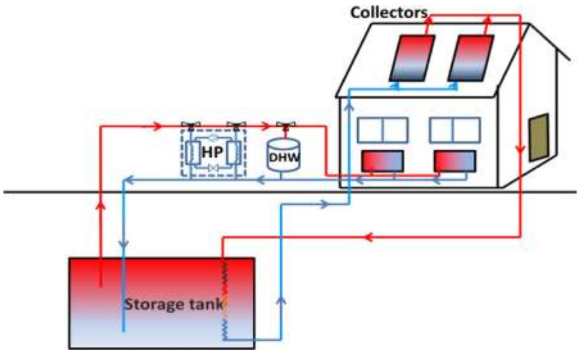

Fig. 4. Hot water tank thermal storage with a heat pump and solar collectors.

Table 3
Operation mode of STES-HP based on the temperature produced by solar collector.

Temperature by solar collector	Solar collector	Heat pump	Seasonal thermal energy storage
Greater than 50 °C	To produce heat directly for DHW	Not in use	No extraction, charging mode when the demand is satisfied
Between 20 and 50 °C	To produce heat directly for heating depending on heating system	Not in use	No extraction, charging mode when the demand is satisfied
Between 5 and 20 °C	As a source for evaporator of heat pump	In operation with high COP	No extraction, charging mode when the demand is satisfied
Less than 5 °C	Not in use	In operation	Discharging mode, as a heat source of heat pump or directly used for DHW or heating

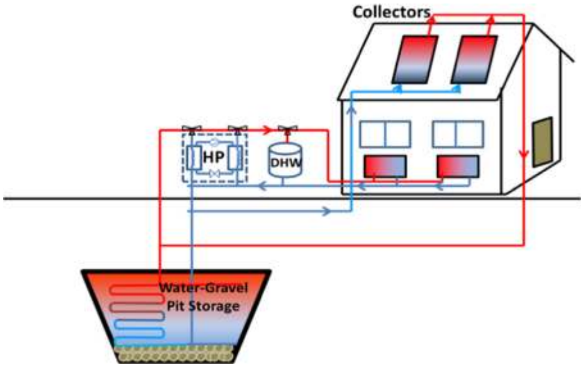

Fig. 5. Water-gravel pit storage with a heat pump and solar collectors.

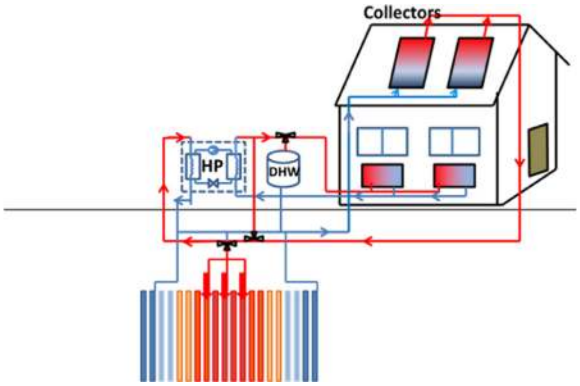

Fig. 6. Borehole thermal energy storage with a heat pump and solar thermal collectors.

the campus of Stuttgart University. Initial measurements during the first two years showed a failure in heat pump performance with low COP. The heat pump was then changed to a better one with an average COP of 4. Based on 15 years monitoring, this system has worked satisfactorily with a COP of 4.5 and solar fraction of 60%. Another recent WGPS-HP was built in Eggenstein, Germany as the first system for providing heating for renovated buildings [70]. This system was designed to cover 35–40% of total heating demand for a school, gym, pool, and fire station, with total heated floor area of 12,000 m^2.

4.3. Duct thermal energy storage with heat pump (DTES-HP)

Fig. 6 shows a diagram of the DTES-HP system. To reduce heat loss and heat conduction from the pipes to the ground, the supply pipes were connected to the center of storage and the return pipes were at the boundaries. Different configurations of this system allow for charging the system by solar collectors. Kjellsson et al. [29] theoretically compared the following three alternatives: (a) all solar heating used for recharging the borehole during the whole year, (b) all solar heating used for DHW production with uncharged ground-coupled heat pump for heating, and (c) all solar heating from November through February used for charging the borehole and for the rest of the year all solar was fully used for DHW production. The study parameters were COP of heat pump and energy savings. The COP of case “a” was higher through the whole year due to higher evaporator temperatures. However, the case “c” showed a higher energy savings due to sufficient natural recharging of the borehole during summertime and more efficient use of solar heat for domestic hot water in this period.

The application of DTES-HP for both heating and cooling has also received much interest. A beneficial aspect of this system is that in cooling mode, injected surplus heat from the building also can be used to heat the ground. The control of this DTES-HP system can be based on the temperatures produced by solar collectors and desirable for thermal comfort [71,72]. Wang et al. [71] experimentally investigated this system in a small residential house. In the control system three modes were defined. One was for charging the ground from April to October when the temperature of carrying fluid in solar collectors is higher than 25 °C. The second mode was cooling by the half of the heat exchanger via radiant floor cooling from July to August when the indoor temperature was not between 24 and 26 °C. The cooling was supplied without heat pump interaction. The third mode was to heat the building using the solar collectors directly or with a heat pump using seasonal storage from October to April. The result showed that 88% of total demand was covered by DTES-HP and the average COP of the heat pump was 4.3.

In addition, the performance of DTES-HP for large applications was investigated. The system in Kungsbacka [65] in Sweden was able to cover the 64% heating demand of a school building with 1500 m^2 of collector area and 85,000 m^3 of storage volume [73]. A recent DTES-HP in Crailsheim, Germany [13] was designed to supply 50% of DHW and space heating for 260 flats and a school building with solar energy [74]. This system consists of 37,500 m^3 of storage volume and 7300 m^2 collector area.

4.4. Aquifer thermal energy storage with heat pump (ATES-HP)

A combination of aquifer thermal energy storage and heat pump is shown in Fig. 7. Paksoy et al. [75] found a 60% increase in COP of the ATES-HP, when compared to a COP of a conventional HP using ambient air. In ATES-HP, depending on the required temperature level, it is optional to artificially charge the aquifer using, for example, a solar collector or waste heat from industry. Due to high temperature of underground water, many projects, e.g. [75–77] investigated the performance of low temperature uncharged ATES-HP for heating and cooling of buildings. Ghaebi et al. [76] evaluated the performance of ATES for three configurations in a residential complex located in Tehran, Iran, using numerical simulation. The first one used ATES for cooling only, the second configuration consisted of ATES-HP for both heating and cooling, and the third one used charged ATES with solar collector for heating only. The investigation showed that the second possibility, i.e. ATES-HP was the best in terms of a high COP, i.e. 17.2 and 5 for cooling and heating, respectively.

Andersson et al. [37] compared the energy savings, thermal capacity and payback time for different configurations of uncharged ATES-HP in Sweden. The systems investigated were for providing heating and cooling, and also heating only. The energy saving for the former system was 80–87% with 1–3 years payback

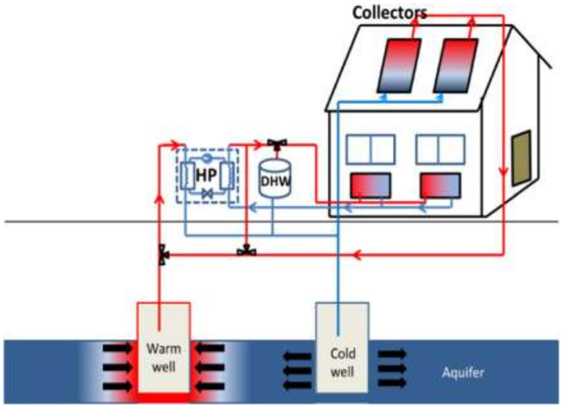

Fig. 7. Aquifer thermal energy storage combination with a heat pump and solar thermal collectors.

time. For the latter system there was a saving of 60-75%, with payback time of 4–8 years. The average heating storage capacity for the latter system, however, was 50% higher than the former system.

In a Belgian hospital with 440 beds [77] un-charged ATES-HP was used either directly or as a source for heating and cooling by a heat pump. The maximum seasonal performance factor (SPF) of this system including direct heating and cooling during three years of operation was 6.4 for heating and 57.9 for cooling. In this ATES-HP project 75% of primary energy was saved compared to a conventional HVAC system in a typical Belgium hospital, i.e. using boiler and cooling equipment.

The application of ATES-HP for office buildings was applied in Scarborough, Canada [78]. This system was used mainly for cooling 30,470 m^2 floor area. The system consisted of 750 m^2 of solar collector for providing DHW and 530,000 m^3 of storage volume for heating and cooling. The solar fraction for DHW was 19% with a high COP of heat pump, i.e. 5–6. In addition, 46% savings was achieved for cooling production due to using ATES-HP. Furthermore, the application of ATES-HP in multi-family houses was installed in Rostock, Germany [13,79]. This system consisted of 20,000 m^3 storage volume and 980 m^2 of solar collector. This system met the designed solar fraction (50%) by covering 57% of the annual demand for 7000 m^2 floor area. However, the heat loss from this system was high due to a relative small storage volume [80].

4.5. Combining two seasonal storage systems with a heat pump

To achieve the optimum in terms of cost or efficiency a combination of a more cost-effective storage system, e.g. ATES or DTES with high heat capacity storage, e.g. HWTS is advised. For instance, in Kerava Solar Village (KSV) project [81], which was the first large scale seasonal storage in Finland, water pit and borehole thermal energy storage were integrated with a heat pump. This system consisted of 1100 m^2 collector area with 1500 m^3 water storage and 11,000 m^3 duct storage. This solar heating system was designed to provide 75% of heating demand for 44 flats [43], but monitored results showed a solar fraction of only 26%. This failure was due to heat pump malfunction, lower storage capacity than calculated and lower solar collector efficiency (24%) than assumed (43%) due to higher return temperature to the collector. Another recent investigation of combined STES was in Attenkirchen, Germany [82,83] for supplying heat for 30 single family houses. This system consisted of 836 m^2 of collector area with 500 m^3 HWTS and 9350 m^3 DTES. The solar fraction for this system was relatively high, i.e. 74%. In addition, the COP of the heat pump connected to DTES and HWTS were rather high, that is 3.9 and 4.4, respectively.

5. Combination of low-temperature heating system with low temperature seasonal storage

In a low-temperature heating system, the supply temperature is reduced to below 45 °C due to a large surface area or an enhancement in the forced convection of heat transfer. Examples could include floor heating, ceiling or wall heating of a large surface area, or a ventilation radiator [52] or fan radiator as forced convection radiators. These systems favour sustainability and efficient use of energy; that is, they have high exergy saving potential due to their use of low-grade energy sources such as renewable energy stored in ground, air or water. By using a high-temperature heating system (for example, 80 °C) or burning fossil fuels and generating 1000 °C, a great deal of exergy is destroyed as the thermal comfort temperature in the room is only 20 °C. Therefore, low-temperature heating systems could be one type of sustainable and efficient heating system.

Combination of a low-temperature heating system and a low temperature storage can lead to an efficient system, as a result of a higher solar fraction due to lower heat loss and lower return temperature to the collector. This condition also favours exergy efficiency due to lower temperature difference between heat source and heat demand. In addition, this can support a heat pump in terms of COP as it needs less compressor work to upgrade the temperature to a suitable level. Furthermore, a low-temperature heating system would be more sustainable and environmentally friendly than a high temperature system. Additionally, the use of a low-temperature heating system with seasonal storage decreases the need of an auxiliary heat source. Nordell and Hellström [84] theoretically investigated the performance of seasonal DTES connected to low-temperature heating emitters, i.e. under-floor heating. This system was designed to cover 60% of the total heat demand of 90 single family houses in Danderyd, Sweden. Moreover, the application of low-temperature heating emitters and seasonal DTES was studied experimentally by Trillat-Berdal et al. [72]. They showed a solar fraction of 60% and average COP of 3.75 for the heat pump. Furthermore, the application of seasonal ATES with low-temperature radiators and a heat pump was investigated in Rostock, Germany [13]. In this system the high solar fraction of 62% was achieved for 108 apartment buildings.

6. Selection criteria

Selecting a suitable STES method depends on many factors, including heating or cooling demand, size of the application, ground conditions, local hydrological and geological site, features, and cost [85]. For instance, it is recommended to use ATES-HP only for large applications with a need for cooling. For single family houses with both heating and cooling demand, a single borehole is recommended. Hot water storage tanks and gravel-water storage systems can be built at any location for both small and large applications with heating demand. However, the cost for these systems is high. Fig. 8 shows a decision tree incorporating selection criteria as well as some appropriate design tools for different storage methods.

6.1. Existing design tools

To model the thermal energy storage system there are different simulation programs including TRNSYS, MINSUN, Solarthermie-2000 [86], and SOLCHIPS [87]. TRNSYS [88] developed in University of Wisconsin is an open and modular structure simulation program for the transient simulation. This program is used to design and simulate solar systems as well as building components in detail. MINSUN program as a system simulation and optimization program was developed in 1985 as a part of task VII (Central Solar heating Plants with Seasonal Storage) of the International Energy Agency, IEA [89]. Much of the structure of MINSUN is based on TRNSYS program. The main difference between TRNSYS and MINSUN is the time step used in simulation. For TRNSYS the time step can be less than 1 h, but for MINSUN it is a day [84]. TRNSYS is more advanced and provides a detailed model compared to MNISUN which is mainly used for the pre-design phase. MINSUN was used to design the first seasonal solar heating system in Germany as a water-gravel pit storage with a heat pump [42]. Simulation results were in a good agreement with measured data [65]. In addition, MINSUN was used to re-optimize the duct thermal energy storage in Vaulruz project [90]. Argiriou [91] used MINSUN and SOLCHIPS simulation programs to pre-design a

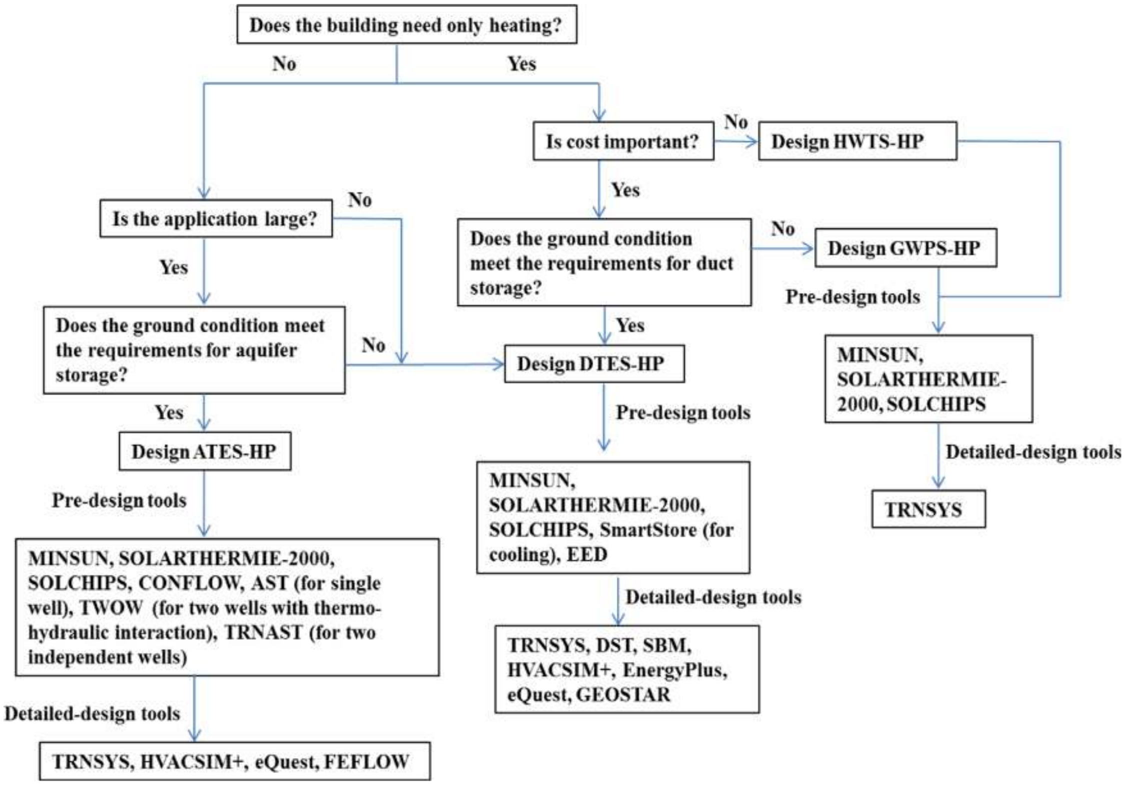

Fig. 8. Decision tree and available tools for designing Seasonal thermal energy storage utilizing a heat pump.

storage system consisting of hot water tank storage, water-gravel pit storage and duct thermal energy storage in Greece. Results using these two simple simulation tools were in good agreement with the design values calculated by a detailed tool.

Currently these programs, i.e. TRNSYS, MINSUN, SOLCHIPS and Solarthermie-2000, are used to simulate large scale seasonal thermal energy storage in terms of hot water storage, aquifer storage, gravel-water storage and borehole systems. However, there are some programs such as FEFLOW, CONFLOW, and TRNAST which were developed to exclusively model aquifer thermal energy storage, or EED, Geostar and SBM for duct thermal energy storage modelling.

To model DTES there are a number of simulation programs. SmartStore [92] as a simple pre-design model is used for a fast estimation of heat losses, the optimum required borehole length and minimum storage cost, but due to the simplified nature of the model, it is almost impossible to fit a real load variation into the program. This program is suitable for borehole storage systems without any heat extraction, i.e. free cooling. However, based on monthly heat injection or heat extraction Earth Energy Designer (EED) [93,94] is used to predict the fluid temperature variation and required borehole length. In EED there are many pre-defined borehole configurations that a user can choose from. EED is based on pre-computed dimensionless temperature response functions called g-function by a detailed SBM model for those specific geometries [95]. The g-function depends on the borehole depth and space between boreholes. When modifying borehole depth or borehole distance, however, interpolation between stored g-function in the data file can cause computing errors [96]. Therefore, the program has limited accuracy.

The Duct Ground Heat Storage (DST) model is available independently and as a TRNSYS module [97]. DST model is used to calculate the ground temperature, outlet temperature heat balance and transferred heat to the ground using analytical solution. In this model it is assumed that the boreholes are evenly distributed throughout the cylindrical storage region. Similar to the DST model, Superposition Borehole Model (SBM) [98] is available independently and as a TRNSYS module [99]. SBM is more advanced in terms of giving a detailed 3D output of the transient thermal process, i.e. heat balance, heat transfer rates, fluid temperatures, and temperature field in the ground. In addition, in SBM it is possible to define any configuration for vertical or inclined boreholes. However, the execution time in SBM is higher than DST.

In addition there are a number of building simulation programs integrated with DTES models [96] to calculate building heating and cooling modes. Spitler et al. [100] used EnergyPlus [101,102], eQuest [103], HVACSIM+ [104], DST-TRNSYS [105] and Geostar [106,107] simulation programs to predict the performance of borehole thermal energy storage. Then in order to investigate the accuracy of models the results were compared to measurement data. The study showed that EnergyPlus and TRNSYS were able to predict the DTES performance in a reasonable way with a maximum disagreement of 11%. However, the HVACSIM+ program gave the largest divergence of 24% between measurements and simulation results.

Chapuis and Bernier [108] used the DST-TRNSYS simulation program [109] to model the first high temperature DTES on the north American continent built in Canada in 2006 [110,111]. The aim was to investigate the efficiency of the existing DTES system when combining it with a heat pump. This DTES, called Drake Landing Solar Community (DLSC), was also the first solar heating system in the world which covered close to 90% of the space heating demand. Simulation showed that due to lower storage temperatures in the system with a heat pump, the solar collector efficiency increased from 23% to 58% and the thermal loss decreased by 73% compared to the original system without any heat pump.

As mentioned earlier, to model ATES there are a number of simulation program available, such as CONFLOW [112], AST [113], TWOW [113], TRNAST [114,115], FEFLOW [116], here ranked from the simplest for pre-design to the most advanced one for detailed design. In the more advanced programs the simulation results are more reliable as the higher number of data inputs increases the accuracy of the model [117].

CONFLOW as a simple and fast simulation program is suitable to be used for the pre-design phase in well configuration [113]. CONFLOW is able to calculate only 2D hydraulic and thermal processes without energy transport. Three models of AST, TRNAST and TWOW are used to predict both energy and entropy of ATES. The AST simulation program is used to model the heat conduction and convection in the porous medium of the ATES system. Nevertheless, AST is able to model the thermal behavior and a flow field of a single well. To model two wells, TWOW and TRNAST simulation programs, which are based on the AST program, can be used. The TWOW model allows for thermo-hydraulic interaction between the two wells. However, TRNAST is appropriate for thermally and hydraulically independent wells with no interaction and is applicable within the simulation environment of TRNSYS. A more advanced program to be used for detailed design is 3D model FEFLOW. In addition to the hydraulic and thermal field, FEFLOW is able to calculate solute transport in porous media under saturated and unsaturated conditions for two wells. Also, chemical reactions and degradation mechanisms are considered in FEFLOW. This program is highly time consuming, however.

Kranz and Bartels [118] used TRNAST and FEFLOW to model ATES-HP used in the German Parliament Building [119]. The aim of simulation was to enhance the storage efficiency in terms of the energy recovery factor. The simplified model of TRNAST was verified with a detail model of FEFLOW.

7. Discussion

Table 4 gives a summary of past projects regarding different seasonal thermal energy storage systems in combination with a heat pump. As can be seen, the mean COP of most of these storage systems are in the vicinity of 4. The review showed that the applications of a heat pump with duct thermal energy storage are wider compared to other systems, as many references are assigned to DTES-HP. The reason could be due to lower stored temperature in DTES than other systems and a need for a heat pump as auxiliary heating system. In addition, investigation of past projects indicated that in ATES-HP the solar collector was not mainly used for charging the energy storage but was used for providing DHW. Therefore, as shown in Table 4 most examples of ATES-HP lacked a large collector area. Almost all ATES-HP listed in Table 4 were used for both heating and cooling in large applications. Hence, in large buildings with both heating and cooling demand this type of storage system is recommended.

The COP of a heat pump and solar fraction improved with increasing storage volume and solar collector area. Based on energy conservation given by Eq. (2) COP, SF, collector area and storage volume are related. There are many studies, e.g. [120,45,57,62,121,122], that have conducted sensitivity analyses to investigate which factor has the most influence on efficiency of the system. Increasing storage capacity would cause higher temperature during winter time and lower temperature during summer time [57,121,122] in the storage. This would be favourable for the COP of a heat pump during the heating season. Therefore, increasing storage volume improved the COP of the heat pump by reducing the compressor work [123]. However, when the storage volume was large enough, then the effect of volume on COP of the heat pump became negligible [124].

In addition, increasing storage volume would also affect the solar fraction [125]. By increasing the storage volume, the temperature in storage would not fluctuate very much. This would cause an approximately constant temperature in the storage system over the year. This favoured collector efficiency [62] due to there being no sudden jump in inlet temperature to the collector. However, this correspondence between storage volume

Table 4
Past projects showing a range of combinations of seasonal thermal energy storage with heat pumps.

	Energy demand (GJ)	Total heating area (m^2) type of the building	Collector area (m^2)	Storage volume (m^3)	TES temp. (°C)	Mean COP, heating/cooling	Saving, SF (%)	Application	Refs.
HWTS-HP									
Gaziantep, Turkey	44	100, Single house	20	300	14–40	5–6	83	Heating	[57]
Lambohov, Sweden	3,000	7,000, 55 Houses	2,875	10,000	5–70	4.4	37	Heating, DHW	[64,65]
Södertuna, Sweden	23,000	525 Dwelling + 3,500 m^2	13,000	55,000	15–65	2.3	66	Heating, DHW	[66]
Herlev, Denmark	4,520	6,900, 92 Houses	1,050	3,000	10–85		35	Heating, DHW	[65,128]
Munich, Germany	8,280	24,800, 300 Apartments	2,900	5,700	30–95	1.7	47	Heating, DHW	[67,68,129]
WGPS-HP									
Eggenstein, Germany	3,276	12,000, School, sport center	1,600	4,500	10–80		37	Heating	[13,130]
Stuttgart, Germany	349	1,375, Institute building	211	1,050	10–50	4	60	Heating, DHW	[131,65]
DTES-HP									
Harbin, China	144	500, Detached house	50	5,100	3–8	4/21	88	Heating, cooling	[71]
Crailsheim, Germany	14,760	40,000, Houses and school	7,300	37,500	20–85	4.9	50	Heating, DHW	[83,13,74]
DLSC, Canada	2,328	7,410, 52 Detached houses	573	88,000	10–16	6.2	78	Heating	[108]
Sunclay, Sweden	4,000	15,000, School building	1,500	85,000	7–15		64	Heating	[22,65,73]
Kranebitten, Austria	4,400		400	60,000	−6–10		53	Heating, DHW	[22]
ISPRA. Italy	280		180	2,250	5–60		80	Heating, DHW	[22]

Table 4 (*continued*)

	Energy demand (GJ)	Total heating area (m^2) type of the building	Collector area (m^2)	Storage volume (m^3)	TES temp. (°C)	Mean COP, heating/cooling	Saving, SF (%)	Application	Refs.
Langen, Germany	1,600	44,500, Office				6		Heating, cooling	[83]
Lesnik, Poland	6,826	4,223, Sanatorium	245			3.1	37	Heating	[83]
Treviglio, Italy	3456	9,200, Residential area	2,727	43,000	4–30	4.2	72	Heating, DHW	[10,65]
Kullavik, Sweden	1,116	3,500, 58 Apartments	490	8,100	<55		60	Heating, DHW	[65,73]
Vaulruz, Switzerland	1,228	3,200, Office and garage	520	3,300	7–53		54	Heating, DHW	[65]
France		180, Single family house	1,275		4–16	3.75	68	Heating, cooling, DHW	[72]
ATES-HP									
Rostock, Germany	1,789	7,000, Multifamily house	980	20,000	10–50	4	62	Heating, DHW	[13,132,79]
Tehran, Iran	1,900	12800, Multifamily house	–	337,080	3–14	5/17		Heating, cooling	[76]
Scarborough, Canada	21,312	30,470, Office building	750	530,000	4–50	5–6	46	Heating, cooling, DHW	[22,133,78]
Antwerp, Belgium	22,100	440 Beds hospital	–		8–18	5.6/26.1	86	Heating, cooling	[77]
Mersin, Turkey		1,400, Supermarket	–		<18	4.18	36	Heating, cooling	[75]
France, Aulnay	8,900	225 Houses	1,275	85,000	4–14	3.9	66		[134]
HWTS+DTES-HP									
Attenkirchen, German	1,753	6,200, 30 Single-family	836	500+9,350	15–50	4.15	74	Heating, DHW	[82,83]
Kerava, Finland	2,000	3,756, 44 Flats	1,100	1500+11,000	21–49	3.3	26	Heating, DHW	[81,65]

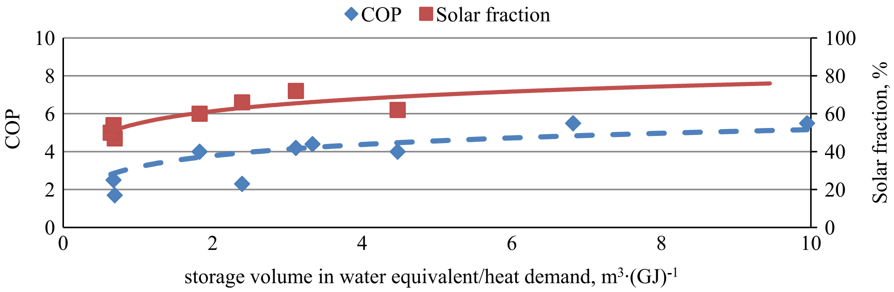

Fig. 9. COP of heat pump and solar fraction vs. ratio of storage volume in water equivalent to energy demand for different seasonal thermal energy storage systems.

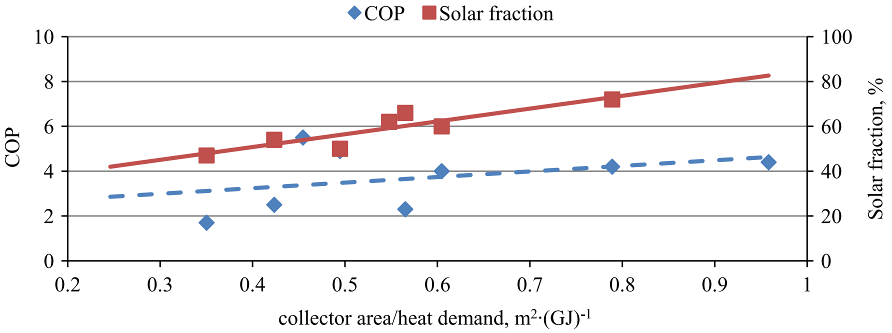

Fig. 10. COP of heat pump and solar fraction vs. a ratio of collector area to energy demand.

and solar fraction gradually tapered off [45] until the storage volume became sufficient to store all heat collected by solar collector. In high latitude countries the size of the storage tank is very important as the seasonal variation of solar energy is considerable [126]. The size of seasonal storage is more important, however, in northern climates for providing a large SF [85].

Increasing the collector area would affect both COP and SF. Larger collector area would capture more solar energy leading to a higher solar fraction. Beckman et al. [127] showed an approximately linear trend for solar collector area and solar fraction in a solar heating system. This trend was also confirmed in a solar-assisted heat pump, by Freeman et al. [62]. In addition, increasing the collector area would increase the average storage temperature [62] which acts as a source for the heat pump. Therefore, increasing collector area favours the heat pump in terms of higher COP [124].

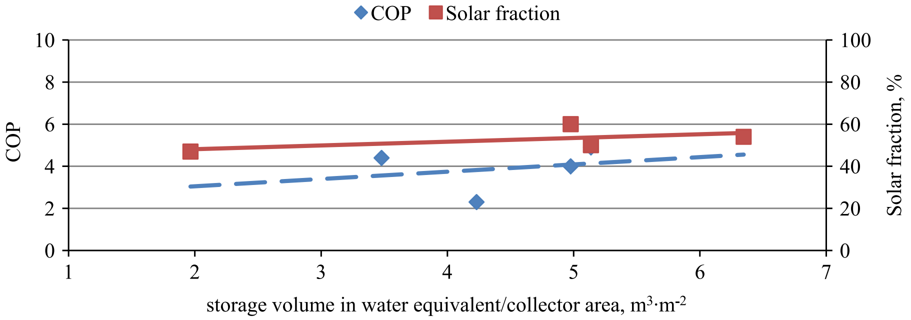

Fig. 11. COP of heat pump and solar fraction vs. ratio of storage volume to collector area.

Based on the results of previous studies given in Table 4, correlation between storage volume, collector area, COP and SF is shown in Figs. 9–11. In Figs. 9 and 10, in order to be able to compare different systems with different heating demand regardless of weather conditions and the building type, a ratio of solar collector area and storage volume to the annual energy demand was calculated. In addition, in Fig. 9 to make all storage methods comparable, the equivalent storage volume of water for all storages was considered. Equivalent storage volume of water corresponds to water volume that would store the same amount of heat. As can be seen in Fig. 9, as the ratio of storage volume to energy demand increased the COP and solar fraction increased. However, as mentioned earlier when the storage volume became large enough then there was no increase or little enhancement in COP and SF with increasing volume. It means that as storage was further increased the performance of the system in terms of COP and SF improved slowly. In Fig. 10 the relation between SF and COP with collector area is shown. As can be seen, both COP and SF increased linearly with expanding collector area. In addition, Fig. 11 shows how the COP and solar fraction varied as a ratio of storage volume to collector area changed. As can be seen, a higher ratio resulted in higher COP and higher solar fraction.

8. Future prospects

The paper provides a basis for development of new intelligent energy storage methods for sustainable building. This approach could be defined as combining e.g. photovoltaic-thermal system (PV/T) and heat pump [135] with seasonal thermal (ST) and electrical energy storage (EES), called PV/T-ST/EES-HP. The beneficial aspects of this system could be:

- Higher PV efficiency due to cooling down of the PV cells by the collector.
- Seasonal electrical storage for heat pump.
- Higher SF due to providing the electrical energy required for a heat pump by solar energy through PV.
- High COP of a heat pump.

However, the cost of this system for energy efficient buildings should be considered.

9. Conclusion

The overall aim of this paper was to conduct an extensive literature review of early and recent applications of seasonal thermal energy storage with a heat pump, both in large and small scales. Seasonal thermal energy storage can contribute significantly to the needs of energy efficient and environmentally friendly heating and cooling systems, as the replacement of conventional systems with renewable energy considerably reduces CO_2 emissions. Thermal loss from seasonal thermal energy storage has always been a consideration, however. Thermal loss from seasonal storage can be decreased by lowering the stored energy temperature. The low temperature storage also favors collector efficiency. Nevertheless, this temperature should be sufficient for covering the energy demand in the building. Therefore, seasonal thermal energy storage can be combined with a heat pump as an efficient heating system to increase the stored energy temperature to the appropriate level. Both heat pump and seasonal storage of solar energy are two promising methods of increasing the renewable energy consumption. In addition, the heat pump helps to make the storage stratified through decreasing the return temperature to the storage. Stratification is beneficial in terms of increasing the efficiency of the solar collector and increasing the exergy saving.

In this review study some well-known existing methods for seasonal thermal storage were introduced. Those methods were: hot water tank storage, gravel-water pit storage, duct thermal energy storage and aquifer thermal energy storage. Then, the combination of heat pump with those seasonal energy storages was discussed. The selection of suitable STES depends on many factors, including geological conditions, heat demand, and cost. Each of the studied storage systems has its own advantages and disadvantages. For instance, a water tank is easy to install and no special geological condition is needed, but the cost is high. Then again, aquifer thermal energy storage is cheap but extensive geological investigation is needed. Nevertheless, with careful consideration of the application of the system, size requirements and heating or cooling demand, the appropriate system can be chosen. In large and small buildings with only heating demand hot water tank storage with heat pump and gravel-water pit storage with heat pump can be installed. For large buildings with only cooling demand aquifer thermal energy storage with heat pump can be an option. This would cause considerable savings in expensive electricity during peak hour for large applications with high cooling demand. For small applications with only cooling demand duct thermal energy storage with heat pump is suitable. For applications with both heating and cooling demand aquifer and duct thermal energy storage with heat pump would be appropriate.

Two main factors influence the efficiency of seasonal thermal energy storage with a heat pump. These are the COP of the heat pump, and the solar fraction. Both factors are a function of solar collector area and storage volume. In this study a relation between these two factors based on past projects was found. The review showed that higher solar fraction and higher COP of a heat pump result from a higher energy storage volume and collector area. In addition, a higher ratio of storage volume to collector area causes a higher solar fraction and higher COP of a heat pump. It is difficult to generalize from this experience to other applications, however.

All reviewed papers showed that seasonal storage is a promising technology for energy saving, but its cost did not make it applicable to all projects. Nevertheless, due to many benefits seasonal thermal energy storage in high latitude countries was found to be cost effective [136]. In addition, when it comes to STES it is more economical and efficient to have a community development rather than single family houses [26,10]. In community energy storage the investment cost per square meter of collector area is between 20 and 30% of that of a single family house [10]. This is due to lower specific construction cost and smaller relative thermal loss in the larger energy storage volume. However, although having a seasonal storage at a community scale is more economical, it should be noted that the single family houses constitute 64% of the total European residential built floor area [4]. This value is 49% in Canada [137] and 45% in Sweden [138]. This shows that it is also important to consider the single family house sector. For single family houses depending on cost and geological conditions, heat pumps can be combined with seasonal thermal storage in DTES, HWTS or WGPS.

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