Energy-Efficient and Sustainable Heating System for Buildings:

Combining seasonal heat storage with heat pumps and low-temperature heating systems

1. Arefeh Hesaraki, 2.Sture Holmberg, 3. Fariborz Haghighat
1,2. Department of Civil and Architectural Engineering, KTH – Royal Institute of Technology, Stockholm, Sweden
3. Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada
Corresponding Author E-mail: Arefeh@kth.se

Abstract

During gaps between high heating demand in winter and high heating production in summer, the application of seasonal thermal energy storage becomes important. However, heat loss from seasonal thermal energy storage has always been an issue. Therefore, in order to decrease heat loss and increase solar collector efficiency, low-temperature heat storage is recommended. Nevertheless, this temperature is not sufficient throughout the heating season, which means that a heat pump is recommended in order to use this low-grade source to produce a suitable temperature for the heating system. In addition, heat pumps have better efficiency when working with low-temperature heating systems. This study investigated the seasonal thermal storage in combination with heat pump and low-temperature heating systems, with the aim of finding a suitable size for thermal energy storage and collector area. The study showed that 300 m^3 of storage volume and 55 m^2 of collector area could cover 80 % of the total energy demand using solar energy.

Keywords*:* Seasonal thermal energy storage, Heat pump, Low temperature heating system

1. Introduction

Nearly half of the world's final energy consumption is used for heating [1], and more than 40 % of this heating consumption is used in residential sector. Globally, approximately 80 % of heating is produced by fossil fuels, which cause significant CO_2 emissions. More than 20 % of total global CO_2 emissions come from the building sector, predominantly from heating systems. The environmental impact and scarcity of fossil fuels means it is vital to find replacements for them. Renewable energy, as a sustainable and efficient source of energy, is a promising replacement for fossil fuels, but suffers from intermittent availability. During summer time, there is plenty of solar radiation available with no heating demand, while during winter time, when the heating demand is highest, there is a shortage of renewable sources. One way to address this problem could be seasonal thermal energy storage. In seasonal storage, thermal energy is collected through solar collectors during summer and accumulated in a storage system, then used in the winter. There are two main types of solar energy storage: the first stores heat overnight, and the second stores heat for a long period and can be used inter-seasonally. Short-term storage contributes to 10–20 % of the total energy demand and is cheaper than seasonal storage. With seasonal storage, however, 50–100 % of the total energy demand can be covered by renewable energy. Short-term storage is mainly used for domestic hot water, but the main use of seasonal storage is to cover space heating.

1.1 Seasonal Thermal Energy Storage

One type of seasonal thermal energy storage involves storing the heat in the water, preferably in a tank buried under the ground (see Figure 1). The cost of this system is quite high, and can be reduced by adding gravel to the water pit storage; this system is called water-gravel pit storage (see Figure 2). The advantages of these two systems are that they have high heat capacity and are easy to install. In addition, they do not need any special geological conditions in order to be installed. However, if the geological condition is suitable for digging with respect to the ground type and condition of the water table, borehole thermal energy storage and aquifer thermal energy storage can be used. In borehole thermal energy, storage ducts are excavated into the ground and tubes of heat carrier medium are inserted into the duct (see Figure 3). This method involves storing heat in the ground during summer for winter usage. In aquifer thermal energy storage, two wells are dug deeply into the ground until they reach the aquifer (see Figure 4). One well acts as a cold well and the other as a warm well. During the charging process in summer, the water is extracted from cold well, heated by a heat source and injected into a hot well. In the heating season, however, the cycle is reversed for the discharging process; that is, hot water is extracted from the warm well, cooled by the heat sink and injected into the cold well. The application of aquifer thermal energy storage is only suitable for large applications and preferably with cooling demand.

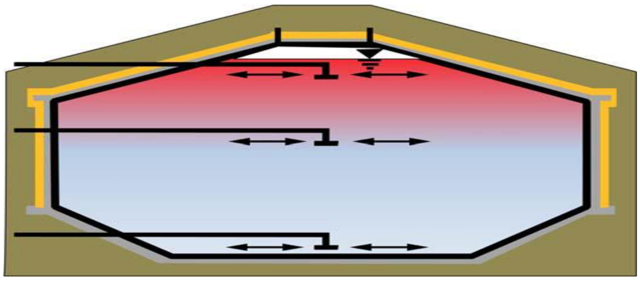

Figure 1 Hot water tank seasonal thermal energy storage

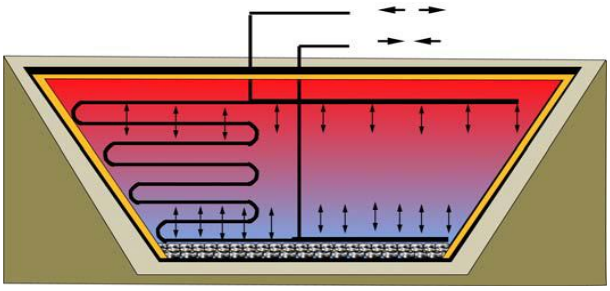

Figure 2 Gravel-water tank seasonal thermal energy storage

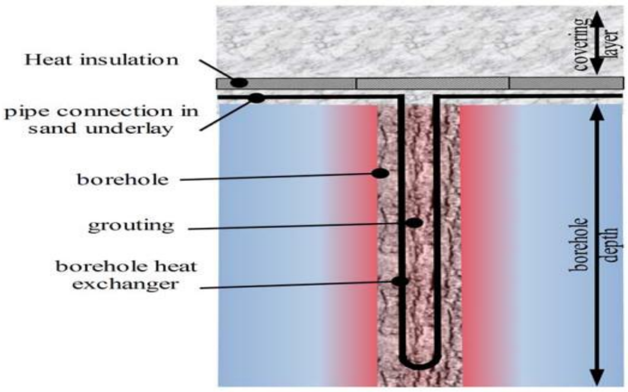

Figure 3 Borehole thermal energy storage

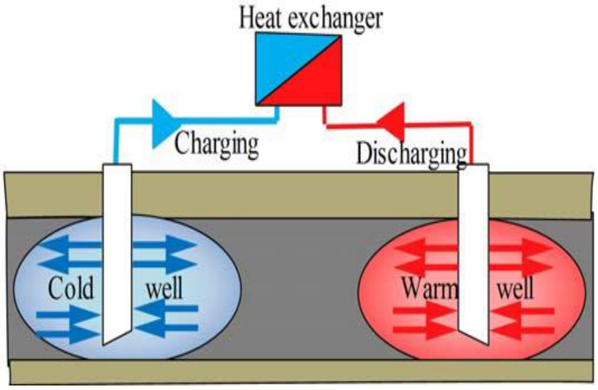

Figure 4 Aquifer thermal energy storage

1.2. Heat Pump

Heat pump has been known for many years as an energy efficient heat source. Heat pump uses renewable energy and by consuming a small amount of electricity it produces a useful form of heat. The lower the temperature of the heating system, the less work is required by the heat pump and the more efficient the system becomes. Low-temperature heating systems work with supply temperatures lower than 45 °C. The coefficient of performance (COP) of a heat pump is equal to the ratio of produced useful heat to the consumed electricity by the heat pump, see Eq. (1).

$$COP = \frac{Q_{hd}}{W} \tag{1}$$

1.3. Low-Temperature Heating System

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 or fan radiator as forced convection radiators. These systems favour sustainability and efficient use of energy; that is, they have high exergy- (quality of energy) 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.

In this study, hot water thermal energy storage is considered for a single family house located in Stockholm, Sweden. The aim is to find a suitable size for seasonal thermal energy storage when combined with a heat pump and a low-temperature heating system.

2. Description of the Building

The building studied is located in Stockholm and has three stories with a floor area of 160 m^2. The building was built in 2011 with low heat loss and a low infiltration rate. The heat demand of this building was monitored for one year, including the demand for domestic hot water and space heating.
The seasonal solar heating for this building as shown in Figure 5 was assumed as follows:

1. The solar collector on the roof is used to charge the tank buried under the ground. This collector is used as long as the temperature difference between the storage and the carrier medium of the collector is higher than 5 °C. The heat production from solar collector can be used directly if the produced temperature is high enough. Otherwise, it is used to charge the water tank.
2. The hot water tank is buried deep under the ground, so the thermal loss is reduced due to not depending on outside temperature variation. In this case, the storage is exposed to a constant ground temperature over the year. This storage is used directly for DHW or heating demand as long as the temperature is sufficient for direct usage.
3. The heat pump is served by the hot water tank as a heat source when the temperature of storage is not enough to be used directly.

4. The house has a low-temperature heating system including domestic hot water usage.

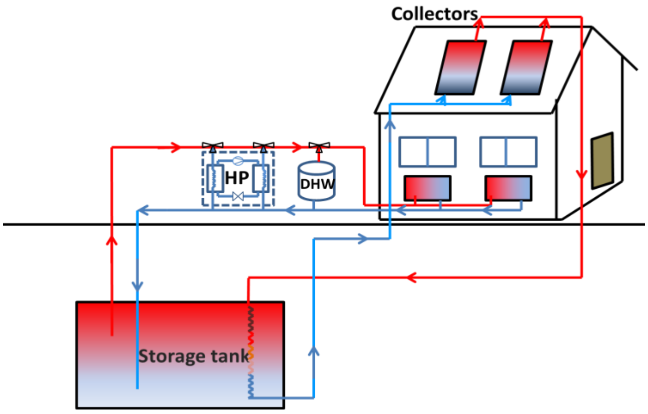

Figure 5 Seasonal thermal energy storage system, including solar collector, storage tank, heat pump and low-temperature heating system

3. Method

The boundary condition around the seasonal thermal energy storage is shown in Figure 6. The mathematical relations are given in Eqs. (2-6).

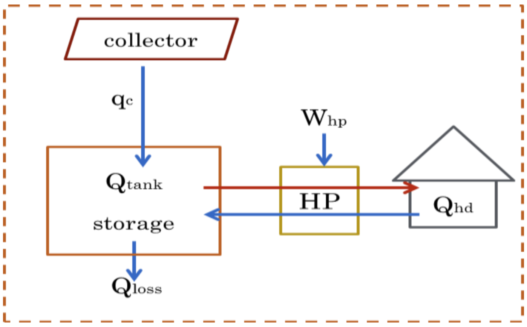

Figure 6 Boundary condition around seasonal thermal energy storage

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

$$W_{hp} = \frac{Q_{hd}}{COP} \tag{3}$$

$$Q_{tank} = \rho \cdot V \cdot c_p \cdot (T_{max} - T_{min}) \tag{4}$$

$$Q_{loss} = U_{tank} \cdot A_{tank} \cdot (T_{tank} - T_{ground}) \tag{5}$$

$$q_c = E_c \cdot \eta \cdot (1 - a \cdot (\frac{T_{in}-T_a}{L}) + b \cdot \left(\frac{T_{in}-T_a}{L}\right)^2) \tag{6}$$

where Q_{tank} is the stored heat in the tank (kWh), q_c is the solar collector output (kWh), W_{hp} is the work required by the heat pump (kWh), Q_{hd} is the heating demand in the building (kWh), Q_{loss} is the thermal loss to the surrounding ground from storage (kWh), COP is the coefficient of performance of heat pump, ρ is the water density (kg/m^3), V is the volume of storage (m^3), c_p is the heat capacity of water (kj/kg K), T is the temperature (°C), U_{tank} is the heat transfer coefficient of storage tank (W/m^2 K), A is the area of the storage tank (m^2), E_c is the average amount of energy received by the solar collector (kWh), η is the efficiency of the solar collector, a and b are experimentally determined coefficients for solar collector, and L is the average monthly value of atmosphere lucidity.

The WINSUN program was used to calculate the heat output of the solar thermal collector (q_c). WINSUN [2] is a system simulation program developed in Lund University for designing solar collectors and PV depending on the location of system, azimuth, tilt, tracking mode, and efficiency of PV.

In addition, the COP of the heat pump was assumed to be 3, as this is an average value for most heat pumps. However, it would be higher when working with a low-temperature heating system. Furthermore, to calculate the thermal loss from the storage tank, the U_{tank} was assumed to be 0.05 W/ (m^2 K). In addition, the ground temperature was assumed to be the average annual temperature for Stockholm, which is 6.6 °C.

4. Results and Discussion

4.1. Storage Size

The heat storage capacity of water is 60-80 kWh/m^3. In this study, 70 kWh/m^3 was considered as the average value. The total heating demand including domestic hot water and space heating in this building was measured as 20,920 kWh. Therefore, the required volume for storing this amount of heating demand is around 300 m^3.

Moreover, the ratio of 0.6 was considered between the height and diameter, i.e. $\frac{H}{D} = 0.6$ of the storage tank.

4.2. Collector Area

Figure 7 shows the result of heat production by 1 square meter of thermal collector calculated by the WINSUM simulation program.

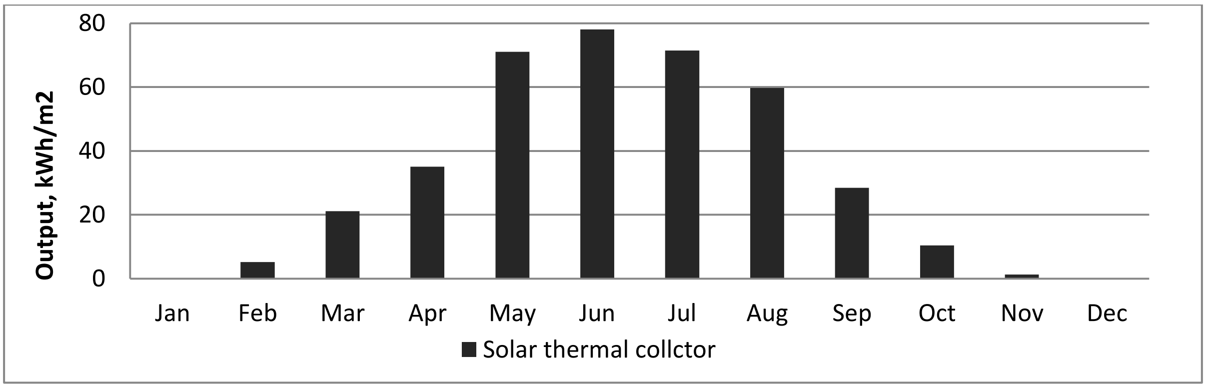

Figure 7 Heat output of a solar collector in Stockholm

The annual heat production is 385 kWh/m^2. Therefore, to cover 20,920 kWh of heat demand, the area needed is almost 55 m^2. This means that the whole roof of the building will be covered by solar collector.

4.3. Monthly Heat Balance

Based on 55 m^2 of collector area and 300 m^3 of storage volume, Eqs. (2-6) were solved in order to study the performance of the system month by month. Figure 8 shows the heat balance of the system, month by month.

As shown in Figure 8, the heat produced by the solar collector can either be used directly as immediate use or stored into the storage. However, some of this heat is lost to the surrounding ground due to temperature difference between the ground and the storage tank. When the heat produced by the solar collector is not enough to meet the building heating demand, the stored heat is discharged from the storage. As shown in Figure 8, the entire heating demand for months from October to January is discharged from the storage without use of any auxiliary heating system. However, for February and March the heat produced by solar collector is not sufficient and the heat pump is used as an auxiliary heat source. To calculate the solar fraction (that is, the amount of energy provided by the solar heating system divided by the total energy demand), the total heat provided by solar energy is divided by the total demand. A solar fraction of 80 % is achieved by installing 55 m^2 collector area and 300 m^3 of hot water storage tank (see Figure 9).

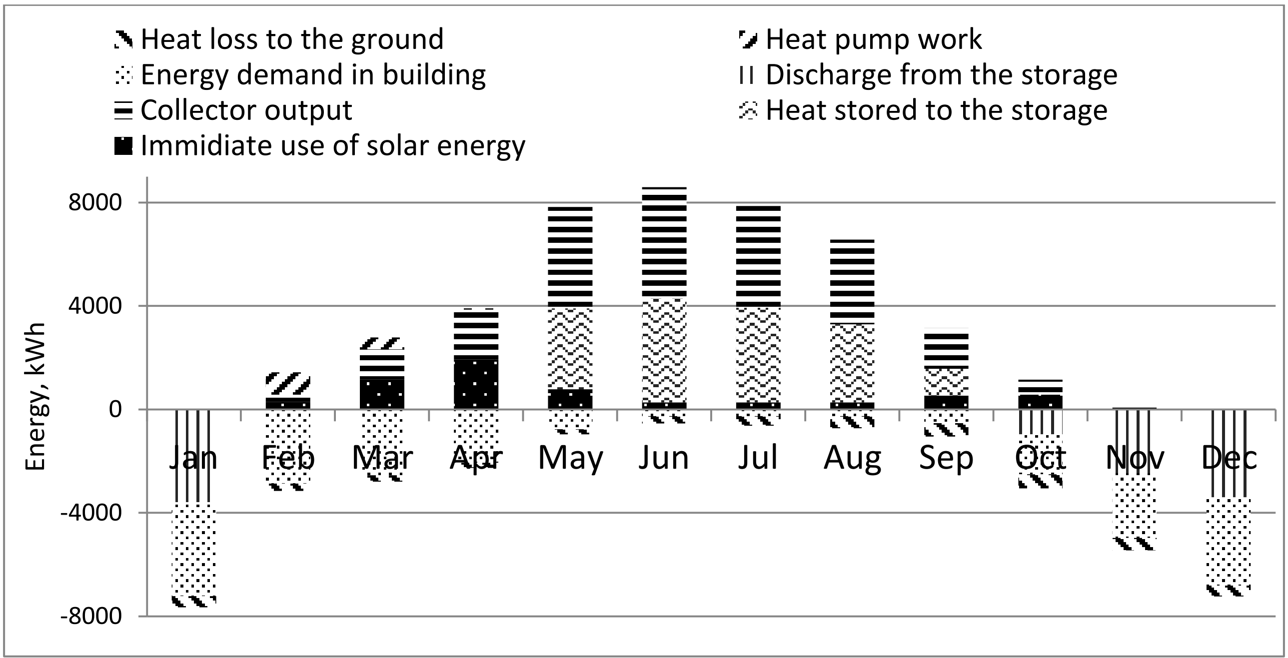

Figure 8 Monthly energy balance of the seasonal thermal energy storage system

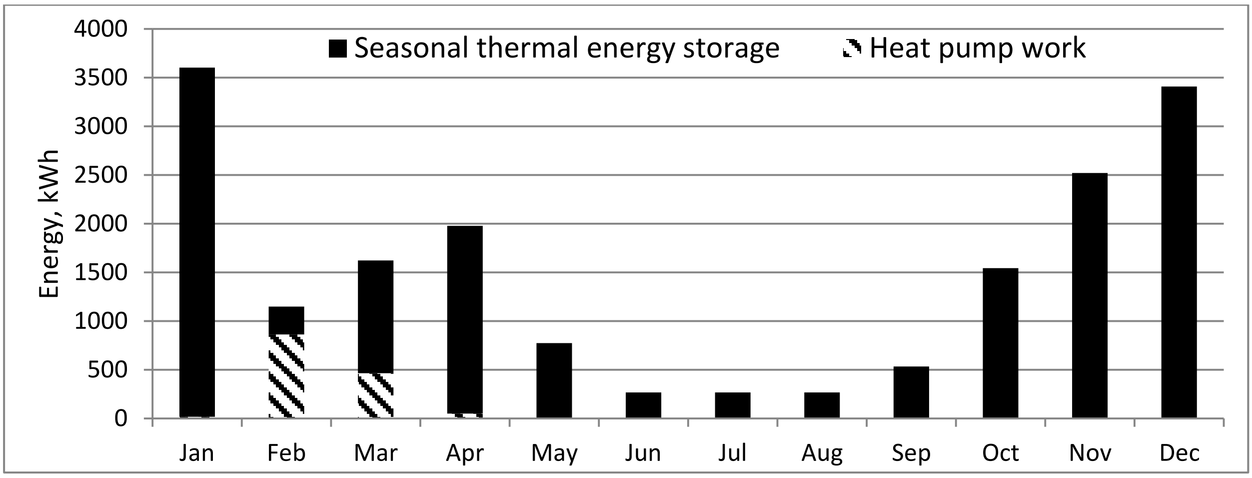

Figure 9 Heating demand covered by seasonal thermal energy storage and heat pump

5. Conclusion

Energy consumption in the building sector is growing much faster than predicted due to unpredictable living habits and the economic situation. This situation has created a need to find a solution for heating systems in the buildings of tomorrow. Due to the scarcity of fossil fuels and the high cost of electricity, renewable energy sources are becoming increasingly important. However, when it comes to renewable energy, there is a seasonal gap between energy demand and energy production. To fill this gap, seasonal thermal energy storage can be introduced to store solar energy during summer for later usage. The present study considered seasonal underground hot water tank storage. The studied building is located in Stockholm, Sweden, with 20,920 kWh heating demand, including space heating and domestic hot water. The size of seasonal storage was considered to be 300 m^3 of storage tank and 55 m^2 of collector area. The study showed that this system made it possible to cover 80 % of the total energy demand in this building using solar energy. This sustainable and energy efficient heating system reduced the CO_2 emissions from the residential sector considerably, which is essential to slow down the rate of global warming.

Acknowledgements

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