Solar Thermal Collectors and Multi-Source Heat Pump Systems

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Abstract

Combining one or more types of solar thermal collectors in a hybrid or multi-source heat pump system offers a potentially more cost-effective method for heating buildings compared to traditional approaches. This means a lower total cost of ownership. The initial cost of the system can be lower than a conventional ground source heat pump system because of a significantly smaller total ground loop (less borehole drilling), and the electricity use can be relatively low because the ground loop (or loops) will provide better efficiency than any air source heat pump. Even the recent “cold climate” heat pumps will never compare with a ground loop when the air temperature is either below freezing or above 100°F. The laws of physics do not allow high efficiency for any air source system at those temperatures, but a ground loop gives high efficiency at any outdoor air temperature.

Keywords: solar thermal collectors, multi-source heat pump, energy efficiency, cost-effective

Introduction

The combination of Solar Thermal Collectors (STCs) with multi-source heat pump systems has paved the way for energy-efficient and cost-effective heating and cooling solutions. This use of a hybrid system has helped channel the use of renewable energy, yielding significant reductions in both operational costs and greenhouse gas emissions.

Former studies have explored the performance and benefits of integrating STCs with heat pump systems. A variety of multi-source system designs were presented by Olson and Yu with seasonal storage and optimized solar/air collection systems (Olson & Yu, 2016; Olson & Yu, 2017). These works highlight the potential for significant energy savings and improved system efficiency.

Additionally, research by Emmi et al. and Kjellson et al., using the TRNSYS simulation program to evaluate various system configurations, highlighted the benefits of using multi-source systems, such as optimized system performance along with reduced electricity demand by integrating ground-source heat pumps with solar collectors (Emmi et al., 2016; Kjellsson et al., 2010).

A study by Chen et al. proposed a hybrid ground source heat pump system and integrated it with concentrated photovoltaic thermal (CPC-PVT) solar collectors. This hybrid system exhibited higher primary energy ratios (a measure of the system's efficiency in converting primary energy into useful outputs and exergy efficiency versus the conventional system, highlighting the benefits of combining geothermal and solar resources for performance enhancement (Chen et al., 2019).

In another study conducted by Han et al., a multi-source hybrid heat pump system (MSHPHS) was simulated to be located in the cold region of Harbin, China. By using solar, geothermal, and air energy, the MSHPHS maintained a high coefficient of performance (COP) of 3.06 and showed a higher energy efficiency of 29.84% compared

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to a standard ground-source heat pump system. This showed the effectiveness of integrating STCs and multi-source heat pump systems (Han et al., 2017).

There are different types of STCs that can be useful for multi-source heat pump systems, as listed below:

1. Glazed flat plate collectors: Primarily used for domestic heating for decades, these collectors are most effective at temperatures up to 200°F. They are not useful for cooling the types of systems described here because the glazing panel is intended to prevent convection cooling of the absorber plate.
2. Unglazed flat plate collectors (also known as polymer flat plate collectors): These are cost-effective and versatile since there is no glazing. They are suitable for both heating and cooling applications. They are used especially in swimming pool heating and have much lower output temperature than the glazed collectors. For the cooling application, they collect cold from both cold air convection and also radiative cooling into a clear, cold sky.
3. Photovoltaic Thermal (PVT) collectors: These devices are considered to be dual-use products, since they produce both electricity and hot water from sunlight. What most people do not realize is that these devices can be made into triple-use products when they are part of a multi-source heat pump system for electricity generation and the production of hot or cold water. These can be made in both glazed and unglazed versions; however, the unglazed type is most widespread. In this case, they are useful for electricity generation, hot water production and also cold-water production (when the sun is not out and the air temperature is low). It is possible that the useful life of a PVT panel might be longer than that of a plastic unglazed pool solar collector since the solid PV layer on the top of the panel gives protection to the pipes and other material used for hot or cold-water collection below the PV layer.
4. Evacuated Tube Collectors: Evacuated tube collectors with vacuum insulation inside multiple glass tubes are highly efficient at higher temperatures and are less influenced by the external weather conditions, but are less useful for collecting cold, i.e., heat removal. They can attain higher temperatures when combined with curved reflectors for sunlight concentration.

The objective of this paper is to evaluate the design, performance and energy-efficiency potential of a newly-developed multi-source heat pump system equipped with various sources, such as ground, air, and/or solar. It examines the design optimization and configurations using numerical simulations in the TRNSYS environment (TRNSYS 18). This study also compares multiple cases (operation modes) with conventional systems to quantify efficiency and energy savings. It highlights the potential of the multi-source system developed, demonstrating its potential as a sustainable and cost-effective solution for residential heating and cooling.

Multi-Source Heat Pump Systems

In recent years, there have been improvements and simplifications in the multi-source system designs, reducing the number of pumps and valves needed to accomplish full functionality. Perhaps the simplest form of a multi-source system (but not with full functionality) is one that has two sources and allows a selection of one or the other to connect to a water source heat pump. Fig. 1 shows three versions of this.

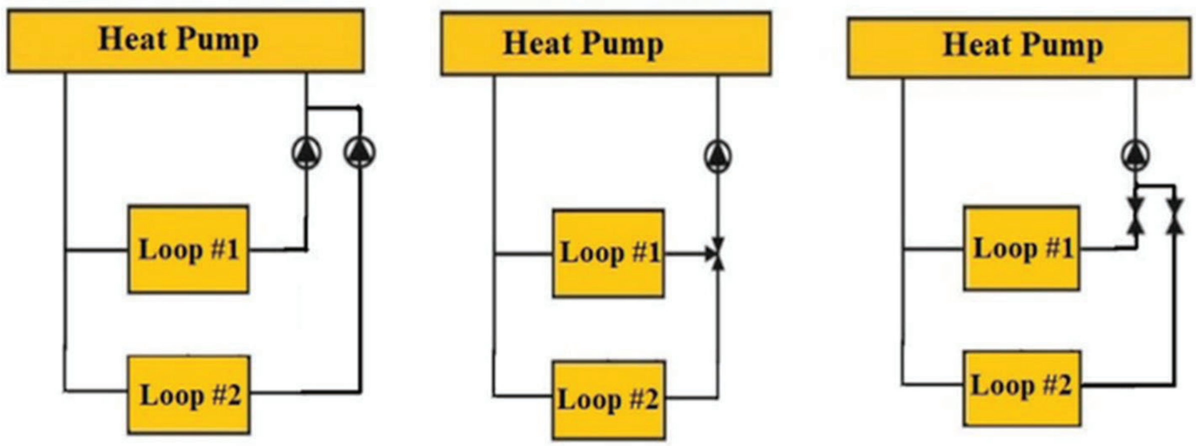

Fig. 1. Dual Source Heat Pump Configurations

Note that Fig. 1 also allows a mode which has source water from both sources simultaneously (parallel mode). By including one more pump or one more valve, there could be three optional sources rather than just two. There are also many sources to choose from beyond STCs:

1. Ground loop (either borehole or trench)

2. Cooling tower (evaporative or dry)

3. Open loop from a conventional water well

4. Surface water (lake, pond, or river)

Certainly, many other sources beyond those above are also possible.

If the system has just a single ground loop, the addition of a second source such as a STC allows what might be called a preconditioning mode. With this mode, the ground around the loop can be either preheated or precooled to gain an improvement in heat pump efficiency at some future time. For example, in the summer and/or fall of the year, a STC can circulate very hot water through the ground loop pipes in preparation for the upcoming winter. This technique has been widely used and can sometimes convert a failing ground loop system from total failure into a long-term success.

A simple example of a single-loop system with preconditioning is shown in Fig. 2.

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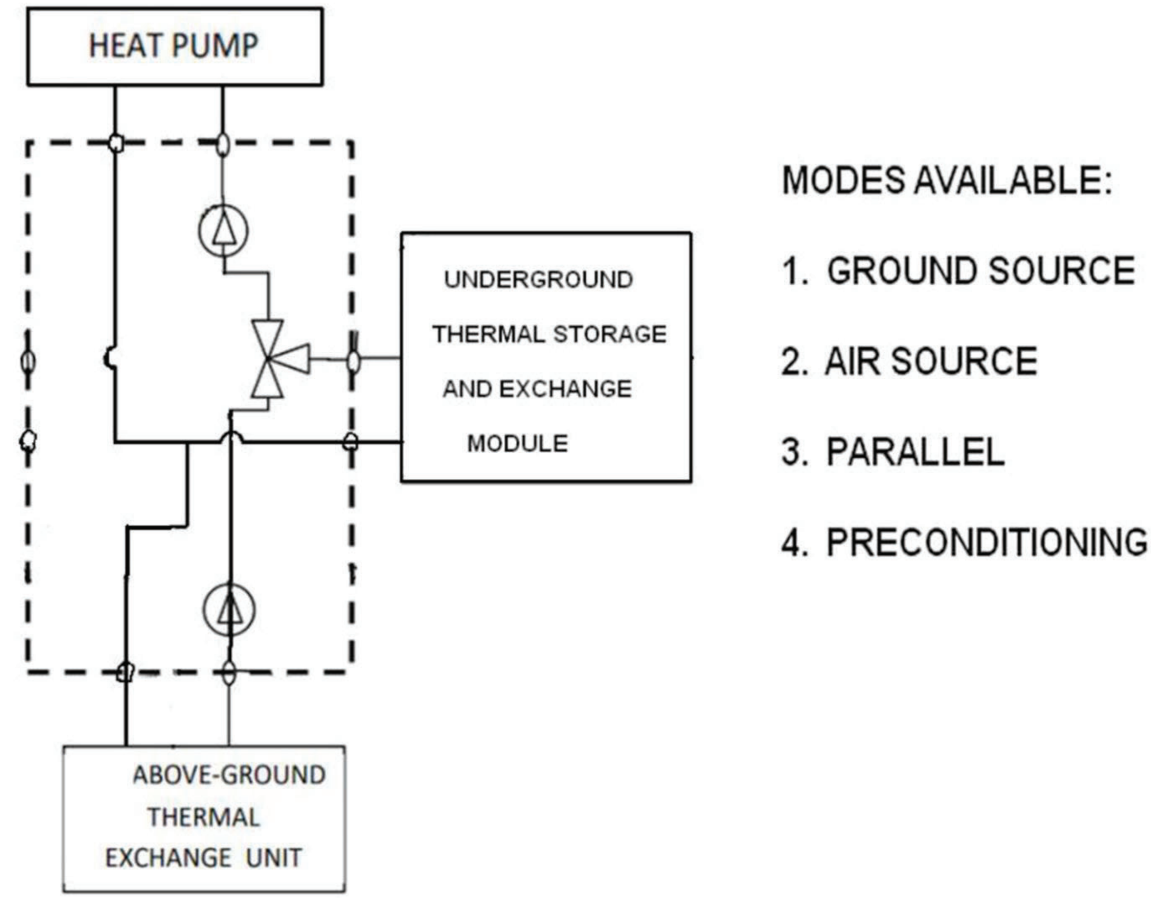

Fig. 2. Single ground loop system with preconditioning

Numerical simulations have been conducted to evaluate the energy-saving potential of the system depicted in Fig. 2. These simulations were performed in the TRNSYS environment (TRNSYS 18) for a heat pump system incorporating underground regions, STCs, and a buffer tank as illustrated in Fig. 3. The system is designed to provide heating and cooling for a single-family house (Fig. 4) located in Bismarck, North Dakota. Details about the house and the system are presented in Table 1 and Table 2.

The operational strategies for this system are categorized into four control modes, as shown in Fig. 5. Based on these modes, three specific cases were analyzed in this study:

- Case 1: Alternates the heating source for the heat pump between the underground loop and the solar buffer tank (Modes 1 & 2).
- Case 2: Builds on the setup of Case 1 by also enabling simultaneous use of both the underground loop and the solar buffer tank, splitting the flow equally (Mode 3) when both sources are advantageous.

- Case 3: Extends the functionality of Case 2 to include charging the underground region using the solar buffer tank (preconditioning – Mode 4) when space heating is not required.

The performance of these cases was compared to a baseline scenario, where a conventional air source heat pump system is used for heating and cooling in the target building, as depicted in Fig. 4.

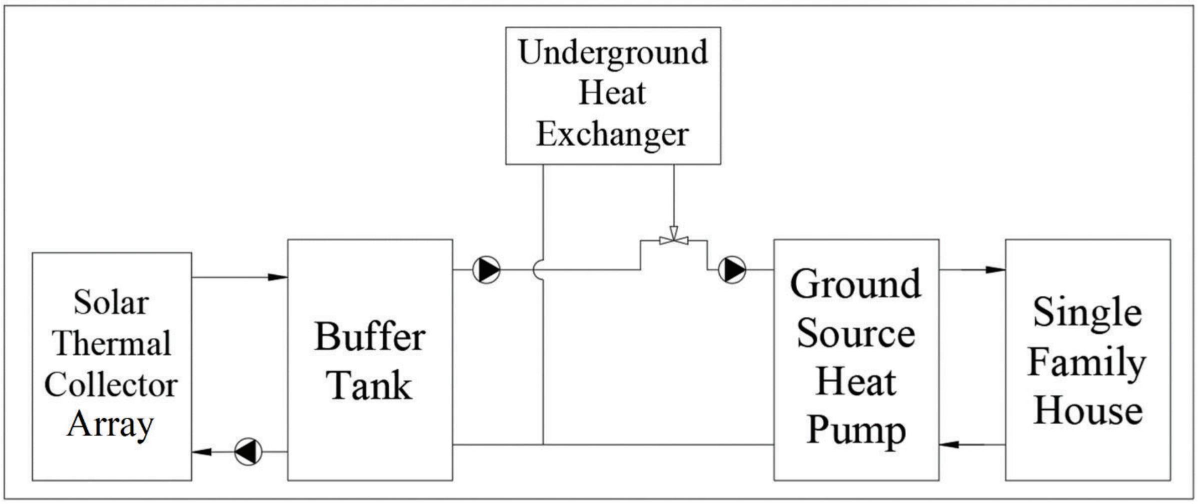

Fig. 3. Single ground loop system with solar collectors for simulations

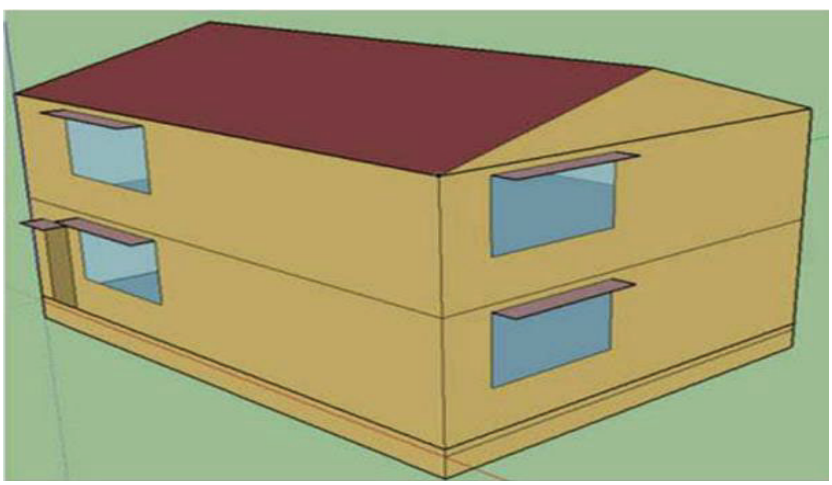

Fig. 4. Single-family house for simulations

Table 1. Building Information

Building Type	Single-Family House
Number of Floors	2

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Building Total Area [m^2]	334.5
Total Conditioned Area [m^2]	223.1
Window-Wall Ratio	14.1%
Gross Roof Area [m^2]	219.8

Table 2. System Information

Borehole Type	Vertical Closed Loop
Number of Boreholes	4
Borehole Depth [m]	61
Borehole Separation Distance [m]	6.1
Number of Heat Pump Units	Water-to-Air HP: 1
HP Air Flow Rate [L/s]	774.0
HP Water Flow Rate [L/s]	0.76
HP Rated Heating Capacity [W]	11517.7
HP Rated Heating COP	3.4
HP Rated Cooling Capacity [W]	14184.6
HP Rated Cooling COP	4.8
HP Rated Fan Power [W]	560
Solar Thermal Collector (STC) Dimensions [m]	2.44 ×1.22
Total Number of Evacuated Tube STCs	2
Buffer Tank Size [L]	302.8

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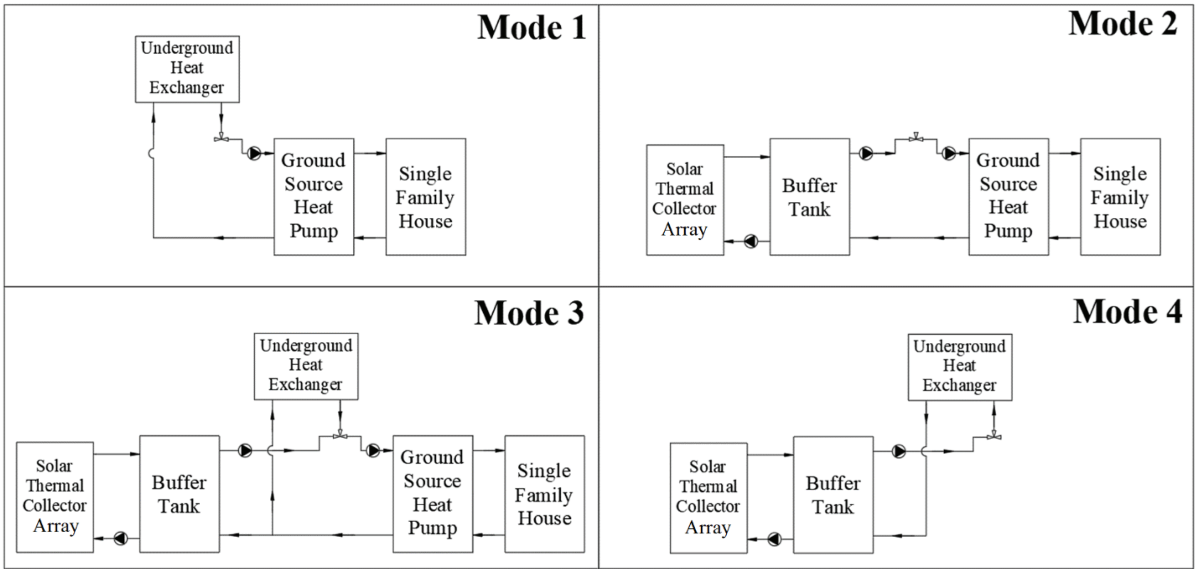

Fig. 5. Diagrams of different operation modes

Fig. 6 displays the monthly averaged heating Coefficient of Performance (COP) for the different cases. The data reveal that higher heating COPs are achieved during the winter months when using the hybrid heat pump system rather than the baseline system, which relies on an air source. Notably, Case 3 exhibits lower heating COPs than Cases 1 and 2 during summer. This reduction is primarily due to the heat stored in the buffer tank being transferred to the underground regions for preconditioning, leaving less available for space heating. Moreover, due to the limited number of boreholes and the small size of the underground regions, a significant portion of this heat is lost through the edges and top of the ground. Consequently, there is no notable improvement in heating COPs after summer, as illustrated in Fig. 6. A higher winter temperature requires different parameters for borehole spacing, solar collection area, and tank size. An even higher temperature will be obtained after 5 or 10 years of use.

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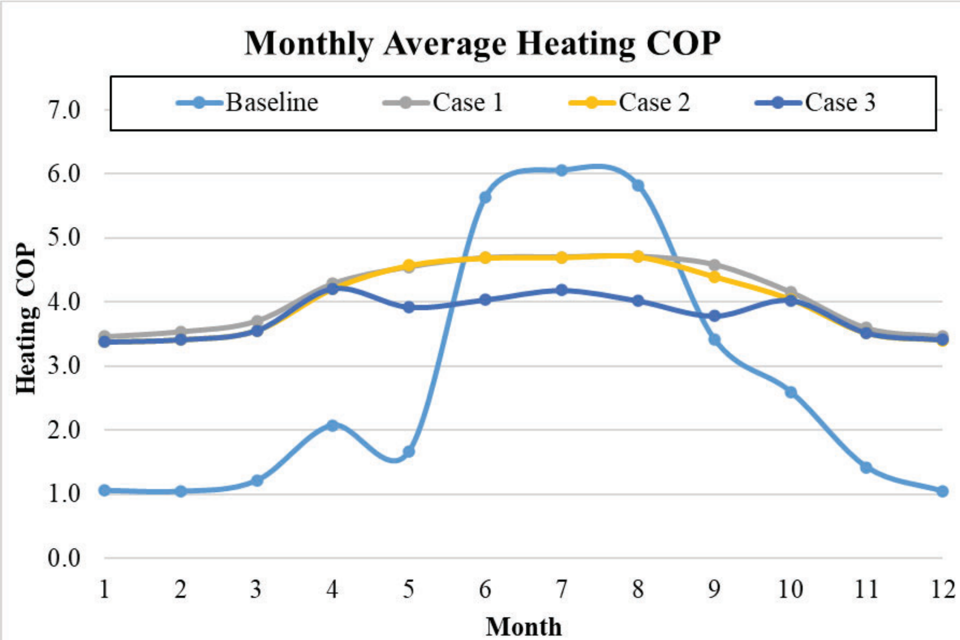

Fig. 6. Monthly average heating COP

Fig. 7 illustrates the monthly energy usage of the heat pump system across various cases. As indicated, Cases 1, 2, and 3 demonstrate significant energy savings compared to the baseline system. The annual energy savings for these cases is approximately 60%, highlighting the energy-saving potential of the hybrid heat pump system over a conventional air source heat pump system in cold climates.

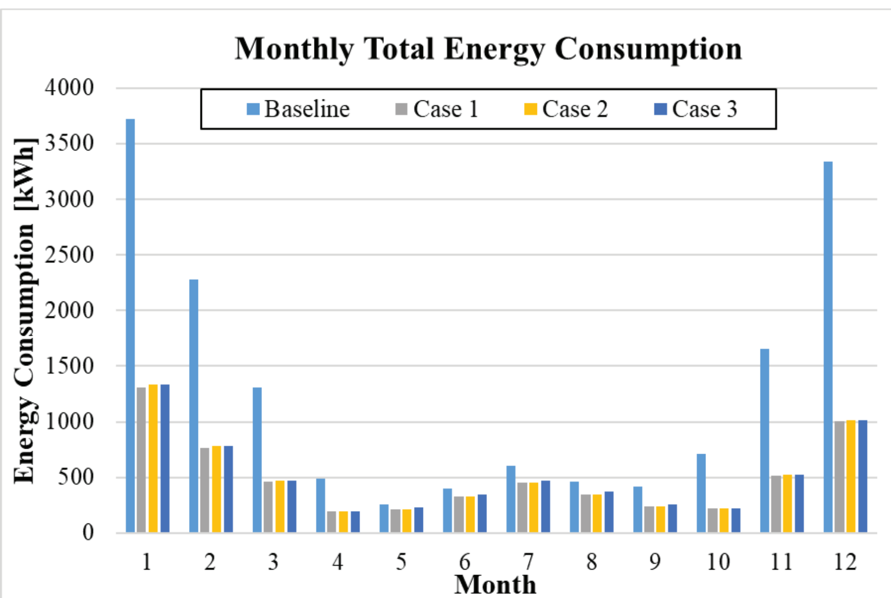

Fig. 7. Monthly energy consumption

For a new system design, there might be two somewhat separated ground loops rather than just one. In this case, it is possible to have preconditioning such that one region underground is warmer than the deep earth temperature in the winter and the other region is colder than the deep earth temperature in the summer. Geothermal heat pump proponents generally claim that their systems are the most efficient heating and cooling systems in the world because of a very stable temperature from the deep earth. With two ground loops and preconditioning, it is possible to have source temperatures even better than stable by providing more desirable temperatures for heating or cooling from the two distinct underground regions. A dual-loop system with preconditioning is shown in Fig. 8.

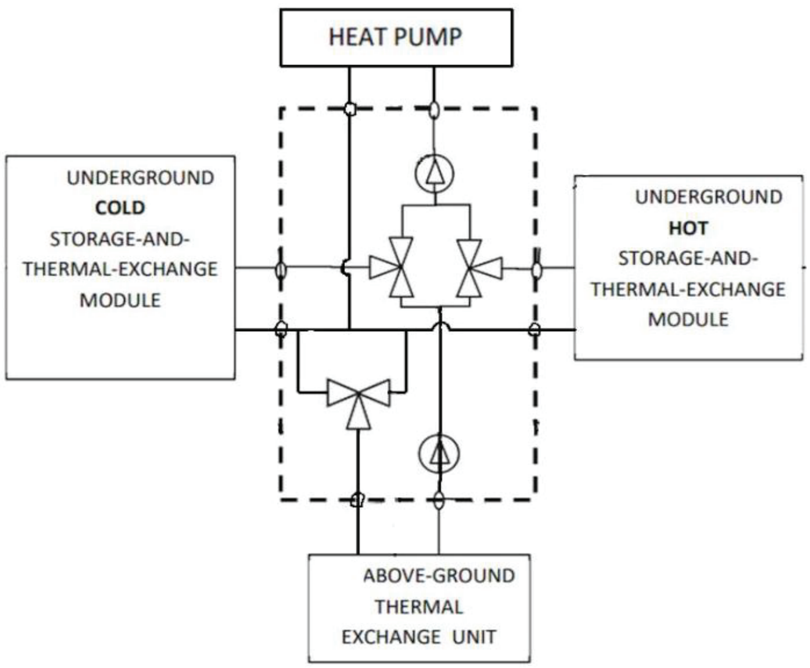

Fig. 8. Multi-source system with two ground loops (Olson & Yu, 2020).

A more complete description of the block diagram of Fig. 8 can be found in U.S. Patent 11105568. It is assumed that the system will have multiple temperature sensors and computer control to automatically change valve settings and pump speeds to give the optimum result for long-term efficiency in operation (optimum heating and cooling and minimum electricity use). Here are the most essential operating modes based on outdoor air temperature, assuming that there is a significant need for both heating and cooling over a full year:

1. At very low air temperatures, the system preconditions by transferring cold from the ambient air to the underground cold region, while simultaneously utilizing the hot region for space heating via the heat pump.

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2. When the temperature from the aboveground unit (e.g., STCs) is close to the hot region temperature, the heat pump may use water from both sources simultaneously (parallel mode).

3. When the aboveground unit has a temperature higher than either of the underground regions and there is a need for heating, the heat pump source water will be from the aboveground unit.

There are also three modes similar to those above for cooling where, at the highest air temperatures, there is preconditioning into the underground hot region while the cold region provides cold water for the heat pump. If this water temperature is lower than 50°F, the heat pump might be used in a bypass or economizer mode for cooling so that power for a compressor is not needed and system efficiency will be very high.

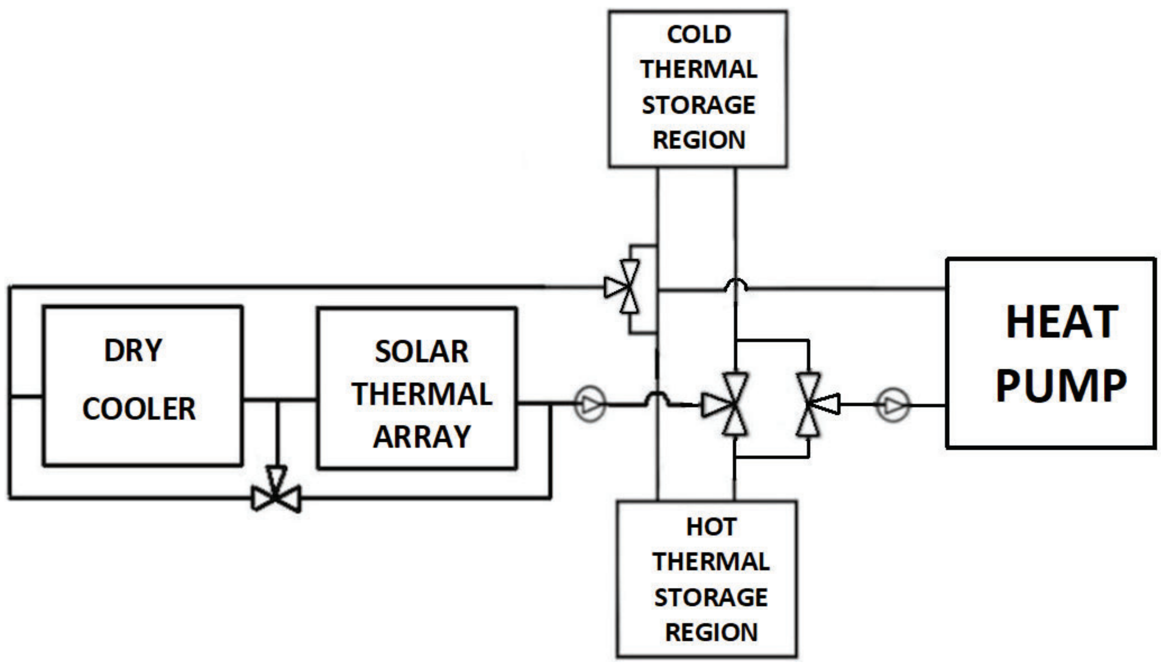

Fig. 9. Multi-source system with higher-temperature solar thermal collection

The system of Fig. 8 is well suited for any climate region. However, for a cold-climate region, there is another option that uses one additional three-way valve but can take advantage of higher-temperature versions of STCs. This configuration is shown in Fig. 9.

Although Fig. 9 shows the use of a dry cooler, this could just as well be an array of unglazed solar or PVT collector types. The solar thermal array in Fig. 9 could be a glazed flat-plate type or any of the vacuum-insulated types. For collection of heat on a sunny but cold day, the leftmost valve can bypass water around the dry cooler, and for preconditioning with very cold air, the solar thermal array can be bypassed.

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Although all of the block diagrams above show the use of just a single heat pump, this could instead be multiple heat pumps and/or water-cooled chillers. For thermal energy networks, where natural gas pipes are being replaced with continuous-flow water pipes, it is possible that the systems above could be more cost-effective than the exclusive use of borehole heat exchangers, which is the current practice.

If there is a need for underground seasonal thermal storage (six months) and on a large enough scale, the best model in North America is at Drake Landing Solar Community in Canada (Drake Landing Solar Community).

The Drake Landing borehole array is designed specifically for thermal storage, not geoexchange. Here are some differences:

1. The spacing between boreholes is 7 feet, which is about 1/3 that of conventional geoexchange systems.

2. The borehole depth is 115 feet, which is about 1/5 of the typical geoexchange depth.

3. The water-circulation path is designed for the hottest region to be always at the center, not at the perimeter.

This design allows for the seasonal thermal efficiency to be as high as 50 percent (ratio of thermal output to thermal input). Widely spaced boreholes will never be close to that efficiency.

The water used for thermal transfer at Drake Landing can have a temperature as high as 175°F, which requires the use of PEX pipe rather than the more common HDPE type. If even higher temperatures are desired, a special version of PEX might be considered that allows temperatures in the 230°F range (trade name Pexgol).

For many solar thermal applications, a buffer water tank is used to allow for an optimization of flow rate and temperature from the (highly intermittent) solar collector output to the underground storage or the end-use equipment (heat pumps or fan coils). The Drake Landing system uses two buffer tanks for this purpose.

Conclusion

In conclusion, using STCs in multi-source heat pump systems can significantly improve building heating and cooling efficiencies. By using various types of collectors like glazed and unglazed flat plates, PVT systems, and evacuated tubes, these hybrid systems can effectively harness solar energy and optimize thermal storage for both heating and cooling. The flexibility in design and the ability to adapt to different climate conditions make these systems versatile. This approach not only significantly improves energy efficiency but also contributes to reducing greenhouse gas emissions, aligning with environmental sustainability goals. The future of building climate control could see a shift towards these innovative, multi-source systems, leveraging renewable energy sources to create more cost-effective, efficient, and environmentally friendly solutions.

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Conflict of Interest

There are no conflicts of interest regarding the publication of this paper.

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