Review

A Review of Geothermal Energy Coupled Hybrid System for Building Heat Supply

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Abstract: Recently, there has been significant emphasis on studying the combination of geothermal energy with other forms of renewable energy. This has become an important area of research in sustainable energy development. The notable characteristic of this integration is its ability to improve the overall efficiency and reliability of the heat supply system. This study reviews the research conducted on the building heating system, which combines geothermal energy with solar energy, wind energy, and air-source energy. A thorough analysis of how previous studies have utilized renewable energy sources to address the drawbacks of geothermal heating systems has been performed, with a specific focus on energy consumption efficiency, soil temperature variations, system power supply, and cost analysis. Geothermal energy coupled with solar energy can mitigate the instability of the solar energy supply and reduce the ground temperature attenuation. The integration of geothermal and wind energy can produce electricity, thereby satisfying the power requirements. The combination of geothermal energy with an air-source heat pump system can enhance the overall performance and reduce the borehole heat exchanger depth. Through the detailed analysis of these hybrid systems, we aim to promote the development and popularization of the coupled system and provide a reference for renewable energy utilization.

Keywords: geothermal energy, renewable energy, hybrid building heating system, coupled system efficiency

1. Introduction

As economic globalization continues to advance, the increasing energy consumption has exerted tremendous pressure on the environment and resources. Therefore, the main direction of energy development is shifting to increase the utilization of renewable energy instead of fossil fuels to decrease greenhouse gas emissions [1,2]. The comprehensive use of renewable energy is particularly important as it contributes to societal sustainability [3], ecological balance [4], and the reduction of atmospheric pollution [5,6]. Geothermal energy is a kind of renewable resource that is widespread and clean [7–10]. It can be efficiently utilized through technologies such as geothermal heat pumps to obtain high-temperature heat sources [11,12]. It is applicable for various purposes, including building heating, electricity generation, greenhouse cultivation, and swimming pool heating [13,14].

Geothermal energy has numerous advantages, such as vast reserves and widespread distribution [15,16]. Its development is currently progressing rapidly. The ground source heat pump (GSHP) technology has been proven to be an effective way for building heating all over the world. The buried heat exchanger (BHE) is the main equipment in the GSHP system and there have been many investigations about the BHE heat transfer mechanism, numerical simulation and performance optimization. However, some problems and limitations arise during the utilization process [17,18]. One of the major unresolved issues is that the long-term operation of BHE will lead to ground temperature attenuation. The BHE is usually buried underground to absorb heat from the high-temperature strata. If the system operates for a long time, the ground temperature might decrease year by year, and the BHE heat extraction efficiency might not satisfy the energy demands [19,20]. Therefore, combining geothermal energy with other renewable energy sources has become a feasible method to solve this problem [21,22]. Through the integration of geothermal energy with other renewable energy resources [23,24], the system efficiency can be improved essentially [25,26]. Typically, combining solar energy with geothermal energy can mitigate the intermittent nature of solar energy and improve the reliability of the energy supply [27,28]. Integrating geothermal energy with air-source heat pump systems can significantly decrease operational expenses and enhance energy consumption efficiency [29,30]. By combining geothermal energy with wind energy, it is possible to have a continuous and reliable source of electricity supply throughout the year, enhancing the dependability of the power grid [31].

This literature focuses on the utilization of geothermal energy combined with other renewable energy sources to improve the reliability and efficiency of the building heating system. The primary goal is to assess the advancements in geothermal energy-coupled hybrid systems. In pursuit of this objective, we will review recent literature that focuses on the technical aspects, system design, and performance analysis of coupled systems [32–34]. Firstly, an introduction to the development of the geothermal heating system, including the classification, development, and theoretical studies about the prediction methods, will be carried out. Then a thorough investigation will be conducted on the geothermal energy hybrid system using solar energy, wind energy and air source heat pump. Finally, summaries will be given after each section and at the end of the study. A comprehensive examination of system configuration, operating principle, investigation methods and system efficiency is crucial for advancing the integration of geothermal energy with other renewable energy sources, which will help promote the development of renewable energy applications.

2. Geothermal Heating System

2.1. Development of Geothermal Heating System

Geothermal energy is a type of clean and widely distributed renewable energy that has been utilized for decades. Swiss scientists first introduced the notion of a "ground source heat pump" through patents in the early 20th century, which led to a global study on shallow geothermal energy [35]. By 1999, ground-source heat pumps have been widely adopted in developed countries like Europe and Japan, dominating residential heating systems. By the end of 2019, the global installed capacity for direct geothermal energy reached 107,727 MWt, marking a 52.0% increase from 2015 [36]. Standards guiding geothermal energy applications have been implemented in Canada, Europe, and other regions. By the end of 2017, China has the largest utilization area in terms of shallow geothermal energy for heating and cooling [37]. These demonstrate the significant global expansion and international focus on geothermal energy.

One of the main ways to use geothermal energy is to extract the heat contained in the underground rock and soil bodies or underground water through certain means and then transfer it to the above-ground equipment for building heating [38]. According to different ways of heat extraction (as shown in Figure 1), geothermal energy utilization systems can be divided into water source heat pump (WSHP) and GSHP [39,40]. The WSHP extracts high-temperature groundwater for immediate use, and then reintroduces it back into the aquifer [41,42]. In contrast, the GSHPutilizes a BHE to exchange heat with the surrounding rock and soil. This allows the system to continuously transport the heat from the rock and soil to the above-ground equipment using a circulating fluid, typically water [43,44].

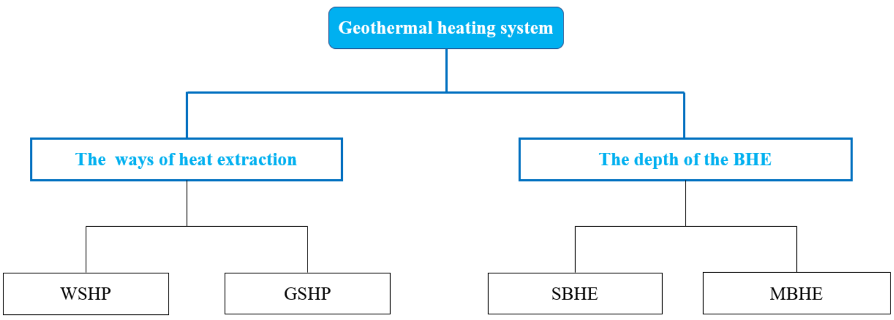


Figure 1. Geothermal heating system classification.

Further, according to the depth of the BHE, the geothermal heating systems can be further classified into shallow buried heat exchanger (SBHE) systems and medium-deep buried heat exchanger (MBHE) systems [45]. SBHE is notable for its ability to be used for both heating and cooling purposes [46,47]. MBHE stands out due to its superior thermal efficiency for heat supply and ability to maintain constant operating temperatures over a relatively long period of time. MBHE also has a longer lifespan, making it ideal for larger-scale applications [48]. The characteristics of these two categories, in terms of their suitability and effectiveness, highlight their substantial capacity for use in a wide range of energy applications.

2.2. Research Advancements

The BHE is the equipment responsible for directly exchanging heat with the exterior soil in the use of geothermal energy. It is also the key component that significantly impacts the overall performance of the geothermal system. Due to the high costs associated with drilling, logging, and pipe burial in the early stages, the evaluation of the BHE performance is particularly important [49,50]. On this basis, various evaluation methods have been established to guide the design and operation of the BHE system for project application (as shown in Figure 2). These methods can be theoretically divided into analytical approaches, numerical approaches utilizing software, and other self-developed numerical calculation methods such as finite element and finite difference methods [51–53].

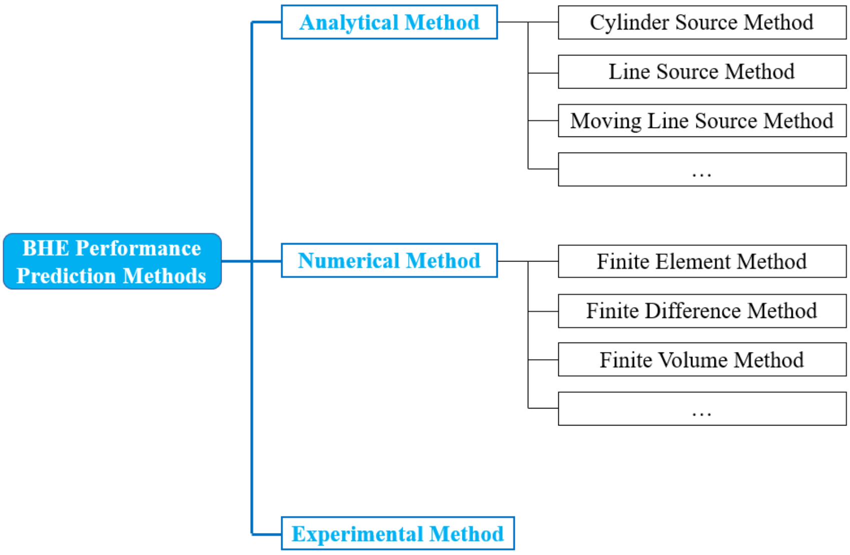


Figure 2. Different methods for BHE performance prediction.

Analytical methods solve the governing equations directly and have the benefit of fact computation speed, rendering them appropriate for quick design with appropriate simplifications. Contrarily, numerical methods contain detailed boundary conditions, including complex geological conditions and BHE configurations. This enables the attainment of more precise outcomes considering real geological and BHE structural parameters. Experimental approaches yield tangible data and empirical proof, which is necessary for verifying the simulation methods and bolstering the dependability of the design. By integrating these approaches the design and operation of BHE systems can be optimized. This ultimately leads to more efficient utilization of geothermal energy.

3. Geothermal Energy Coupled Hybrid Heating System

As previously mentioned, the research focusing on geothermal energy applications has become well-developed. The performance of the system depends on many factors. For example, in horizontal BHE, system efficiency generally enhances with an increase in pipe diameter, length, and flow rate. In the case of medium-deep coaxial BHE, increasing the thermal conductivity of the outer pipe or diminishing the thermal conductivity of the inner pipe can enhance system efficiency.

For long-period operations, when the building heat load and BHE inlet temperature are consistent, the heat extraction rate will exceed the ground temperature recovery rate. This results in a decrease in the geothermal temperature, which in turn reduces the thermal efficiency of the BHE year after year. For example, by conducting a 20-year simulation on a closed MBHE system with a depth of 2000 m, Luo et al. [54] found that the soil temperature decreased by approximately 6 °C at a depth of 1600 m. Liu et al. [55] found that after 30 years operation of a 2500-m closed MBHE system, the output temperature was reduced by almost 15% and the system performance decreased by 7.5% due to ground temperature reduction. Thus, it is necessary to find ways to allow the ground temperature to recover and maintain the BHE performance at a higher level. One of the feasible ways is to couple geothermal energy with other energy sources to jointly provide heat to the building. The following part will give a detailed introduction to three types of commonly investigated hybrid systems, including solar-geothermal energy hybrid systems, wind-geothermal energy hybrid systems and air source-geothermal energy hybrid systems (as shown in Figure 3).

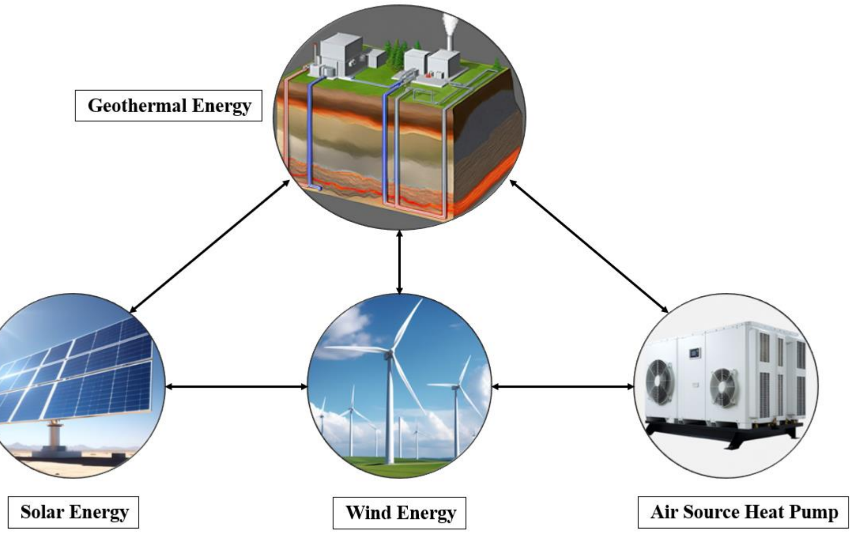


Figure 3. Multi-Energy Hybrid Systems.

3.1. Solar-Geothermal Energy Hybrid Systems

The integration of solar and geothermal energy sources offers a promising approach to enhancing the sustainability and reliability of heat supply systems. The classification of two typical types of solar-geothermal energy hybrid systems is based on their functions and configurations: (1) hybrid solar-assisted ground source heat pump (SAGSHP) system for heating, (2) hybrid ground source heat pump-photovoltaic thermal (GSHP-PVT) system for both heating and power generation. Integrating the benefits of these two sustainable energy sources improves system efficiency, enhances economic viability, and diminishes environmental impact.

The GSHP-PVT system is an integrated energy system of GSHP with photovoltaic thermal (PV/T) systems. The PV/T system is used for two purposes, i.e., providing electrical power for the GSHP and offering heat to the heat exchange medium in the system. During periods of low heat demand, the system alternates between utilizing geothermal energy or solar energy separately. During periods of higher heat demand, solar and geothermal energy are used simultaneously. In the non-heating season, solar energy can be utilized for thermal recharging to address the problem of soil temperature attenuation and overcome the BHE performance deterioration. Existing research concentrates on optimizing the design of the GSHP-PVT system by utilizing numerical simulations and experimental validation. These studies include not only the technical performance investigation but also the economic study of the system. The objective of utilizing these research methodologies is to attain solutions that are more efficient, cost-effective, and environmentally sustainable.

As shown in Figure 4, a typical GSHP-PVT system usually contains the PV/T component, heat storage tank, BHEs, and heat pump, utilizing solar and geothermal energy to achieve efficient heating. The system leverages the PV/T components for dual solar energy conversion. The photovoltaic portion converts solar energy into electrical power, which is then converted to alternating current via an inverter to power internal devices such as circulating pumps and valves. Any excess electricity is stored in a battery. The thermal portion absorbs solar radiation and transfers the generated heat to a fluid, which is then directed to the heat storage tank. The heat storage tank can store excess heat during periods of ample sunlight and release it when needed to supply to the heat pump. The BHE extracts heat from the ground for heating during winter or injecting excess heat into the ground during summer to balance the system's thermal load. The heat pump extracts heat from either the heat storage tank or the BHE, raises it to the appropriate temperature, and delivers it to the user end for heating purposes.

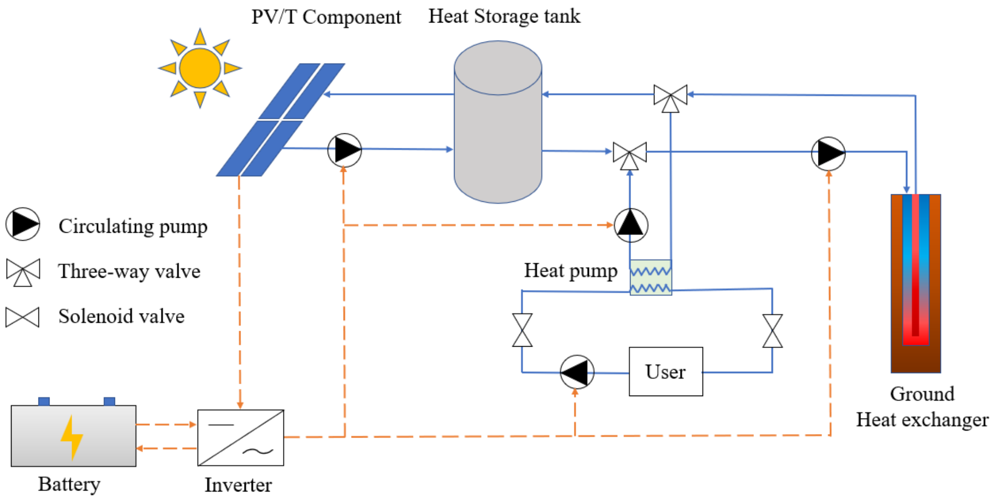


Figure 4. Schematic diagram of solar-geothermal energy hybrid systems.

3.1.1. Hybrid SAGSHP System for Heating

Rad et al. [56] investigated the application and feasibility of a SAGSHP system located in Milton, Canada. The BHE part consisted of four vertical closed-loop circuits, each 55 m in length (as shown in Figure 5). The BHE circuits were connected in parallel with the solar collectors. In cooling mode, the desuperheater absorbed a portion of the high-temperature waste heat from the compressor's discharge and transferred it to a secondary water stream, typically connected to the domestic hot water tank. In heating mode, the desuperheater released the energy absorbed by the liquid stream, which was then used not only for space heating but also for domestic hot water heating. By integrating solar thermal energy storage, the BHE length was reduced by approximately 30 m. Cost analysis indicates that the proposed system is 3.7–7.6% more cost-effective compared to a conventional GSHP system. By focusing on the heat pump's coefficient of performance (COP) and average entering fluid temperature (EFT), it is shown that, in heating mode, the SAGSHP system has an 18.26% higher EFT and a 2.84% higher COP than the GSHP system, indicating that a hybrid GSHP system with a solar thermal collector is a feasible choice for heating load is much larger than cooling load.

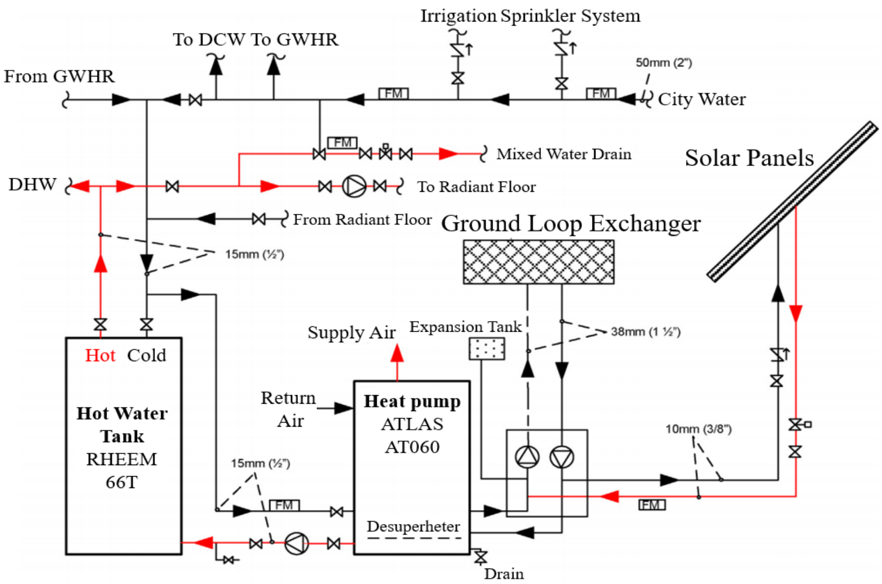


Figure 5. Schematic diagram of SAGSHP system configuration by Rad et al. [56].

Eslami-nejad et al. [57] presented a novel double U-tube borehole system with two independent loops (as shown in Figure 6), one circuit was connected to a GSHP operating in heating mode, while the other was linked to thermal solar collectors. The BHE system was a closed-loop system with a length of 142 m. The system could operate in three different modes: heat pump only, solar charging only, or simultaneous operation. Solar thermal energy was stored underground in the summer and extracted in the winter for use by the GSHP. This reduced the operating hours of the GSHP, leading to lower energy consumption. A 20-year energy simulation comparison between the double-U-tube well system and the single ground-source heat pump system reveals a 3.5% reduction in energy consumption. Additionally, the well depth can be reduced to 117 m, which represents a 17.6% decrease in length. The average temperature of the heat pump fluid in the dual U-tube borehole system can be maintained without decreasing.

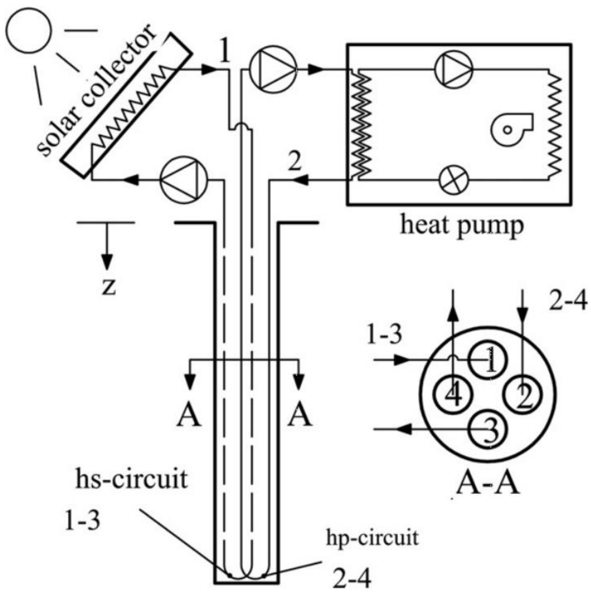
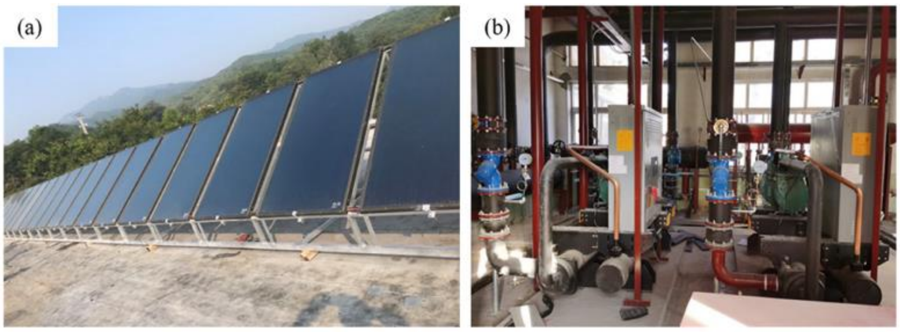
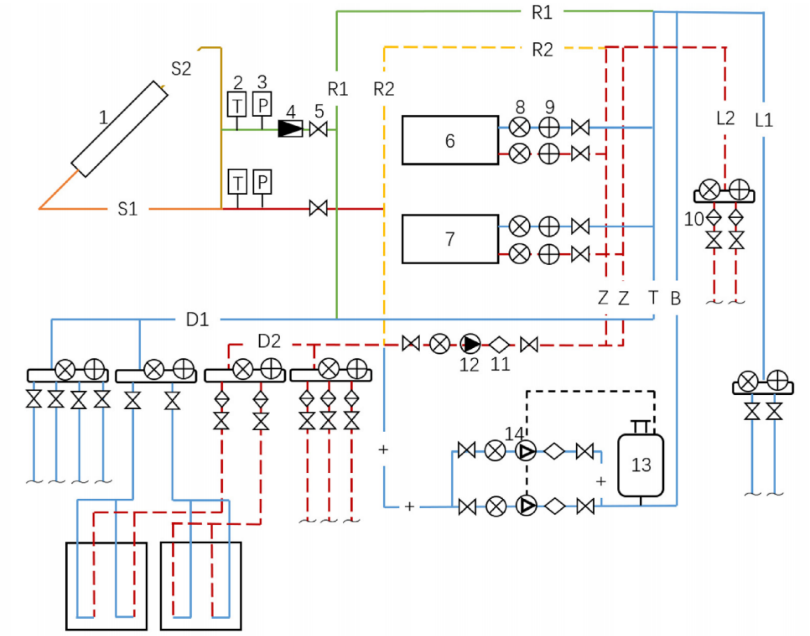


Figure 6. Schematic diagram of a novel double U-tube borehole system configuration by Eslami-nejad et al. [57].

Chen et al. [58] investigated a building located in Tongzhou, Beijing, which used a parallel operation mode of solar energy and a hybrid GSHP system. The test field encompassed a total area of 2600 m^2. An experimental study was conducted on a BHE array that included double U-tube BHEs with lengths of 150 m and 300 m, single U-tube BHEs with a length of 300 m, and enhanced coaxial BHEs with lengths of 150 m and 300 m (as shown in Figure 7). The parallel operation mode integrating solar energy with a hybrid ground-source heat pump (HGSHP) system was implemented to fulfill the building's heating requirements in winter and/or cooling needs in summer. When the temperature of the solar water tank reached the cooling or heating standard, solar energy was directly used to supply energy to the building. Otherwise, the GSHP was used for heating or cooling. During a heating period, the SAGSHP system has a 2.3% lower outlet temperature drop than the HGSHP system. When operating in a single season, the temperature drop rate of the soil and rock is reduced by 0.78%.





(**c**)

Figure 7. (**a**) Solar collector; (**b**) plant room system; (**c**) Design diagram of SAHGSHP system by Chen et al. [58].

Liu et al. [59] studied an experimental platform located in Tianjin, which belongs to a cold region. The BHE system was a closed-loop system with a burial depth of 120 m (as shown in Figure 8). The system was divided into two parts: the first part was the heat storage system, which operated in the non-heating season to transfer water heated by solar radiation to the BHE, where it exchanged heat with the soil and the heat was thereby stored in the soil. The second part was the GSHP heating system, which operated in winter to extract the stored heat through buried pipes for building heating. The solar energy utilization efficiency achieved 50.2% and soil temperature was raised by 0.21 C. The study focused on solar radiation and soil heat storage. The total solar radiation was 265,830.92 kWh and the soil heat storage was 133,416.41 kWh. It was 2.03 times the average heat extraction, indicating that the soil heat balance can be achieved through the coupling of solar energy storage and GSHP technology.

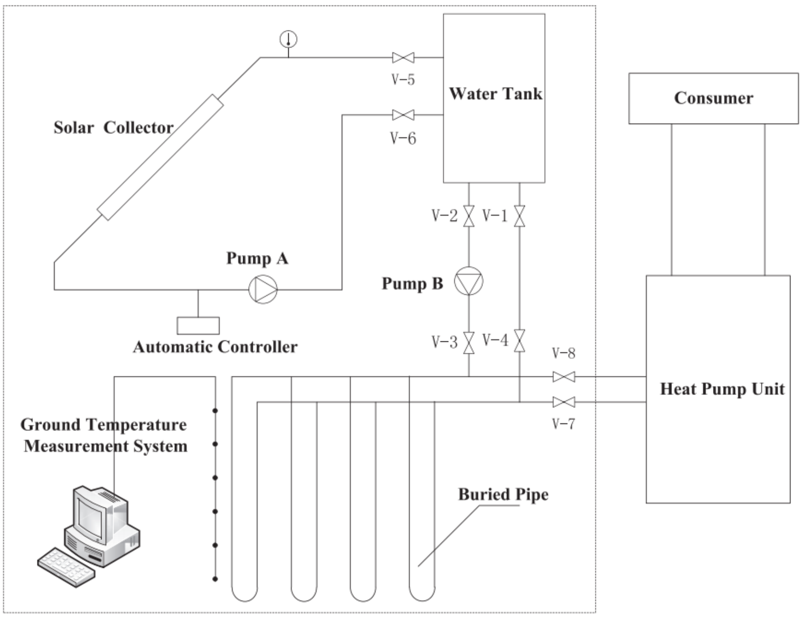
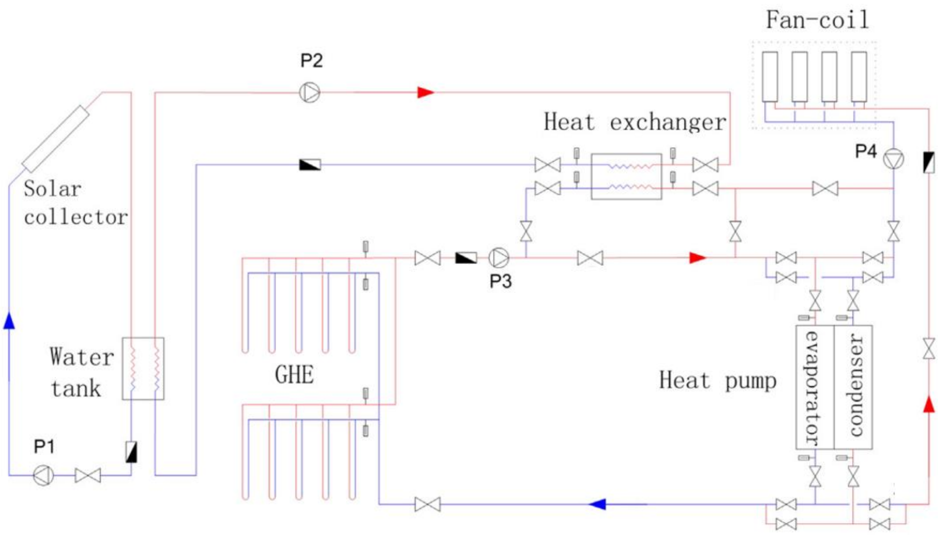


Figure 8. A central solar seasonal storage system based on GSHP by Liu et al. [59].

Yang et al. [60] studied a set of SAGSHP experimental devices located at Yangzhou University, which were used for air-conditioning for laboratories and office buildings. The BHE system was a closed-loop system with a length of 80 m. The system consisted of the following parts: a solar water storage circulation system (the heat absorbed by the solar collector was stored in the water tank), a storage water tank, and a plate heat exchanger water circulation system (heat exchange between the BHE system and the storage water tank). As shown in Figure 9, the solar collection and storage water cycle, the heat storage tank plate heat exchanger water cycle, the GHE water cycle, and the inner terminal water cycle could each be activated by operating the water pumps P1, P2, P3, and P4, respectively. The operation of the combined operation mode, the GSHP daytime operation mode, the GSHP daytime stop mode, the ground intermittent storage mode, and the ground continuous storage mode were analyzed and compared. The SAGSHP system operated in combination mode, where the ground and solar heat sources were dynamically coupled through a flat plate heat exchanger and a water tank. In this configuration, the ground served as an energy storage medium to retain excess solar energy. Under the experimental conditions described in this paper, the average unit COP and collection efficiency for the combination operation mode were 3.61 and 51.5%, respectively.

(**a**)



(**b**)

Figure 9. The experimental set-up of solar-ground source heat pump system investigated here by Yang et al. [60]. (**a**) Experimental system and (**b**) Schematic diagram of the experimental system.

Si et al. [61] studied a building located in Beijing, which used a new SAGSHP to provide heating, cooling and domestic hot water for the building (as shown in Figure 10). Two operation modes were compared: the first is SAGSHP, in which the working fluid first flowed through the solar collector and then entered the BHE. When there was sufficient heat in the solar collector, the excess solar heat could be stored in the soil to maintain the soil temperature. The second was SAGSHP, in which the heat collected by the solar collector during the day was stored in a storage tank and released to the BHE at night to restore the soil temperature. The BHE system was a closed-loop system with a length of 160 m. After 10 years of operation, the soil temperature of the former was only 0.8 °C lower, while that of the latter was 1.6 °C lower. A new operational strategy was proposed in which the heat pump was turned off during transitional seasons and the GHE was directly connected to the fan coil unit heat exchanger. This approach can reduce annual electricity consumption by 20.86%.

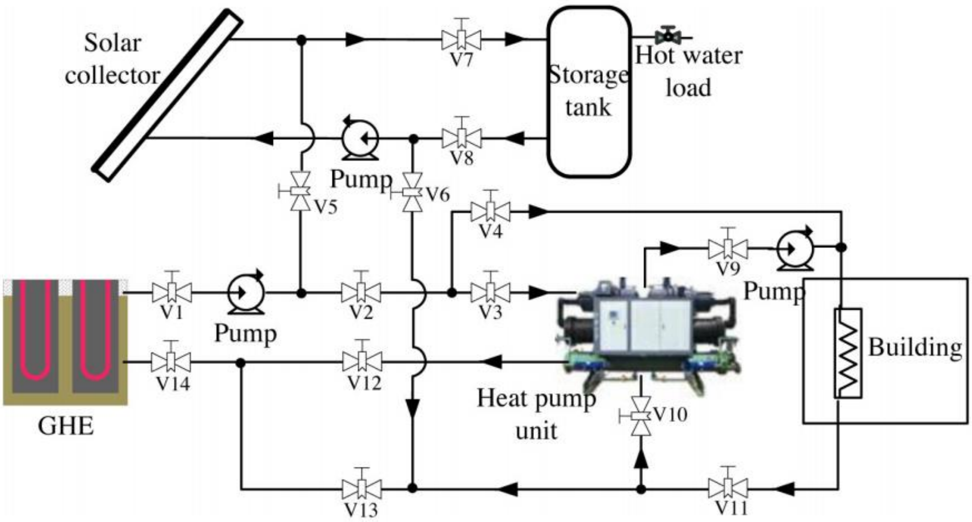


Figure 10. Schematic of SGSHPS(s) and SGSHPS(r) by Si et al. [61].

Yang et al. [62] investigated a SAGSHP installed in Nanjing, China. The system comprised five main components: BHE, heat pump unit, indoor terminal fan-coil system, solar collecting and storage system, and circulating water pump (as shown in Figure 11). The experimental system consisted of two U-tube vertical closed-loop boreholes, each with a depth of 30 m. The boreholes had a diameter of 110 mm and were spaced 4 m apart. The study analyzed four different operational modes: sole use of the GSHP mode, combined operation mode of solar collectors and GSHP, daytime operation with solar collectors and nighttime operation with GSHP, and nighttime operation with GSHP supplemented by solar thermal recovery. Comparison of the hybrid mode, day-night alternating mode, solar-powered U-tube heat exchanger mode, and GSHP mode, experimental and simulation results showed that the hybrid mode achieves COP values of 2.69 and 3.67 respectively, indicating superior comprehensive efficiency.

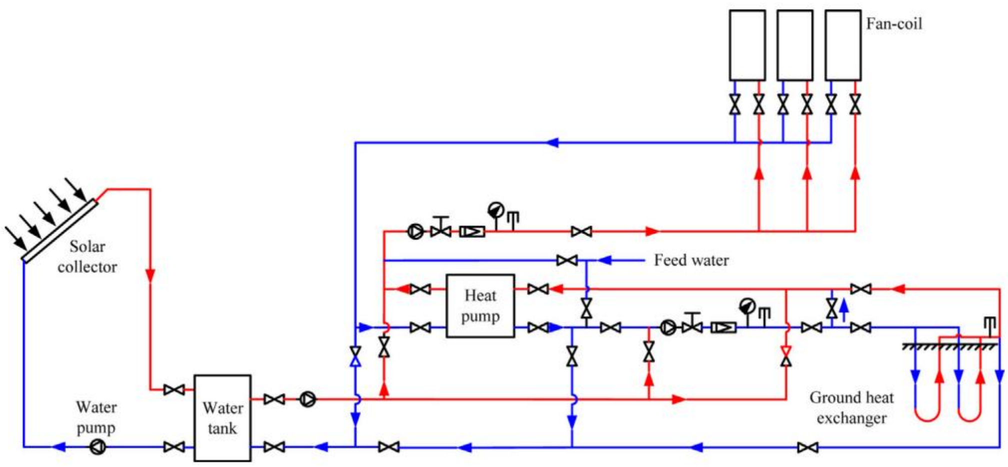


Figure 11. Schematic diagram of SAGSHP experimental system by Yang et al. [62].

Wang et al. [63] presented experimental research on a solar-assisted ground source heat pump system in Harbin. The GHE consisted of two sets of a total of 12 vertical single U-tubes. They were installed below the house with an individual depth of 50 m. The GSHP system functioned for both summer cooling and winter heating. However, during the winter heating season, the heat extracted from the ground significantly exceeded the heat injected into the soil during summer, leading to a potential deficit in thermal energy. Therefore, during non-heating seasons, solar collectors were employed to store heat in the soil, which could be utilized by the GSHP system during the heating season. After a year of operation, the solar system stored 70.76 GJ of thermal energy, while the GSHP system extracted 54.45 GJ of thermal energy. This storage strategy contributes to the stability of the GSHP system over extended periods and enhances the system's COP.

3.1.2. Hybrid GSHP-PVT for Both Heating and Power Generation

Li et al. [64] selected a residential area in Handan, China as the research object and proposed a GSHP-PVT system, to solve the problem of medium-deep ground temperature decay during long-term operation. The BHE system was a closed-loop system with a length of 1500 m. The system included three operating modes: (1) the GSHP extracted heat from geothermal wells to supply the user side; (2) the PV/T module heated the geothermal well water via the thermal storage tank, while simultaneously generating electricity; (3) the water from the PV/T module's thermal storage tank released heat into the soil through the geothermal well heat exchanger. Compared with the traditional GSHP system, the average soil temperature decreased by 1.4 °C after 20 years of operation, while the average soil temperature of the GSHP-PVT system increased by 0.09 °C, effectively solving the problem of ground temperature decay during long-term operation. An analysis of the first-year power balance shows that the system can generate 196,850 kWh of electricity, meeting a demand of 121,920 kWh, with the surplus available for sale to the grid.

Yan et al. [65] studied the GSHP-PVT system located in Tikanlik, China (40.63° N, 87.70° E). The principle of the system (as shown in Figure 12) was that when the temperature of the solar panel exceeded 50 °C, water was used to transfer the heat from the solar panel to the soil. When the solar panel temperature fell below 48 °C, the water pump was turned off. This approach reduced the temperature of the solar panel and improved the efficiency of the PV system. The BHE system was a closed-loop system with a length of 100 m. By cooling the system, the typical daily panel temperature was reduced by 26.8%, and compared with the traditional PV system, its PVT efficiency and annual power generation were increased by 4.1–11.1% and 7.9%, respectively. After ten years of simulated operation, the ground temperature increased by approximately 6.7 °C.

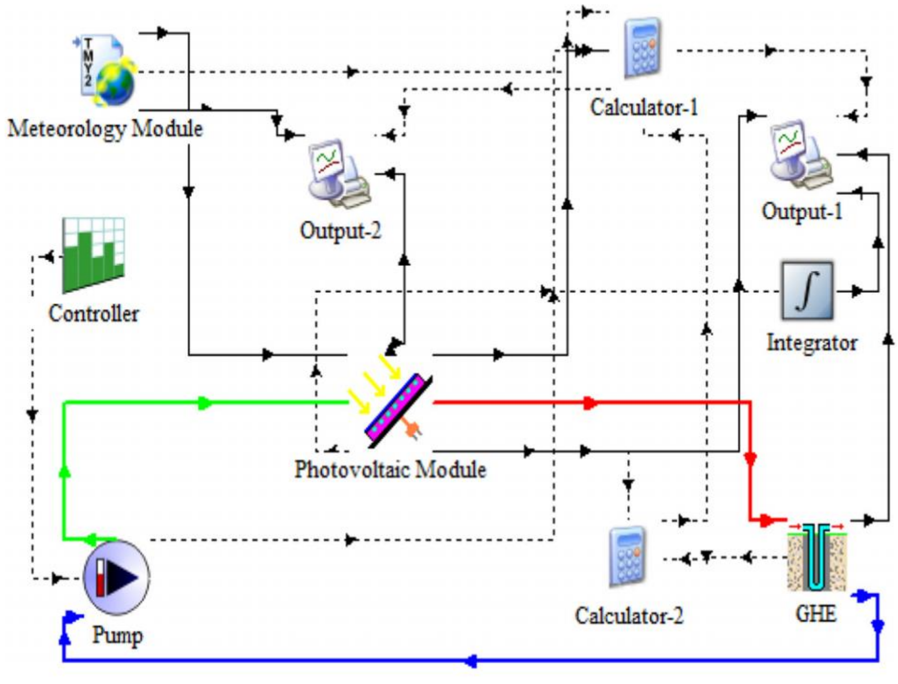


Figure 12. Schematic diagram of a GSHP-PVT system model built using TRNSYS by Yan et al. [65].

Jeong et al. [66] proposed a GSHP-PVT system for a simulated standard residential building in Seoul, South Korea (as shown in Figure 13). The BHE system was a closed-loop system with a length of 150 m. The operation mode was classified into three distinct categories: heating and cooling mode, heat storage mode, and subsurface heat storage mode. The building heating load was predominantly satisfied by the GSHP system. The GSHP system alone was used for cooling during the summer, PVT and storage tanks were used for heating and hot water supply in winter. By using the PVT system, 19% of the total heat supply can be provided, and the operating time of the GSHP system can be reduced by 12%. The system has a 55.3% higher seasonal performance factor (SPF) than the

GSHP system. Due to the power generation from the solar photovoltaic system, the average SPF during the heating period increased to 5.33, which is a 102% increase compared to the building's existing daytime system.

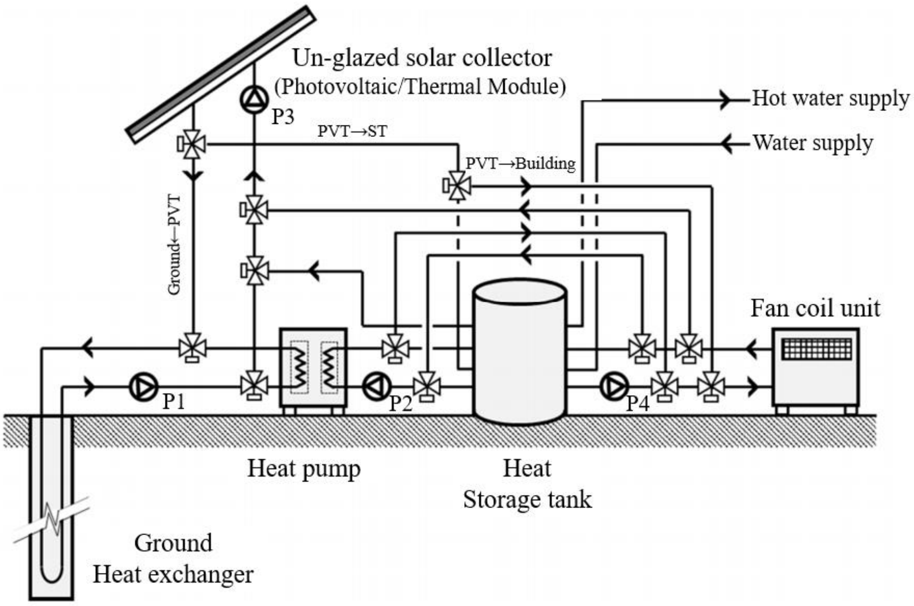


Figure 13. System concept of GSHP-PVT system by Jeong et al. [66].

Xia et al. [67] proposed a design optimization strategy for GSHP-PVT systems to address the design challenges of hybrid systems. A model based on Artificial Neural Network (ANN) was utilized to forecast performance, while a Genetic Algorithm (GA) was implemented as the optimization strategy. A total of 180 scenarios were designed and simulated. Based on a typical Australian residential building, the optimal design option is compared with two baseline design cases, and the annual CO_2 emissions are reduced by 29.5% and 31.4%, respectively. Under the 20-year operating conditions, the life cycle cost (LCC) of the GSHP-PVT system is reduced by 20.1% and 10.2%, respectively.

Pourier et al. [68] studied a building located in Stockholm, Sweden, and analyzed the technical and economic feasibility of integrating free cooling and PVT collectors into a residential GSHP system. With 4 boreholes, 5 m borehole spacing, and 300 m borehole depth, the system compared with GSHP system can improve the SPF by 1.3% over a 20-year system operation.

Lazzarin et al. [69] presented the refurbishment of a school building in northern Italy, where PVTs were coupled with a GSHP system. Solar radiation was used to generate electricity, power the heat pump, provide domestic hot water, and store heat in the ground. The system extracted 14,695 kWh of heat from the ground annually, while 19,722 kWh of heat were injected. The design of the plant, modeled through dynamic simulation, evaluated five alternatives by expanding the solar field (20–40–60 m²) and reduced the ground field (500–400–300 m), in comparison to a conventional system utilized a natural gas boiler and an air/water chiller. A solution with 60 m^2 of PVTs and 300 m of borehole was identified through dynamic simulations as the one with the best performance and lowest cost. A comparison between the proposed scheme and the conventional approach in terms of operation shows that the system yields a net annual savings of €3470.

Jakhar et al. [70] investigated the hybrid system integrating a PV/T solar system with an earth-water heat exchanger. The experimental apparatus was situated in Rajasthan, India. The earth-water heat exchanger system consisted of pipes with a diameter of 0.02 m, each 80 m in length, buried in flat, dry soil at a depth of 3 m. The system enhanced the electrical generation efficiency of photovoltaic panels by cooling them with water and transferring the heat through water to the ground for cooling. Different experiments were conducted to determine the optimal flow rate for the system. Compared to a system without cooling, the electrical generation efficiency of the system increased by approximately 1%.

Kastner et al. [71] studied the application of seasonal solar heat storage in aquifers under typical basin geology in Germany. The wells are connected to the formations over a vertical distance of 200 m with lengths ranging from 150 to 350 m. During loading mode, thermal solar energy is harvested and stored in a subsurface aquifer by means of hot water bodies (as shown in Figure 14). In unloading mode, the injected water bodies are produced form aquifer and reinjected into the water supply well after heat extraction at surface. The annual schedule includes a thermal storage period from April to September and a thermal supply period from November to February. During the thermal storage period, the total amount of solar energy stored can reach 4,580,000 kWh. After five years of system operation, the fluid temperature increased by at least 13 °C during low and medium flow conditions.

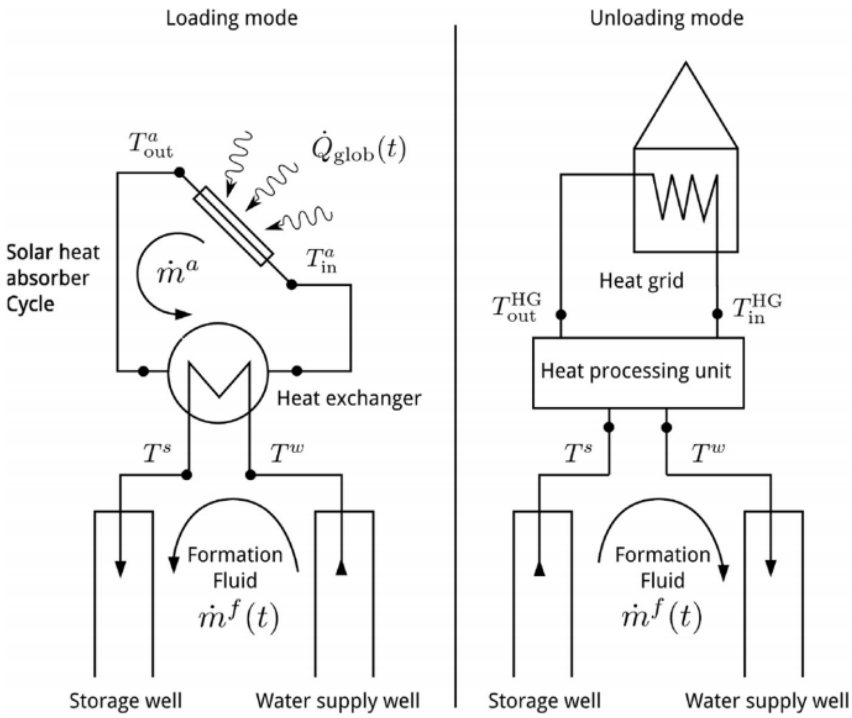


Figure 14. Schematic diagram of an ATES-equipped solar energy supply system by Kastner et al. [71].

3.1.3. Geothermal System Coupled with a Solar Chimney

The solar chimney is another way to improve the effectiveness and functionality of the geothermal system. By establishing a connection between the solar chimney and the geothermal system using ducts, the overall performance of the system can be improved. The design can be customized according to the specific climate and building layout in order to optimize system flexibility and efficiency in various seasons and weather conditions.

Noorollahi et al. [72] proposed a novel configuration that integrated a solar chimney with a waste geothermal spring, taking advantage of Iran's abundant geothermal spring resources. This integration aimed to generate stable and clean electricity by combining solar and geothermal resources, thereby improving electricity generation efficiency. The system consisted of a solar chimney at the center, surrounded by transparent collectors and a geothermal spring at the bottom (as shown in Figure 15). Solar radiation and heat released from the spring heated the air, increasing its velocity through the heating process and the chimney effect. The accelerated air drove a turbine inside the chimney to generate electricity. The system could utilize low-temperature geothermal energy for nighttime power generation, significantly reducing the storage costs of the solar chimney system. By comparing full geothermal mode (FGM), full solar mode (FSM) and geothermal solar mode (GSM), the heat transfer rate under GSM was 585.12% greater than that under FGM and 17.1% greater than that under FSM. Due to the combined effects of solar radiation, hot geothermal water, and ambient air temperature variations, the power generation under GSM exceeded the sum of that under FSM and geothermal heat exchange power generation. By comparing the power generation of the system, the combined solar chimney and geothermal spring system generated 21.06% more electricity than the solar chimney system alone.

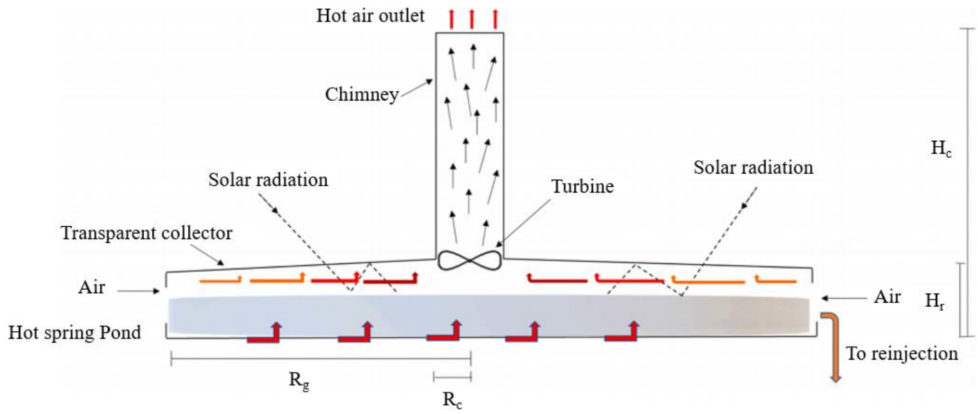
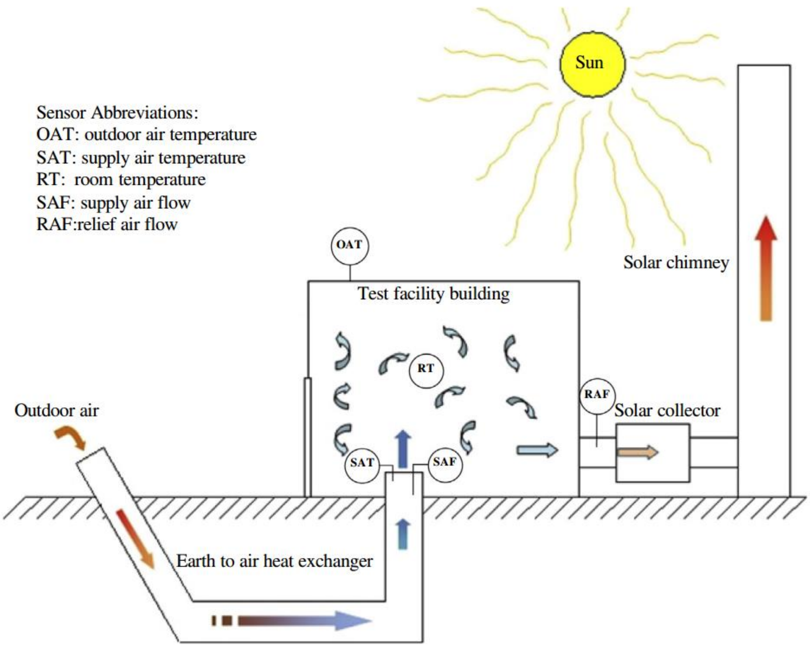


Figure 15. Schematic diagram of the cooling process by the coupled geothermal system by Noorollahi et al. [72].

Yu et al. [73] constructed an EAHE-solar chimney coupled geothermal system in Omaha, Nebraska, USA. The purpose of the system was to provide ventilation and cooling for an experimental building. The principle of the system was that the air in the solar collector was continuously heated by solar radiation, creating a temperature difference with the air in the solar chimney, which caused indoor air to be drawn into the solar chimney, and the indoor space became negatively pressurized, continuously drawing in outdoor air into the EAHE. After entering the EAHE, the air was heat-regulated through pipes and soil, providing cooling capacity for the indoor space. Analysis of experimental data on outdoor air environment, indoor air environment, and soil temperature showed that in most cases, the EAHE-solar chimney coupled geothermal system met indoor environmental requirements. From Figure 16, the variation of soil temperature closer to the EAHE tube was more pronounced compared to locations further from the tube. For instance, the underground soil temperature at 0.3 m above the EAHE remained at approximately 17.8 °C during the initial passive cooling period. However, it increased to 21.1 °C during the forced airflow test and even exceeded the temperature curve at 1.2 m above the tube. Subsequently, the temperature gradually stabilized at around 18 °C over the course of two weeks. Passive cooling methods are more stable than active cooling methods, and excessive heat extraction from the soil in forced air mode may lead to soil saturation around the pipes, requiring a significant amount of time for recovery.



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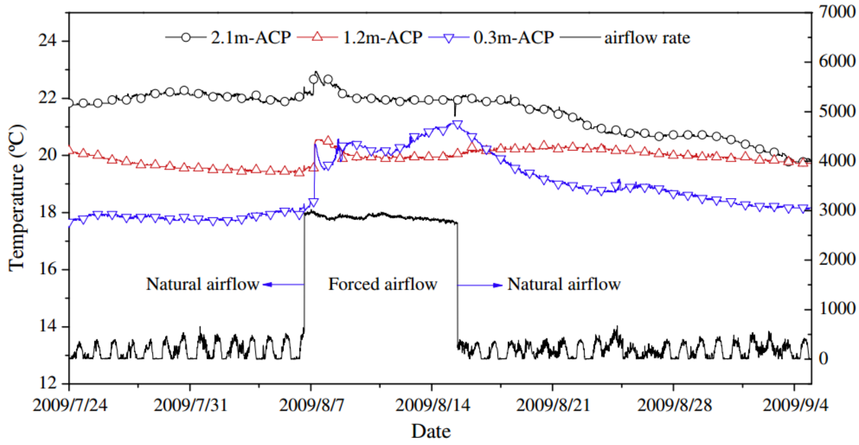


(**b**)

Figure 16. The coupled geothermal system by Yu et al. [73] (**a**) Layout of the system and (**b**) The underground soil temperature at three different heights above EAHE.

Elghamry et al. [74] presented an experimental investigation of a combined solar chimney and geothermal air duct for indoor heating and ventilation of buildings in the hot semi-arid climate conditions of New Borg El Arab city, Alexandria, Egypt. The geothermal air duct was used to provide fresh and preheated air to the building, and the solar chimney effect was utilized to draw the air from the duct into the building. Additionally, photovoltaic (PV) panels were installed at the back of the solar chimney, which both reduced heat loss from the chimney, enhanced the chimney effect, and generated some of the electricity required by the building. By comparing the indoor temperature and ventilation rate with and without the PV system in the chimney, it was shown that the proposed system could meet the heating and ventilation requirements of the building, while also generating electricity to power the building. The maximum temperature increases inside the room were 7.2 °C, 6.4 °C, 5.1 °C, and 4.3 °C for the forced convection system, natural convection system without PV, natural convection system with PV at 45°, and natural convection system with PV at 30°, respectively. The daily ventilated air volumes for the natural geothermal system coupled with the solar chimney were 374.2 m^3, 289.17 m^3, and 232.47 m^3 for the solar chimney without PV, the solar chimney with PV at 45°, and the solar chimney with PV at 30°, respectively.

3.1.4. Summary of Solar-Geothermal Hybrid Heating Systems

Solar-geothermal hybrid heating systems can utilize solar energy to assist geothermal heating in cold regions during winter. The solar thermal storage in a hybrid system can reduce the length of the BHE required by a traditional GSHP. This reduces the construction costs of the system.

The research on geothermal and solar energy coupled systems primarily encompasses system optimization and efficiency improvement, technical applications, economic evaluations, as well as control strategy. Key areas of investigation include: optimizing system design through algorithms, analyzing the dynamic performance of the coupled system under various operational strategies (such as utilizing solar thermal storage to release heat into the BHE to restore soil temperature or using the solar energy system to assist in heating and reduce the operational time of the GSHP), evaluating the economic viability of the coupled system (such as reducing BHE length by using solar thermal storage) and integrating emerging research technologies. Some important points, including the region, research methodology, system characteristics and conclusions of the reviewed studies have been summarized in Table 1.

Table 1. Summary of the solar-geothermal hybrid heating systems.

Reference	Region	Research Methodology	System	System Characteristics	Main Conclusions	Remark
[56]	Milton, Canada (43.52° N, 79.88° W)	Simulation	SAGSHP	Desuperheater-equipped liquid source heat pump	BHE length was reduced by 30 m. An 18.26% higher EFT and a 2.84% higher COP than the GSHP system.	Heating-dominated regions
[57]	Montréal, Canada (45.50°N, 73.57°W)	Simulation	HGSHP	Double U-tube BHE	In energy savings of 3.5% and 6.5%. BHE depth was reduced by 17.6%.	Well-insulated buildings with heating demand only
[58]	Tongzhou, Beijing (39.90° N, 116.65° E)	Experiment and simulation	SAGSHP	An array of BHEs with multiple types and lengths	The temperature drop rate of the soil and rock was reduced by 0.78%.	Constant temperature of rock and soil and sufficient solar energy
[59]	Tianjin, China (39.34° N, 117.36° E)	Experiment and simulation	SAGSHP	Thermal equilibrium research for solar seasonal storage system coupling with GSHP	Total solar radiation was 2.03 times the average heat extraction. Soil heat balance can be achieved by coupling the solar energy storage	Heating-dominated regions
[60]	Yangzhou, China (32.39° N, 119.43° E)	Experiment and simulation	SAGSHP	Different heat source coupling modes	Combined operation mode has the highest collection efficiency of 51.5%.	Heating-dominated regions
[61]	Beijing, China (39.90° N, 116.40° E)	Simulation	SAGSHP	Solar heat is released to the BHE at night to restore the soil temperature.	Annual electricity consumption was reduced by 20.86%. Soil temperature was only 0.8 °C lower after 10 years of operation.	In transition seasons, keeping the heat pump off
[62]	Nanjing, China (32.06° N, 118.79° E)	Experiment and simulation	SAGSHP	Multi-mode operational SGSHPS experimental system	The combined operation mode achieved COP values of 3.67.	Heating-dominated regions
[63]	Harbin, China (45.80° N, 126.53° E)	Experiment	GSHP-PVT	Seasonal thermal storage, 12 vertical U-tube BHEs	After a year of operation, the system stored 70.76 GJ thermal energy, while the GSHP system extracted 54.45 GJ.	Severe cold regions
[64]	Handan, China (36.62° N, 114.48° E)	Simulation	GSHP-PVT	1500 m MBHE	Average soil temperature increased by only 0.09 °C, effectively solving the problem of ground temperature decay. The system can generate 196,850 kWhof electricity.	Cold regions
[65]	Tikanlik, China (40.63° N, 87.70° E)	Simulation	GSHP-PVT	Solar panel temperature is controlled between 48 °C and 50 °C	PV efficiency and annual power generation increased by 4.1–11.1% and 7.9%, respectively. Ground temperature increased by approximately 6.7 °C after 10 years.	The arid climate
[66]	Seoul, South Korea (37.56° N,	Simulation	GSHP-PVT	Use the PVT system to reduce the GSHP operating time	The system has a 55.3% higher SPF than GSHP system.	Temperate monsoon climate

	126.97° E)					
[67]	Australian (25.27° S, 133.77° E)	Simulation	GSHP-PVT	ANN model was used for performance prediction. GA was employed as the optimization technique	Annual CO_2 emissions were reduced by 31.4%. LCC of the GSHP-PVT system was reduced by 20.1%.	Temperate marine climate
[68]	Stockholm, Sweden (59.32° N, 18.06° E)	Simulation	Free cooling + GSHP	Integration of free cooling and PV/T into a GSHP system in a severe winter climate	Free cooling + GSHP system can improve the SPF of the GSHP system by 1.3% over a 20-year system operation.	Temperate marine climate
[69]	Belluno, Italy (46.20° N, 12.21° E)	Simulation	GSHP-PVT	Solar radiation for generating electricity, powering the heat pump, providing domestic hot water, and storing heat in the ground	The system extracts 14,695 kWh of heat from the ground annually, while 19,722 kWh of heat are injected.	A rather severe climate in wintertime
[70]	Rajasthan, India (75.61° E, 28.38° N)	Experiment	PV/T solar system with earth-water heat exchanger	80 m horizontal BHE	Experimental electrical efficiency of IPVTS increased by 1.02–1.41% after cooling with EWHE.	The semi-arid regions
[71]	Berlin, Germany (52.52° N, 13.40° E)	Simulation	Solar ATES model	Enhancing the Energy and Economic Efficiency of ATES Systems by Solar Thermal Energy and Electricity	After five years of system operation, the fluid temperature increased by at least 13 °C during low and medium flow conditions.	A sedimentary setting typical
[72]	Iran (33.15° N, 58.78° E)	Simulation	Solar chimney with waste geothermal spring	Integration of abandoned geothermal springs with solar chimneys	The combined solar chimney and geothermal spring system generated 21.06% more electricity than the solar chimney system alone.	An abandoned hot spring
[73]	Omaha, Nebraska, USA (41.25° N, 95.94° W)	Simulation	EAHE-solar chimney coupled geothermal system	An EAHE-solar chimney coupled geothermal system in natural and forced airflow conditions	Excessive heat extraction from the soil in forced air mode may lead to soil saturation around the pipes, requiring a significant amount of time for recovery.	Free space cooling in summer
[74]	New Borg El Arab, Alexandria, Egypt (31.2° N, 29.91° E)	Simulation	Combined solar chimney and geothermal air duct	Study of air flow in the geothermal pipe environment influenced by solar chimneys	The maximum output PV power was 117 W, representing about 86.7% of the maximum PV power outside the chimney.	Mediterranean climate

3.2. Wind-Geothermal Energy Hybrid Systems

Wind and geothermal energy hybrid systems employ wind turbines to produce electricity, which is subsequently utilized to operate a geothermal heat pump. The generated electricity can be utilized to meet the electrical requirements of the building or be sold to the power grid. Geothermal energy addresses the base load demands of buildings, while photovoltaic and wind power supply electricity and supplement demand during peak periods. This approach is utilized simultaneously for both building heating and power generation.

3.2.1. Hybrid Wind and Geothermal Energy Systems

Aryanfar et al. [75] investigated a hybrid system in Shanghai, China, which consisted of a geothermal heat pump with a wind turbine (as shown in Figure 17). The wind turbine generated electricity to meet the power needs of the GSHP and the building, with any excess electricity fed back into the grid. The geothermal pump extracted heat from the ground. During cooling, the refrigerant absorbed heat before it was pressurized and heated by the compressors. Then it released heat through the condenser. In heating mode, the heat was transferred from the refrigerant to the indoor environment. By studying the effects of variations in condenser pressure, evaporator pressure, intermediate pressure, ambient temperature, and soil temperature on the net power output of the heat pump system, it was observed that increasing the condenser pressure from 350 kPa to 500 kPa resulted in an increase in the system's net power output from 21.98 kW to 22.14 kW. The total installed capacity of wind turbines in Shanghai was 49.33 kW, which could meet the electricity demand of the heat pump system. The wind turbine can provide stable and clean electricity for the system when the grid electricity consumption reaches its peak.

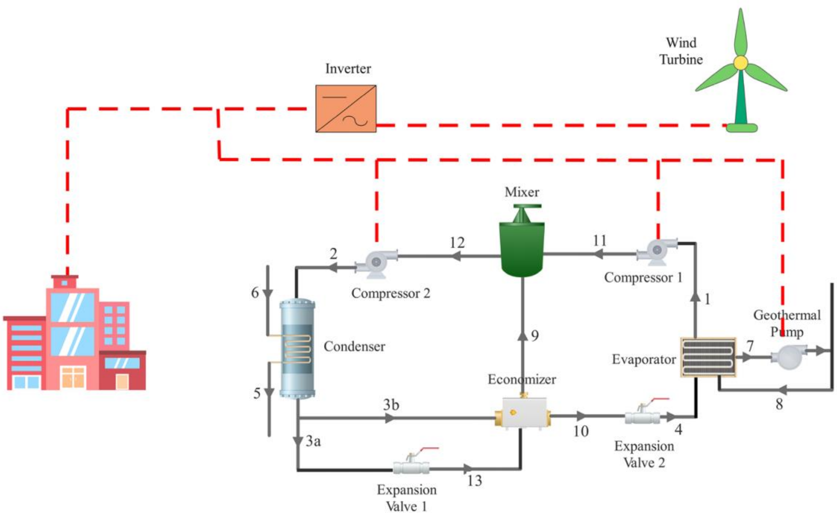


Figure 17. Schematic of geothermal heat pump and wind turbine hybrid system by Aryanfar et al. [75].

Ciapala et al. [76] presented a model study of a system consisting of a geothermal heat source, thermal energy storage systems and a wind turbine in Warsaw (Poland). Wind energy was used to power electric heaters or heat pumps, which were connected to large, insulated tanks employed for thermal storage. The wind turbine was used to increase the peak performance of the GSHP system, which was used to compensate for the limitations of geothermal energy due to soil conditions and provide energy for the heating system. In the Warsaw climate, to provide electricity for a 1000 m^2 house, the system requires 4800 kWh of thermal storage, 45 kW of geothermal source and 5 kW of wind source. A system designed in this manner would minimize wind curtailment, optimize the utilization of geothermal resources, and enhance the reliability of the supply.

Bamisile et al. [77] presented a wind-geothermal hybrid multi-generation system designed to produce electricity, hydrogen, hot water, cooling, and seawater desalination (as shown in Figure 18). The wind turbine transformed incoming wind energy into mechanical energy, which was then converted into electrical energy. The produced electricity was initially directed to the control center before being distributed to the various subsystems. The majority (70%) of the generated power was supplied to the end users, while 15% of the total electricity was utilized in the power desalination system to produce fresh water. Additionally, 10% of the total power output was used by the cooling system to generate cooling effects, and the remaining 5% was allocated for hydrogen production. By integrating the Kalina cycle of geothermal energy with wind power generation, the system ensured stability. Under both electricity-only and multi-generation conditions, the system's energy and exergy efficiencies were significantly improved, from 17.73% and 22.45% to 81.01% and 52.52%, respectively. The total electricity generated by the geothermal-Kalina system and wind power system was 9,940,000 kWh/year and 2,540,000 kWh/year, respectively.

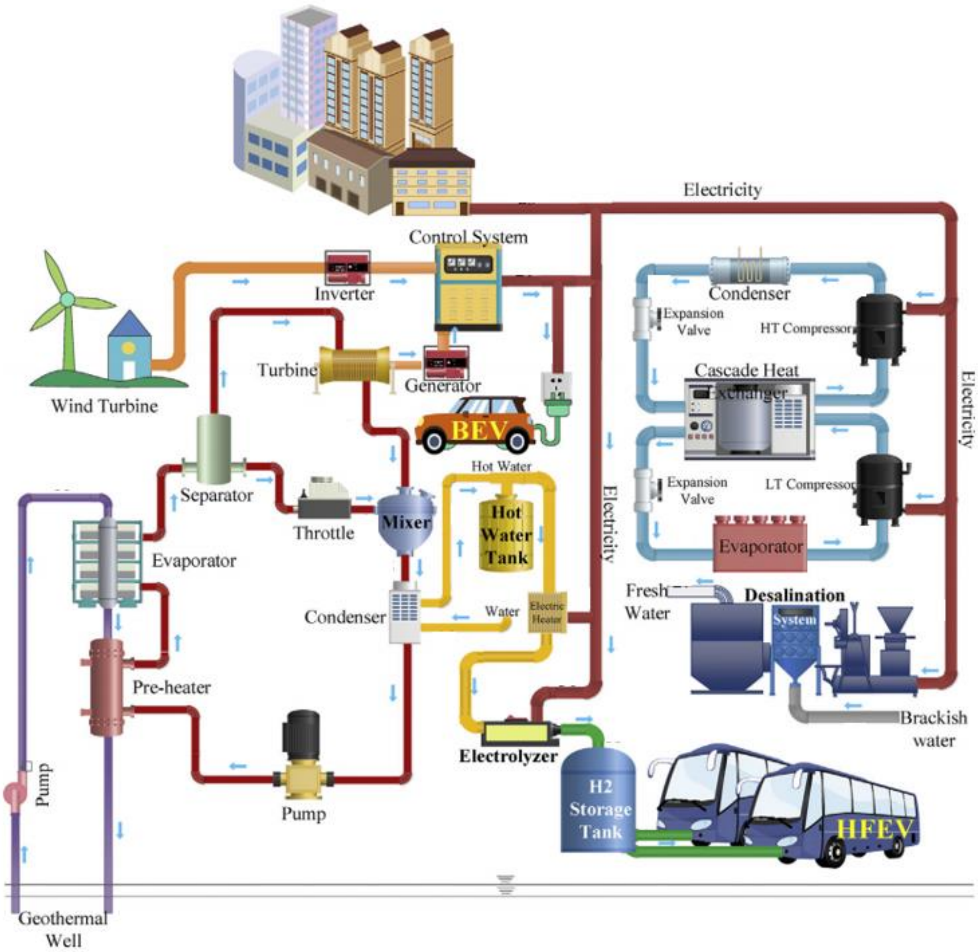


Figure 18. Schematic diagram of the proposed geothermal-wind multigeneration system by Bamisile et al. [77].

3.2.2. Hybrid Wind, Solar and Geothermal Energy Systems

Wind energy, solar energy and geothermal energy are also used simultaneously for building heating and power generation. Xu et al. [78] proposed a multi-energy supply coupling framework to construct a renewable energy system that can provide electricity, heating, and hydrogen for communities by utilizing the complementarity of geothermal energy, solar energy, and wind energy (as shown in Figure 19). The system comprised a solar thermal system, wind turbines, GSHPs, and an electrolyzer. In the framework of the energy hub, hybrid renewable energy was first converted into electrical energy, thermal energy, and hydrogen carriers through PV/T system, wind turbine, GSHP, and electrolyzers. Subsequently, it was transformed, regulated, and stored through BES systems, hydrogen tanks, and combined heat and power (CHP) units. At the output end, it was converted into community electricity, thermal energy, and hydrogen loads. This system reduced energy loss and efficiently coordinated multiple energy and energy storage systems. The accommodation of solar and wind energy can be enhanced by up to 1.59%.

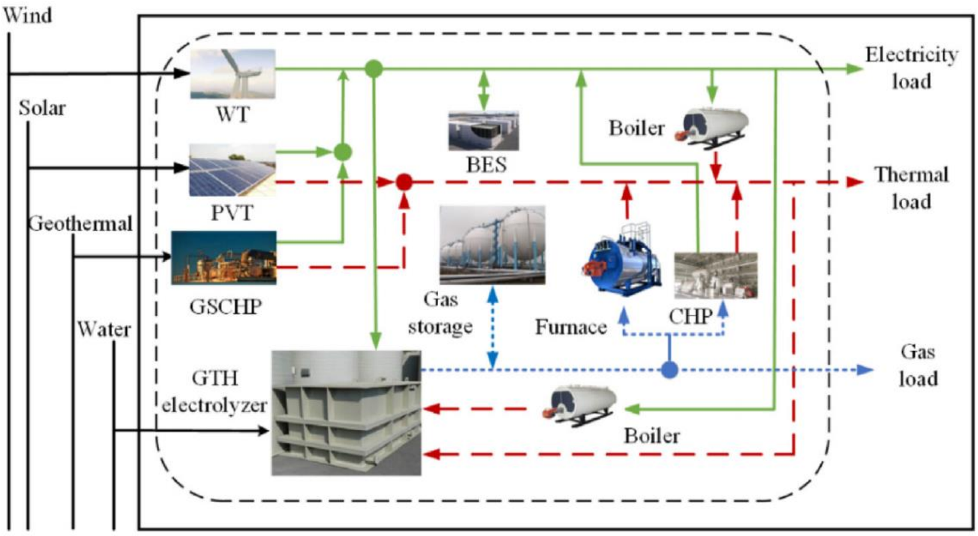


Figure 19. Geothermal-solar-wind renewable energy hub framework by Xu et al. [78].

Kazmi et al. [79] investigated a hybrid geothermal-photovoltaic-wind power system for a village in Pakistan. The system operated normally using geothermal energy to meet the community's basic load demand throughout the year, while the photovoltaic and wind power plants supplied electricity to the grid, and supplemented the demand during peak periods. Through an integrated simulation of the region's geothermal, solar, and wind resources, a hybrid system with capacities of 250 kW, 250 kW, and 100 kW for geothermal, photovoltaic, and wind power, respectively, was found to be a feasible design, with a Net Present Cost (NPC) of 234.11 million Pakistani Rupees and an interest rate of 5%. The system could meet an average daily load demand of 7350 kWh, with excess energy sold to the grid. The proposed system had a Cost of Energy (COE) of 7.50 Pakistani Rupees/kWh and was expected to avoid 1.8 million kilograms of CO_2 emissions and other air pollutants.

Geng et al. [80] proposed a multi-energy complementary heating system integrating solar energy, wind energy, and geothermal energy based on the meteorological conditions and geothermal resources in Zhengzhou, Henan Province. The system consisted of four subsystems: the solar collector subsystem, the geothermal subsystem, the wind energy subsystem, and the two-stage reheat subsystem. The solar collector subsystem heated the heat transfer fluid using solar collectors and stored energy in a thermal storage tank. The geothermal subsystem raised the temperature of the circulating water by applying work, predominantly through the operation of an inverse Carnot cycle. The wind energy subsystem generated electricity to drive compressors, and the geothermal subsystem enhanced the circulation of water. Finally, the two-stage reheat subsystem adjusted water temperature to meet user-side demands. The wind turbine system outputted power ranging from 0 to 3000 kW, ensuring the normal operation of the geothermal system. The average heat exchange efficiency during the heating season reached 90%, effectively meeting user requirements.

3.2.3. Summary of Wind-Geothermal Hybrid Heating Systems

In regions with abundant wind energy resources, utilizing wind power generation to meet electricity demands while simultaneously harnessing geothermal energy for heating is an effective approach.

Current research on wind-geothermal hybrid heating systems encompasses several key areas: the design of the coupling system (including determining the number of wind turbines and the borehole depth for ground-source heat pumps), the integration of the system and the design of control systems and energy management strategies (such as using wind power to meet the electrical needs of the ground-source heat pumps and buildings or for other industrial purposes), and the use of auxiliary systems (such as two-stage reheat subsystems). The main characteristics of the reviewed systems in this part have been summarized in Table 2.

Table 2. Summary of wind-geothermal hybrid heating systems.

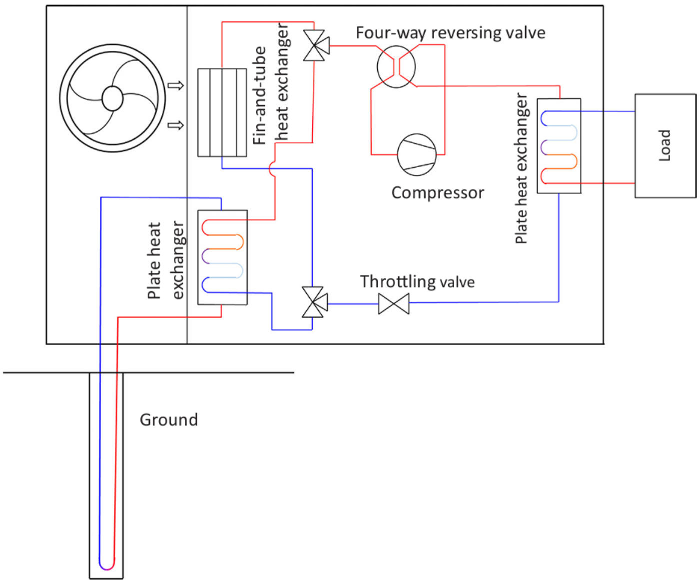
Reference	Region	Research Methodology	System	System Characteristics	Main Conclusions	Remark
[75]	Shanghai, China (31.23° N, 121.47° E)	Simulation	A geothermal heat pump with an intermediate economizer and a wind turbine	The wind turbine generates electricity to meet the power needs of the GSHP and building, with excess electricity fed back into the grid	Increasing the condenser pressure from 350 kPa to 500 kPa resulted in an increase in the system's net power output from 21.98 kW to 22.14 kW.	To provide the heat and electricity required during the winter
[76]	Warsaw, Poland (52.22° N, 21.01° E)	Simulation	Geothermal heat source combined with thermal storage and a wind turbine	Wind power generation fulfills peak demand	Provide electricity for a 1000 m^2 house, the system requires 4800 kWh of thermal storage, 45 kW of geothermal source and 5 kW of wind source.	Cooler periods (winter)
[77]	Inner Mongolia Autonomous Region, China (40.80° N, 111.65° E)	Simulation	Wind-geothermal hybrid multi-generation system	Produce electricity, hydrogen, hot water, cooling, and seawater desalination	The total electricity generated is 9,940,000 kWh/year and 2,540,000 kWh/year, respectively.	Temperate continental monsoon climate
[78]	/	Simulation	A multi-energy supply coupling framework to construct a renewable energy system	A multi-energy supply coupling system that can provide electricity, heating, and hydrogen for communities	The solar-wind accommodation can be improved by at most 1.59%.	/
[79]	Pakistan (33.61° N, 73.94° E)	Simulation	A hybrid geothermal-photovoltaic-wind power system	Using geothermal energy to meet the community's basic load demand, while photovoltaic and wind power plants supply electricity to the grid, and supplement the demand during peak periods	The system COE is 7.50 Pakistani Rupees/kWh and is expected to avoid 1.8 million kilograms of CO_2 emissions and other air pollutants.	Abundant resources of geothermal, solar, and wind energy
[80]	Henan, China (34.75° N, 113.66° E)	Simulation	An integrated heating system technology that combines solar energy, wind energy, and geothermal energy	Two-stage reheat subsystem	Wind turbine system outputs power ranging from 0 to 3000 kW. Average heat exchange efficiency during the heating season reaches 90%.	/

3.3. Air Source-Geothermal Energy Hybrid Systems

The geothermal energy is also combined with the air source heat pumps (ASHP) for building heating. The BHEs possess the advantage of high efficiency and the initial cost of ASHP is relatively low. The coupled system involves the simultaneous operation of the geothermal heat pump and the air source heat pump, where the geothermal heat pump is responsible for meeting the primary heating and cooling needs. The ASHP serves as an additional source of assistance during periods of high demand or when external air temperatures are more advantageous. This strategy can maximize energy efficiency, save operational expenses, and improve the overall dependability of the heating and cooling system.

3.3.1. Air Source-Geothermal Energy Hybrid Systems

Grossi et al. [81] studied the energy performance of a dual-source heat pump system (DSHP). The yearly simulation results were carried out based on a residential building in Bologna, Italy (as shown in Figure 20). The building's heating loads were much larger than the cooling loads. The ASHP was used to reduce the ground temperature attenuation after BHE's long-term operation. The DSHPs were conducive to overcoming the thermal unbalance of the ground caused by unbalanced heating and cooling loads. A reduction of the BHE length of 30% to 50% could be achieved with larger energy performance in the presence of strongly unbalanced loads. The investment cost was reduced concerning a GSHP of a percentage variable from 6% to 32%.



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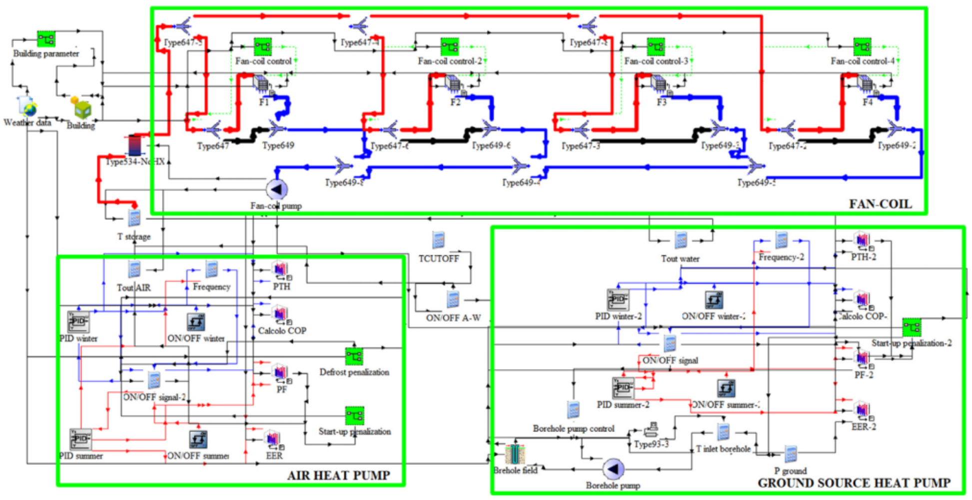


(**b**)

Figure 20. DSHP system by Grossi et al. [81] (**a**) Layout of the system and (**b**) DSHP system constructed in TRNSYS.

You et al. [82] also proposed a multi-mode air-source heat compensator (AHC) integrated GCHP to eliminate the thermal imbalance in cold regions. A hotel in Harbin, China with an 8700 m^2 air-conditioning area was selected for simulation. The AHC served as the auxiliary unit, which could inject heat into the soil, and supply heat directly for space heating simultaneously (as shown in Figure 21). It was found that the ASHP can inject the heat into the ground with the average COP ranging from 4.49 to 15.09. Compared to the conventional "boiler + split air conditioner" system, the coupled system achieves an energy savings rate of up to 23.86%.

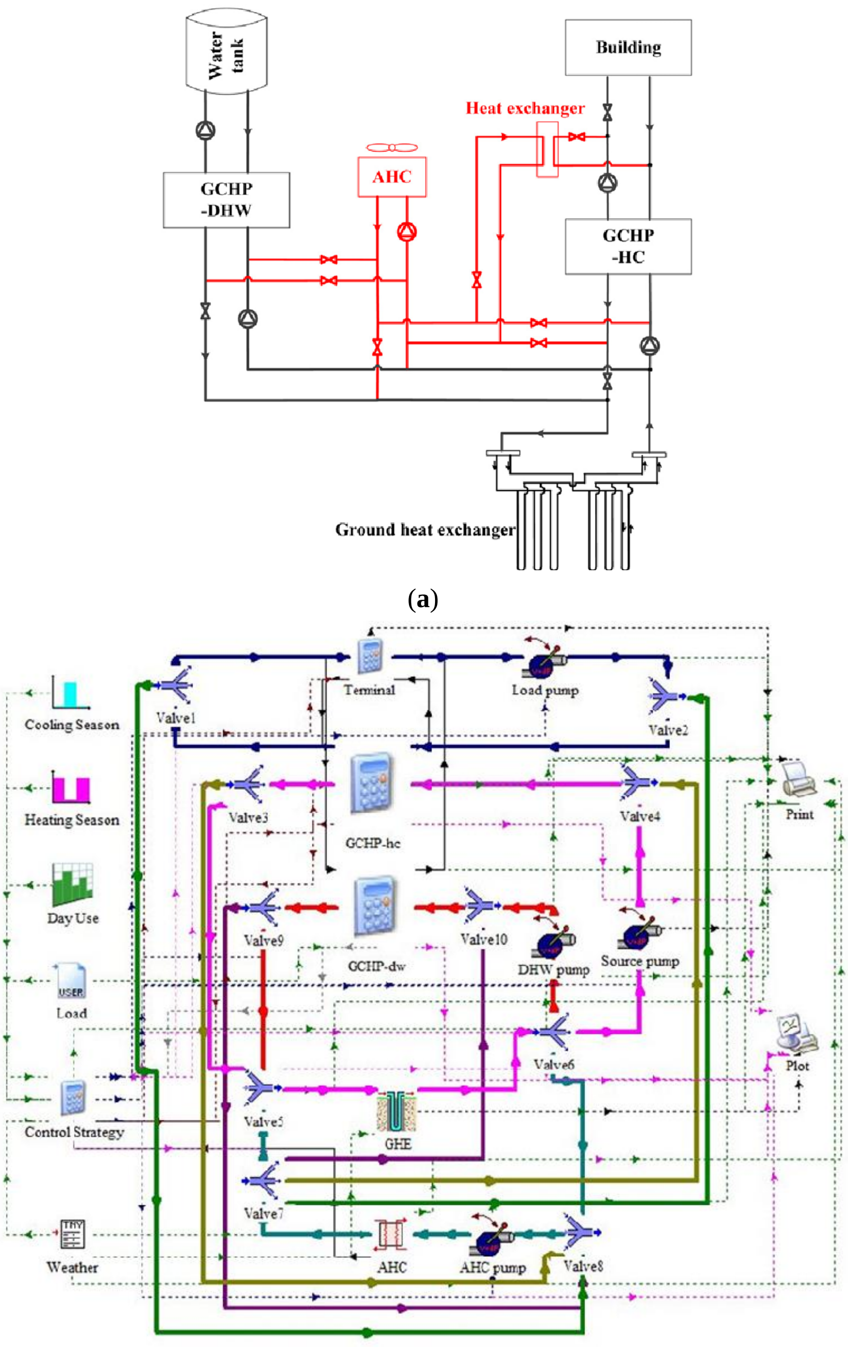


Figure 21. DSHP system [82] (**a**) Layout of the system and (**b**) DSHP system constructed in TRNSYS.

A hotel building energy supply system in northern China was taken as the research object to study the feasibility of a coupled air and GSHP system with energy storage [83]. An ASHP and a WSHP were utilized as supplementary heat sources for a portion of the heat provision (as shown in Figure 22). At a temperature of −6 °C, the average COP of the system approached 2.3. The integration of energy storage equipment enabled the power grid to shift peak loads and minimized system running costs. The findings demonstrated that using an optimal defrosting control system could enhance the heating capacity of the ASHP by 13.9%. The proposed system has the capability to not only maintain the soil heat imbalance rate at 2.6%, but also to decrease the running cost. The unique system has an annual operation cost that is just 58% of the typical GSHP system, and it can minimize carbon emissions by 7.14%. The CAGHP system with energy storage offers a 42% reduction in operation costs compared to the typical GSHP system. Additionally, it results in a 7.14% decrease in carbon emissions and has an investment payback period of 3.16 years.

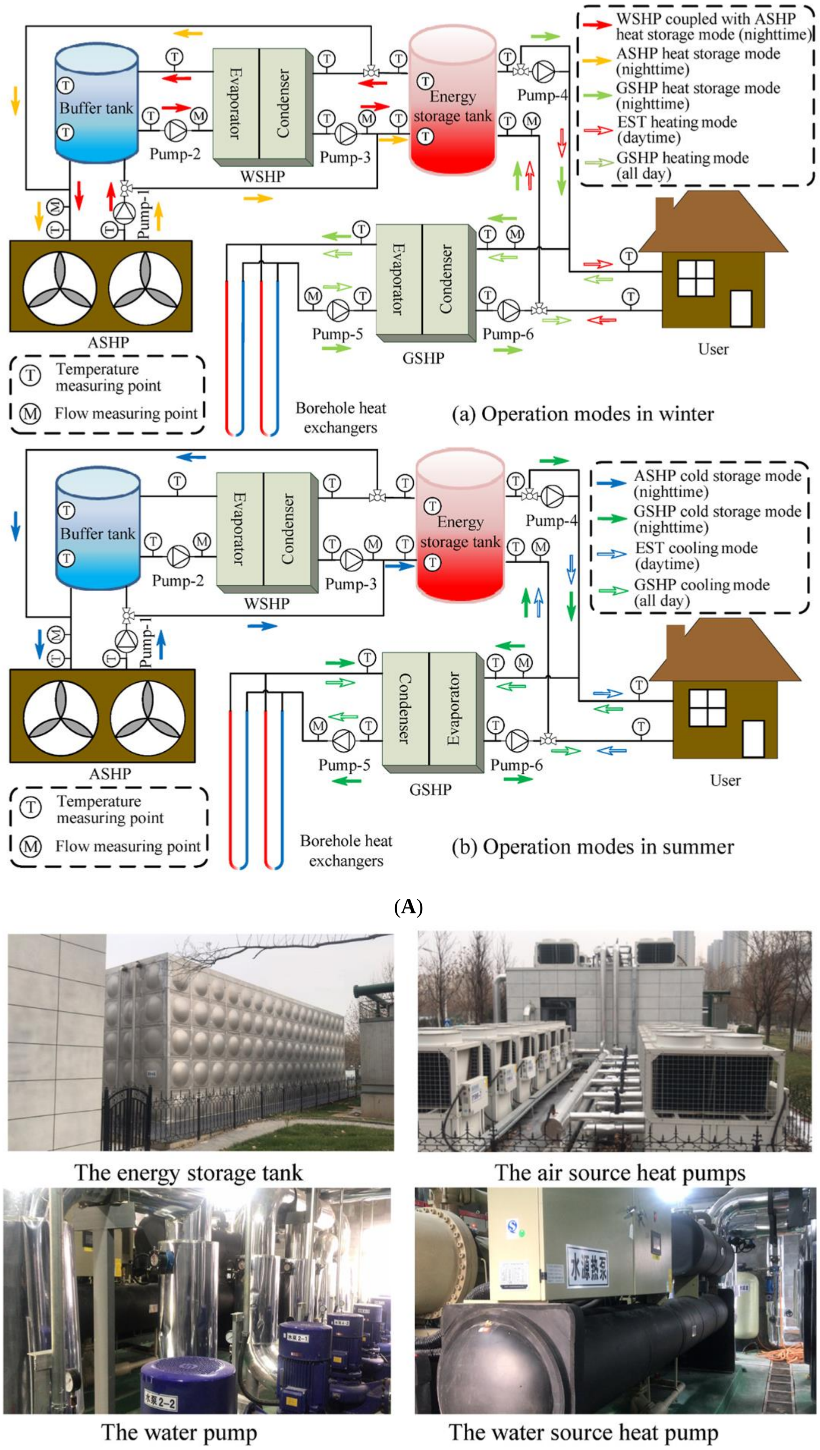
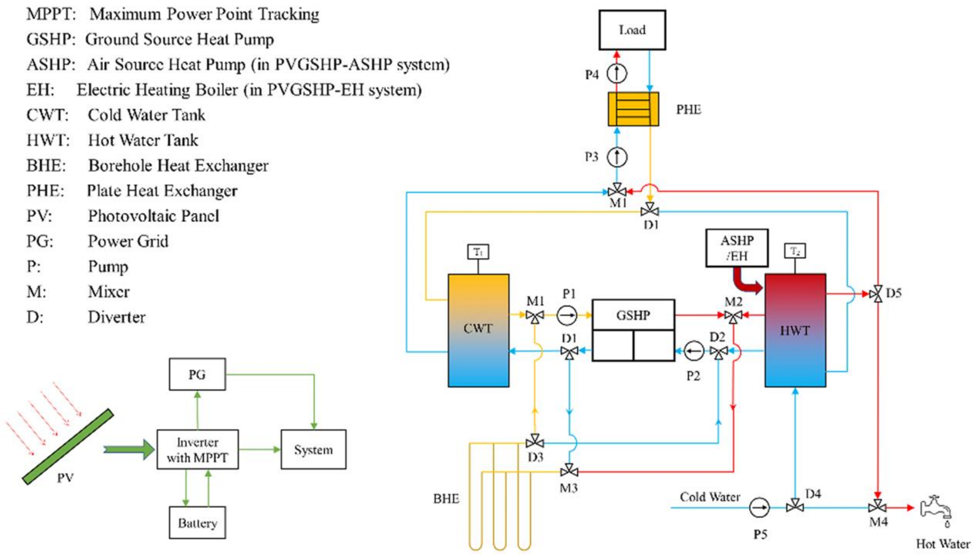


Figure 22. DSHP system [83] (**A**) Layout of the system and (**B**) Actual project photo.

Zheng et al. [84] investigated the performance of a photovoltaic-assisted GSHP and PVGSHP-ASHP for a campus building in Changsha, China. Three kinds of hybrid systems, i.e., the PVGSHP-ASHP system, photovoltaic assisted ground source heat pump and electric heater (PVGSHP-EH) system and photovoltaic assisted ground source heat pump system (PVGSHP) were simulated for performance and economy comparison (as shown in Figure 23). The number of the BHEs was 86 and the rated power was assumed to be 69 kW. The TRNSYS simulation results showed that the soil temperature decreased from 18.1 °C to 11.8 °C after 15 years of operation for the traditional PVGSHP-EH system. This led to a decrease in the annual COPGSHP from 3.2 kW/kW to 2.9 kW/kW and an increase in the annual electricity consumption from 77,468 kWh to 85,384 kWh. The PVGSHP-ASHP system effectively addressed the issue with its high annual COPGSHP and COP values of 3.49 kW/kW and 4.69 kW/kW, respectively. Additionally, it consumed just 71,700 kWh of power annually. In terms of cost, its annual lifespan cost was the lowest at 99,223 CNY, which is 8.1% lower than the PV-aided GSHP system. Following optimization, the PV-assisted GSHP-ASHP system achieved an annual lifecycle cost of 91,158 CNY, which represented an 8.1% reduction.



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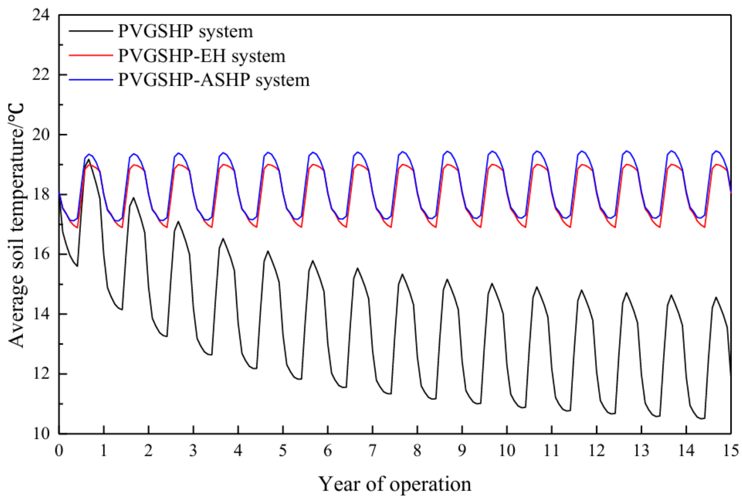
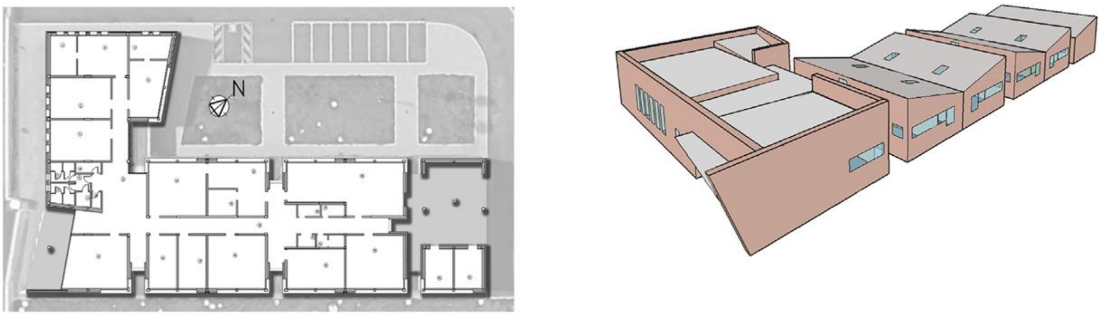


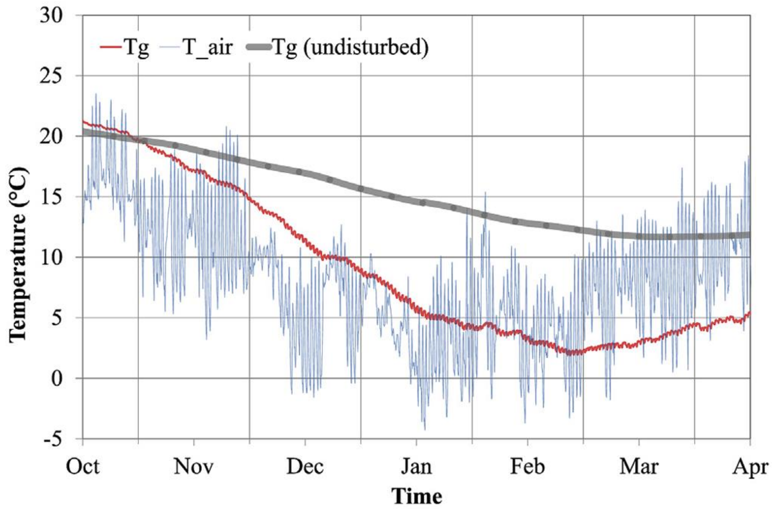
(**b**)

Figure 23. PV-assisted GSHP system by Zheng et al. [84] (**a**) Schematics of the PV-assisted GSHP system and (**b**) Average soil temperature changes for different systems.

Bottarelli et al. [85] numerically studied the DSHP system coupled with a flat-panel as a horizontal ground heat exchanger (HGHE) using COMSOL Multiphysics (as shown in Figure 24). The EnergyPlus software was used to simulate the TekneHub laboratory in Ferrara, Italy as a reference. A 2D computational domain was established, consisting of a flat-panel HGHE (2.5 m deep with a consistent heat flux) cross-section and a 6 m wide × 10 m deep soil domain, for soil temperature simulation. At flat-panel volume-to-length ratio r = 30, which represented around 17% of the standard r = 5, the ground heat extraction per meter of Flat-Panel was roughly 78 kWh/m for a temperature difference of 0 K and 33 kWh/m for a temperature difference of 10 K. The mean thermal dissipation rate was approximately 130 W/m for a temperature gradient of 0 K and 150 W/m for a temperature gradient of 10 K. Utilizing a DSHP might result in a substantial decrease in the size of the Flat-Panel HGHE, leading to a reduced cost for installation.



(**a**)



(**b**)

Figure 24. DSHP system with HGHE [85] (**a**) 3D model of TekneHub laboratory in Energy Plus and (**b**) Temperatures of air, undisturbed ground and Flat-Panel surface in the of GCHP.

3.3.2. Summary of Air Source-Geothermal Hybrid Heating Systems

In the hot summer and cold winter regions, air source-geothermal hybrid heating systems can effectively reduce the drilling length of BHE, thereby lowering the overall cost of the system.

Current research on GSHP-ASHP systems primarily focuses on two aspects. One aspect involves evaluating the performance of these systems. For example, how much heat can air source heat compensators inject into the soil to mitigate the decrease in system efficiency caused by soil temperature decay, or how much heat can ASHPs and water source heat pumps supply as auxiliary heat sources. The other aspect involves developing and evaluating methods designed to optimize performance, reduce energy consumption, and enhance stability, such as integrating BHE arrays or HGHE to improve system efficiency. The main characteristics of the reviewed systems have been summarized in Table 3.

Table 3. Summary of air source-geothermal hybrid heating systems.

Reference	Region	Research Methodology	System	System Characteristics	Main Conclusions	Remark
[81]	Bologna, Northern Italy (44.49° N, 11.34° E)	Simulation	GSHP-ASHP	ASHP is used to reduce the ground temperature attenuation	BHE length can be reduced by 30% to 50%.	A typical climate of Northern Italy
[82]	/	Simulation	AHC-GCHP	AHC can inject heat into the soil	The AHC-GCHP system effectively keeps the soil thermal balance and saves 23.86% energy compared with a traditional "boiler + split air conditioner" system.	/
[83]	Zibo City, China (36.81° N, 118.04° E)	Experiment and simulation	GSHP-ASHP	ASHP and WSHP were used as auxiliary heat sources for part of the heat supply	The proposed system can maintain the soil heat imbalance rate to 2.6%. Compared with traditional GSHP system, the annual operation cost of the novel system is only 58%. Carbon emission was by 7.14%.	Cold regions
[84]	Changsha, China (28.22° N, 112.93° E)	Simulation	PVGSHP-ASHP	86 shallow BHEs	The PVGSHP-ASHP system could solve load imbalance problem with high annual COP-GSHP and COP-sys values of 3.49 kW/kW and 4.69 kW/kW, respectively with only 71,700 kWh of the annual electricity consumption.	Hot summer and cold winter regions
[85]	Ferrara, northern Italy (44.83° N, 11.61° E)	Experiment and simulation	GSHP-ASHP	Coupled with a Flat-Panel HGHE	The use of a DSHP can offer a significant size reduction of the Flat-Panel HGHE and therefore a lower installation cost.	Humid continental climate, with a harsh and humid winter

4. Conclusions

As geothermal energy utilization has become widespread, it has emerged as a highly advantageous renewable energy source. In order to overcome the performance degradation during the utilization process and improve the efficiency of the renewable energy system, the ground-source heat pumps are combined with various kinds of renewable energy sources to mitigate the decline of utilization efficiency over the long-term operation. This paper provides a comprehensive review of the research on the integration of geothermal energy, solar energy, wind energy, and air-source energy into a coupled system. The main conclusions are as follows,

(1) There is rapid progress in the investigation of geothermal energy, particularly in the areas of collecting, utilizing, storing, and optimizing of the geothermal energy system design. An essential problem of geothermal energy systems is accurately forecasting and maximizing their performance. Traditionally, predictive methods consisted of three primary classifications: analytical methods, simulation methods, and experimental methods. Combining these methods can enhance the efficiency of GSHP systems. However, there are still several ongoing issues, including the decrease in the system long-term performance caused by ground temperature reduction. There has been a growing interest in the implementation of multi-source coupling systems.

(2) Solar-geothermal energy hybrid systems can be utilized for heating and cooling buildings. By combining solar thermal collectors to accumulate heat during the day and storing it underground, these systems address the issue of reduced COP due to soil temperature decline during long-term operation. Geothermal heat pump systems can compensate for the instability of solar systems and provide cooling for solar photovoltaic components, thereby enhancing the overall system efficiency. Current research focuses on several key areas: optimizing the design of the dual heat source coupling methods, investigating the ground temperature drop during long-term operation, analyzing the dynamic performance under different operational strategies, and evaluating the economic impact of the coupling system.

(3) Wind-geothermal energy hybrid systems utilize wind turbines to generate electricity, which is then used to operate a geothermal heat pump, meet the building's electrical needs or be sold to the power grid. Hybrid wind, solar and geothermal energy systems utilize geothermal energy to meet the base load of buildings, while photovoltaic and wind power systems provide electricity and supplement demand during peak periods. Additionally, energy storage devices can be integrated to address peak demand. Current research focuses on several key areas: the design of coupled systems, the impact of variations in system parameters, the optimization of energy management and the generation cost, and the production of multiple types of energy (electricity, heating, and hydrogen, etc.).

(4) Air source-geothermal energy hybrid systems are widely employed for building heating. During periods of increased demand, air-source heat pumps are usually selected as supplementary sources to provide additional energy. By combining these two systems, we may improve the energy efficiency and effectively address the long-term temperature decline problems of geothermal systems. Current research focuses on several key areas: system energy consumption analysis, BHE size reduction, soil thermal imbalance, and carbon emission.

Current research on multi-energy coupled systems indicates their potential to significantly improve overall efficiency and reliability, while reducing cost, environmental impact and energy consumption. However, the coupled system also faces challenges such as high system complexity, difficulties in selecting appropriate operating methods, and reliability. Future research directions may focus on developing more intelligent coupling methods and control strategies, improving system reliability, reducing more costs and carbon emissions, and expanding the system's range of applications.

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Nomenclature

ASHP	Air Source Heat Pump
BHE	Buried Heat Exchanger
COE	Cost of Energy
COP	Coefficient of Performance
EFT	Entering Fluid Temperature
EAHE	Earth-Air Heat Exchanger
GSHP	Ground Source Heat Pump
WSHP	Water Source Heat Pump
GSHP-PVT	Ground Source Heat Pump-Photovoltaic Thermal
GSHP-ASHP	Ground Source Heat Pump-Air Source Heat Pump
HGSHP	Hybrid Ground Source Heat Pump
LCC	Life Cycle Cost
MBHE	Medium-deep Buried Heat Exchanger
NPC	Net Present Cost
PV/T	Photovoltaic Thermal
PVGSHP-ASHP	Photovoltaic Ground Source Heat Pump - Air Source Heat Pump
SPF	Seasonal Performance Factor
SBHE	Shallow Buried Heat Exchanger
SAGSHP	Solar-Assisted Ground Source Heat Pump

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