Energy demand reduction in the built environment using shallow geothermal integrated energy systems: Part II – Hybrid ground source heat pump for building heating

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Abstract

The research collection aims at finding the various possible opportunities for the effective integration of shallow geothermal energy (SGE) to decrease the energy demand in the built environment and to reduce emission associated with it. The direct utilization of SGE using a ground source heat pump (GSHP) has been reviewed in comprehensive review part I and part II. From the extensive review, it is found that the hybrid GSHP is needed to avoid ground thermal imbalance and peak demand. Hybrid GSHP can adopt various supplemental heat sources and sinks according to the local climatic conditions and the balance of energy demands. The primary focus on the integration of subsystems such as biomass, solar energy (PV, PVT, and collector), phase change material, micro gas turbine, and absorption heat pump with GSHP is presented for heating application. This comprehensive review part III highlights [1]the recent research findings and potential research points in the hybrid GSHP for further research and developments.

Keywords: Building heating, peak demand, renewable energy, ground source heat pump, hybrid GSHP, combined heat and power

Abbreviations

A – Area
COP – Coefficient of performance
ACOP – Average coefficient of performance
SCOP – Seasonal Coefficient of performance
EER – Energy efficiency ratio
EG – Ethylene glycol
ES – Energy storage/energy source
PB – Polybutylene
PE – Polyethylene
PVC – Polyvinyl chloride
HDPE – High-density polyethylene
Ref – Refrigerant

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SPF – Seasonal performance factor

Suffix

h – Heating
c – Cooling
s – System

Contents

1. Introduction

The concept of integrating GSHP with subsystems such as renewable energy and the auxiliary unit is to offset the peak demand, energy consumption, and GTI, and to increase the performance [1]. The GSHP system can be used for primary building demand by considering the effect of cost in the hybrid system, and the subsystem may be employed to connect the building's peak demand. The study reveals that decreasing the building peak load size by 40% and decreases the borehole length by 44.5% for heating and 69.2% for cooling [2]. Similarly, the analysis concerning the space heating and cooling load of the typical building in Greece reveals that the total heating and cooling load is 150 kW and 270 kW, correspondingly. The vast difference between the design load is due to high solar radiation [3]. Hence to avoid oversizing the system, it is essential to integrate auxiliary units.

The addition of a boiler, cooling tower, and solar thermal with GSHP will considerably reduce the peak demand, size, and cost. The detail of the hybrid GSHP unit is shown in Table 2. A review on the hybrid GSHP system for the warm and humid and cold climate is presented [4] and concluded that solar thermal could be added for cold climate, similarly, the cooling tower can be added for hot climate. An additional boiler can be used for space heating during peak demand. Likewise, an additional pond can be integrated with GSHP to remove the excess heat in cooling dominated buildings [5], [6]. Similarly, the authors studied the integration possibilities of cooling towers [7] and ground-air heat exchanger (GAHE) [8] with GSHP. They demonstrated that when there is a high ground temperature in a hot climate, this integration reduces the borehole length and installation cost. The boiler and cooling towers can be added with the GSHP system for composite climate [9]. Their findings reveal that the integration boiler and cooling tower reduces the GTI, and it increases the system performance. The maximum performance improvement is 18% higher than the GSHP system. The economic feasibility and optimum system sizing depends on local climatic conditions, peak and mean demand, operating hours, inflation rates, and operating costs.

A numerical investigation has been used for the comparative analysis of the individual system, such as GHE [10] and cooling tower [11] with a heat pump. The study concludes that the integration of GHE increases the system performance significantly, and the performance highly depends on soil thermal conductivity. The performance of the GSHP in intermittent operating strategies is relatively advanced compared to continuous operating strategies of the HGSHP system since the heat dissipation rate will be maximum. An optimal intermittent operating condition that favors both energy consumption reduction and soil temperature recovery. Similarly, the optimum combination and operation of different components such as heat pumps, cooling towers, air-water heat exchangers, and solar collectors have been investigated using TRNSYS for the residential buildings located in China (Shanghai, Harbin, and Lhasa) [12]. The WSHPs have a higher COP than ASHPs when the ambient dry-bulb temperature is greater than the wet-bulb temperature. Hence, the integration of the cooling tower with WSHP increases the COP of the system during the summer. Since the condenser inlet temperature is almost close to the wet-bulb temperature.

Three different hybrid systems are suggested for the different climatic conditions in China. The first combination - a hybrid HP system with cooling towers and air to water heat exchangers can be used for both hot summers and severe cold climatic conditions (Shanghai). The second combination - hybrid HP with GHEs and air to water heat exchangers can be used for cold and severe cold climatic conditions (Harbin). The third combination – hybrid HP system with solar collector and air to water heat exchangers can be used for the climate, which has a high intensity of solar radiation (Lhasa). The author concludes that a single heat sink (cooling tower or GHE) might not work effectively throughout the year. Hence, multiple heat sink integrated with HPs will be suitable for year-round operation in different climatic conditions. Compared to conventional HPs, the proposed hybrid system saves energy by 15% with a payback period of approximately five years.

The paper presents a comprehensive overview of recent developments of HGSHP coupled with auxiliary heating source devices (fossil fuel, solar thermal energy, and waste heat), auxiliary cooling source devices (ice storage and cooling tower), sensible and latent thermal energy storage devices (soil storage and ice storage) are presented [13]. This paper reviews the progress of GSHP combined with hybrid energy systems and surveyed the development of HGSHP in China [14]. The review has detailed information on GSHP with different subsystems such as solar collector, waste heat, boiler, and cooling tower. These review articles do not emphasize the integration of different subsystems integrated with GSHP to develop a sustainable solution. In this review part III, the primary focus has been given to develop a sustainable solution for the heating application. In this regard, the integration of subsystems such as biomass, solar energy (PV, PVT, and collector), phase change material, micro gas turbine, and absorption heat pump with GSHP are presented. There are no studies to analyze the recent research with the aspect of integrating PV, PVT, combined heat and power (CHP), combined cooling heating and power (CCHP), ejector cooling, and absorption heat pump with GSHP system. From the above discussion, it is of interest to identify a suitable hybrid GSHP system for the heating application. Finally, comprehensive data of research articles have been presented in Table 2, which will help the readers to understand the existing work done. Hence, this review is very much needed for sustainable development using HGSHP for heating applications.

The papers carefully chosen in this review are available in recent years or have a significant contribution to the research. Among the articles selected, 74 articles cover the past 5 years (from 2016 to 2020) and 82% of the studied articles are associated with the past 10 years (2011–2020), and only 18% of papers are associated with pre-2011 years that has been tried to use the most important papers.

2. Hybrid GSHP systems

2.1 Boiler + GSHP

The feasibility of the GSHP unit integrates with the boiler that has been studied to decrease the GTI in the cold climatic condition (Figure 1) [15]. The integrated unit has been analyzed using TRNSYS software and the results imply that the total energy consumption is considerably less related to the standard heating system. The integrated system increases the soil temperature by 6.8 °C related to the typical system over the ten years of operation in the cold climate. Exergy analysis of individual components in the boiler + GSHP system has been carried out in detail, and it shows the possibilities of performance improvement in each component. The exergy analysis of the GSHP system with the addition of a heat source or sink is minimal. This hybrid system has the potential for installation due to lower installation and operating costs. Hence, it is crucial to improve the boiler + GSHP system performance.

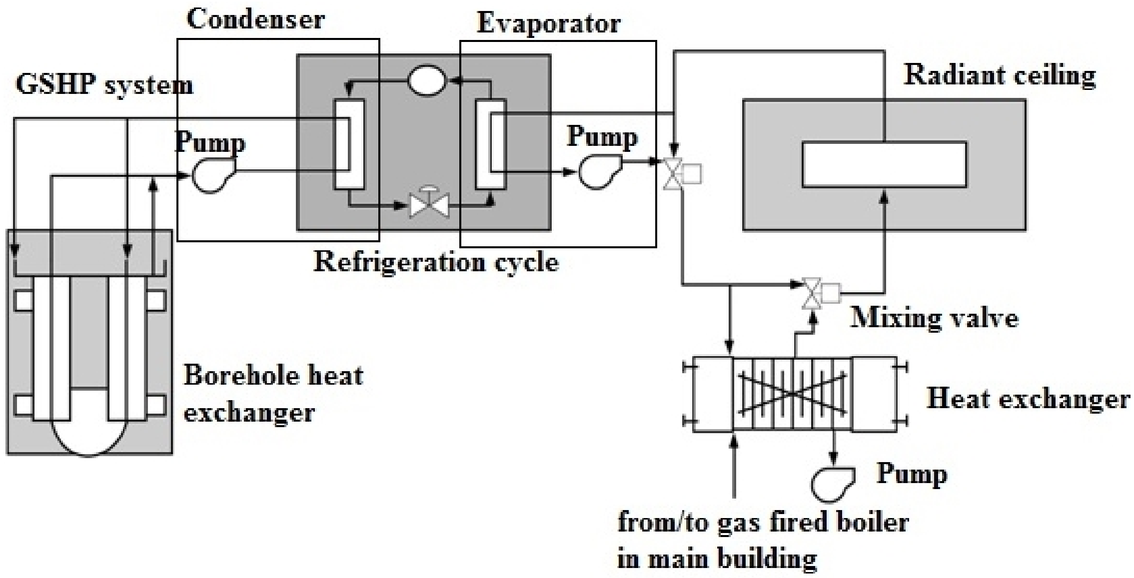


Figure 1 Schematic of GSHP with TES [16]

2.2 Thermal energy storage + GSHP

A three-dimensional numerical model developed to study the performance of underground thermal energy storage is placed 6 m below the ground surface [17]. The authors reveal that the TES controls the entering of HTF in the GSHP for more effective operation than a conventional GSHP. TES + GSHP system reduces the investment by reducing the borehole size (10 times) compared to conventional GHE. Also, it reduces the total operating cost by shifting the peak demand. TES + GSHP system has been reviewed in detail, and it can be grouped as Latent Heat Thermal Energy Storage (LHTES) (PCM and ice) and Sensible Heat Thermal Energy Storage (SHTES) (water and soil) [18]. The TES + GSHP system can be classified into five groups: ice storage + GSHP, solar collectors + GSHP, soil + GSHP, water tank + GSHP and Phase Change Materials (PCM) + GSHP. A buffer tank has been integrated with the GSHP system to reduce the peak demand and system oversize. The result concludes that peak energy consumption (25 cycles) for cooling decreases from 68 kWh to 54.3 kWh [19]. The performance optimization shows that the integration of the buffer tank also increases the COP by 8%. However, the LHTES is attractive since it has higher density and capacity, and it requires less space compared to SHTES.

Energy and exergy analysis of the LHTES unit and system optimization has been reviewed in detail [20]. It concludes that PCM offers LHTES with moderate temperature difference, and it performs a crucial role in energy saving. The review also reveals that the development of suitable TES material according to the application and optimization of the system needs to be carried out extensively. The variation in the cooling demand of the building can be regulated using PCM, and the stored thermal energy will be supplied to the indoor based on the demand. Different types of PCMs, such as organic, inorganic, and hydrate salts and thermophysical properties, are presented [21], [22]. Based on the application, PCM material can be selected.

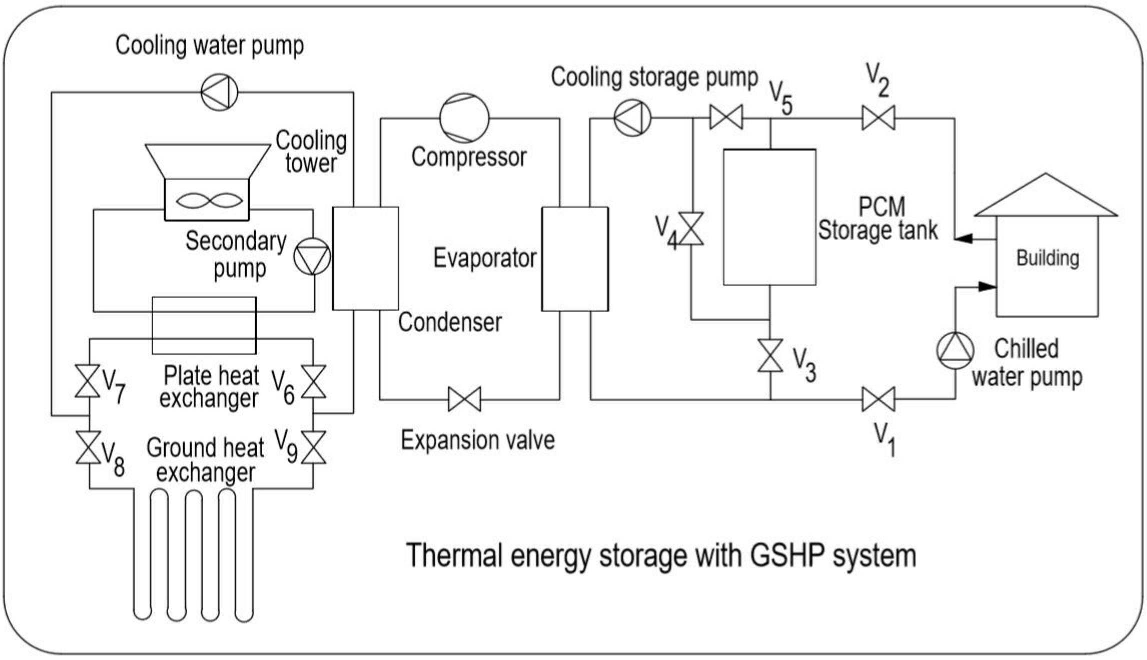


Figure 2 Schematic of GSHP with TES

PCM + GSHP connection is explained in Figure 2. The set-up comprises a heat pump, GHE, circulation water pump, circulation water tank, cooling tower, emergency water heater (extreme cold air), storage tank and control units, and other auxiliary apparatus [23]. The plate heat exchanger and the cooling tower have been combined to reduce the GTI. The PCMs such as $CaCl_2.6H_2O$, polyethylene glycol, paraffin, and $Na_2SO_2.10H_2O$ are mostly used for heating applications. The performance analysis of TES + GSHP has been done experimentally, and the COP_{hp} and COPs are in the range of 2.3–3.8 and 2.0–3.5, respectively. Calcium chloride hexahydrate solution has been used as a TES material. The HGHE has been used to heat the space, and a brine solution has been used as an HTF. Material charge time is shorter during the summer days and longer when discharging, and the process is reversed during the colder days [23]. The thermal cycle test conducted for $CaCl_2.6H_2O$ demonstrated that $CaCl_2.6H_2O$ displays a small difference in the latent heat of fusion, and it melts in the desired temperature range [24].

The outcome of the experimental investigation of TES + GSHP system performance revealed that the COP of the hybrid system increases by 0.04 in summer and 0.37 in winter [25]. In a continuous operation, the total running cost reduces by 35.2% due to the reduction in peak electricity prices. In some cases, this hybrid GSHP system reduces the initial investment. However, there is a need for detailed research in cost evaluation. Further, the exergy of the hybrid GSHP unit is minimally related to the standard GSHP system. Most of the studies have been carried out only on energy analysis. Hence the comprehensive exergy analysis of the hybrid system is highly needed.

2.3 PV + GSHP

The effective integration possibilities of solar energy with the GSHP system are reviewed in detail [26]. The solar energy + GSHP competes for an important role in lowering the PEC, and the economical calculation of solar energy + GSHP employing tri-generation methods led to the lowest payback time of 5 years. In the following sections, the research studies on different solar energy + GSHP system such as PV + GSHP, PVT + GSHP and solar collector + GSHP are highlighted.

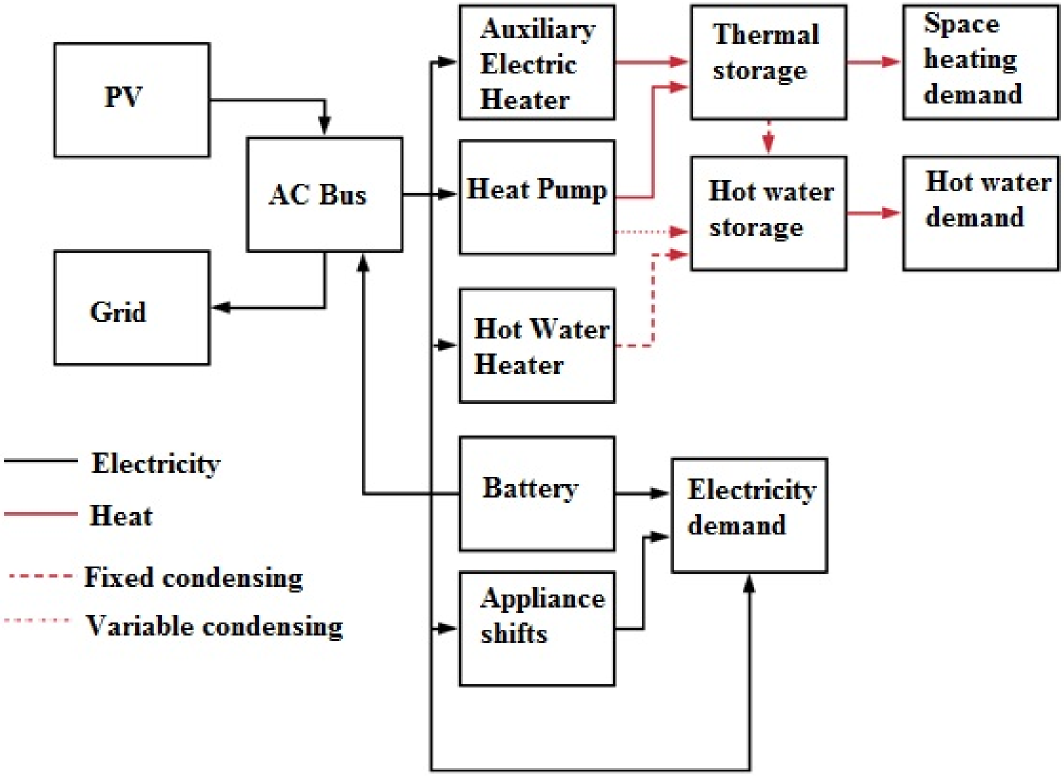


Figure 3 schematic diagram of PV- GSHP system

PhotoVoltaic (PV) technology is highly attractive due to the decentralized form of energy generation, and it can be integrated with the GSHP system with the aim of reducing the building energy demand. The primary objective is to generate on-site electricity from PV and to lower the grid energy consumption for space heating and cooling application. PV + GSHP system (Figure 3) feasibility has been studied for residential buildings by improving the self-energy consumption (peak demand of 3.7 kW) [27]. The objective of the study is to enhance the sustainability of the GSHP system. Based on the COP of the system, which is in the range of 3.5 to 4 it can be concluded that the performance highly depends on local climatic conditions. Similarly, the PV + GSHP system for the residential building has been studied for the different climatic conditions in the USA with an objective of the net-zero nation through net-zero energy building [28]. The USA has eight climatic zones, and the climate zones are classified based on the cooling, heating degree days, and humidity (ASHRAE 90.1 standard). PV + GSHP system requires less PV area and capacity compared to PV + ASHP system. The PV + GSHP system saves energy considerably, 24.3% to 39.2%, in cold climatic conditions like Chicago through Duluth. However, PV + ASHP is recommended for hot climatic conditions due to the high installation cost of GHE. The GHE cost makes GSHP less cost-effective even though the reduction in PV size meets the net-zero energy.

The solar PV system may be used to satisfy the building energy demand, and the excess energy can be fed into the grid. This study deals with the bidirectional energy flow from the solar PV to the grid and grid to appliances [29], [30]. Very few research studies are only available concerning the PV + GSHP system with grid interaction. The electricity from the solar PV system is partially used for operating the GSHP, and the remaining is used for other appliances [31]. Energy, economic, and environmental analysis have been carried out by considering the peak demand of both buildings and the grid. Further, the optimum size of the PV, battery capacity, and GSHP capacity have been analyzed. Since the peak demand of the building, grid, and electricity generation are mismatching, most of the generated electricity will be fed into the grid. The increasing battery storage decreases the electricity feeding into the grid. Also, increasing battery storage reduces PV size. However, the investment cost is relatively higher due to the presence of solar PV and batteries. In another study, water is used as TES and it significantly effects the self-consumption [32]. The cost-effective and shiftable loads based on the market electricity price have been effectively investigated for adequate bidirectional energy flow [33]. A similar approach needs to be studied for PV + GSHP, and it is essential to obtain the best possible design and control algorithm based on the real-time forecast for effective utilization.

A novel control algorithm based on the weather data has been developed to operate the PV + GSHP system with storage devices using TRNSYS software for hot water and space heating applications [34]. The integration of controllers based on weather reduces the building energy consumption by 7%. However, during the design stage, the GSHP system capacity is 50% downsized based on the peak demand and yearly average demand. Hence, the proposed system significantly reduces the size of each component with the addition of a TES system. Further, an increase in the TES size has less impact on the GSHP system sizing.

2.4 PVT + GSHP

Environmental benefit encourages the usage of solar energy. Different types of solar energy collection techniques are presented in detail with regard to heat and power generation [35]. PVT collectors are used to producing simultaneous heating and power. Waste heat from the photovoltaic panel is extracted using HTF, and this technique is called PVT. The advantage, limitations, applications, and efficiency of the flat plate solar PVT technique [36] and concentrated PVT [37] are presented, and the efficiency of the PVT is in the range of 60 to 80%. The SGE integrated with a PV panel to reduce the panel temperature using VGHE increases the panel efficiency by 14.3% [38]. Further, the electricity, cooling, and heating (tri-generation) demand issues in the building can be solved by combining GSHP and photovoltaic thermal. A study on the community-scale performance of the PVT + GSHP unit revealed that energy demand is reduced by 11% compared to the conventional GSHP system [39].

PVT + GSHP hybrid system has been simulated using MATLAB [40] for space heating and cooling application (Figure 4). The description of the process and operating conditions are presented for the integrated unit. The purpose of the integration is to power the electrical component such as compressors and pumps and to collect the heat energy to enhance the performance of the evaporator system. A storage unit is applied to decrease the fluctuations in demand and supply. The heat energy will be forced into the soil when the soil temperature is lower than the PVT outlet temperature.

The performance of the PVT + GSHP system has been experimentally investigated mainly for heating applications in the UK [41]. The heat energy from the PVT system is injected into the ground using VGHE, and the injection of heat increases the ground temperature up to 4 K. Hence, increasing the temperature reduces the soil freezing potential during winter. The average monthly SPF is reported as 2.51. This study deals with the energy and exergy analysis of the PVT + GSHP unit for heating applications [42] using Engineering Equation Solver (EES). The thermodynamic modeling reveals that the maximum exergy destruction rate happens at PVT and evaporator compared to other components present in the hybrid unit. The exergy destruction increases with an increase in ambient temperature and intensity of radiation.

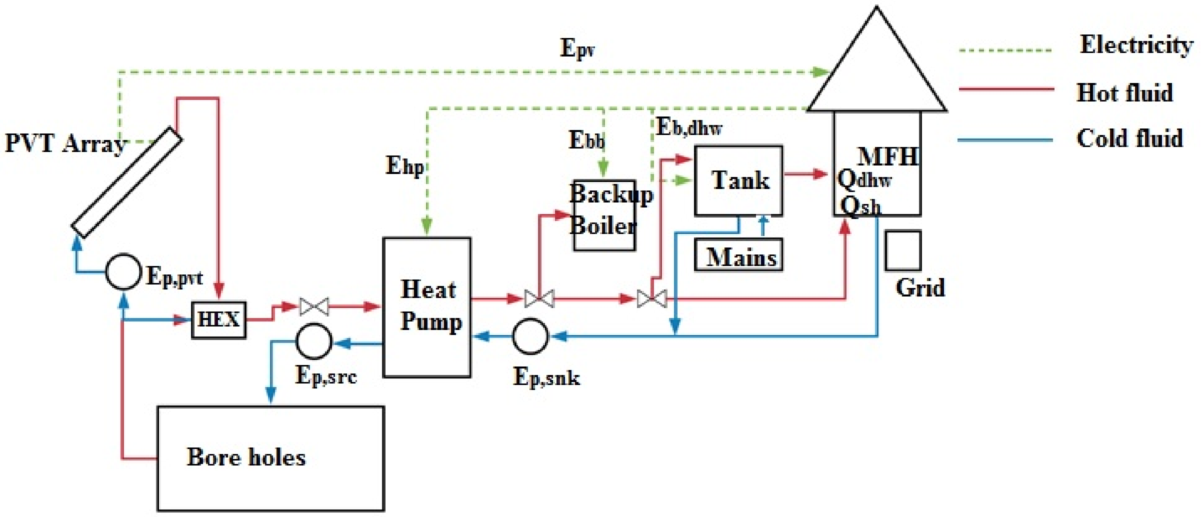


Figure 4 schematic diagram of PVT-GSHP system

The performance of the integrated system has been analyzed for dominant heating buildings in Jordan using TRNSYS software [43]. HTF increases the PV performance by 9.5% and reduces the PV panel temperature by 36%. The COP of the integrated system is 6.2, and it is 1.13 times higher compared to the conventional system. Here, the hybrid system is modeled using TRNSYS, and the parametric analysis has also been carried out [44]. The PVT system performance highly depends on storage system size and demand. An increase in the tilt angle increases the specific heat productivity by 3.47%, and this energy is directly used for space heating and to reduce the storage system size. Usually, the integrated system performance is evaluated using the SPF or COP matrics, and the SPF does not give full details about the total energy generated using renewable energy. Hence, it is crucial to develop new evaluation criteria for the integrated system by considering the collector area and GHE.

The fuzzy logic control signal has been used to operate the PVT + GSHP in two different loads. The PVT + GSHP system is operated at low capacity when the signal is less than or equal to 0.5, and it is operated at full capacity when the signal is greater than 0.5. From the control signal, a 5% energy-saving reduction is reported [40]. The economic analysis reveals that the NPV value increases by 13.2% and the life cycle of the system decrease by 3.9%. In the same way, an investigation conducted in Sweden on the integration benefit revealed that 18% of the borehole length could be reduced for heating applications [45]. The PVT + GSHP system is highly suitable compared to the PV + GSHP system since there is no need for additional space. However, PV + GSHP and PVT + GSHP systems have not been studied in detail. There is a lack of design optimization and control algorithms based on the application.

2.5 Solar collector + GSHP

Flat plate collector plays a crucial role in the conversion of solar energy into thermal energy due to environmental benefits, and the thermal energy can be used for both space and water heating applications [46]. The main objective of the integration of solar thermal and GSHP is to store the heat energy produced from the collector in the ground, and it can be extracted for space heating through GSHP and to reduce the borehole length [47]. The arrangements of the heat pump, flat plate collector, and borehole are shown in Figure 5 for heating application. The GHE is connected with the evaporator. HTF in the collector is circulated using a pump, and it maintains the flow rate and outlet temperature. Alike, only a few research studies have ventured on the direct integration of solar collectors and heat pumps. The solar collector is directly integrated with the evaporator so that the integration increases the instantaneous performance of the heat pump [48], [49]. The addition of a solar collector lowers the GHE cost, and auxiliary heaters are essential for continuous operation when there is no sun. The arrangements entirely depend on local climatic conditions.

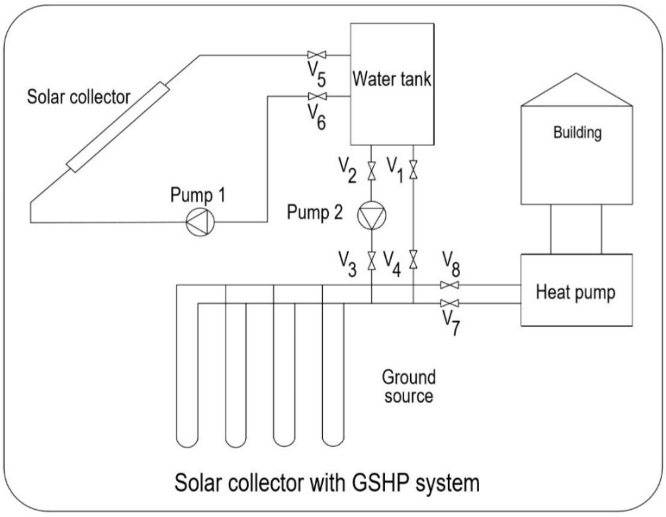


Figure 5 Schematic diagram of solar collector – GSHP system

System Performance: TRNSYS software is frequently used for the performance analysis of the hybrid solar collector + GSHP system [50]–[54]. The integration (Solar collector + GSHP) system leads to an increase in the heat pump COP by 2.84% for heating and a decrease in heat pump COP by 0.46% for cooling [50]. The Solar collector + GSHP has been studied for heating application through experimental study in Polytechnic University [53], and findings showed that collector efficiency is reached by 50.2% and soil temperature is increased by 0.21 °C irrespective of borehole depth. Also, another study has been carried out in a 100 m^2 residential building for the effective integration of solar thermal and GSHP [54]. The performance factors have been simulated for ten years, with five different operating conditions. The maximum COP of the system is reported as 3.75, and it is 8.7% [54] and 10% [55] higher than conventional GSHP.

Seasonal performance: This study deals with the seasonal performance factors of flat plate collector and storage tank integrated with GSHP [56]. The integration of the solar thermal + GSHP system reduces the overall power consumption by 6.1% related to the conventional GSHP unit for cold climatic environments. Seasonal energy storage that can be defined as energy generated from solar collectors during spring and autumn is used to store in the ground using GHE, and it can be extracted during the winter for space heating and hot water application. 49.7% of the total heat energy is distributed by the solar collector during the heating mode, and the system and heat pump COPs are 6.55 and 4.29, respectively [57]. Similarly, in another study, the hot water tank acts as temporary storage [58]. The water absorbs solar energy using a flat plate collector, and it is heated up with an efficiency of 57.06%, and 40.64% of heat energy, which is stored in the ground directly.

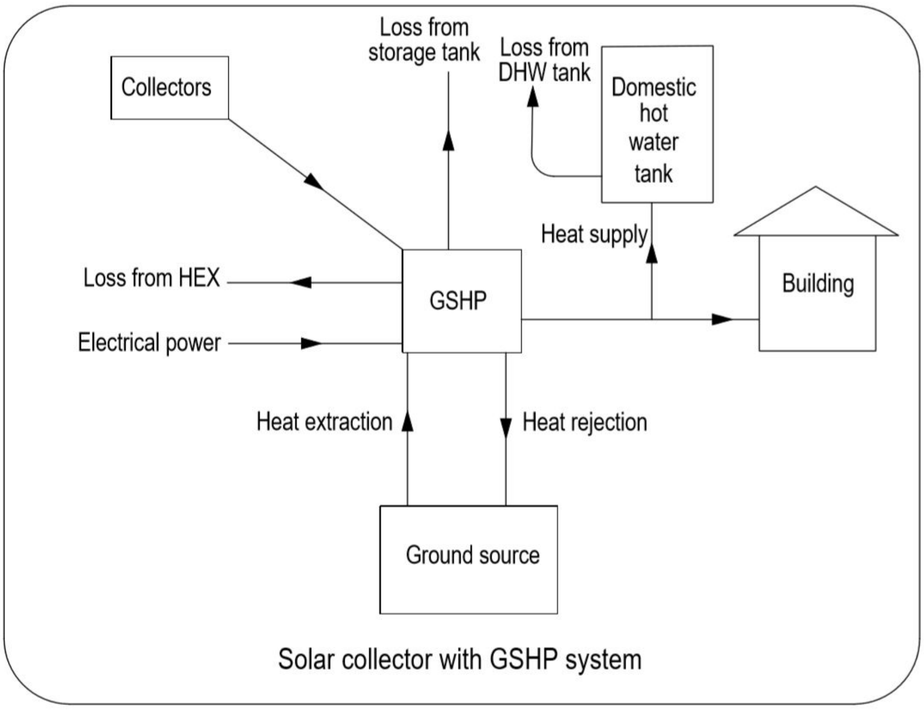


Figure 6 Energy balance of the solar collector integrated with GSHP [59]

Energy distribution: The energy balance of solar + GSHP is shown in Figure 6. The Solar collector (40 m^2) operated with an efficiency of 55.4%generates 2399 GJ of heat energy. The total electrical energy for operating the electrical component in the solar + GSHP system is 666 GJ, and the heat extracted from the ground is 947 GJ. Useful heat for space heating and hot water application accounts for 2366 GJ and seasonal energy storage accounts for 1417 GJ. Heat loss due to storage and heat exchanger accounted is 259 GJ [59]. The combined operation modes have a notable energy conservation effect related to the standard GSHP system [60]. It can be concluded that the performance of the solar + GSHP highly depends on the size of the hot water storage tank and collector. The optimum ratio between water tank volume and collector area is 33 L/m^2.

Ground thermal imbalance: The effect of heat accumulation during daytime and extraction during nighttime using solar energy has been investigated experimentally for space heating application. The results reveal that GTI significantly affects system performance [61], [62]. Experimental investigation of solar collectors + GSHP using R22 refrigerant has been done for heating, cooling, and dehumidification, and the COP varied from 2 to 3.3 [63]. The performance of heating is significant due to GTI. The performance of the solar collector + GSHP unit investigated experimentally for space heating application revealed that the system COP increases by 3.4%, with the addition of ground temperature of 0.25 °C [64]. Experimental investigation on the solar collector + GSHP system has been analyzed for four different operating modes for heating applications. It is concluded that compared with the traditional GSHPs, the addition of solar collector has a positive effect on the soil temperature recovery rate in severe cold climates [65]. Whereas, in mild climatic conditions, the system performance significantly gets affected. It is concluded that GTI is reduced with the effective integration of control strategies.

TES: To resolve the year-round GTI, the authors integrated the TES technique with solar collector + GSHP. It is clear that the proposed technique significantly reduces the GTI and also saves around 32% of energy consumption [66]. Energy and exergy analysis of solar thermal + HP unit with LHTES and SHTES presented for space heating application revealed that LHTES has significant advantages compared to SHTES [67]. The role of LHTES using phase change material (PCM) with solar collector + GSHP has also been investigated. The report says that the integration of the LHTES increases the COP by 9% compared to the solar collector + GSHP system [68]. The practice of PCMs melting temperature approximately by 40°C will permit to store heat energy effectively. Also, the phase change will take place in cloudy days while sunshine is low. However, an effective on-off control strategy is important to improve the system performance during peak hours.

Borehole: Optimization of solar collector, vertical borehole length, and borehole spacing have been carried out for 16 different cases [69]. Through the results, it is determined that an increase in the solar collector and borehole spacing area reduces the borehole length. The reduction in borehole length due to the injection of solar heat is reported as a maximum of 33.1% [70] and 29% [69]. Optimization of collector area and borehole length have been carried out for heating applications using the Taguchi technique and utility concept [71]. The optimum design of collector and borehole length is 7.34 m^2 and 280.52 m, respectively, and the COP is reported as 4.23. Another research work deals with the study of simulating the relationship between the collector area and GHE length using TRNSYS software (Table 1) [59]. The GHE length reduces when increasing the collector area in Beijing, China. When the collector area is varied from 0 to 90 m^2, the minimum inlet temperature to the heat pump is guaranteed from freezing safeguard in the range of 6 °C. Likewise, the relationship between solar collector and GHE length is optimized for Beijing, China, based on the COP using TRNSYS software. It is inferred that the variations of borehole length had more influence on system COP than variations of the collector area [72].

Table 1 The relation between collector area and borehole length

Collector area (m^2)	**Borehole length (m)**	**Minimum inlet source temperature in operation (°C)**
0	420	6.07
10	396	5.92
20	330	5.98
30	294	6.04
40	264	6.08
50	255	6.07
60	252	6.05
70	246	5.99
80	243	6.10
90	240	6.06

Payback and Economic analysis: The performance of solar + GSHP has been analyzed for the cold climate region, and the COPhp is in the range of 3.0 to 3.4 [73]. The system COP is 5–20% lower than the standard heat pump COP. The climatic data for 19 European cities is taken from the US department of energy and used to analyze the solar + GSHP systems for a residential building. The COP of the system varies between 4.4 and 5.8. The payback period of solar + GSHP lies between 8.5 to 23 years based on the environmental condition, and it is observed that the system is highly sensitive to climate data. It is reported that solar + GSHP is highly suitable for maximum solar irradiance and cold climate regions (hilly regions in southern Europe) [74], [75]. Performance optimization of solar collector integrated GSHP has been analyzed experimentally and numerically, and the payback period for the solar + GSHP is about 5–8 years [76]. Economic analysis carried out for a solar + GSHP system using the NPV technique revealed that the minimum payback period is 13 years for large-scale applications [77]. Even though the performance enhancement of the system is quite low for a moderate climate, it shifts the building peak demand considerably.

Comparative analysis: Energy and economic analysis of boiler + GSHP, PV + GSHP, and solar collector + GSHP system have been carried out for district heating application in a milder climate condition located in Italy [78]. Boiler + GSHP system reduces energy consumption by 30-35% related to the standard boiler heating method. PV + GSHP and solar collector + GSHP considerably reduces the PEC by 50-60% and 70-80%, respectively compared to standard system. The PV + GSHP system has a lower payback period compared to solar collector + GSHP and conventional GSHP system [78], [79]. Boiler + GSHP system are easy to retrofit with existing building compared to solar collector + GSHP system.

A comparative analysis of PVT + GSHP and solar collector + GSHP system has been carried out in three different mild climate cities such as Venice, Berlin, and Barcelona [80]. The operating conditions of a solar integrated GSHP system that gives combined heating (space and water) and cooling during ten years are simulated. It was found that the PVT + GSHP system uses more heat from the heat pump compared to the solar collector + GSHP, and it has a higher COP for all the cities. Similarly, research and development are required for other climatic conditions. Very few research studies are only available in the comparative analysis of hybrid GSHP.

Multi-system integrated with GSHP: A multi-system (free cooling, solar thermal, and TES) integrated with GSHP is shown in Figure 7. The proposed system is highly suitable for heating and cooling applications [81]. The operation strategies based on the climatic condition have been developed. In this case, the hot water generated from solar energy is circulated to the GHE, and based on the requirement, it is also used for building air heating. Three different case studies have been carried out, and the maximum seasonal performance factor is reported as 4.78. The research and development of integration are very limited. Hence, it is important to find the techno-economic feasibility of the system.

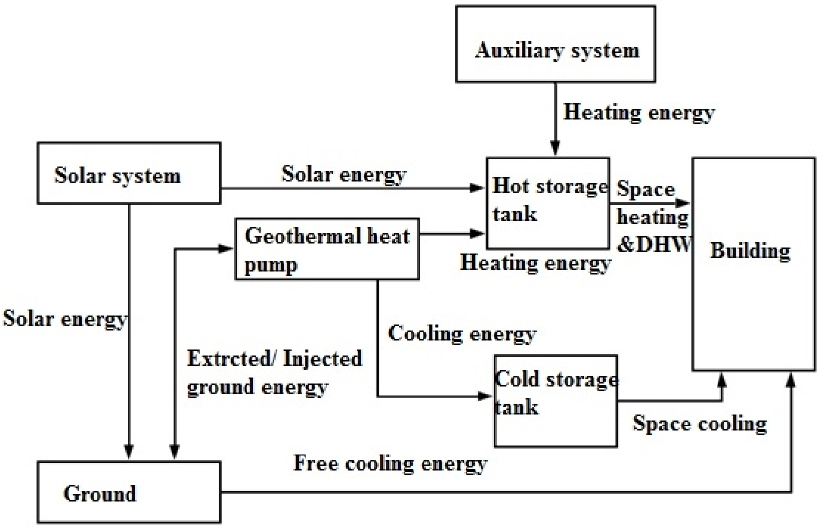


Figure 7 A schematic of multiple systems with GSHP

2.6 CHP + GSHP

One of the objectives of integrating Combined Heat and Power (CHP) with GSHP is to decrease the grid electricity and to offset the impact of growth in population, commercial space, and build area. Figure 8 shows the integration of CHP with a GSHP unit. The integrated system will generate heating and power simultaneously. Natural gas is used as a fuel, and the combustion of natural gas takes place in the combustion chamber. The average temperature of the flue gas is in the range of 400 – 600 °C and this energy will be converted into electricity. Heat energy from the flue gas is transferred to the cold water. The cold water temperature rises from 20 °C to 55 °C, and it satisfies the domestic hot water demand. Depending on the flue gas composition and temperature (~140 °C), it is released into the atmosphere. The compressor and auxiliary unit in the integrated system could be operated using the electricity produced from CHP (Figure 8).

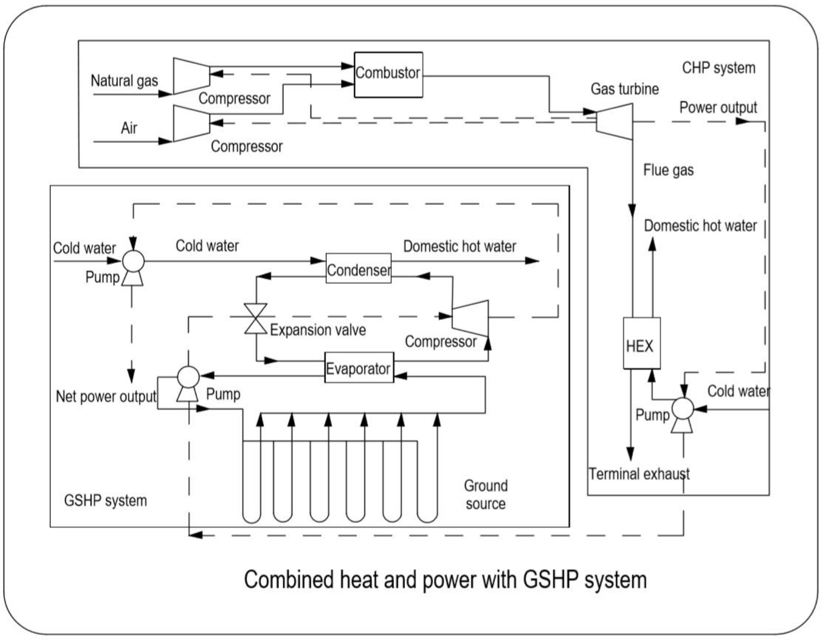


Figure 8 A schematic of combined heat and power with GSHP for water heating and power

This study deals with the experimental investigation of the CHP system integrated with GSHP [82]. The author has included an additional heat exchanger component in the conventional system to remove the sulfur content in the flue gas and to reduce the exhaust gas temperature. Energy and Exergy efficiency increases by 8.9% and 3% with the addition of a heat recovery unit. Coldwater is heated separately using waste heat available in the heat exchanger and condenser, and the integrating technique is to supply hot water at higher temperatures. The integrated system COP increases from 5.06 to 6.95 [83]. Two different heat recovery techniques are presented in this paper, such as series and parallel flow, and it is calculated that the COP of the GSHP is in the range of 3.6 to 6.

The advantages of the micro gas turbine such as ease of integration with building, compact size, high flexibility to operate, and renewable fuels are increasing the popularity of the system among the researchers, and the major disadvantage is exhaust gas emission to the atmosphere at a higher temperature. A detailed review shows the usage of renewable fuels in a gas turbine for power generation [84]. The integration of ground with micro gas turbine added a new dimension to generate small-scale combined heating and power. The micro gas turbine integrated with GSHP consists of a compressor, combustion chamber, turbine, heat exchanger, GHE, heat pump, and control system, as shown in Figure 9. The significant advantage and disadvantage of the integrated system is waste heat recovery and higher installation cost, respectively. A collection of literature about the seasonal TES in the ground using waste heat is presented [85]. The waste heat from the micro gas turbine is accumulated in the ground using spiral GHEs. The economic analysis reveals that the payback period of the micro gas turbine integrated with GSHP is five years [86].

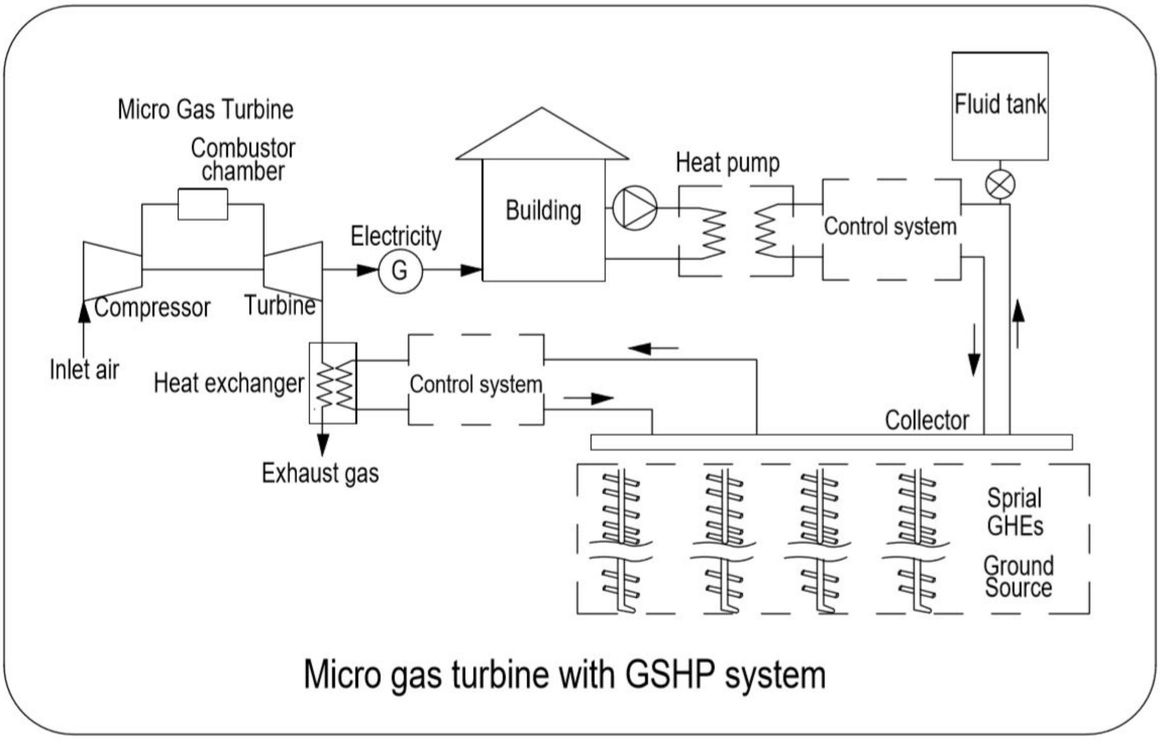


Figure 9 Schematic of a micro gas turbine with GSHP for space heating and power

The CHP and gasifier integrated with the GSHP system contain four major subsystems: (1) gas turbine subsystem; (2) steam turbine subsystem; (3) partial gasification of biomass subsystem; (4) heat pump subsystem. The integration of multi-systems such as combined heat and power, partial biomass gasification, and GSHP is presented in Figure 10. A detailed review of biomass gasification [87] and modeling [88] of the system is presented. Partial gasification of the biomass subsystem has four primary processes, namely drying, pyrolysis, oxidation, and reduction.

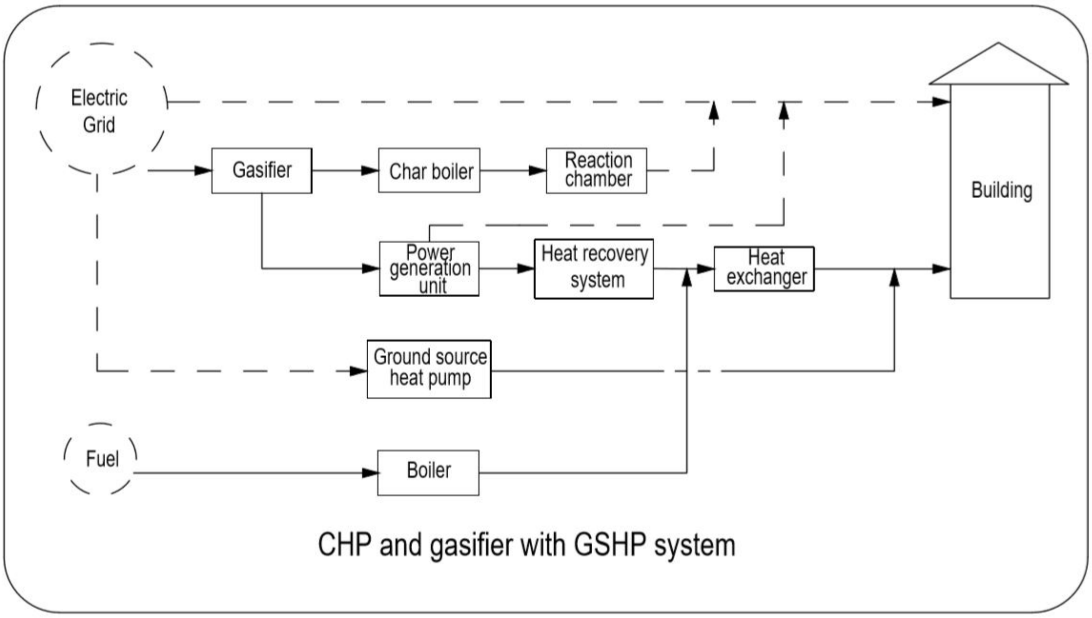


Figure 10 Schematic of simplified integration of CHP and gasifier with GSHP

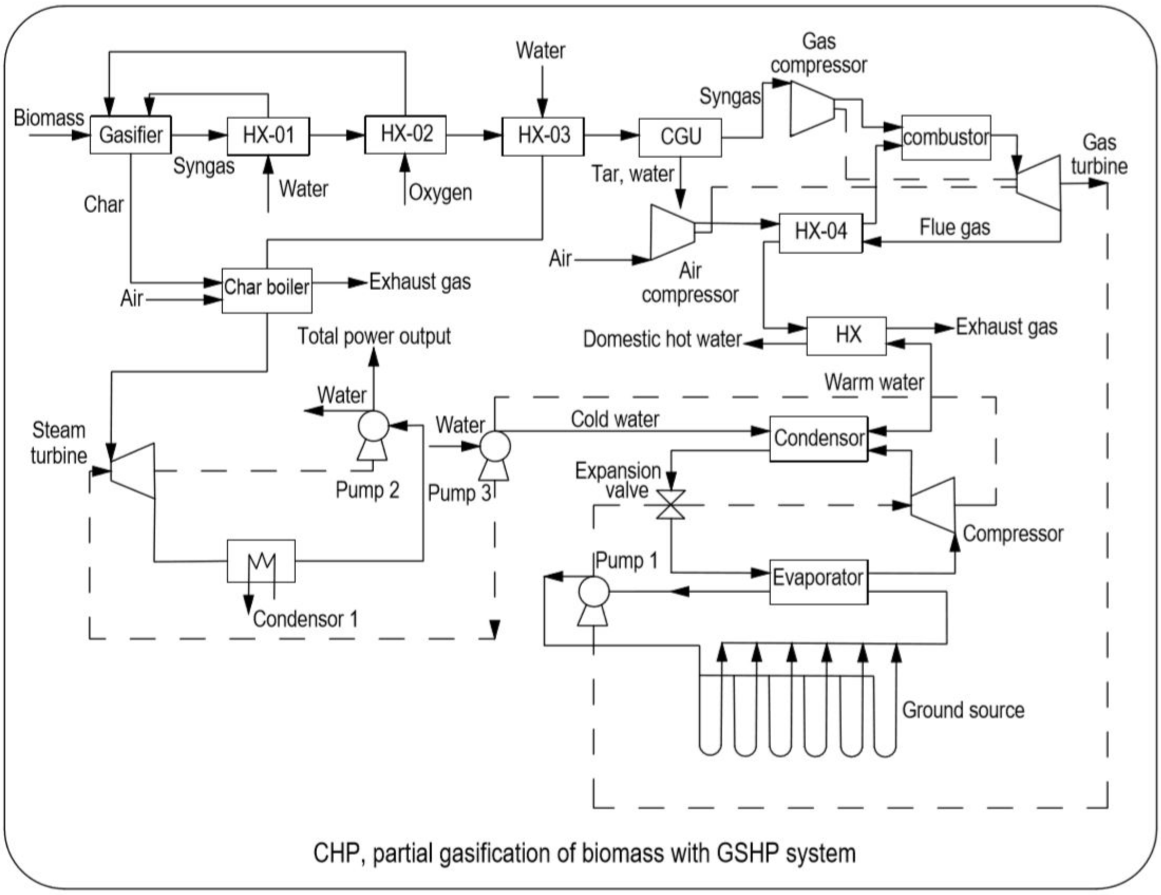


Figure 11 Schematic of integrated CHP, partial gasification of biomass and GSHP

Biomass fuel is supplied to the gasifier along with steam from the heat exchanger (1) at a temperature of 400 °C and preheated air from the heat exchanger (2) at a temperature of 400 °C as shown in Figure 11. Syngas from the gasifier can be used to preheat the water and air. The syngas and char exit the gasifier after partial gasification takes place. Scrubber and cyclone are used to remove the impurities from the syngas, and then the syngas enters the gas turbine subsystem for power generation. The compressed syngas flows to the combustion chamber along with preheated compressed air from the heat exchanger (4), and flue gas is generated from the combustion chamber. The flue gas enters the gas turbine for power generation with extreme temperature and pressure, and then it goes to the heat exchanger (4) for preheating the compressed air. The unutilized heat from the flue gas is again recovered using a heat exchanger for reheating the warm water, which comes from GSHP.

At the same time, char enters the steam turbine subsystem along with atmospheric air. The heat energy is generated in the char boiler, and it is used to convert the water into steam at high temperatures and pressure. The exhaust gas temperature from the char boiler is maintained at around 150 °C to avoid acid formation, so this heat energy cannot be used further. The stream flows into the steam turbine for generating the power, and then steam is condensed in the condenser completely. Then it is preheated using a heat exchanger (3) before being recirculated to the boiler. R22 refrigerant is used in the GSHP system, and the evaporator is connected with the GHE in the winter because the ground temperature is higher than the ambient. The cold water is heated up in the condenser, and it flows to the heat exchanger, as shown in Figure 11.

The thermodynamic analysis of CHP with partial gasification using biomass and GSHP system is presented. The results reveal that the GSHP system COP increases from 4.4 to 6.2 [89]. The exergy efficiency of the above unit is 13.65%. The significant destruction in exergy takes place in the biomass gasifier and combustion chamber because of the chemical reactions [90]. Further, the optimization of the integrated system has been studied and resulted in the best performance achieved when load and warm water temperatures are to be at 276 kW and 25 °C, respectively. In another study, the GSHP system has been powered using biomass and fuel cell to reduce the exergy destruction, and the system performance has also been investigated in the ASPEN plus environment [91]. The total power generation and heating capacities are 303 kW and 306 kW, respectively. The investigation reveals that energy and CO_2 savings are achieved by 24.9% and 13.9%, correspondingly. The integrated system exergy efficiency and thermal efficiencies are 29.2% and 67.3%, respectively. The GHE exit temperature significantly influences the system performance. The above system can be effectively integrated for space heating and water heating application using agricultural waste.

The combined heating and power + GSHP system performance is increased by extracting internal combustion engine waste, and this waste heat has been used to preheat the evaporator [92]. A multi-criteria optimization has been carried out to maximize the performance based on the demand. The reduction ratio in primary energy consumption (PEC), carbon dioxide emission (CDE), and annual total cost (ATC) is 30.26%, 53.20%, and 40.80%, respectively. A minimal research study has been carried out on the above CHP + GSHP system. Several studies have been carried out in colder climates. The suggested system shows the possibility of achieving net-zero energy building and zero peak building. This system is highly suitable for the community scale, considering the installation cost. However, the suitability needs to be analyzed for mild climatic conditions for further development.

2.7 CCHP + GSHP

The combined cooling, heating, and power (CCHP) system is also called a trigeneration system, and it became popular in the last few decades. CCHP system is energy efficient and eco-friendly since it recycles the waste heat for cooling, heating, or dehumidification application. CCHP system is highly suitable for large-scale applications such as commercial buildings and industries [93]. Nowadays, Micro-CCHP is being employed for small-scale applications (small community scale) [94]. Figure 12 consists of two parts, one is separate heating and cooling system, which is operated from grid energy, and it is shown on the left side. The second part is CCHP on the right side. The energy required in the buildings is electricity (light and other equipment), space cooling and heating, and hot water. Fuel is given to the power generation unit (gas turbine) to generate electricity. The waste heat from the power generation unit is used for building space heating and cooling by integrating the heat pump. The boiler is used to supply additional heat energy.

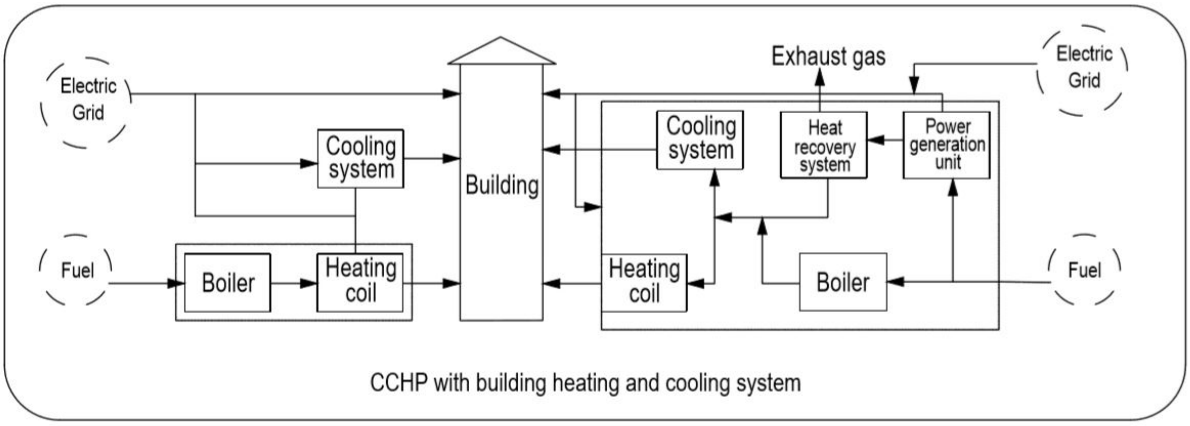


Figure 12 Schematic of separate building heating, cooling system, and CCHP

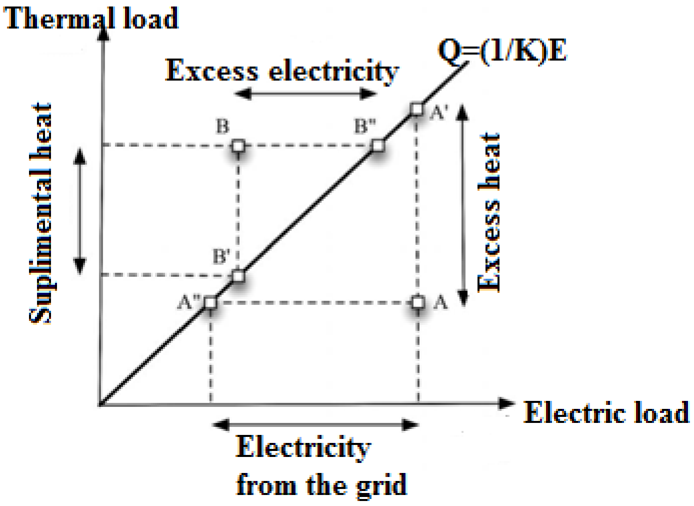


Figure 13 Schematic of operating regime [94]

CCHP system model [95], optimization [96], feasibility [97], and evaluation [98] have been studied in detail to improve the system performance. Since the building load conditions vary frequently, it is crucial to research the operational strategies of the integrated system. The CCHP normally operates using two strategies, namely, thermal demand management (TDM) and electricity demand management (EDM), [99], and the outcome reveals that EDM gives more benefit during winter in terms of PEC, CO_2 emission, and operating cost. TDM and EDM have been studied for five different climate zones in China, and it concluded that TDM is suitable for cold climates, and EDM provides more benefits in mild climate zone [98].

The relation between thermal and electrical loads of the building is shown in Figure 13. Points A and B in Figure 13 shows typical operating cases of micro CCHP. Considering point A, if the micro CCHP works on EDM, it meets the electrical demand but exceeds the thermal load of the building (refer to point A′ in Figure 13). Alternatively, if the system works on TDM, it meets the thermal load of the building (refer to point A″). In this case, electricity is supplied from the grid to meet the additional electricity demand. Considering point B, if the system works on TDM, it meets the required thermal load but exceeds the electricity generation. In this case, the energy storage device is needed. Alternatively, if the system works on EDM, it will generate the required electricity but insufficient thermal load. An additional heating device is needed for this case. However, no matter how the system is operated, the thermal and electrical load of the building is not satisfied 100% due to the continuous variations in building loads [100]. To suppress the space heating and cooling demand and to solve the operating issues, CCHP is integrated with heat pumps such as the absorption machine [101], electric heat pump [102], ejector heat pump [103], and GSHP [104], [105]. Integration CCHP and GSHP have a significant advantage, but the exhaust waste energy is not utilized at its best. The organic Rankine cycle is introduced to increase the system performance further.

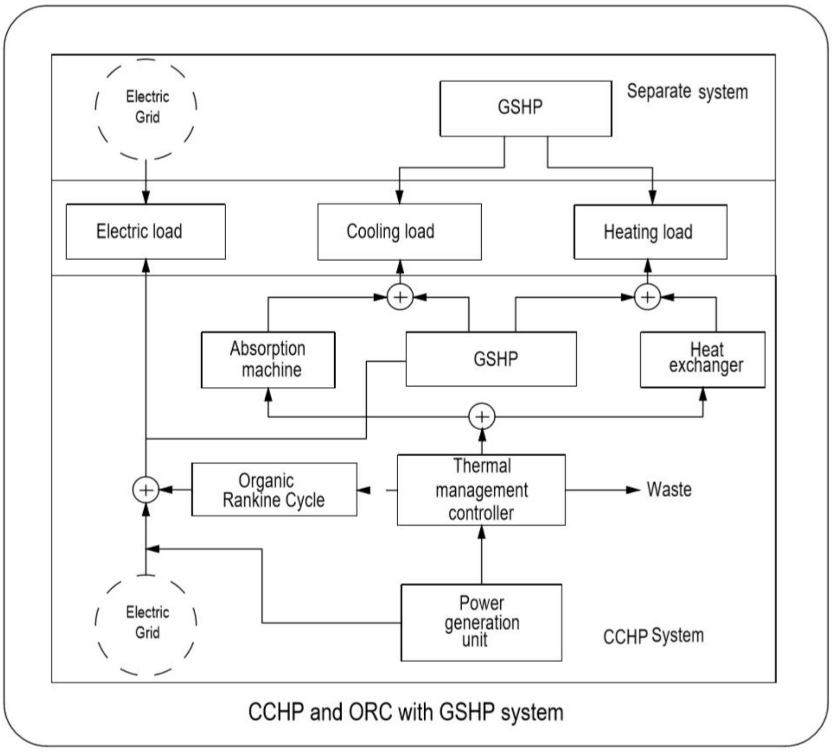


Figure 14 Schematic of integrated CCHP – ORC – GSHP system and the separate system

Figure 14 shows the integration of the five different systems, such as the Organic Rankine Cycle (ORC), power generation unit, absorption machine, and GSHP. The power generating unit is mechanically connected with the absorption machine or heat exchanger. The thermal management controller (TMC) is added to control the heat recovery towards the ORC or the absorption machine under different operating conditions. The absorption heat pump is an accessible non-vapor compression technology due to its higher COP values compared to adsorption, desiccant heat pump technologies, and it is operated using waste heat or solar energy [106]. The power generating unit generates electricity using natural gas, and it is used for electrifying the building. The waste heat generated from the power generating unit is regained, and it is used to power the absorption machine to produce cooling or to produce heating. The GSHP will start functioning when the building's thermal energy demand is higher than the generation of absorption machines or heat exchangers. When the building electric energy demand is greater than the power generation, the shortage of energy can be imported from the grid. The paper aims to reduce the difference between energy demand and supply and to avoid the excess output of electricity by integrating CCHP – ORC with GSHP, as shown in Figure 14 [100]. Two different operating strategies, such as thermal demand (heating and cooling demand) and electricity demand, have been studied in the Sino-Singapore eco-city. The PEC, carbon dioxide emission (CDE), annual total cost (ATC), and operating cost (OC) have been investigated. Three different operating strategies (TDM, EDM, and TMC-ORC) are used to improve system performance. TMC-ORC operating strategy shows the best results, and the annual reduction in PEC, CDE, ATC, and OC is 77.4%, 50.8%, 10.3%, and 38.3%, respectively. The maximum total efficiency and thermal efficiency were reported as 86.3% and 43.3%.

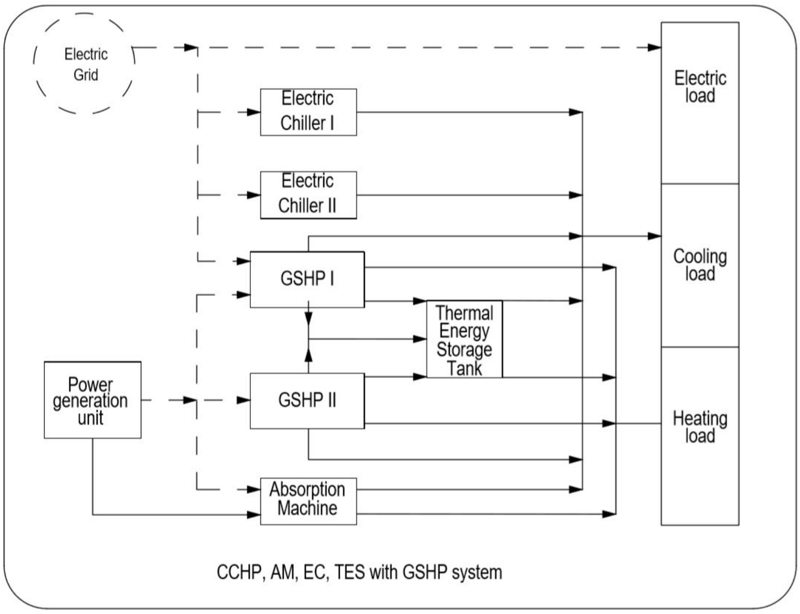


Figure 15 Schematic of integrated CCHP, absorption machine, GSHP, electrical chiller, and TES systems

Multi-system such as power generating unit, absorption machine, electric chiller, GSHP, and TES are grouped to lower the energy demand in the built environment, as shown in Figure 15 and Figure 16. Experimental investigation of the absorption machine operated using waste heat is presented [107], and the results reveal that the proposed absorption machine achieves more thermal energy recovery compared to condensing heat exchanger. The TES is used to balance the peak and off-peak in building energy by both thermal and electrical, and it reduces the operating cost due to the price difference between non-peak and peak operating hours. An office building is analyzed for different energy systems such as space heating and cooling, power, hot water, and cold water.

The hourly-based operating technique of a multi-integrated system such as two GSHP, two electric chillers, absorption machine, power generation unit, and TES tank is analyzed, as shown in Figure 15. The results reveal that the integrated system has excellent environmental and economic benefits [108]. From the same research laboratory, an integrated system has been analyzed, which contains the absorption machine, GSHP, power generation unit, and storage tank, as shown in Figure 16. Four operating strategies have been used for the optimization of the integrated system based on the building thermal and electrical load [109]. Two different algorithms have been proposed to optimize the capacity and operation strategy of an integrated system such as CCHP, GSHP, absorption machine, and boiler, namely, generic algorithm and multi-population genetic algorithm [104], [105]. The reduction in PEC, CDE, ATC, and OC is 26.10%, 35.02%, 15.13%, and 25.42%, respectively, compared to an individual conventional system.

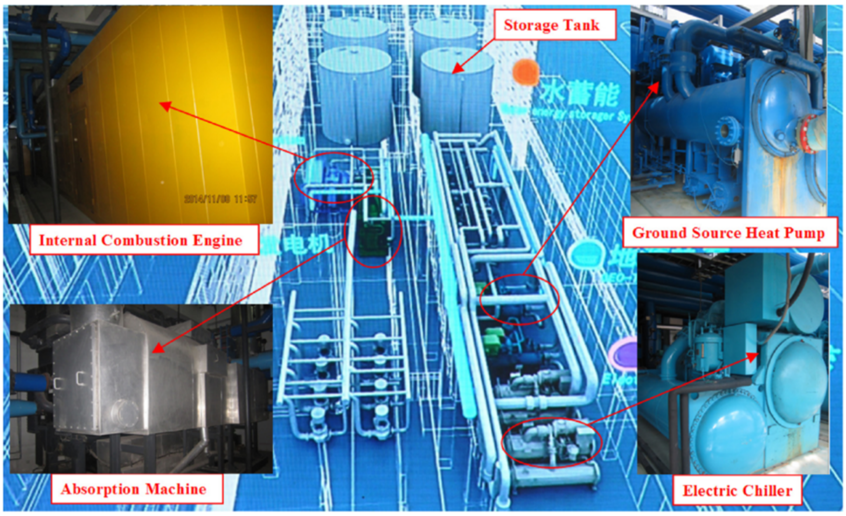


Fig. 2. Picture of the CCHP system and components.

Figure 16 Picture of CCHP system with other techniques [108]

Natural gas, renewable energy, and geothermal energy are integrated to decrease the energy demand in the built environment. The integration of multi-system is a combination of cooling heating power, photovoltaic, absorption machine, boiler, GSHP, and other auxiliary systems (Figure 17). Natural gas is used to power the gas engine and auxiliary boiler [110]. PV is used to generate electricity from solar energy and it is used to reduce the peak demand. GSHP can be operated in both heating and cooling modes. In the cooling mode, the heat exchanger is used to produce hot water. This unit is fitted in a large building in Beijing, China [111]. The technical, economic, and environmental parameters of the system are studied. The PV significantly reduces the building's peak demand, and GSHP also helps to reduce the thermal demand of the building during peak hours. The integrated system (CCHP + GSHP) performance has been optimized and compared with the standalone GSHP system. The result reveals that annual energy savings and CO_2 emission reduction have been reported as 31.79% and 51.34%, respectively [112]. Another study proposed a similar system and optimized it using a multi-objective optimization technique [113]. Based on the hourly electricity price, peak demand, and cost of the natural gas, the GSHP system operation is controlled, and authors have not recommended a battery storage system since it requires a high cost of installation. The optimized system increases the overall efficiency.

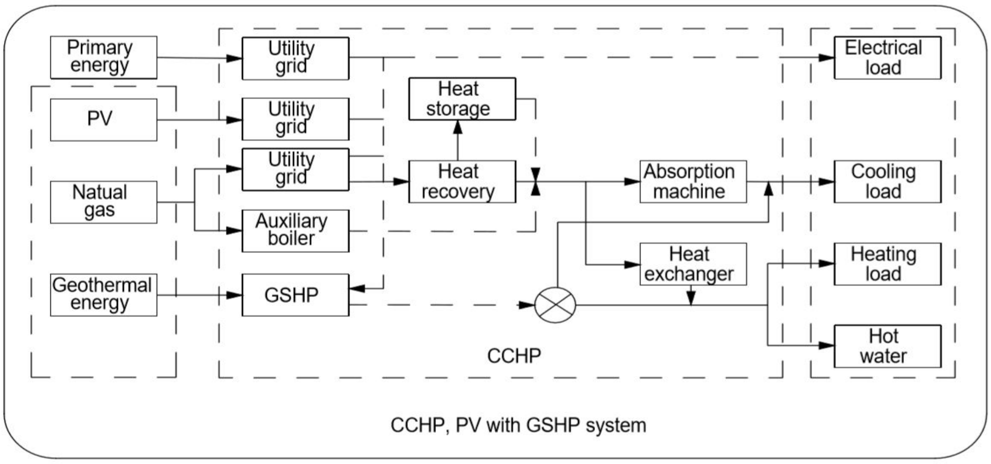


Figure 17 Schematic of integrated CCHP, PV, and GSHP system

2.8 Absorption heat pump + GSHP

Ground source absorption heat pumps (GSAHP) and GSHP are integrated to reduce heating and cooling demand in the built environment, as shown in Figure 18, and it has been integrated with a parallel configuration. The HTF from the GHE flows through valve 1 and valve 2 to the respective heat pumps. The HTF mixes before it enters the ground. The water from the heat pump enters the building, and it is separated when it leaves the building. Hence, the HTF flow control strategy needs to be developed to get maximum performance. The GSHP system has more COP compared to GSAHP in both cooling and heating mode of operation (COP heating: GSHP = 3.6, GSAHP = 1 to 1.8; COP cooling: GSHP = 4.0, GSAHP = 0.6 to 1). The soil temperature is 4 to 6 °C higher in ten years of operation of GSAHP compared to GSHP. To reduce the GTI in a cold climate, the GSHP system can be integrated with the absorption machine [114]. The variation in the soil temperature for the integrated system is reported as 0.2 °C/year.

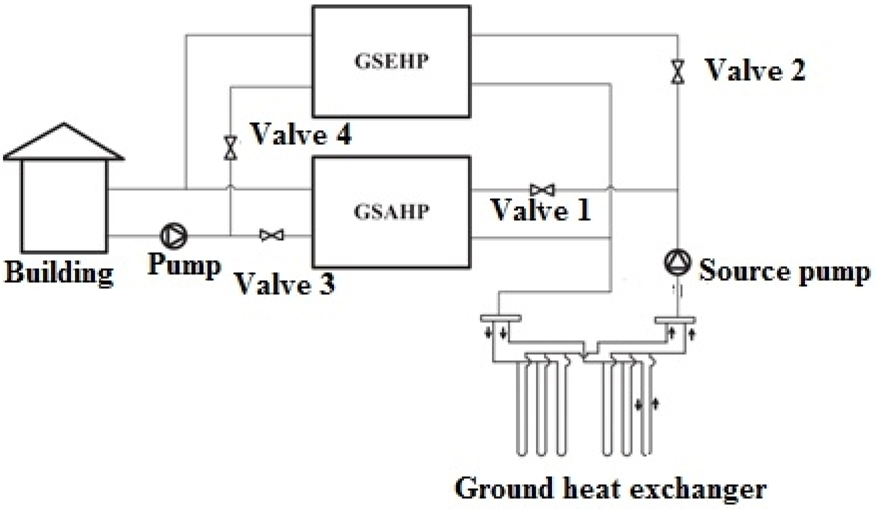
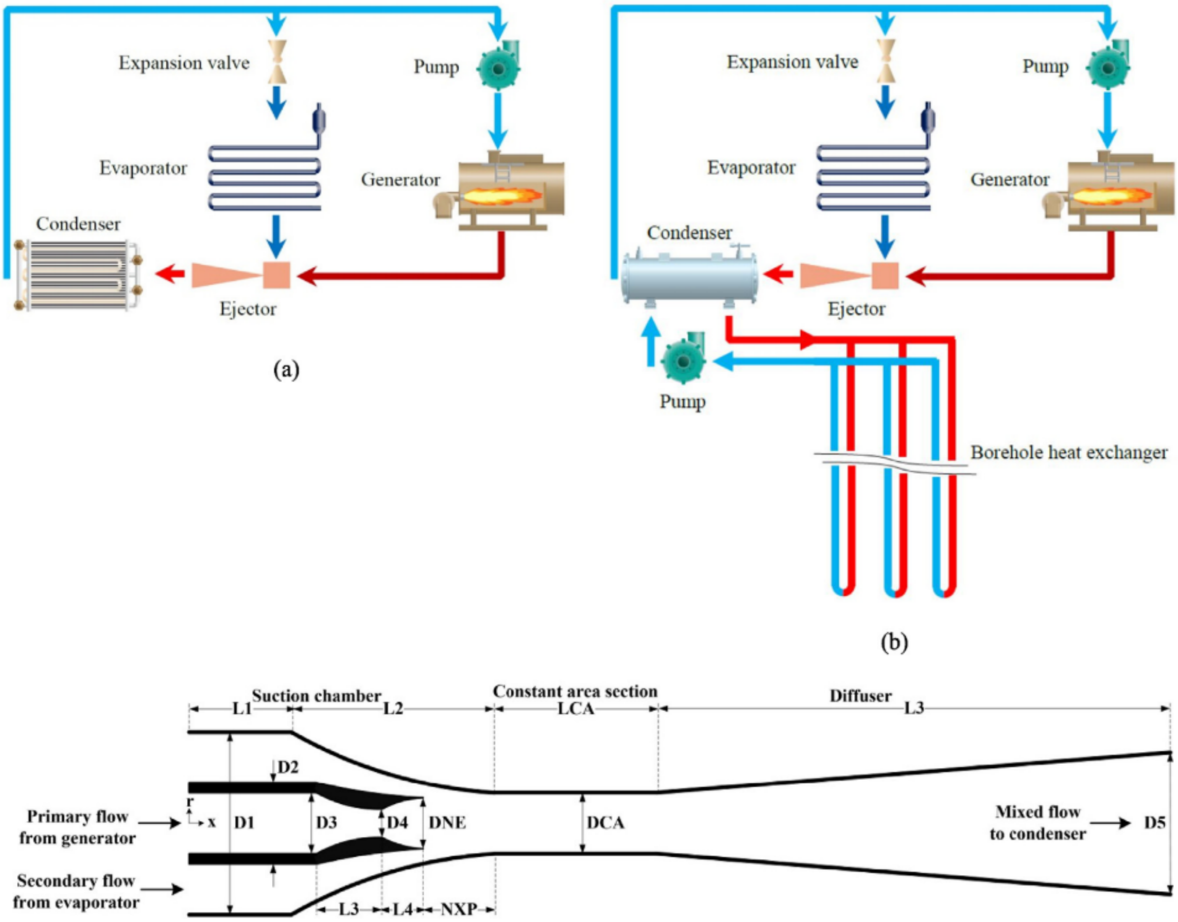


Figure 18 Schematic of GSHP integrated with absorption heat pump

2.9 Ejector cooling + Geothermal energy

Vapor compression cycles are mainly used for air-conditioning and refrigeration. Due to their high COP and reliability, they are considered the most favorable residential cooling system. However, they run on electricity and are responsible for summer peak electric loads. Thermally driven heat pump systems such as ejector and absorption cooling systems have been studied by many researchers as a potential substitute for conventional vapor-compression systems. The ejector cooling system needs lower initial investment and maintenance costs and has high reliability in comparison with absorption systems. Therefore, ejector cooling systems as a sustainable alternative to replace conventional cooling systems have come into the limelight in recent years. Though their significant advantages, they suffer from relatively low COP and working condition restrictions.

The schematic of the air-cooled ejector cooling system (ACEC), ground-coupled ejector cooling system (GCEC) systems, and supersonic ejector is shown in Figure 19. The ACEC system is composed of six main components, including a generator, an air-cooled condenser, a pump, an evaporator, an expansion valve, and an ejector. The only difference between the ACEC and the GCEC system is that the air-cooled condenser of the ACEC system is replaced by a water-cooled condenser and a geothermal cycle. The geothermal cycle itself is composed of a GHE and a circulating pump. The geothermal cycle exchanges heat with the ejector cooling system through the water-cooled condenser. The GHE type considered in this study is the BHE. Therefore, the GCEC system is composed of two separate cycles, the ejector cooling cycle and the geothermal cycle.


(a)

(b)

Figure 19 Schematic view of (a) an air-cooled ejector cooling system (ACEC) and (b) a ground-coupled ejector cooling system (GCEC) (c) supersonic ejector [115]

The ejector is composed of four main parts, including the primary nozzle, suction chamber, mixing section, and diffuser. The ejector has two inlets, i.e., primary and secondary, and one exit. In an ejector cooling cycle, the generator uses a heat source to evaporate the high-pressure liquid refrigerant from the pump. Then, the high-pressure vapor (primary flow) enters the primary convergent-divergent nozzle of the ejector. Thus, a supersonic low-pressure vapor leaves the primary nozzle and hence, entrains the vapor from the evaporator (secondary flow). The two flows mix after experiencing several shocks in the mixing section of the ejector. At the end of the constant area mixing section, the mixed flow has low speed and high pressure. As this mixed flow passes the ejector diffuser, its pressure increases even more. The high-pressure, high-temperature vapor leaves the ejector and enters the condenser. In the condenser, the flow exchanges heat with the cooling medium and condenses. Ambient air is the cooling medium of the ACEC system, and the circulating water of the geothermal cycle is that of the GCEC system. At the condenser exit, the flow splits into two parts. One part goes through the pump, and its pressure increases significantly and then enters the generator. The other part goes through the expansion valve, and after an isenthalpic process, its pressure drops drastically. The low-pressure and low-temperature flow enters the evaporator to create the cooling effect of the cycle.

To the best of the authors' knowledge, only a small amount of research has been dedicated to GCEC systems, limited to introducing this system and cursory evaluation of its performance. A comprehensive numerical simulation has been performed to evaluate the techno-economic performance of the ACEC and GCEC systems [115]. It was found that the least relative payback period is five years, which is for the case with a natural gas price of 8 \$/GJ, borehole cost of 20 \$/m, and soil thermal conductivity of 3.5 W/m K.

2.10 Absorption machine, cooling tower, and solar collector integrated with GSHP

An arrangement of subsystems such as absorption machine, GSHP, solar collector, ground water-free cooling, variable refrigerant volume, and the cooling tower is shown in Figure 20. In summer, hot water produced from two solar collectors is sufficient to drive the absorption machine; otherwise, GSHP can be operated to produce heating and cooling. The other subsystem, such as VRV and water loop heat exchanger, are operated simultaneously. In the winter, the solar collector system integrated with GSHP and thermal energy systems can deliver direct heating to the radiant floor. Both GSHP unit works in the winter season. A partial cooling load in the building is required during spring and autumn, and the requirement of the temperature to cool the building is relatively low. It can meet using ground water-free cooling with the support of a heat exchanger. During spring and autumn, there is no need for space heating, and also this period has enough sunshine. The energy collected from solar collectors during this period can be stored in the ground using a GHE, and it can be used in the winter. The cooling tower is used to solve the long-term temperature imbalance of the ground.

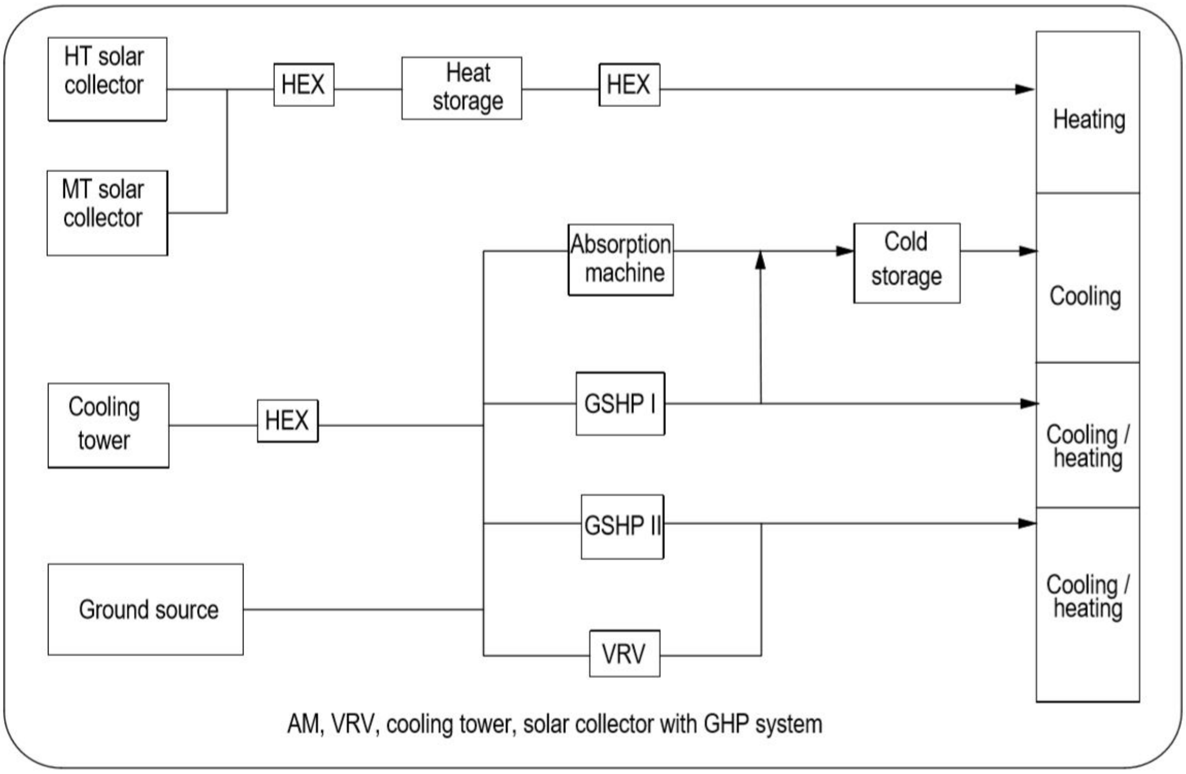


Figure 20 Schematic of a multi integrated subsystem for heating and cooling

Experimental investigation of the GSHP system and its performance for nearly zero energy building integrated with some other techniques is presented [116], [117]. The COP of the GSHP varies from 3.9 to 5.4. The integration of GSHP, cooling tower, absorption machine, and solar collector subsystems is controlled using three different modes based on atmospheric temperature, and the proposed system reduces the primary energy consumption by 44.4%. The soil temperature measured in a different position after two years of operation reveals no changes in its first level, and it is balanced because of the cooling tower and solar collector [118].

Table 2 Brief literature collection of hybrid GSHP systems

Technique	Exp./Simulation	Citation	Usage	Ref. and ES details	GHE Type/ material	GHE HTF	COP
Auxiliary heater + GSHP	TRNSYS	[15]	Heating	-	U-tube VGHE	Water	COPh = 2.79 COPc = 3.71
Boiler + GSHP + Cooling tower	Experiment (7 kW)	[9]	Heating and cooling	Ref - R410a	U-tube VGHE	Water	COP = 5.5 COPs = 18%↑
	eQUEST Version 3.64	[7]	Heating	-	U-tube VGHE	Water	-
Free cooling + GSAHP and GSEHP	TRNSYS	[119]	Heating and cooling	-	U-tube VGHE / HDPE	EG + water	
TES + GSHP	Experiment	[23]	Heating	Ref – R22, ES - Calcium chloride hexahydrate	HGHE /PE	Brine	COP = 2 - 3.5
	Experiment	[19]	Heating and cooling	ES - water	HGHE	Water	COP = 4.94
	ANSYS / FLUENT	[17]	Heating and cooling	-	U-tube VGHE	Water	-
	TRNSYS	[25]	Heating and cooling	-	U-tube VGHE	Water	COPh = 3.37 COPc = 3.44
PV + GSHP	TRNSYS	[34]	Heating	ES - water	U-tube VGHE	Water	
	TRNSYS	[31]	Heating and cooling	-	U-tube VGHE	EG + water	COP = 4
	TRNSYS	[32]	Heating	-	-	Water	-
	Experiment	[27]	Heating and cooling	Ref – R407	U-tube VGHE	-	COP = 3 - 4
PVT + GSHP	MATLAB Fuzzy logic toolbox	[40]	Heating and cooling	-	-	-	
	Experiment (3 kW)	[41]	Heating	Ref – 410a	U-tube VGHE (1.5 m) / HDPE	EG + water (30%)	SPF = 3.58
	TRNSYS	[44]	Space and water heating	-	U-tube VGHE (1.5 m)	EG + water (30%)	COP = 2.51
	Modeling	[42]	Heating	Ref – 134a	U-tube VGHE	Water	COP = 1.12 and 0.79
	TRNSYS	[43]	Heating	-	U-tube VGHE	Water	COP = 6.2
	Simulation	[37]	Heating and cooling	Ref -R134a	-	Water	COPh=4.18 COPc=5.45
	TRNSYS	[45]	Heating	-	U-tube VGHE	Water	SCOP = 5.3
Solar collector + GSHP	TRNSYS 17	[72]	Heating, cooling and hot water	ES - water	U-tube VGHE	Water	
	TRNSYS 16	[53]	Heating	ES - water	U-tube VGHE	Water	
	Experiment and numerical	[76]	Heating, cooling and hot water	Ref – R22, ES - water	U-tube VGHE / HDPE	Water	
	Numerical modelling	[120]	Heating	ES - water	U-tube VGHE / HDPE	Water	COP > 3.1
	Microsoft Excel	[75]	Heating	Ref – R410a, ES - water	HGHE /HDPE	EG + water (35%)	
	Simulation	[60]	Heating	-	U-tube VGHE / PVC	Water	COP = 3.40
	Taguchi method	[71]	Heating	-	HGHE	Water	COP = 4.23
	Experiment	[52]	Heating and cooling	-	U-tube VGHE	Water	COP = 3.75

	TRNSYS 16	[121]	Space and water heating	ES - water	U-tube VGHE	Antifreeze - water	
	MATLAB	[68]	Heating	ES - water	U-tube VGHE	-	
	Modeling	[122]	Heating and cooling	Ref – R744, ES - water	U-tube VGHE	Water	
	TRNSYS and Earth Energy Design	[48]	Heating, cooling and hot water	ES - water	U-tube VGHE	-	
	Experimental	[49], [123], [124]	Radiant under floor space heating	ES - water	Double U-tube VGHE / HDPE	Water	
	TRNSYS	[66]	Heating and cooling	ES - water	U-tube VGHE / HDPE	EG + water	
	TRNSYS	[59]	Space and water heating	ES - water	U-tube VGHE / HDPE	Antifreeze - water	
	Experiment	[73]	Space heating	Ref - R134a, ES - EG + water	U-tube VGHE	EG + water	
	Experiment	[57]	Heating and cooling	Ref – R22	U-tube VGHE / HDPE	EG + water	COP = 4.29 COPs = 6.55
	Experiment and visual basic	[58]	Heating and cooling	ES - water	U-tube VGHE	Water	
	Experiment and TRNSYS simulation	[51]	Heating, cooling and hot water	ES - water	U-tube VGHE / HDPE	EG + water (35%)	
	TRNSYS 16	[50]	Heating, cooling and hot water	ES - water	U-tube VGHE (length 55 m) / HDPE	Water	COPh = 2.78 (2.84%↑) COPc = 7.54 (0.63% decrease)
	Experiment	[61]	Heating	Ref – R22, ES - water	U-tube VGHE	Water	
	Experiment	[63]	Green house heating, cooling and dehumidification	Ref – R22, ES - brine	U-tube VGHE / HDPE	EG + water (10%)	
	Experiment	[62]	heating	Ref – R22, ES - water	U-tube VGHE / HDPE	Water	
	2D analytical model	[70]	Space heating	-	Double U-tube VGHE	Water	-
	FLS	[69]	Space heating	ES - water	U-tube VGHE / HDPE	Water	COPh = 3.1 COPc = 3.2
	Experiment	[56]	Space and water heating	-	U-tube VGHE	Water	SPF_{HP} = 2.85 SPF_{SAHPS} = 2.09
	TRNSYS	[54]	Space and water heating	ES - water	U-tube VGHE	Water	COP = 3.75
	Modeling	[125]	Highway heating and cooling	Ref – R116, ES - EG + water	U-tube VGHE	EG + water	
Solar Thermal + GSHP + Free cooling + TES	TRNSYS	[81]	Heating and cooling	ES - EG + water (Cp = 3,795 kJ/kg K)	U-tube VGHE	Water	COP = 3.25 EER = 4.6
Solar Thermal + TES + GSHP	Experiment	[65]	Heating	Ref – R22, ES - water	U-tube VGHE	Antifreeze - water	
	Experiment	[64]	Heating	ES - water	U-tube VGHE	Water	COP = 3.07
	COMSOL, MATLAB	[77]	Heating and cooling	-	U-tube VGHE	EG + water	COPh = 4 COPc = 3
	Experiment	[67]	Heating	ES - paraffin	U-tube VGHE	Water	SPF = 4.38

Solar PV + GSHP and Solar thermal + GSHP	TRNSYS and EED	[78]	District heating and cooling	-	U-tube VGHE	Water	
CHP + GSHP	Experiment and ASPEN Plus	[82]	Heating and power	Ref – R22, ES - natural gas	U-tube VGHE / HDPE	Water	
	Modeling	[92]	Heating	-	U-tube VGHE	Water	COP = 4.17
	ASPEN Plus	[83] [126]	Heating and power	Ref – R22, ES - natural gas	U-tube VGHE	Water	
Micro Gas Turbine + GSHP	COMSOL	[86]	Space and water heating	-	Spiral heat exchanger	EG + water	
GSHP with biomass partial gasification + CHP	Aspen Plus and STEAM-TA	[89] [90]	Heating, cooling and power	R22, ES - Biomass fuel	U-tube VGHE	Water	
Biomass-based solid oxide fuel cell + GSHP	Aspen Plus	[91]	Heating, cooling and power	ES - Biomass fuel (rice husk)	U-tube VGHE / PE	Water	$\eta_{thermal}$ = 67.3% η_{exergy} = 29.2%
CCHP + GSHP	DeST	[109]	Cooling, heating and power	ES - natural gas	-	-	
	Multi-population genetic algorithm (MPGA)	[105]	Cooling, heating and power	ES - natural gas	-	-	
	Genetic algorithm	[104]	Cooling, heating and power	ES - natural gas	-	-	
CCHP + ORC + GSHP	Intuitive matrix model	[100]	Cooling, heating and power	ES - natural gas	-	-	
CCHP + PV + GSHP	Multi-objective optimization method	[111]	Cooling, heating and power	ES - natural gas	-	-	
	Multi-objective optimization method	[113]	Cooling, heating and power	ES - natural gas	-	-	-
CCHP + TES + GSHP	Experiment	[108]	Cooling, heating and power	ES - natural gas	-	-	
	Particle swarm optimization	[112]	Cooling, heating and power	ES - natural gas	-	-	Energy savings = 31.79%
GASHP + GSHP	TRNSYS	[114]	Heating and cooling	GSAHP - NH_3/H_2O	U-tube VGHE / PE	Water	Energy Savings = 9.8 to 25.7%
Solar thermal + absorption machine + GSHP	Experiment	[117]	Heating and cooling	-	U-tube VGHE	Water	
	TRNSYS	[127]	Heating and cooling	-	U-tube VGHE	Water	
	TRNSYS	[118]	Heating and cooling	-	U-tube VGHE	Water	
Air source heat pump + furnace + GSHP	eQUEST MATLAB	[110]	Heating and cooling	Ref – R410a, ES - natural gas	U-tube VGHE	Water	
Solar collector + PVT + GSHP	Simulation	[80]	Heating and cooling	-	Double U-tube VGHE / Pe-Xa	EG + water (30%)	COPh = 2.3 COPc = 7

3. Summary and future perspective

The aim of the research collection is to find the various possible opportunities for space heating and water heating applications using shallow geothermal energy and to save energy and environment in the built environment. The focus on the effective utilization of shallow geothermal energy through GSHP, DX-GSHP, and hybrid GSHP systems has been increasing around the globe due to its energy and environmental benefits. Several hybrid GSHP systems proposed by the researchers have been extensively reviewed and highlighted. Based on the above comprehensive review, the following points can be noted.

- Simple integration of solar collectors + GSHP can be used to save energy and the environment in cold climatic conditions. However, the exergy and economic aspects need to be studied.

- The boiler + GSHP system has the potential for installation due to lower installation and operating costs. Hence, it is crucial to improve the boiler + GSHP system performance.

- In some cases, the TES + GSHP system reduces the initial investment. However, it is important to find the techno-economic feasibility of the system. Also, using phase change material as grout material may lead to serious soil pollution, which is easy to be neglected, and this pollution is irreversible.

- The PVT + GSHP system is highly suitable compared to the PV + GSHP system since there is no need for additional space. However, PV + GSHP and PVT + GSHP systems have not been studied in detail. There is a lack of design optimization and control algorithms based on the application. Similarly, an effective on-off control strategy is important to improve the system performance during peak hours.

- Usually, the integrated system performance is evaluated using the SPF or COP metrics, and the SPF does not give full details about the total energy generated using renewable energy. Hence, it is crucial to develop new evaluation criteria for the integrated system by considering the collector area and GHE.

- The exergy of the hybrid GSHP unit is minimally related to the standard GSHP system. Most of the studies have been carried out only on energy analysis. Hence the comprehensive exergy analysis of the hybrid system is highly needed.

- Very few research studies are only available in the comparative analysis of hybrid GSHP. The research and development of integrated systems are very limited.

- It is essential to obtain the best possible HGSHP system design and control algorithm based on the real-time forecast for effective utilization.

- HGSHP systems have many degrees of freedom; there are trade-offs between the reduction in the size of the ground loop heat exchanger, the size of supplemental heat rejecters, and the control strategy. The development of an optimal design procedure could simultaneously optimize all of the parameters of interest.

- Researching on system configurations and the interaction of different components to increase the performance and minimizing the life-cycle cost. The influence of operation cost on time-of-day electricity rates and diverting the extra energy storage for an independent DHW system should be studied.

- Effects of the HGSHP system on emissions of carbon dioxide and environment should be taken seriously and become an evaluation indicator to measure the feasibility of the system.

For heating-dominated buildings, three common auxiliary resources: fossil fuel, solar energy, and waste heat are widely used. Among them, boiler + GSHP is appropriate for buildings with a lower degree of thermal imbalance due to the low investment. When the boiler takes on about 20%-60% heating load, HGSHPs can achieve a lower degree of thermal imbalance and a better economy. For newly built and green buildings, solar energy is becoming popular in supplying heating and eliminating soil thermal imbalance of GSHP system, with an increase of 2℃- 5℃ in soil temperature and improvement of 10%-15% in system COP.

A minimal research study has been carried out on the CHP + GSHP, CCHP + GSHP, absorption system + GSHP and multi-system + GSHP. Several studies have been carried out for heating applications. The suggested system shows the possibility of achieving net-zero energy building and zero peak building. This system is highly suitable for the community scale by considering the installation cost. However, the suitability needs to be analyzed for further development.

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