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Geothermal based hybrid energy systems, toward eco-friendly energy approaches

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ABSTRACT

Geothermal Energy is a very attractive source of naturally-occurring green renewable energy. Exploiting this natural resource is straightforward and causes almost no ill effects to the environment. But, while geothermal does not suffer the intermittence of other renewable sources, its extraction efficiency is fairly modest as compared to other sources. As a result, there has been significant interest recently in hybrid systems that integrate geothermal and other forms of energy to increase the output efficiency. This work will survey the different possible integrations involving geothermal energy. A review of the literature shows that the most common hybrid systems implementation involve the integration of geothermal with solar (45% of systems) followed by the integration of a cooling tower into the geothermal system (30% of systems). This work will also investigate the applications for geothermal hybrids and show that 44% of systems are designed for heating applications. Another 44% are used for cooling while only 12% are designed for electrical power generation. Complexity of control remains as the main obstacle facing hybrid multi-source energy systems including those involving geothermal energy.

1. Introduction

As the population of our planet increases, so does the need and demand for energy [1]. Until recently, this demand has been met mostly through the consumption of traditional mainly fossil-based fuels. The consumption of these carbon based fuels has been shown to be directly linked to global warming, pollution and a deterioration of air quality. This issue is of particular concern due to its widespread effect. The latest report by the World Health Organization (WHO) released in May 2018 states that "*90 percent of people worldwide breathe polluted air*" [2]. Governments around the world are increasingly investing in renewable energy sources (RES) as possible replacements (to some extent) for fossil-based fuels and their ill effects on the environment. RES are able to meet a significant portion of the energy demand without the harmful greenhouse gases and the associated pollution. All forms of RES are being investigated: solar (both photovoltaic and thermal), wind, ocean, marine, hydropower, as well as geothermal and biomass among others. One of the issues affecting most RES is their stochastic intermittent nature. The energy source is not available all the time, and sometimes it is not sufficient even when available.

This is where geothermal energy has an advantage over most other RES, its availability is approximately deterministic and independent of ambient conditions. While it may be geographically limited, wherever geothermal energy is present it is useable all the time at approximately the same level. Geothermal energy has the added advantage of actually attaining lower operating cost compared to traditional systems [3,4].

Another advantage of geothermal energy is that the energy reservoir (the ground) can act as a source as well as a sink

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depending on the need. Compared to air, soil has a much higher heat capacity. As a result, seasonal variations of soil temperature deep in the ground are much lower than those of the surrounding ambient air. At depths higher than about 20 m, soil temperature becomes approximately constant year-round. This makes deep earth warmer than ambient air in the winter and cooler in the summer. Ground heat exchangers have been designed to leverage this air-to-soil differential to condition the ambient air temperature.

There are three different configurations for a ground heat exchange: vertical, horizontal and spiral (see Fig. 1). The type of configuration depends mainly on available space and soil conditions. The horizontal configuration is typically constructed at a depth less than 1.5 m [5], while the vertical configuration (commonly known as the borehole heat exchanger (BHE)) typically reaches depths more than 50 m [6]. Under appropriate circumstances, it is possible to create a combination of vertical and horizontal configurations that will produce better thermal performance [7]. The ground heat exchanger is usually surrounded by grout material (such as cement or a mixture of sand and bentonite) to protect ground water and improve heat transfer. Geothermal energy is typically considered in hybrid combinations because it is characterized as a low grade source of energy. Adding a geothermal source serves mainly to decrease the operating cost and environmental effects compared to conventional plants. This paper discusses applicable combinations of geothermal energy with other sources while presenting the differentiating factors between the different hybrid combinations.

2. Geothermal power plant

Geothermal Energy can be used as a source for power generation plants through the use of an Organic Rankine Cycle (ORC) as an example. Replacing conventional plants with geothermal ones is an attractive proposal for implementing ecofriendly systems [8]. Geothermal plants produce far lower emissions as compared to fossil fuels for the same given load. However, geothermal energy is characterized as a low grade energy source and generally suffers from low energy extraction efficiency. Additional sources of energy can be combined through a hybrid system to improve the efficiency and meet the requirements that geothermal energy alone may not able to deliver [9,10].

Geothermal energy systems used in heating (or cooling) dominated applications suffer an efficiency degradation due to heat depletion (or accumulation) that may lead to eventual system failure or ground fouling [11–13]. Adding a hybrid power source will allow time for recovery and thermal build-up (or dissemination). In addition, hybridization helps in decreasing the required capital and operating costs, and hence shortening the payback period of geothermal energy installations as well as addressing high peak loads [14,15]. This could be achieved by taking advantage of optimal conditions for each source in the hybrid combination. Geothermal energy systems require a significant upfront initial investment. On the other hand, they require very low operational running costs. A balance can be achieved by incorporating a second abundantly available energy source into the hybrid plant. The expense profiles of the two sources can be balanced against each other to lower the overall costs of the hybrid plant.

3. Hybrid geothermal systems (HGS)s

Hybrid Geothermal Systems (HGS) used for heating and cooling applications are commonly encountered in the form of a hybrid ground source heat pump (HGSHP) [16] or a hybrid ground coupled heat pump (HGCHP) [17,18]. Fig. 2 shows the difference between the conventional and hybrid ground source heat pump (GSHP) designs.

Another type of ground coupled heat exchanger (GCHE) is the earth air heat exchanger (EAHE) based on circulating fresh air underground using a blower as shown in Fig. 3 [20].

M. Alavy et al. [21] investigated the use of an HGSHP for district heating and cooling through a common water loop distribution. The system showed high potential that depends mainly on building size and type as well as weather conditions and location. One of the most important parameters to be studied in these hybrid systems is the ratio between the heating and cooling loads in order to design the optimum ground regeneration cycle. Regenerating the ground potential can be achieved by adding a second energy source as mentioned above, or through a traditional heating, ventilating and air conditioning (HVAC) system based on an air source heat pump (ASHP). On the other hand, it is possible to achieve the required regeneration using a dry cooler. The cooler can be used to inject ambient heat in to the cold bore field in the winter and extract it from the warm bore field in the summer. This would require the use of a dual bore field [22]. Choosing the best hybrid system is not straightforward because each HGS has to be considered from a different perspective such as initial or operating cost [23].

Geothermal energy can be coupled with many different energy sources depending mainly on availability and effect on system's performance. In the following sub-sections, we will discuss a

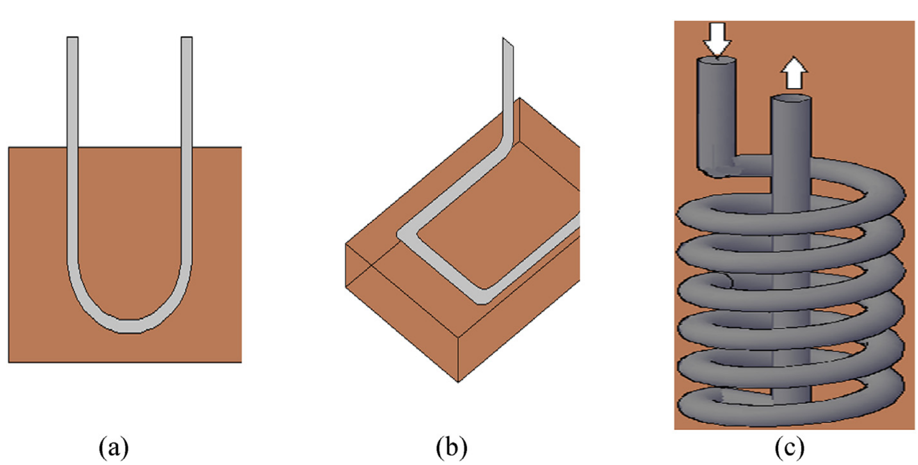

Fig. 1. GHE configurations; (a) vertical, (b) horizontal and (c) spiral.

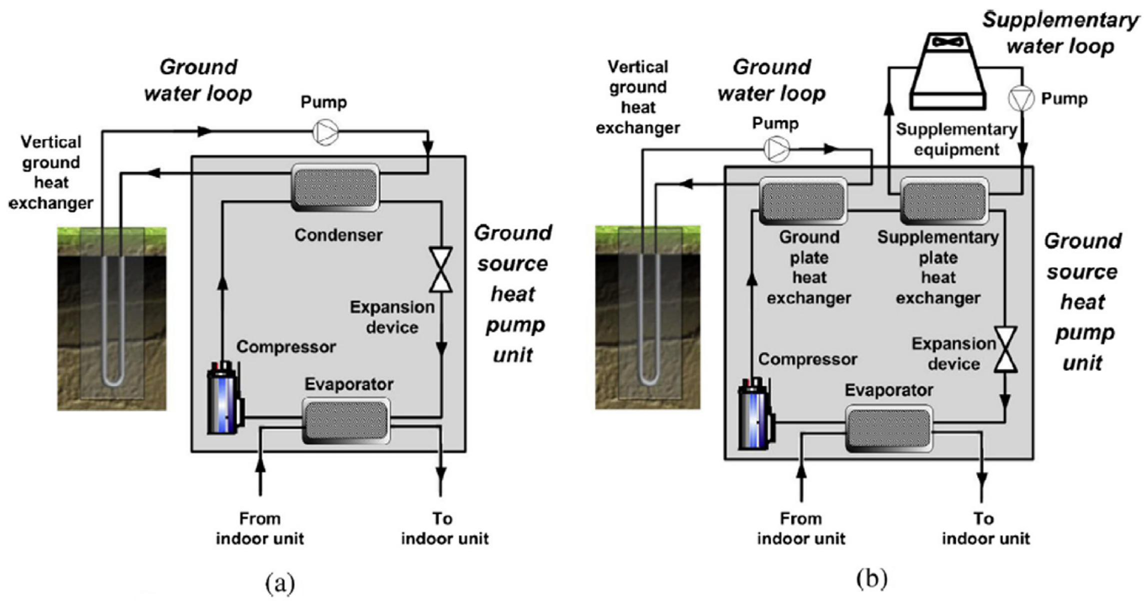

Fig. 2. Difference between (a) GSHP and the (b) HGSHP [19].

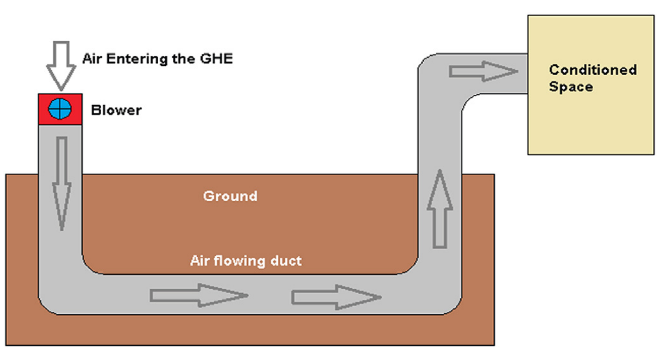

Fig. 3. Earth air heat exchanger system.

number of possible integrations that involve geothermal energy systems.

3.1. Integration of geothermal and solar energy systems

There is a number of ways that solar and geothermal energies can be integrated to form a hybrid energy system [24]. For example, thermal solar collectors can be used to generate additional heat energy to shore-up any deficit from the geothermal system. A common hybrid solar-geothermal combination is the solar assisted ground source heat pump (SAGSHP) [25]. While there may be different implementations, the main objective of this combination is the reduction in annual operating costs and CO_2 emissions. Thermal solar collectors can also be used for ground heat recovery and help stabilize the geothermal system. Conversely, a geothermal heat exchanger can be used as a second heat source to support a solar thermal plant [26–28]. This combination has the ability to increase the overall efficiency by 3.6% compared to the combined individual systems [29]. Another motivation for integrating geothermal and solar thermal systems might be the need to increase the steam flow in the geothermal cycle [30]. Researchers have been able to reduce the initial costs associated with a geothermal system by using a solar assisted ground source heat pump to reduce the required borehole heat exchanger field size. It is also possible to use a supercritical ORC based on a geothermal system integrated with a concentrated solar power system to increase peak loads for demand-side management [31,32]. While most hybrid systems are designed for heating applications, it is also possible to integrate a ground heat exchanger with a solar cooling system to improve its performance [33].

Solar thermal systems suffer from seasonal deterioration in energy output depending on the sun's position and ambient air temperatures. One way to improve the seasonal coefficients of performance is to use the geothermal system as a seasonal energy storage. A vertical ground heat exchanger may be used to store seasonal excess energy generated by a solar thermal system. The system would be composed of solar collectors, short-term thermal storage devices, a heat pump, and a borehole heat exchanger for long-term storage. A staged series of ground heat exchangers can be used to reduce temperature differences and maintain the effectiveness of the storage system for an elongated period [34]. Ground water flow may be the main limiting factor against the use of such an integration [35]. Ground water flow levels at the site must be low enough to ensure that the induced thermal plume is not dissipated. Researchers have determined that seasonal heat storage is not reliable for solving the thermal imbalance if ground water seepage velocity is large.

As can be seen from the above examples, integrating a solar thermal system with a geothermal plant can either assist in producing additional power, or reducing the consumed geothermal energy [36]. An essential factor to consider in the design of hybrid solar-geothermal systems is the state of the available ground fluid. If the available fluid is in the steam-liquid state, then a flash cycle (see Fig. 4 and Fig. 5) would be the preferred design [37,38]. Incorporating the solar system contributes to superheating and evaporating the geothermal fluid and therefore boosting the generated power [29].

A photovoltaic thermal hybrid system (PVT) can be integrated with a GSHP to produce different forms of energy at the same time (as shown in Fig. 6). While the GSHP system works on extracting thermal energy from the ground, the PVT system produces electrical energy from the incident sun light and at the same time extracts additional thermal energy from the sun's heat. Careful consideration for the working fluid is necessary to ensure best

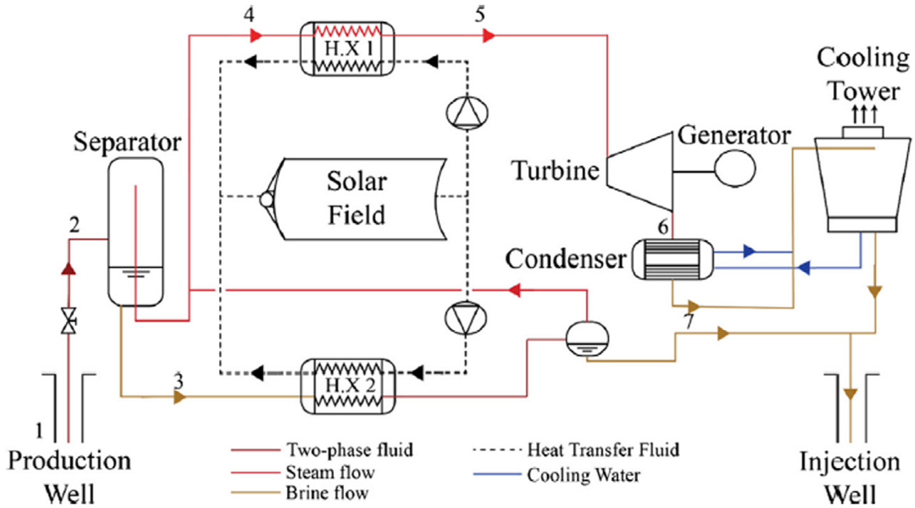

Fig. 4. Single-Flash Hybrid Power Plant [37].

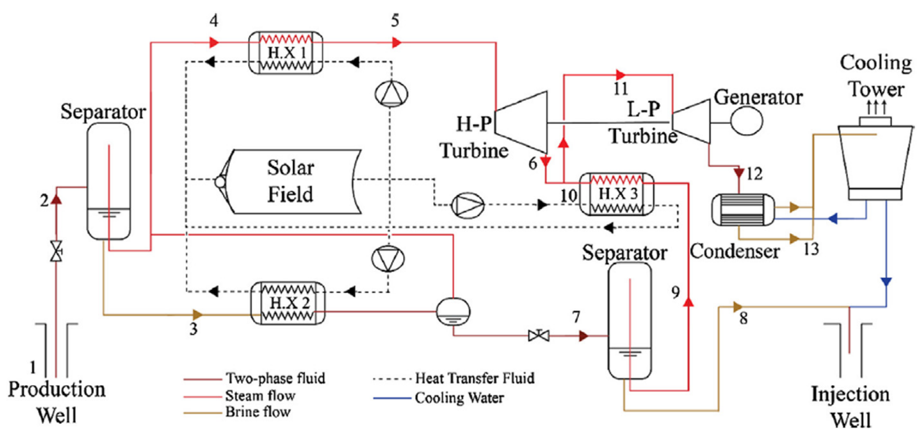

Fig. 5. Double-Flash Hybrid Power Plant [37].

results from these systems. Most designs have concentrated on using organic fluids [39]. However, it is also possible to use a refrigerant fluid like CO_2 in which case the cycle would require some modification such as the incorporation of a reverse trans-critical cycle [40–42]. Other studies have also investigated the use of hybrid systems for water distillation in addition to energy generation [43]. Recently, poly-generation and tri-generation systems are becoming more common. The system presented in Ref. [44] shows a solar-geothermal system being used for generating electricity, cooling and hydrogen production. The energy and exergy efficiencies were found to be 19.6% and 19.1% respectively.

Because of inherent uncertainties and nonlinearities, all of the mentioned hybrid systems suffer from issues related to control. This has motivated researchers to find new control methods such as fuzzy logic (FL) controllers [45] and model predictive control (MPC) [46].

3.2. Integration of a cooling tower into the geothermal system

It has been shown that it is advantageous to incorporate a cooling tower with the ground source heat pump (as shown in Fig. 7) to improve the cooling efficiency [19]. This hybrid system is able to maintain soil thermal balance such that the annual overall COP of the system was found to be 3.96 (3.93 for cooling and 4.09 for heating) [47]. The capacity of the cooling tower needs to be chosen taking into consideration the difference between peak and average load values or the cooling load percentages [48,49]. Simulation models have shown that the cooling tower needs to be activated two years after initial heat pump operation. An optimal auxiliary cooling ratio (ACR) needs to be chosen based on the system's configuration (as demonstrated in Fig. 8) [50].

It has been recommended in the literature that the cooling tower be integrated in a serial configuration (as depicted in Fig. 8) to avoid heat accumulation [52]. In addition, it is necessary to keep the temperature of the water circulating in the cooling tower as low as possible in order to increase the coefficient of performance (COP) [53]. If the cooling load is very high for a standard cooling tower, then a traditional HVAC system can be added to meet the cooling demand [54]. It is also possible to incorporate a second cooling tower that has the same capacity as the ground heat exchanger to serve as an alternator or accumulator [55].

After studying three different strategies for controlling the geothermal-CT system, researchers have determined that the most optimal was the wet bulb temperature control method. This method is based on the difference between outlet fluid temperature and the temperature of wet bulb [47]. The aim of this method is to make full use of heat exchange between air and soil [56]. It concentrates on deriving the most benefit from ambient capacity by prioritizing the use of ambient air as the cooling source. Artificial Neural Network (ANN) models were developed to predict the

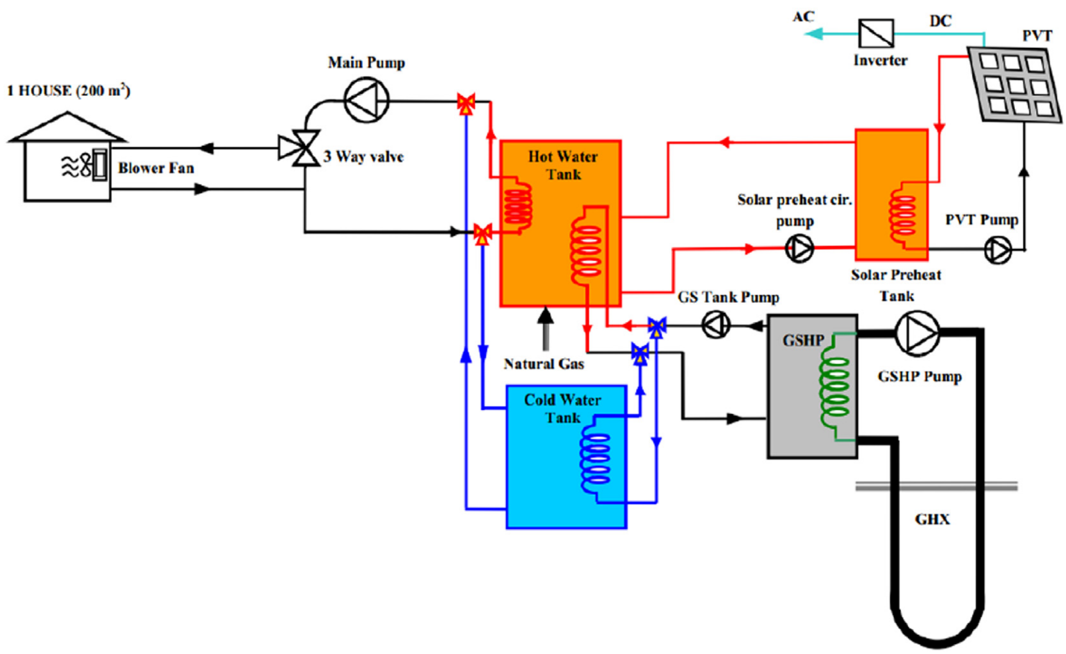

Fig. 6. (PVT) – GSHP [45].

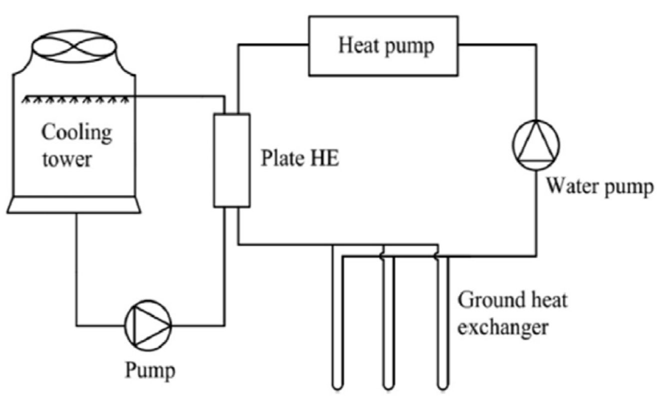

Fig. 7. GSHP coupled with a cooling tower [51].

temperature of the water existing the GHE in comparison to that of the cooling tower. The ANN showed an absolute error of about 0.2 °C [57].

Another control method that has been suggested for hybrid geothermal-CT systems is extremum seeking control (ESC) [51]. This feedback based method (depicted in Fig. 9) is based on a comparison between the total power consumption, flow rate entering the CT, and pump speed. ESC has been shown to provide 9.3% energy savings as compared to other methods. This method will be very helpful in applications where the system consists of multiple bore hole exchangers. In such a system, it would be advisable to normally operate only some of the BHEs and limit operation of all BHEs together to peak load periods only [58].

3.3. *Less-common hybrid geothermal systems*

There are some less common hybridization techniques that can integrate geothermal energy with other sources of energy. For example, it is possible to integrate geothermal with waste heat recovery (another source of low grade energy) in an electricity generation system. Another example would be the injection of industrial waste heat into geothermal boreholes. This integration exploits the thermal storage characteristics of the boreholes and allows the extraction of waste energy exhausted by industrial processes.

A geothermal installation can be integrated into an existing coal fired power plant to improve efficiency and lower costs. The geothermal system can be used to preheat the boiler's feed water and can also be used as a carbon capture storage. Researchers have determined that a serial configuration for geothermal preheating is better at temperatures below 140 °C [59]. A detailed analysis of available conditions with regards to coal sufficiency and availability of geothermal hot water are needed before such a system can be contemplated [60]. Another integration can see the utilization of the coal plant for electricity generation and the geothermal system for providing additional capacity to meet high heating demands [61,62].

Geothermal energy can be used to preheat the organic fluid in a dual-fluid biomass system to achieve the highest possible output power (see Fig. 10) [63]. Researchers have determined that it is advisable to integrate a pre-heater and evaporator into the geothermal system to achieve the combined heat and power system improvements [64].

One of the main issues affecting geothermal sourced heat pumps is the thermal imbalance. It has been shown that increasing the size of the heat exchanger can alleviate this issue. However, this may not be always feasible if the available space is limited. If the load is cooling dominated, then a chiller can be integrated into the geothermal system to improve the system's performance [65]. Adequate consideration should be given to factors affecting the chiller's design such as required cooling, compressor efficiency, and climate conditions.

A geothermal system can be integrated with a floor cooling system to provide a secondary cooling source [66]. The geothermal system would provide elimination of the floor condensation due to excessive heat that would be generated if the floor radiator is used by itself.

Several studies have shown that hybrid systems integrating

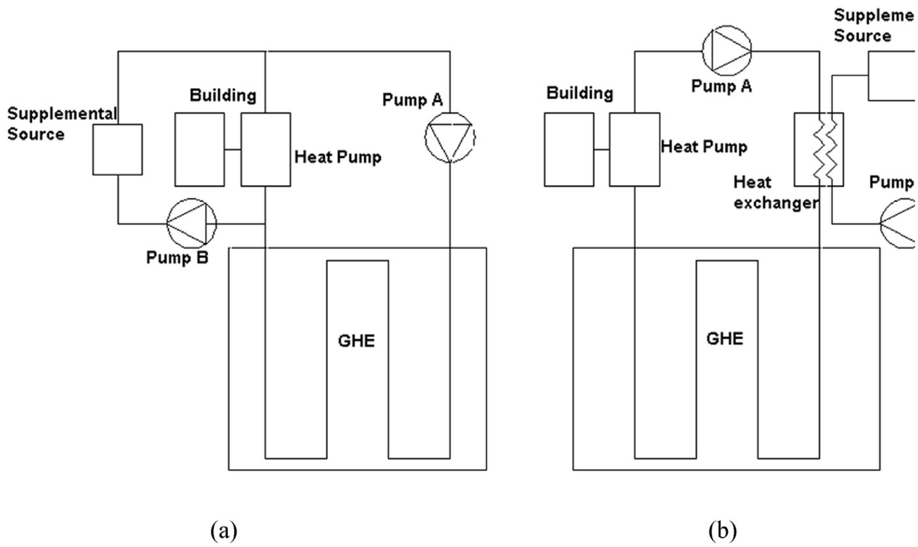

Fig. 8. Parallel (a) vs. Serial (b) Hybrid GSHP Configurations.

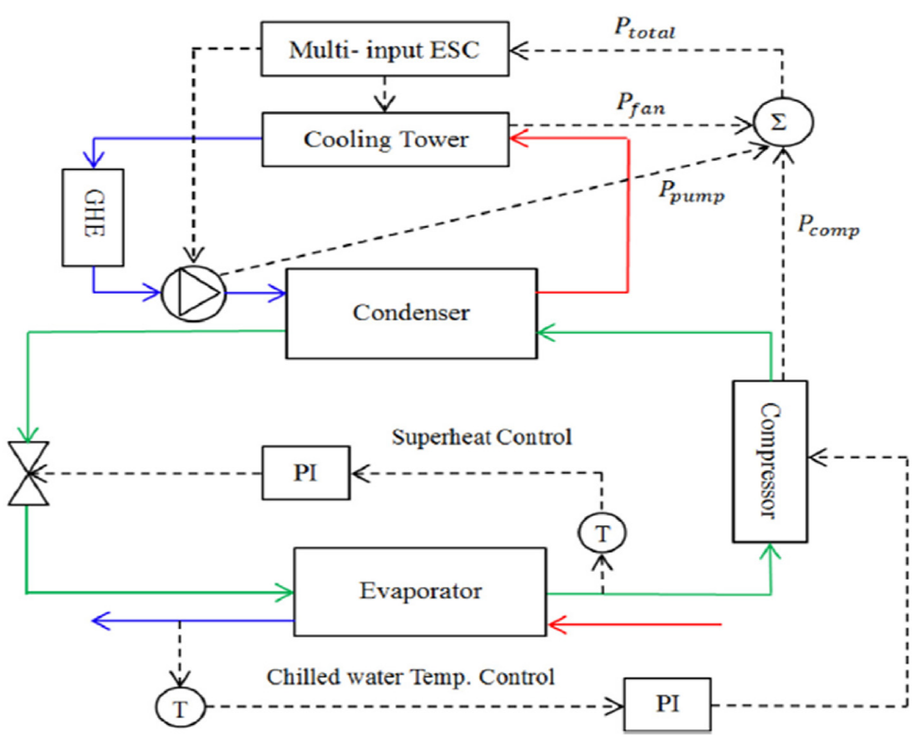

Fig. 9. ESC control for optimizing efficiency of HGSHP system [51].

geothermal energy into existing energy systems can provide improvements in efficiency as well as economics. P. Cui et al. have shown that coupling a geothermal source with an electric heater could produce 3.4% savings in energy used for heating and provision of domestic hot water [67].

Various studies have been performed to compare the performance of traditional geothermal systems with hybrids. It was shown that it would be more beneficial to control the temperature of the fluid entering the system when a geothermal system is integrated with a gas boiler and electric air-conditioning system [68]. In Ref. [61], a COP of 2.79 was achieved while combining the gas boiler with the GSHP to provide heating. On the other hand, it would be more beneficial to vary the temperature of the fluid exiting the system when a geothermal system is integrated with a cooling tower and a boiler [69].

4. Discussion

It has been found that it is best to use geothermal energy in hybrid systems. The combination of geothermal energy with other sources provides various advantages especially associated with cost of energy. Table 1 highlights the advantages and disadvantages of hybrids as compared to conventional geothermal systems.

There has been increasing interest in research related to the

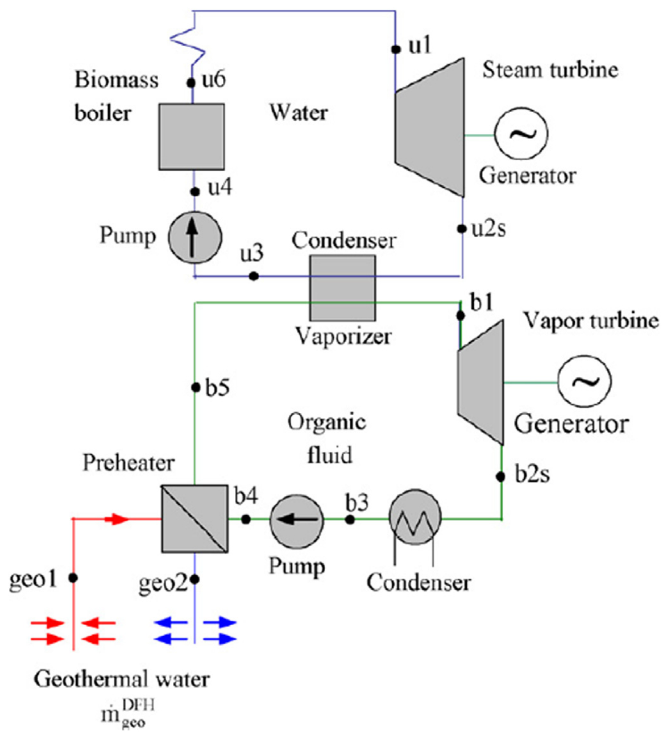

Fig. 10. Dual Fluid Hybrid Geothermal-Biomass Power Plant [63].

Table 1
Advantages/disadvantages of geothermal hybrids.

Advantages	Disadvantages
Low energy consumption	More complex
Lower cost of electricity	Control problems
Support higher peak loads	Connection troubles
Low capital cost	
Low operating cost	
No ground fouling	
Smaller bore field area required	

hybridization of geothermal energy systems. Fig. 11 presents the trend of publications in the literature related to hybrid geothermal systems. It can be seen that interest in such systems has increased tremendously during the past five to six years.

Hybrid systems involving geothermal energy are capable of providing different forms of energy. The diagram in Fig. 12 shows that hybrid geothermal systems are utilized mostly in the form of heat pumps with approximately equal share (44% each) for heating and cooling applications. The remaining 12% of hybrids reported in the literature are utilized for generation of electrical energy. The tendency to use these systems for thermal applications (heating and cooling) is directly related to the thermal nature of the energy source.

The previous section discussed numerous possible integrations of geothermal and traditional or renewable energy systems. These combinations depend on many factors including resource availability, environmental effects, desired performance, energy price target, capital costs, operational costs, etc. The diagram in Fig. 13 shows the prevalence of the different types of systems integrated with geothermal installations as reported in the literature. The most common combination is geothermal-solar (about 45% of reported systems) followed by geothermal with a cooling tower (about 30%) of systems.

There are several factors that could affect the geothermal hybrid system's efficiency and economic feasibility (see Fig. 14). This depends highly on the consistency between the ground and the other source used in both cases; power generation and heat pump. That's why it is very important to pre-study the two combined sources to check out if they could fit as one system from a thermodynamic

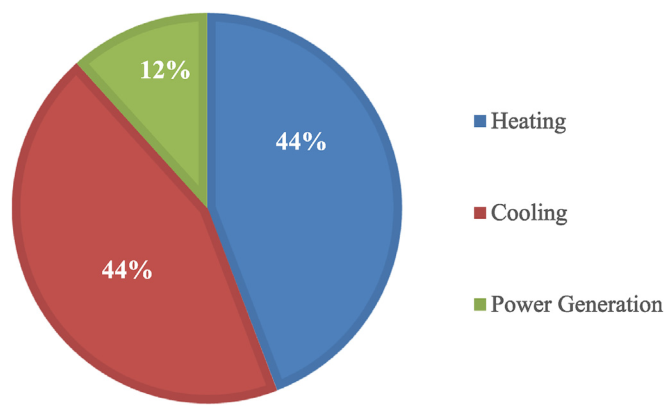

Fig. 12. Different applications of geothermal hybrids.

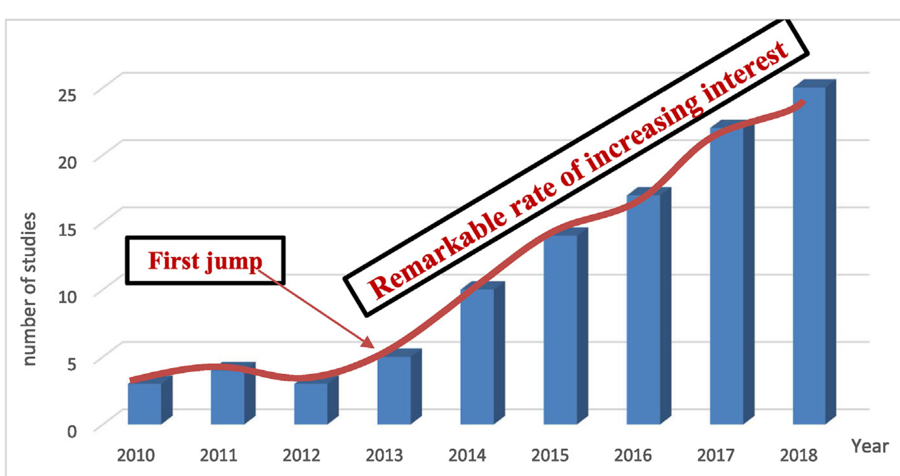

Fig. 11. Evolution of research in hybrid geothermal system.

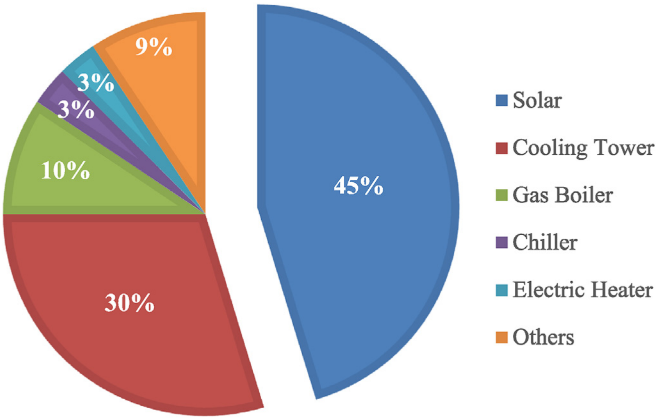

Fig. 13. Types of systems integrated into geothermal hybrids.

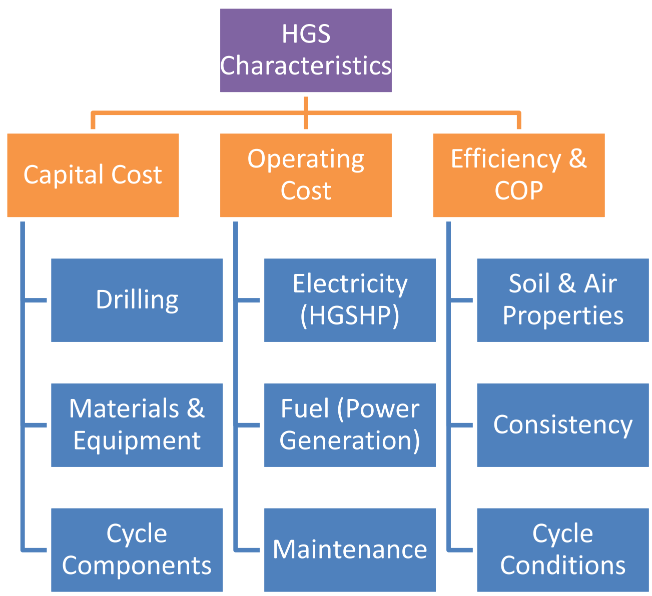

Fig. 14. Factors affecting the HGS characteristics.

point of view while examining the energy that could be generated with respect to time. This will highlight the expected problems that could mainly be solved by the help of energy storage systems. Actually, the initial and operating costs vary significantly from one country to the other based on the availability and abundance of energy sources and equipment.

4.1. Recommendations

Based on the literature, it is recommended first to determine the dominant load (cooling, heating or power) in order to specify the preferable supplementary source in addition to the geothermal one. With this in mind, geothermal energy is prioritized over the other energy sources while avoiding thermal imbalance or heat accumulation. Moreover, the supporting source must be highly abundant and has low impact on the environment. Therefore, increasing renewable energy and waste heat recovery utilizations is the most favorable method to encourage people toward ecofriendly systems.

5. Keys for future work

Nowadays hybrid system design and development is one of the most significant areas of contribution towards the increased utilization of renewable energy. There is a lot of room where significant research contributions can be made. The following are some key areas for further investigation:

1. Potential of specific types of hybrid geothermal systems and especially the most common integrations such as geothermal and solar.
2. Hybrid system optimizations.
3. New hybrid geothermal system combinations such as the integration of geothermal and wind systems or the integration of geothermal and wave energy systems.

6. Conclusion

The use of renewable energy sources helps in reducing pollution and gas emissions associated with traditional fossil based fuels. In particular, geothermal energy has not been reported to have any significant negative impact. Geothermal energy is characterized by an almost steady supply as compared to the intermittent and fluctuating nature of most other types of renewable energy sources. However, geothermal energy is considered a low grade source of energy and cannot independently support high load applications. Therefore, hybrid systems have been studied to overcome the inherent weakness of geothermal systems. In this work we have discussed numerous integration possibilities of geothermal into hybrid systems. We have shown that geothermal can be integrated with solar energy systems, cooling towers, gas boilers, biomass reactors, electric heaters and chillers, among others.

A review of the available literature on geothermal hybrids has shown significant growth in interest since about 2013. The literature showed that the most frequent combination involved geothermal and solar energies. This was followed by geothermal systems integrated with a cooling tower. Hybrid systems have been shown to be utilized for heating and cooling with equal proportions (about 44% each) and to a much lesser extent for power generation (12%). The comparison between the different HGSs showed that each system has its own characteristics. Definitely, the combination of geothermal energy with other renewable sources is the most preferable hybridization followed by waste heat recovery and especially from an environmental point of view. On the other hand, it is quite important to mention that the efficiency, COP and plant capital and operating costs aren't only related to the energy sources used. There are several other factors such as soil properties, ambient conditions, drilling cost, materials, equipment and cycle conditions.

The main deterrent against the implementation of geothermal hybrids is control complexity. When different energy sources are combined into a hybrid system, a flexible adaptive control method should be selected to maximize the overall energy production. The control method should take into consideration the characteristics of each energy source. This is the most crucial aspect of the integration problem and this is where research effort is significantly lacking.

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