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Upgrading both Geothermal and Solar Energy

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ABSTRACT

Geothermal energy has many advantages over solar and other renewables. These advantages include: 1) weather-proof; 2) base-load power; 3) high stability and reliability with a capacity factor over 90% in many cases; 4) less land usage and less ecological effect; 5) high thermal efficiency. The total installed capacity of geothermal electricity, however, is much smaller than those of solar energy. On the other hand, solar energy, including photovoltaic (PV) and concentrated solar power (CSP), has a lot of disadvantages and problems even it has a greater installed power and other benefits. Almost all of the five advantages geothermal has are the disadvantages of solar. Furthermore, solar PV has a high pollution issue during manufacturing. There have been many reports and papers on the combination of geothermal and solar energies in recent decades. This article is mainly a review of these literatures and publications. Worldwide, there are many areas where have both high heat flow flux and surface radiation, which makes it possible to integrate geothermal and solar energies. High temperature geothermal resource is the main target of the geothermal industry. The fact is that there are many geothermal resources with a low or moderate temperature of about 150^{o}C. It is known that the efficiency of power generation from thermal energy is directly proportional to the resource temperature in general. Alternatively, solar could be used to increase the temperature of geothermal fluids significantly and then improve the efficiency of geothermal power generation significantly. Geothermal fluids could be served as the storage systems of solar energy, which may solve the problems of solar such as weather dependence and stability. It is concluded that the integration of geothermal and solar systems could upgrade the quality of both geothermal and solar energies in terms of either efficiency or power generation cost in many cases.

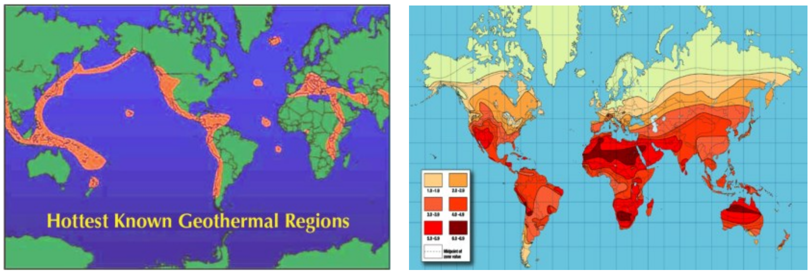
1. INTRODUCTION

The rising energy demand, the limited supply of fossil fuels and their detrimental environmental impacts (e.g. global warming) have intensified the worldwide search for cleaner sources of energy. Achieving sufficient supplies of clean energy for the future is a great challenge. Among renewables, geothermal and solar energies are very appealing because of their vast worldwide resources and its capacity to provide either base-load (geothermal) or distribution (solar) electricity (Li, et al., 2015; Zhou et al., 2013). However, both geothermal and solar energies have merits and drawbacks. For example, geothermal power is a base-load system and is not affected by weather but those with low temperatures may not be economic for power generation. On the other hand, CSP systems can achieve high temperatures over 350°C during the day using a parabolic trough but the temperature is reduced to very low at night or when the sun is not shining. The combination of the two renewables may overcome some of their drawbacks. Fundamentals of solar and geothermal power systems are briefly reviewed in this section.

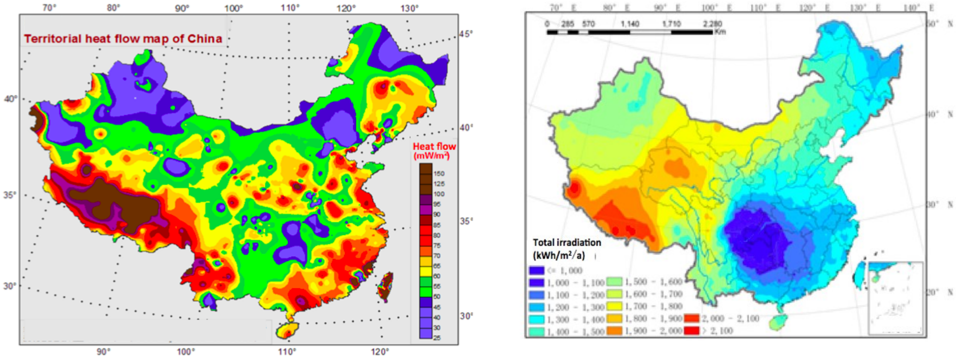
Solar energy can be converted into electric energy by using two different processes: PV in which sunlight is directly converted into electric energy, and solar thermal technologies where a thermodynamic cycle is used (Desideri et al., 2013). PV systems are operated by collecting a fraction of the radiation within some range of wavelengths. Photon energies greater than the cutoff, or band-gap energy are dissipated as heat, and photons with wavelengths longer than the cutoff wavelength are not used by PV devices (Joshi et al., 2009a). PVs convert sunlight into direct current (DC) electricity through the use of thin layers of materials such as semiconductors. The physical processes involved in the conversion of sunlight into electricity include light adsorption, electron transport, and recombination mechanisms, which are determined by the electro-optical properties of the materials (Anyaka and Elijah, 2013). CSP systems convert the sun's energy into high temperature heat using various mirror or lens configurations, and then the heat is transferred to a turbine or engine for power generation (Stoddard et al, 2006).

Figure 1a shows the most promising areas for CSP plants (DOE NREL) worldwide. CSP's growth is much slower than PV systems. After the construction of the 354MW SEGS plants from 1981-1991, commercial deployment restarted in 2007, leading to a 2012 global capacity estimated at 2.5GW (REN, 2013). Also shown in **Figure 1a** is the hottest known geothermal regions. One can see that some of the solar and geothermal "sweat pot" areas are overlapped, which forms the base for integrating the two renewables. **Figures 1b and 1c** show the distribution of solar and geothermal resources in China and the United States respectively, which also demonstrates the distribution consistency, to some extent, of the two renewables in the two countries.

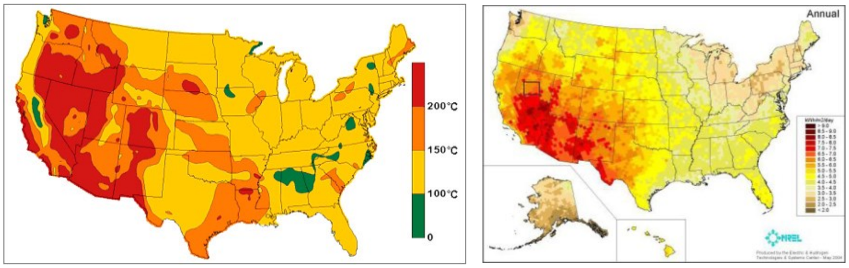
PV systems generated only 753 MW worldwide in 2003. However an annual 30% increase in deployment in the past 5 years makes PV financially viable. The global installations of solar PV reached a record of 2826 MW by June 2007 (Dubey et al., 2013), 10.66 GW in 2009 (Razykov et al., 2011) and 139 GW in 2013 (REN 2014). Four main types of PV installations exist: grid-tied centralized (large power plants); grid-tied distributed (roof/ground mounted small installations); off-grid commercial (power plants and industrial installations in remote areas); and off-grid (mainly stand-alone roof/ground based systems for houses and isolated applications) (Kumar and Rosen, 2011).



(a) World (Courtesy: DOE NREL)



(b) China (Institute of Geology and Geophysics, Chinese Academy of Sciences, 2011; China Meteorological Administration）



(c) USA (Courtesy: DOE NREL)

Figure 1. Distribution of geothermal and the solar energies

As for PV technology's future, the reduction of the cost should be focused. Singh (2013) pointed out that the technologies associated with PV power systems are not yet fully established, and therefore, the price of an energy unit generated from a PV system is an order of magnitude higher than conventional energy supplied to city areas, by means of the grid supply. Razykov et al. (2011) also concluded that the efficiencies of the most leading technologies in PV systems are already satisfactory, and focus should be concentrated on developing cost-effective manufacturing technologies that can significantly lower the module production cost below US$1.5/W.

A photovoltaic/thermal (PVT) hybrid solar system is a combination of PV and solar thermal components to produce both electricity and heat from one integrated system. Chow (2010) reviewed the history of the development of the PVT systems and products. During the early period, the research efforts were focused on the fundamental theories, the consolidation of the conceptual ideas and the feasibility study on basic PVT collector design configurations. In the 1990s, the PVT studies were more related to the collector design improvement and cost-performance evaluation. During the last decade, however, the focus has been generally shifting towards the development of complimentary products, innovative systems, testing procedures, and design optimization. Solar thermal systems and solar PV systems have each advanced markedly, and combining the two technologies provides the opportunity to increase the efficiency and expand the utilization of solar energy. Zondag et al. (2008) studied two adjacent collectors with areas of 1 m^2 each, one for domestic hot water and the other a photovoltaic module. These two collectors were shown to generate 520 kWh of useful thermal energy and 72 kWh electrical energy, respectively, while a combined PVT collector of 2 m^2 area would yield energy outputs of 720 kWh thermal and 132 kWh electricity. A PVT collector could produce about 44% more energy than the single system with similar areas. Joshi et al. (2009b) found that the exergy efficiency of PV system varied from a maximum of 13.8% to a minimum of 7.8%, and that of PVT system varied from a maximum of 15.7% to a minimum of 11.3%. Besides, the payback time for PVT collectors was found considerably lower than individual systems based on an investigation in an Italian climate. Furthermore, an application of the PVT system is building integrated photovoltaic (BIPV), which has been growing in many countries. BIPV reduces installation cost, produces electricity and helps to control heating and cooling loads of buildings.

Geothermal energy is the heat generated and stored in the earth. The total thermal energy of the earth is estimated to be about 10^{13} EJ and is almost immense (Shortall et al., 2015). Geothermal energy has not until recently become a significant source of electricity and heat, with exceptions in countries such as the USA, Indonesia, Iceland and Italy (Bertani, 2012). In 2008, geothermal energy represented around 0.1% of the global primary energy supply, but estimates predict that it could fulfill around 3% of global electricity demand, as well as 5% of global heating demand by 2050. Temperatures above 150^{o}C characterize high-enthalpy resources, which involve a geothermal fluid suitable for power generation. Low-enthalpy resources typically present temperatures below 150^{o}C, and their geothermal potential is still underexploited, making heat generation the main application. Utilization of geothermal can be categorized into two types: electricity generation and direct use such as space heating, balneology, greenhouses, etc. (Shortall et al., 2015). Geothermal energy is one of the most promising energy alternatives to fossil fuels and it is currently utilized in 24 countries worldwide to produce electricity and, in other 74 countries it is applied to various direct uses (Rubio-Maya et al., 2015). Current worldwide installed capacity is around 13 GW (Li et al., 2015; Shortall et al., 2015).

Li et al. (2015) compared the geothermal energy with solar energy from several aspects such as cost, payback time, size of power generation, construction time, resource capacity, characteristics of resources, social and environmental effects. The main reasons why geothermal power has been left behind solar may be high initial investment, long payback time and construction time, and difficulty to modularize. However, geothermal has other advantages such as high thermal efficiency, great stability, weather-proof and base-load abilities, and less land requirement, etc.

In this manuscript, we will discuss the progress in both solar and geothermal systems first. Then we will review the configurations, mechanisms and other features of the hybrid solar–geothermal power generation systems. Finally we will make some conclusions.

2 PROGRESS IN PHOTOVOLTAIC/THERMAL HYBRID SOLAR SYSTEMS

The first generation of PV technologies is made of crystalline silicon (c-Si) cells that are combined to make PV modules, such as mono-crystalline, poly-crystalline, and emitter wrap through. In comparison with c-Si cells, another PV technology-thin film technology-holds the promise of reducing the cost of PV array by lowering material and manufacturing costs without jeopardizing the cells' lifetime as well as any hazard to the environment. Besides, compound semiconductor -a complicated stack of crystalline layers with different band gaps that are tailored to absorb most of the solar radiation-allows the absorption of light most efficiently since each type of semiconductor absorbs different characteristic band gap energy. Limitations seen in other PV technologies are lessened by the introduction of nanoscale components. The ability to control the energy band-gap of those components will provide flexibility and inter-changeability, as well as enhance the probability of charge recombination. Thus, structures from nanotechnology products that can absorb more sunlight are emphasized: nanotubes, quantum dots (QDs), and "hot carrier" solar cells (Chaar et al., 2013). About 90% of total PV market is seen to be based on c-Si, with the shares of mono c-Si and poly c-Si comprising about 42% and 45%, respectively (Mints, 2010). Besides, the efficiency of PV system also depends on several other factors. For example, weather conditions can influence the efficiency of PV system non-linearly by the irradiation level and temperature. A cloud passing over a portion of solar cells or a sub-module would reduce the total output power of solar PV arrays (**Figure 2**). Under certain cloud conditions, the changes can be dramatic and fast (Anyaka and Elijah, 2013).

Figure 2. PV panels (Ritcher et al, 2012)

Technology about PVT system always focus on the solar collector, which converts solar radiant energy into useful thermal energy through a fluid (water, air, glycol, oil, etc.). The collected energy could be applied in many cases, such as space or water heating and steam generation, as well as be stored in a thermal storage for later use (Kumar and Rosen, 2011). The solar collectors can be categorized into liquid heating (PVT/liquid) and air heating (PVT/air) types. Chow (2010) suggested that the usage of which type of collectors should depend on the geographical location and actual application case by case. At location with low level of solar radiation and ambient temperature, space heating is almost required all the year and PVT/air can be useful and cost effective. At locations with high solar input as well as ambient temperature, PVT/liquid can be useful for providing year round water pre-heating services.

3 PROGRESS IN CONCENTRATED SOLAR POWER SYSTEMS

A typical CSP power plant consists of two major subsystems: the solar field that collects solar energy and converts it to heat; the power block that converts heat energy to electricity. Some power plants also contain thermal storage tanks used to store the solar resources, which is called thermal energy storage (TES) system. In practice, the materials chosen for light concentration and absorption, heat transfer and storage, as well as the power conversion cycles are the true deciding factors (Barlev et al., 2011).

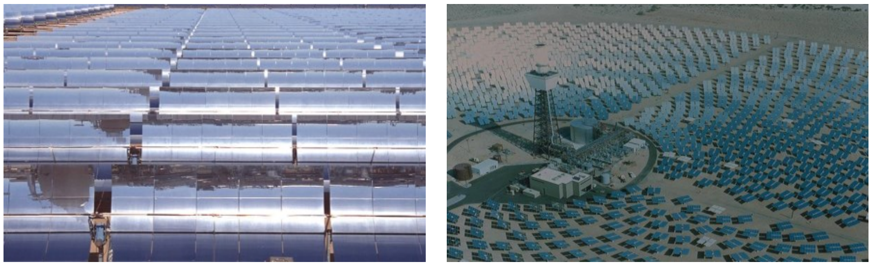
As for solar collectors, there are two general categories. The first type is non-concentrating collectors, in which the same area is used for both interception and absorption of incident radiation. The second one consists of sun-tracking and concentrating solar collectors, which utilize optical elements to focus large amounts of radiation onto a small receiving area and follow the sun throughout its daily course to maintain the maximum solar flux at their focus. Though more costly, concentrating collectors have several advantages over non-concentrating ones, and are generally associated with higher operation temperatures and efficiencies. Generally, the concentrating collectors can be categorized into four types: parabolic trough collectors (PTC), heliostat field collectors (HFC), linear Fresnel reflectors (LFR) and parabolic dish collectors (PDC). **Figure 3** shows those four types of concentrating collectors.

(1) PTC is the most mature concentrated solar power design and an efficient, relatively inexpensive power production scheme. Multiple advances in reflector and receiver design have been made in the last decade to enhance efficiency and reduce losses. The PTC scheme also lends itself to easy storage scheme, as well as to simple integration with both fossil fuels and other renewable energy sources.

(2) HFC technology has been improved greatly over the last few decades, and continues to draw much attention as a suitable scheme for large solar thermal plants. The exceedingly high temperatures at which they operate grant HFC plants excellent efficiencies, while allowing them to be coupled to a variety of applications. The high capital investment necessary for the construction of HFC system is an obstacle of this technology.

(3) LFR technology offers many PTC system's advantages while incurring reflector costs. It can also be easily coupled to Direct Steam Generation (DSG) as well as molten salts for thermal energy transport. The central receiver regime shrinks costs further, but tags on the challenge of maximizing the amount of the solar radiation that can be collected. Innovation in receiver design and reflector organization has made LFR relatively inexpensive in comparison with other CSP technologies. It readily couples to thermal storage and other applications.

(4) PDC has promoted highly efficient yet expensive technology towards the goal of being reasonably affordable. Novel improvements in reflector structure and collector design continue to boost the thermal efficiency of this CSP scheme. The use of stirling engine at a PDC's focus helps alleviate the losses and costs associated with heat transport. However, this regime does not comply with thermal storage in a simple manner, a significant issue in the scope of year-round power production.



(a) parabolic trough collectors **(b) heliostat field collectors**

(c) linear Fresnel reflectors **(d) parabolic dish collectors**

Figure 3. Four types of concentrating collectors (Source: Sandia National Laboratories SunLab; Novatec Solar GmbH)

The conversion of solar thermal energy into electricity generally requires the use of a thermodynamic cycle. The most common thermodynamic cycle used is the Rankine cycle, which usually uses water as its working fluid. The organic Rankine cycle utilizes organic fluid such as toluene or n-pentane as working fluids, which can operate at lower temperatures (70-90^{o}C). Besides, lower temperatures result in lower thermodynamic efficiency, but this may be counterbalanced by the lower heat inputs required to drive the system. The Brayton cycle generally is operated at significantly higher temperatures than the Rankine cycle. Despite this fact, the overall efficiencies of large-scale steam generators and gas turbines seem to be similar. The combined cycle utilizes a hybrid of the Rankine and Brayton cycles, and can achieve higher efficiencies than either. It is important to note that relative costs associated with this step become quite considerable with increased levels of sophistication, a fact that must be weighed against the benefits that the enhanced designs provide.

Different CSP technology and systems have been proposed (Bode, 2010):

(1) Direct Steam Generation (DSG): steam in DSG system is generated directly in the PTC. Usage of DSG could reduce the costs through elimination of traditional heat transfer. This technology also reduces efficiency losses in the heat transfer process and improves the solar field operating efficiency due to lower average operating temperatures and improved heat transfer in the collector receiver.

(2) Integrated Solar Combined Cycle System (ISCCS): the general concept of ISCCS is to oversize the steam turbine to handle the increased steam capacity. At the high end, steam turbine capacity can be approximately doubled, with solar heat being used for pre-heating and superheating steam. Unfortunately, when solar energy is not available, the steam turbine must run at part load and thus reduce the efficiency. Price and Kearney (2003) reported that doubling the steam turbine capacity would result in a 25% design point solar contribution and the annual solar contribution for trough plant without thermal storage would only be about 10% for a base-load combined–cycle plant.

(3) Dry cooling design: CSP plants always require some fresh water for cleaning mirrors, it is possible to reduce the water consumption by about 90% using a dry-cooling design if the CSP plant is built in a location with scarce water resources. Pietzcker et al. (2014) reported that dry cooling reduces electricity production by around 7%, equivalent to a decrease of thermal conversion efficiency by 2-3% relative to a design with water cooling.

(4) Thermal energy storage (TES): three advantages can be achieved through the TES system. (I) buffering: the goal of a buffer is to smooth out transients in the solar input caused by passing clouds; II) delivery period displacement: the storage could shift some or all of the energy collected during periods with sunshine to a later period (possibly periods that have higher tariffs etc.). In addition, TES can shift generation to higher-priced hours, but also adds capital costs and some efficiency losses in the storage cycle; III) delivery period extension: additional thermal energy is collected during the day and is utilized for electric generation after sunset (Pilkington Solar International GmbH, 2000). The extension of delivery period could also allow the power plant to be built with a larger solar field because excess thermal energy can be placed into storage for later use.

TES can be divided into three main categories: sensible heat storage, latent heat storage and chemical storage (Barlev et al., 2011). Sensible heat storage can employ a large variety of solid and liquid materials. It can be put into practice in a direct or indirect manner. Latent heat storage in the solid–liquid phase transition of materials is considered as a good alternative for sensible heat storage. The selection of the storage schemes must be carefully matched to the size (total power output) and operational procedures of a specific plant, as well as to its governing environmental and economic factors.

4 PROGRESS IN GEOTHERMAL POWER GENERATION

Power generation from high-enthalpy geothermal resources generally involves a thermodynamic cycle similar to that of conventional thermal power plants, using a steam turbine, a steam generator, and a condenser. Barbier (2002) reported that the efficiency of the generation of electricity from geothermal steam ranges from 10% to 17%, about three times lower than the efficiency of nuclear or fossil-fueled plants. There are different geothermal power technologies depending on the specific conditions of the geothermal resource (Martín-Gamboa et al., 2015). Typically, there are five geothermal plant technologies in global electricity production: single flash plant, double flash plant, dry system plant, binary plant and back pressure plant (Bayer et al., 2013). Either water or air may be used for cooling, depending on site conditions.

Exploitation has been focused mainly on high-enthalpy geothermal resources, and less on the resources of medium and low enthalpy. In some cases the potential of medium and low enthalpy resources has not been used for power generation due to high initial cost and limited technology availability. In fact, a recent research conducted by Zheng et al. (2015) indicated that for moderate temperatures of geothermal resources, ORCs integrated in hybrid renewable energy power systems are the most effective approach to reducing electricity generation cost, improving plant efficiency and expanding the lifespan of reservoirs. Rubio-Maya et al. (2015) studied the integrated use of the geothermal resource in multiple applications under the concept called cascade utilization. Cascade systems with electricity production are suitable when geothermal resource has temperature greater than 90^{o}C, with more opportunity to integrate various thermal levels as temperature increases. Cascade systems with only thermal uses are appropriate for geothermal resources with temperatures below 90^{o}C. The main benefits are: increased profitability of the facility; maximized use of geothermal resources of medium and low enthalpy; local development of communities and cities; social and environmental benefits.

5 HYBRID SOLAR-GEOTHERMAL

As early as in 1975, Finlayson and Kammer reported an assessment of solar-geothermal hybrid system concepts. In the past few decades, much attention has been paid to the hybrid solar-geothermal power generation (Mathur, 1979; Kondili et al., 2006; Ghasemi et al., 2014; DiMarzio et al., 2015). Because of the mutual compensation in structures, the hybrid system contains both of the advantages of the solar and geothermal sources. Thermodynamically, the hybrid plants were found to outperform the stand-alone plants when a fully optimized operating mode was employed. The net power output of the hybrid plant was found to increase as a result of increasing the solar irradiance and/or geothermal fluid temperature or reducing the ambient temperature. Besides, the hybrid solar-geothermal power plants can be cost-competitive.

Lentz and Almanza (2006) investigated the feasibility of using parabolic trough solar field to increase the enthalpy from geothermal wells' flow in order to raise the steam quantity. The increase in steam-water flow rates made it possible to prevent the deposition of some salts since the salt solubility was increased.

Kondili et al. (2006) proposed an integrated methodology for the design of a geothermal–solar greenhouse to minimize the fossil fuel consumption and replace them with geothermal energy. Besides, the methodology had been implemented in a selected area, which showed that the proposed system configuration was also economically attractive.

Ghasemi et al. (2014) designed a model to hybridize the ORC geothermal system and a low-temperature solar trough system utilized in parallel with the geothermal system to vaporize part of the working fluid. The annual performance of the hybrid system was examined by the given solar data of the considered site and demonstrated a 5.5% boost in annual power generation compared with the optimized stand-alone geothermal system. Furthermore, the hybrid system had a higher second-law efficiency up to 3.4% compared to the case of separate geothermal and solar systems at all ambient temperatures. In addition, the hybrid system showed up to 17.9% solar incremental efficiency.

Ayub et al. (2015) developed an integrated model for a hybrid solar-binary geothermal system and reported that LEC (Levelized Electricity Costs) could be decreased by 2% for the hybrid system compared to the stand-alone geothermal system. An optimization of the stand-alone geothermal ORC resulted in about 8% reduction in LEC.

According to the literature available, hybrid solar–geothermal power generation has been the focus of many studies in recent years, with a range of different hybrid configurations being investigated:

- Solar preheating configuration where solar energy is used to preheat the brine either by increasing the brine temperature or its dryness fraction (i.e. the steam quality).
- Solar superheating configuration in which solar energy is mainly used to superheat the working fluid of the geothermal power cycle.
- Geothermal preheating configuration where geothermal energy is used to preheat the feedwater in a steam Rankine cycle type solar thermal power plant.

Table 1 summarizes the technologies about hybrid solar-geothermal systems from literature. The focus of the technology has been mainly on the solar preheating and solar superheating configurations. Few studies were conducted to study the geothermal preheating configuration. In this section, we mainly discuss the solar preheating and superheating configurations.

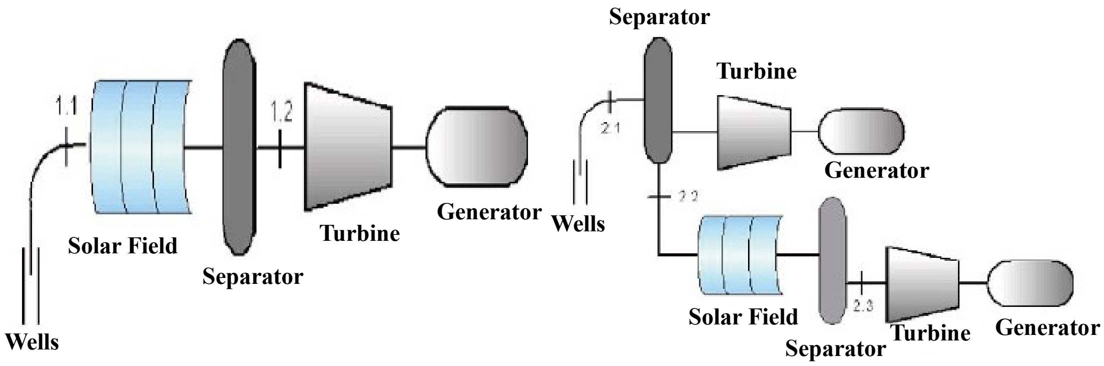
Table 1: Technical assessments of the hybrid solar- geothermal systems

Authors, year	Geothermal power plant (existing /hypothetical) and its location	Geothermal reservoir temperature and brine flow rate	The types of main power cycle	Working fluid	Hybridization approach and operating mode
Ayub et al., 2015	Existing, Nevada, US	135℃, 620kg/s	Subcritical geothermal binary plant (ORC)	Isopentane	Incorporate solar system
Zhou et al., 2014	Hypothetical, Australia	150 ℃, 50kg/s	Supercritical/Subcritical geothermal binary plant (ORC)	Isopentane	Working fluid superheat mode
Peterseim et al., 2014	Hypothetical, Australia	150-200 ℃	Single-flash geothermal plant	Steam	Superheating the vapor fraction of the brine and/or reheating the liquid fraction of brine solar energy
Greenhut et al., 2010;	Existing seven-unit dual cycle binary plant, USA	150℃,100kg/s (brine reinjection temperature：>70 ℃)	Supercritical geothermal flash-binary/binary plant	R-134a (101-180 ℃)	Working fluid superheat mode, brine preheat mode (including brine preheat, recirculation, preheat circulation, and cascade reheat modes)
Manente et al., 2011	Existing, USA	154.5℃, 457.1 kg/s (brine reinjection temperature: >62.8 ℃)	Subcritical geothermal binary plant (ORC)	Isobutane industrial grade	Brine preheat mode
Zhou et al., 2011	Hypothetical, Australia	180℃, 50 kg/s	Subcritical geothermal binary plant (ORC)	Isopentane	Brine preheat mode
Astolfi et al., 2011	Hypothetical, Italy and USA	150 ℃, 100kg/s (brine reinjection temperature)	Supercritical geothermal binary	R-134a (up to 270 ℃)	Brine preheat mode
Mir et al.,2011	Hypothetical, Chile	250 ℃	Single-flash geothermal plant	Steam	Working fluid superheat mode
Boghossian, 2011	Hypothetical, USA	150 ℃,100kg/s	Dual temperature geothermal Kalina cycle	NH_3-H_2O mixture	Working fluid superheat mode
Todorovic, 2009	Existing, Husavic, Iceland	125 ℃, 90kg/s	Geothermal Kalina cycle	NH_3-H_2O mixture	Superheating the vapor fraction of the brine and/or reheating the liquid fraction of brine using solar energy
Alvarenga et al., 2008; Handal et al., 2007	Existing, Ahuachapan geothermal field, USA	154 ℃	Geothermal flash plant	Steam	Working fluid superheat mode
Lentz and Almanza, 2006	Existing, Cerro Prieto, Mexico	300 ℃,44.92kg/s, average steam quality of 34%	Geothermal double flash plant	Steam	Brine preheat mode for increasing the vapor fraction or brine only
Mathur, 1979	Hypothetical, USA	90~300 ℃	Solar steam Rankine cycle with feed water heater	Steam	Brine preheat mode for increasing the vapor fraction of brine only (direct contact)

5.1 Solar preheating configurations

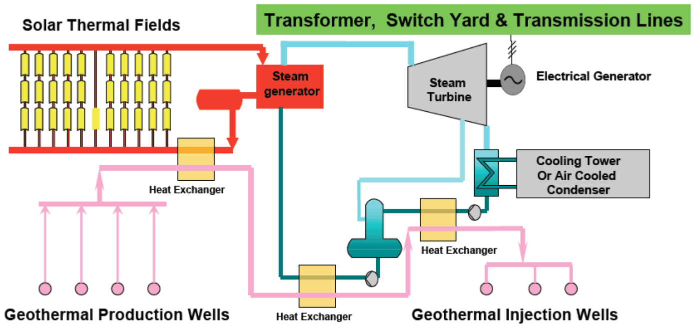
The solar preheating configuration is used to preheat the brine by increasing the brine temperature or the dryness fraction. Those configurations used to increase the vapor fraction can be classified to two types:

1) DSG: The geothermal brine is evaporated by flowing directly into the solar collectors. Two configurations of this type reported by Lentz and Almanza (2006) are depicted in **Figures 4a** and **4b**. Lentz and Almanza (2006) tested the feasibility of the solar-geothermal hybrid system in Cerro Prieto geothermal field in Mexico. The flow enthalpy of the geothermal system can be increased by the solar system. Besides, the steam production rates were also increased because of the addition of the solar units. Miao, et al. (2009) also suggested several configurations for integrating the solar and geothermal resources at different levels (see **Figures 4c** and **4d**).

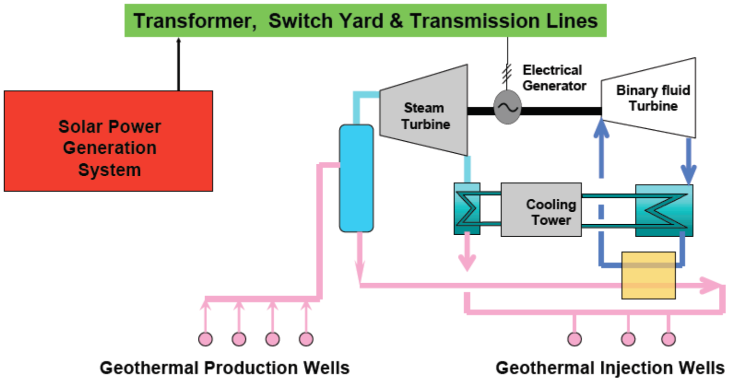


(a) **(b)**

(Lentz and Almanza, 2006)



(c) Miao, et al. (2009)



(d) Miao, et al. (2009)

Figure 4. Different configurations of the Direct Steam Generation systems

2) Indirect Stream Generation: the geothermal system of this type usually obtains the heat of solar system from a heat exchanger indirectly. Typically, the energy conversion flow is designed to be: (I) solar energy to thermal energy; (II) store heat in the heat transfer fluid (HTF); (III) increasing the geothermal steam fraction through a heat exchanger (HE); (Ⅳ) electrical power generation. A typical heat exchanger in the heat transfer system is shown in **Figure 5**. Alvarenga et al. (2008) tested a solar-geothermal hybrid system (**Figure 6**) using oil as HTF in the Ahuachapán geothermal field, Central America. Handal et al. (2007) proposed two configurations of the hybrid solar-geothermal power plants: one was operated under the constant mass flow rate condition, while the other was run under condition that output power equals to the one obtained in stand-alone geothermal power plant. The former had an annual increase of 11.36% in the total energy, and the latter demonstrated an increase of 10.36% in geothermal fluid mass flow rate, which could extend the reservoir life cycle. CO_2 reduction bonus, fiscal incentives, use of efficiency technology to storage and heat transfer are also advantages to invest in a geothermal-solar hybrid system.

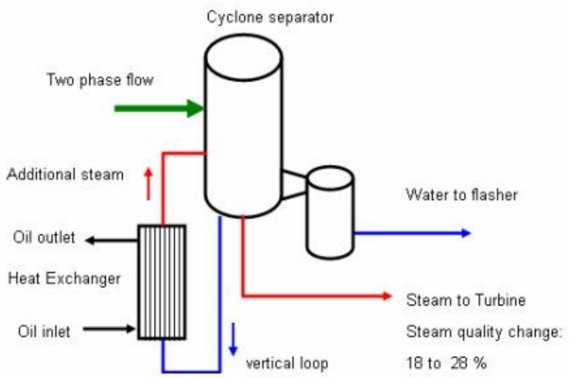


Figure 5. Heat Exchanger for heating water into a cyclonic separator (Handal et al., 2007)

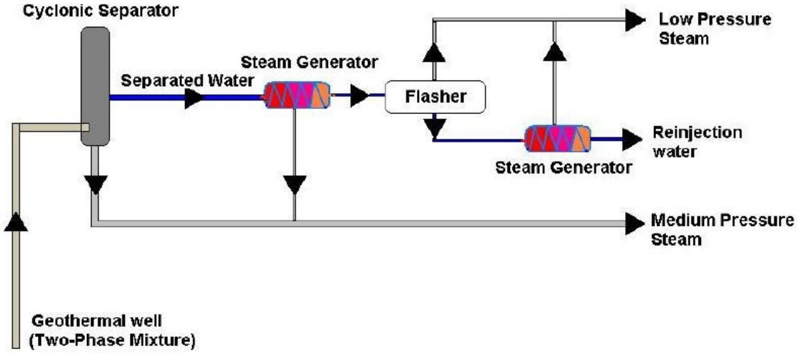


Figure 6. Design of the hybrid solar-geothermal power plant (Alvarenga et al., 2008)

Precipitation of silica dissolved in the geothermal fluid might be a problem in these hybrid systems. Some methods were proposed to quench this problem: injection of hydrochloric acid to a pH of 5; adding an electronic descaler. Lentz and Almanza (2006) proposed a configuration of the hybrid solar-geothermal system (**Figure 7**) by making use of the water from cooling tower. Therefore, the scaling on the pipes from the wells would be lessened and the total salinity decreases when the steam is injected in the brine-steam mixture coming from the well.

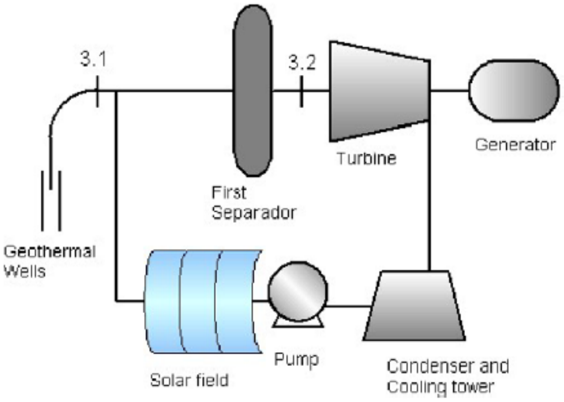


Figure7. Improved hybrid solar-geothermal system with less scaling problem (Lentz and Almanza, 2006)

5.2 Solar superheating configuration

Solar energy in solar superheating configuration is mainly used to superheat the working fluid of geothermal power cycles. Different types of geothermal systems and different solar systems are discussed in this section.

1) Different geothermal systems

Tempesti et al. (2012) investigated two CHP ORC schemes (**Figures 8** and **9**) powered by low-temperature geothermal resource (i.e. 90 °C): single-pressure with heat transfer fluid and dual-pressure with direct-steam collectors. In both configurations, the best performances were obtained with R245fa in terms of cycle and exergy efficiency compared with R134a, R236fa. Besides, single-pressure with heat transfer fluid had a better performance than the dual-pressure with direct-steam collectors.

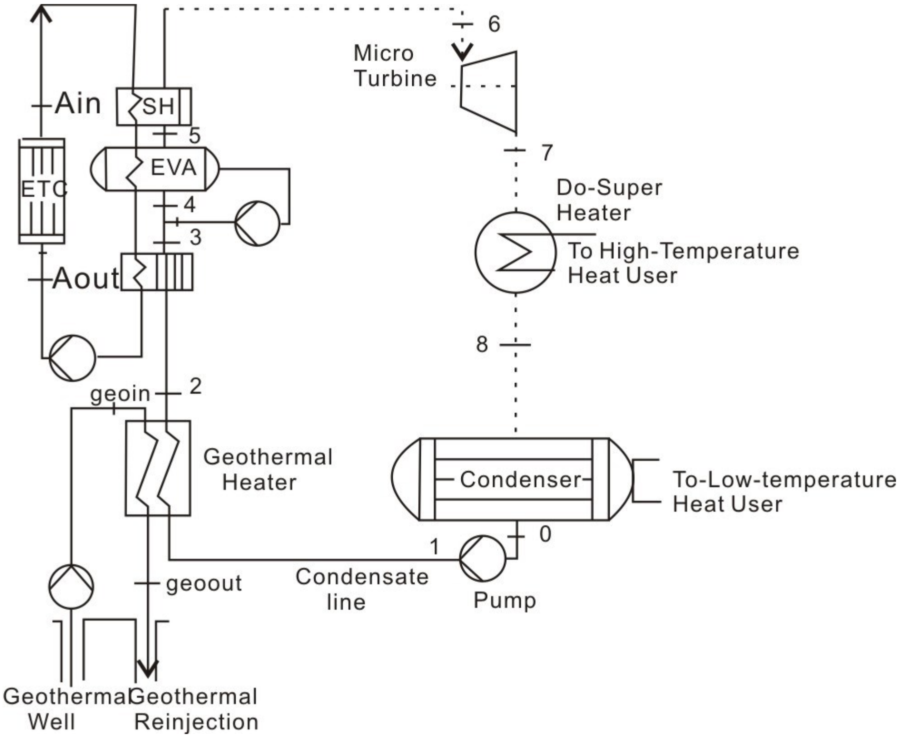


Figure 8. Single-pressure geothermal/solar ORC layout (Tempesti et al., 2012)

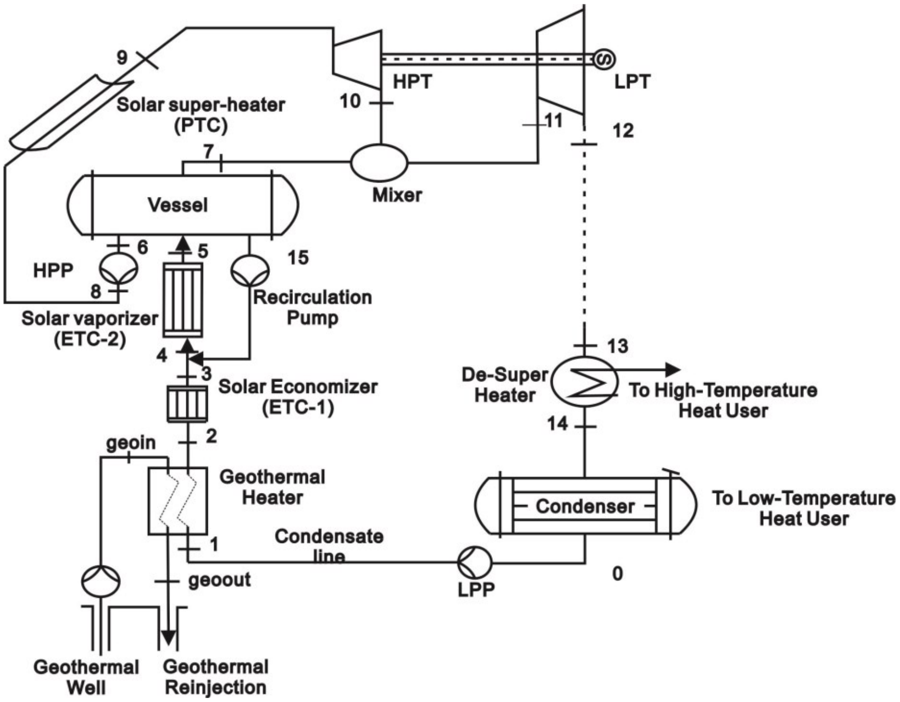


Figure 9: Dual-pressure geothermal/solar ORC layout (Tempesti et al., 2012)

Zhou (2014) studied both subcritical and supercritical ORC platforms in the hybrid solar–geothermal power generation (**Figure 10**). The thermodynamic analysis indicated that the hybrid plant using the supercritical ORC produced approximately 4–17% more power than that using the subcritical ORC at a solar aperture area greater than approximately 8000 m^2 (i.e. solar exergy fraction >66%). The supercritical and subcritical hybrid plants produced a maximum of 19% and 15% more annual electricity than the two stand-alone plants under specific conditions.

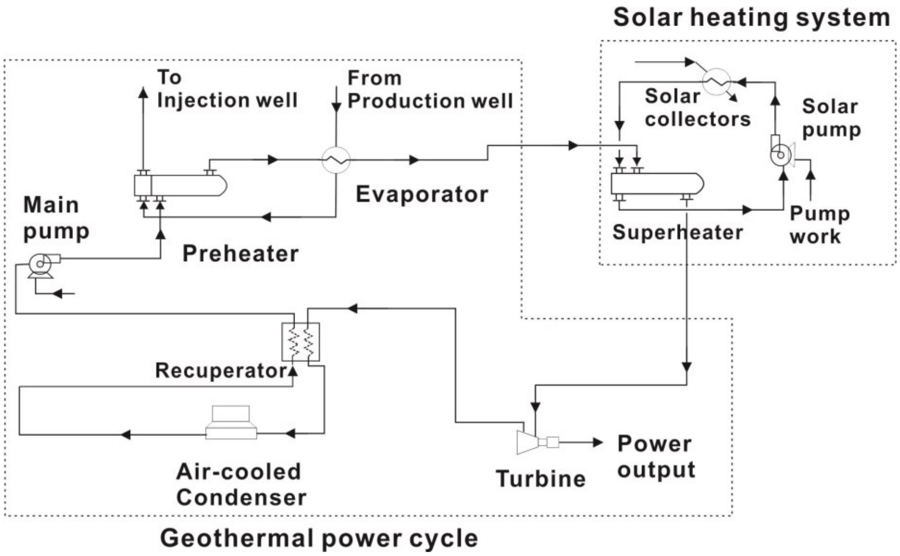


Figure 10: **Schematic of the hybrid solar–geothermal power plant (Zhou, 2014)**

Greenhut et al. (2010) proposed two hybrid solar-geothermal systems: a supercritical binary hybrid plant (**Figure 11**) and a flash hybrid plant (**Figure 12**). They suggested that the low-exergy, low-cost heat source (geothermal) should be used to the maximum extent possible within its temperature limits, while the high-exergy, high-cost heat source (solar) should be used only to increase the temperature of the geothermal fluids. It was found that the flash-geothermal hybrid system showed the most promising performance among the hybrid configurations evaluated.

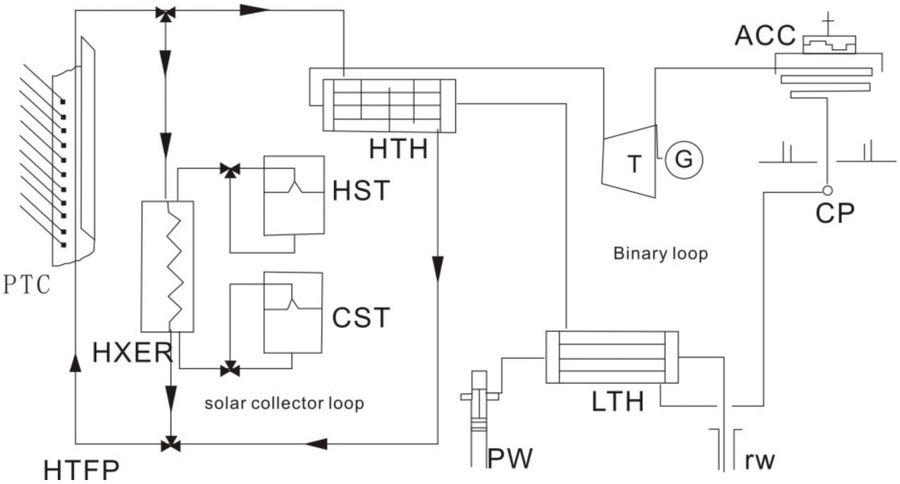


Figure 11: Solar-geothermal superheat hybrid concept (Greenhut et al., 2010)

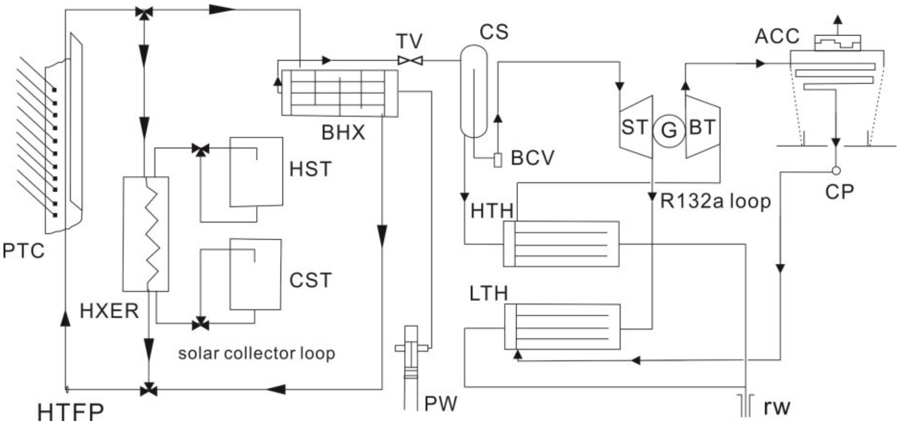


Figure 12: Solar-geothermal flash concept (Greenhut et al., 2010)

2) Different types of solar systems

Zhou et al. (2011) proposed two configurations of the hybrid solar-geothermal systems: one was the direct system in which no storage of solar energy exits (**Figure 13**), the other was the indirect system that contains a storage system **(Figure 14)**. Both of the configurations could improve the performances of the geothermal power plant, while the indirect configuration performed better. The overall performance of the hybrid power plant was directly proportional to the collector surface area. However, when the solar energy was less available or unavailable, the collector surface area had weaker impacts or even no effects on the performances of the hybrid power plant. The direct configuration increased the performance of the hybrid power plant by 12.7% in the net electrical output and 7.5% in the thermal efficiency in maximum, while the indirect one yielded a 29.0% increase in the net electrical output and a 16.6% increase in the thermal efficiency in maximum.

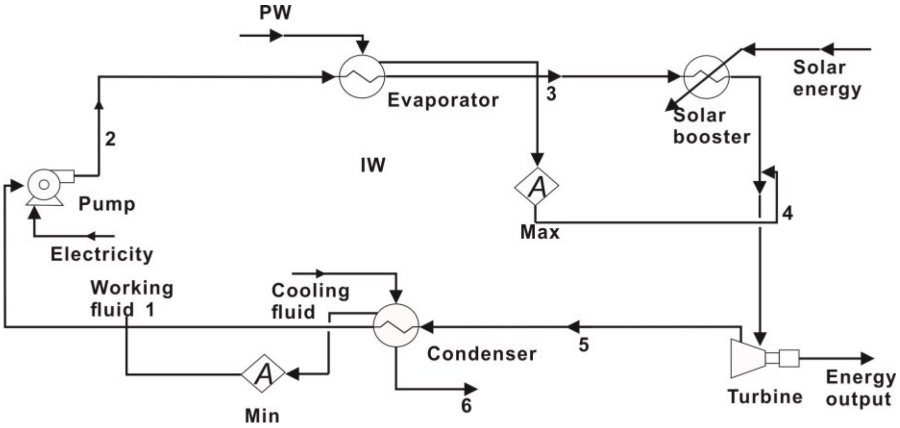


Figure 13: an ORC plant with a direct solar heating system (Zhou et al., 2011)

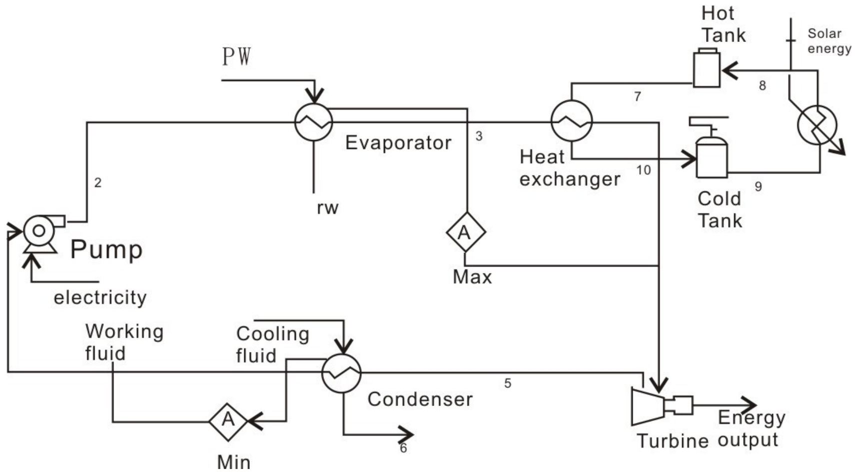
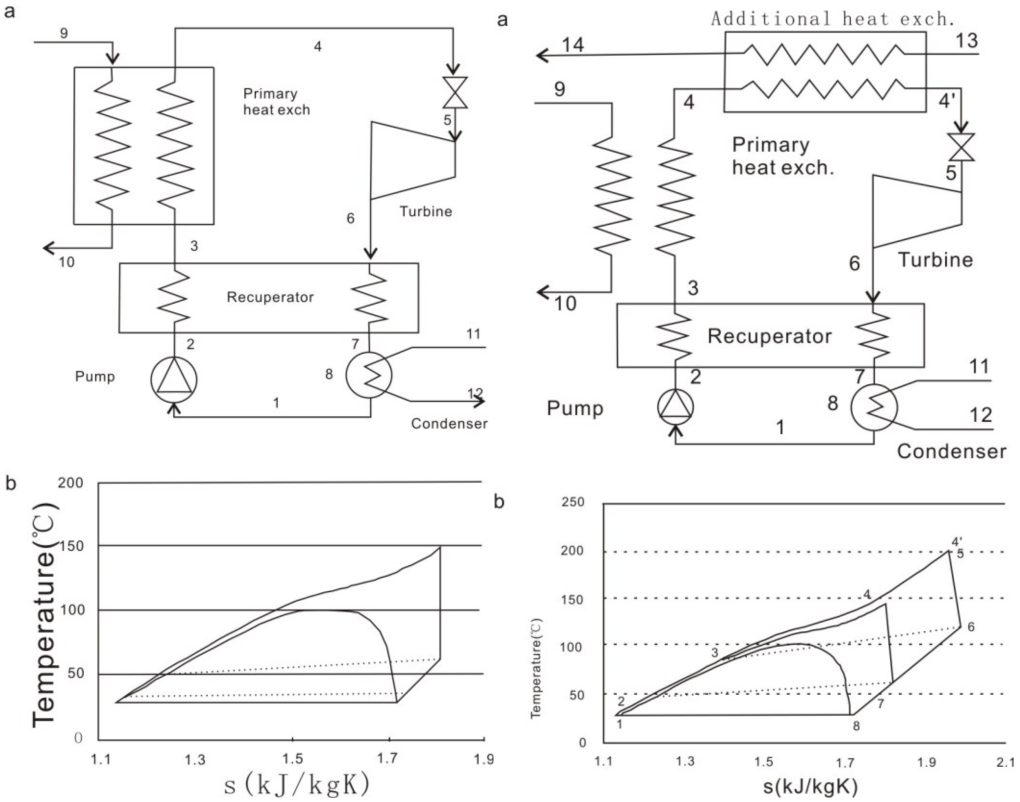


Figure 14: an ORC plant with an indirect solar heating system (Zhou et al., 2011)

Astolfi et al. (2011) proposed a supercritical ORC hybrid plant with a solar parabolic trough field (**Figure 15**) to optimize the utilization of an intermediate enthalpy geothermal source. And the off-design calculations were performed by considering an additional heat exchanger placed after the main heat exchanger of the base plant. Although thermal storage would increase the flexibility of the hybrid plant, it may be unnecessary because of the continuous availability of the geothermal source, which assured rather high overall capacity factors and could guarantee safe operation for the turbine in case of lack of insolation for short periods.



(a) (b)

Figure 15: (a) Schematic of the assumed supercritical regenerative ORC and its representation on the temperature–entropy plane; (b) Schematic of the hybrid configuration used for off-design calculations and its representation on the temperature–entropy plane (Astolfi et al., 2011)

5.3 Example projects of solar-geothermal power plants

A thermosolar-geothermal hybrid system has been built in the Ahuachapán geothermal field (Alvarenga et al., 2008). The reservoir temperature in the main exploitation area was 225°C. For most of the wells, mixed fluids at well head conditions were 4-7 barg, 154-160°C and 15-20% of mass steam fraction. The parabolic trough used in the pilot test is shown in **Figure 16**. A solar field of 300m x 400m, running from 9 a.m. to 5 p.m., could produce 5.8 kg/s of steam, equivalent to 2.5 MWe from a turbine with an inlet steam pressure of 4.4 bar-g. The heat from Solar was used to increase the steam flow rate. They found that the solar efficiency significantly decreases when HTF temperature is higher than 225 ^{o}C.

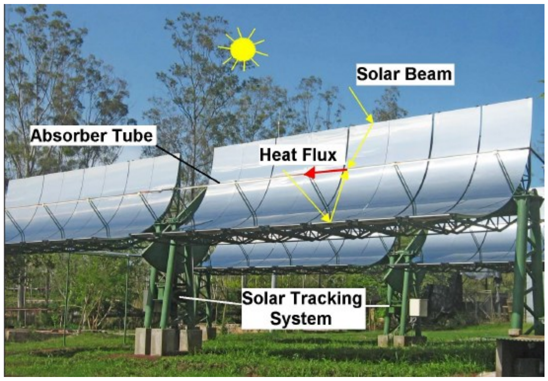


Figure 16: Parabolic Trough used in the Ahuachapán Geothermal Field (Alvarenga et al., 2008)

Enedy and Rudisill (2009) reported that the financial return on investment on a 999.9 kW solar array for partially powering the pump station at The Geysers geothermal field was positive. PV panels, as shown in **Figure 17**, were used to generate electricity in this project.

Figure 17: the PV system with the pump house (in back) for the Southeast Geysers Effluent Pipeline (Enedy and Rudisill, 2009)

In 2012, Enel Green Power developed a commercial scale hybrid geothermal-solar PV plant in Nevada and recently expanded it with a concentrated solar thermal system (DiMarzio et al., 2015). 26 MW of solar PV power was added to the 33 MW geothermal binary plant which was commissioned in 2009. One of the purposes was to use and tailor the solar PV power to complement the geothermal plant output degradation during hot summer temperatures. The geothermal and solar PV output net average production for a typical spring day is shown in the **Figure 18**.

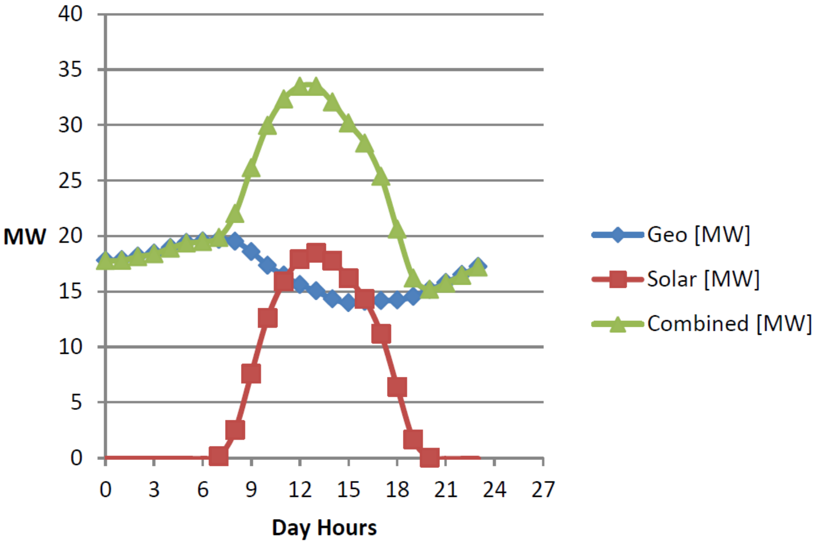


Figure 18: Geothermal and solar PV output net average production for a typical spring day (DiMarzio et al., 2015)

6 ADVANTAGES OF HYBRID SOLAR-GEOTHERMAL POWER SYSTEMS

According to the reports and literature available, there are many benefits if solar and geothermal heat sources are combined in an optimized way. The advantages of hybrid solar-geothermal power plants are:

- Increase the temperature or the steam flow rates of relatively low cost geothermal fluids.
- Improve the utility efficiency of the geothermal power plants because of the increased temperature.
- Geothermal fluids can be served as the storage of solar energy.
- Increase the capacity factor of geothermic power plants by increasing the amount of steam generated with the addition of solar heat.
- Match the power load better than standalone systems. The power load is usually higher during the day time than night time, which is exactly the change trend of the power output of hybrid solar-geothermal power plants.

- Improve land use for gathering energy sources above and below ground. Solar systems need many more areas than geothermal power plants for the same power output.
- Prevent the deposition of some salts because the salt solubility increases with temperatures.
- Reduce the risk of uncertainty in geothermal resources and reservoir performance decline over time.
- Decrease the operation, maintenance and the overall costs in a long term under many specific conditions.

7 DRAWBACKS OF HYBRID SOLAR-GEOTHERMAL POWER SYSTEMS

The disadvantages of hybrid solar-geothermal power plants are listed as follows:

- The complexity of power generation systems is increased, which may bring about the maintenance difficulty.
- The operation of a power plant sometimes requires constant monitoring of the well mass flow rate according to the availability of thermal energy coming from the solar field, which in practice is complex.
- The initial cost is high and it is not cost-competitive in a short term.
- The cost of the hybrid solar-geothermal systems depends on many factors. The low operation pressure and low temperature in geothermal fields demands a large solar energy to produce steam, which impacts the solar field size and so the capital investments.

8. CONCLUSIONS

According to the review and analysis, the following preliminary remarks may be drawn:

(1) It is possible to integrate geothermal and solar energies worldwide because there are many areas where have both high heat flow flux and surface solar radiation.

(2) The low-temperature geothermal fluids could be heated up by the high-temperature solar energy. The low capacity factor problem of solar energy could be compensated by the geothermal energy with a high capacity factor. The quality of both geothermal and solar energies may be upgraded by optimized hybrid configurations.

(3) Hybrid solar-geothermal systems may perform better than stand-alone geothermal or solar power systems in terms of utility efficiency. The improvement depends on the hybrid configurations.

(4) Hybrid solar-geothermal system may be less cost-competitive than the stand-alone system in a short term after the installation while it may become more cost-competitive in a long term because of the accumulative higher power-output.

(5) Although the hybrid solar-geothermal power plants have many advantages, most of the current studies are focusing on conceptual and theoretical aspects without many projects completed for power generation. The main reason may be the high initial cost.

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