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Geothermal Power Generation: Reserves, Technology and Status Review

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Abstract — Growing energy demands and the desire to reduce pollution has increased consideration of unconventional power plant technologies. Electricity production through harnessing geothermal energy is one of the main technologies being explored as an option to replace fossil fuel technologies. Geothermal energy is plentiful and can be harnessed as a renewable source of energy with the use of a variety of systems and technologies. Multiple classifications of geothermal energy exist, that are dependent on the local conditions of high geothermal activity, as well as associated systems to accommodate the conditions for power production. This report explores and reviews geothermal power generation, including resources, energy conversion systems, world status, recent technological advancements and research.

Keywords — Geothermal energy, Geothermal Resources, Power Generation, Renewable Energy

1 INTRODUCTION

Since the industrial revolution there has been a large increase in energy consumption worldwide, a large portion being in the form of electricity produced through the use of fossil fuels.

Fossil fuel combustion is known to affect the environment negatively, while contributing to climate change through greenhouse gas emissions. Meeting growing energy demand through the use of fossil fuels will increase greenhouse gas emissions. Growing energy demands also cause stress on current fossil fuel reserves, with fossil fuel shortages predicted for the future [1]. Hammond [2] states that fossil fuel depletion and greenhouse gas emissions, contributing to global warming, are considerable factors for sustainable and environmentally benign energy systems. Efforts to reduce fossil fuel dependency and greenhouse gas emissions have led to the use of alternative energy sources for power production.

Power production using geothermal energy is a renewable technology that is receiving increased recognition as a viable option for reducing fossil fuel use. The Earth's crust contains a large amount of thermal energy, and the U.S. Department of Energy [3] states that geothermal energy resources exceed those of fossil fuels. Geothermal energy systems are more environmentally benign than fossil fuelled systems [3], [4]. Abundant reserves and low emissions make the use of geothermal energy an attractive choice.

Geothermal energy can be classified in three temperature categories: high, medium, and low [4], [5]. High and medium temperature resources are employed for power production and are created through the transfer of thermal energy from the molten core of the Earth to the Earth's surface or by localized decay. Thermal energy collects in areas of water or rock creating a localized concentration.

Since high and medium temperature resources are fed by energy from the Earth's core, they are often found at considerable depths and have unique characteristics depending on their location. The depth and characteristics of a geothermal resource directly affects the economic and technical feasibility of its use. Geothermal reserves found at reduced depths are advantageous and have proven to offer an economic source of energy for power production.

In this paper, recognized geothermal reserves and systems, and recent developments relating to geothermal power generation, are reviewed. The objective is to improve understanding of present and future technology and thereby enhance its adoption in appropriate applications.

2 GEOTHERMAL POWER PRODUCTION

In 1904 the first geothermal power generating plant was tested at the Larderello dry steam field, in Italy. Originally the plant was able to power only four light bulbs. In 1911 the world's first industrial geothermal power plant began operation, at the same location. This was the only industrial plant until 1958, when another plant was built in New Zealand [5], [6]. Until 20 years ago little progress has been made in geothermal power production, but interest has increased significantly in recent decades.

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The basis of geothermal power generation is the use of heat from the ground to provide the required energy input to operate power generation cycles, similar to those used in conventional power plants. Heat originates from the core of the earth or from radioactive decay of naturally occurring minerals, which travels towards the Earth's surface and is stored in areas of the earth's crust creating geothermal reservoirs [7]. Typical geothermal reservoirs are locations with concentrations of high temperature surroundings that can produce liquid or vapor between 100°C and 350°C [4], [8].

To tap a geothermal reservoir, wells are drilled to the location of high temperature. Hot fluid is extracted from the specific location, or cool fluid is introduced from the surface and then extracted after absorbing thermal energy. The hot fluid is transported to a plant where it is used directly or indirectly in a thermal power generating cycle [9]. Plant systems and cycles differ, depending on location and reservoir temperature. Once used, the fluid is condensed and released above ground or re-injected into the reservoir [4].

3 GEOTHERMAL RESOURCES

A geothermal resource is a subsurface area with sufficiently high temperatures for power plant operation.

The Earth's core is on average approximately 6400 kilometers below the surface and has an estimated temperature of 4982°C [4]. Thermal energy is continuously transported towards the surface of the earth, mostly through conduction and convection; near the core rock melts to form magma and create convective currents that flow towards the surface. As the energy flows it is absorbed within solid rock formations creating high temperature regions, i.e., geothermal reservoirs [10], [11].

The movement of heat from the Earth's core creates of a temperature gradient within subsurface material. As the distance from the surface increases, the temperature increases; an average temperature increase of 3°C to 4°C is observed for every 100 meters of depth from the surface [11]. The gradient depends on such characteristics as porosity of the rock, degree of liquid saturation of the rock and sediments, thermal conductivity, heat storage capacity and vicinity of magma chambers or heated underground liquid reservoirs [7]. When a high temperature gradient is present, the depth of usable geothermal resources is small.

Presently drilling is the only way to determine whether a site contains an economically viable geothermal reservoir. The cost of drilling is substantial, which often discourages its use in the early stages of geothermal exploration especially when risks are significant of not finding viable reservoirs [11]. To reduce risk, geo-scientific surveys and studies of various types (e.g., geological, geochemical and geophysical) are conducted to predict appropriate locations [12]. Techniques used for oil and gas exploration sometimes prove useful in geothermal exploration, although they do not provide the same degree of confidence due to differences between oil and geothermal reserves [11].

In the past geothermal reservoirs were discovered through the observation of surface manifestations, indicating high temperature geothermal activity nearby [8], including hot springs, fumaroles and boiling mud pits. Such phenomena are common around the world, but represent a very small portion of total geothermal reserves [12].

A high concentration of thermal energy is required to assure a practical lifetime for a geothermal reservoir. If a reservoir is too small its temperature decreases rapidly with heat extraction, resulting in low power production over the life of the associated power plant [10], [11]. Consequently, reservoirs are tapped and production wells are thoroughly analyzed before power plants are built. Such production well studies provide designers with the maximum amount of fluid that can be withdrawn from the well, allowing for the development of optimal designs in terms of life of a reservoir, plant size and other parameters [7].

Four types of geothermal resources currently are recognized as suitable or potentially suitable for geothermal power generation: hydrothermal, geopressured, hot dry rock and magma [4], [7], [10].

3.1 Hydrothermal Resources

The most common type of geothermal resource in use are hydrothermal, which are reservoirs formed by water percolating through the Earth's crust and accumulating in areas of fractured and/or porous rock. A hydrothermal reservoir is created as rock is heated by the thermal energy from the Earth's core, which is transferred to the water [3], [7] (Fig. 1). The fluid within these reservoirs is either hot brine, wet vapor (vapor-brine mix) or dry vapor.

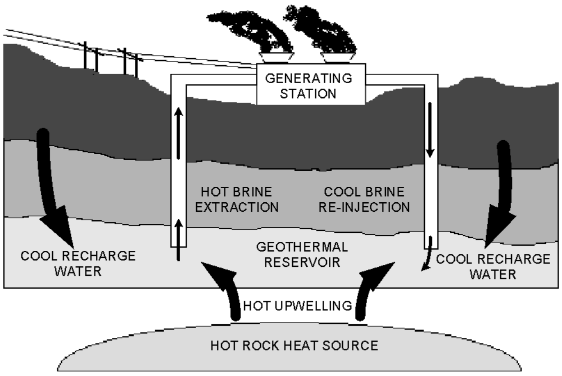

Fig. 1. Diagram of conventional geothermal resource and plant. Modified from Ref. [13].

The most common hydrothermal reservoirs

contain hot brine, and exist in relatively large quantities around the world, specifically in areas of high tectonic activity [11]. In North America there is a high concentration in the western United States, Alaska and the Yukon [4], [13].

The first geothermal plant utilized a dry vapor hydrothermal resource. To date all industrial and commercial geothermal power plants utilize hydrothermal resources [4], [11].

3.2 Geopressured Resources

Geopressured resources are deeply buried reservoirs of fluid that are confined within areas of impermeable rock and clay which inhibit fluid exchanges with the surroundings. Geopressured resources have higher pressures than usual at similar depths; in most cases the pressure exceeds the hydrostatic pressure and in some it approaches lithostatic pressures [14], [15]. These reserves are formed by sediment deposition in basins that have experienced rapid filling with sediments, where non-porous shale settles on top and traps the fluid and sediment to create a wet sand layer. Over time additional layers build up on top of this area creating a region of high pressure. Such reserves typically are found between 6 and 8 km underground, with fluid temperatures of 150°C to 180°C at pressures up to 130 MPa [7], [11].

An important feature of geopressured resources is that they contain various energy forms. Being at high pressures, such reserves often contain dissolved natural gas along with hot fluid. Dissolved natural gas originates from the metamorphic decay of various clays and substances that are common to geological formations that create geopressured resources. Also, natural gas is released from petroleum hydrocarbons contained within the fluid at certain pressures and temperatures [7]. Hence, geopressured reservoirs possess three types of energy that can be exploited: thermal energy from the fluid, hydraulic energy from high pressure and dissolved natural gas [11]

The fluid reaching the surface from a tapped reservoir contains kinetic and potential energy. A hydraulic turbine is used to extract mechanical energy from the fluid flow. As the fluid travels from a reservoir to the surface its pressure drops and the dissolved natural gas dissociates from the fluid [15]. At the surface the fluid is processed where the natural gas is extracted for use in a gas fired power plant or sale, improving project economics.

Geopressured reserves exist in multiple locations worldwide. The most recognized geopressured reserves are in the United States, around Texas and Louisiana and extending into the Gulf of Mexico [4]. These areas were explored for oil and gas when the reserves were found. Due to geological similarities geopressured fields are commonly found in locations with oil and gas reserves [15]. Although exploration indicated large quantities of dissolved natural gas, extraction as an isolated process was found to be uneconomical [11]. As part of an integrated process with three energy resources, however, extraction of dissolved natural gas potentially becomes economical.

A major test of using these reserves was conducted at the Pleasant Bayou site near Houston, where a 1 MW binary power plant, utilizing hot brine, was operated as a demonstration from January to May of 1990. Electricity was also produced by burning natural gas in a reciprocating engine. The concept was proven, but uneconomic at the time compared to conventional power generation. Currently no commercial geothermal systems utilizing geopressured reservoirs exist [7].

It is estimated that the geopressured formations in the Gulf of Mexico hold tens of thousands of megawatts of geothermal energy, and a hundred year supply of natural gas for the United States [12]. This resource may become economic and exploited if conventional energy costs increase or reserve utilization costs decrease sufficiently.

3.3 Hot Dry Rock Resources

Hot dry rock (HDR) geothermal resources, where heat is accumulated in rocks without any fluid to store or transport the heat, are present globally beneath the ground surface. However, the depth, temperature and physical properties of rock vary spatially. The U.S. Energy Research and Development Administration (ERDA) defines HDR geothermal resources as "heat stored in rocks within 10 km of the earth's surface from which energy cannot be economically produced by natural hot water or steam" [7]. The temperature of a HDR reserve is below 650°C (distinguishing it from magma resources).

Three main factors lead to the presence of a HDR resource [7]:

- Rock is near a location of volcanic activity, where heat is transferred from magma currents or stored in dry rocks surrounding magma bodies.
- Heat is conducted to a shallow crust overlying an unusually hot upper mantle (leading to a high temperature gradient).
- Heat is stored locally due to either a presence of highly concentrated radioactive minerals or large scale faulting.

To utilize a HDR reserve, water is pumped at high pressure down to the formation through injection boreholes. The water then passes through fractures in the rock, absorbing heat until it is forced out through a production well as hot water or steam.

Ideally a HDR reservoir has rock that contains natural fractures or is porous [10]. Natural rock fractures allow injected water movement without human intervention. Rock formations generally have low permeability, limiting reservoir capacity and heat transfer rates [4]; thus reservoirs would need to be manufactured. This operation can be accomplished through Enhanced Geothermal Systems (EGS), where the rock is artificially fractured to improve permeability. EGS is a new concept and is discussed further subsequently (see Recent Research and Developments section).

HDR is considered by many to have good potential for providing a large portion of the energy supply in the future. It is estimated on average that cooling one cubic kilometer of rock by 100°C would provide 30 MWe of geothermal power for thirty years [7]. The use of the HDR concept with geothermal power plants has been tested experimentally, demonstrating that use of these resources is feasible but not economically competitive at present [4], [7].

3.4 Magma Resources

Magma is the molten or partially molten rock at temperatures up to 1200°C that is found at depths between three and ten kilometers below the Earth's crust. This thermal resource usually is a commonly used indirectly, as it is the main energy source for other geothermal resources [5]. For utilization, a well would be drilled into bodies of magma close to the surface, and cold water pumped under high pressure into the magma, which solidifies and cracks due to thermal stresses. The water is forced through the cracks in the solid magma and returns to the surface as steam, which likely would be used directly in a Rankine power cycle [14].

Commercial magma systems do not exist and there has yet to be a large scale test of such a system. The main barrier to utilizing these reserves is that technology does not exist for extraction of heat from such areas. The environment involved is extremely high temperature and corrosive, prohibiting the use of standard engineering materials [14].

4 GEOTHERMAL ENERGY CONVERSION SYSTEMS

Geothermal energy conversion systems use geothermal fluids from a production well, process them for use, produce electricity and discard the used fluid. Geothermal power generating plants are similar to conventional power generating stations, with both utilizing such components as heat exchangers, condensers, turbines and ancillaries [3].

Fluid conditions within a production well can vary greatly with between geothermal reservoirs, with the temperature, pressure, and solute content of the fluid being site dependant. For systems to be practical and economic, designs for energy conversion systems should be matched to the reservoir conditions [10].

Hydrothermal resources are currently the only geothermal resources utilized in commercial power production. The extracted geothermal fluid is dry steam, a steam-brine mix, or hot brine [3], and the corresponding commercial plants that use these fluids are categorized as dry steam plants, flash steam plants, and binary power plants, respectively.

4.1 Dry Steam Power Plants

In dry steam plants, steam with very low moisture content (vapor dominated) is extracted from a reservoir and piped to a plant, where it is input to a turbine (Fig. 2). The turbine exhaust is condensed and either released to the environment or reinjected into the reservoir. Dry steam plants are the simplest of the geothermal power plants employed today.

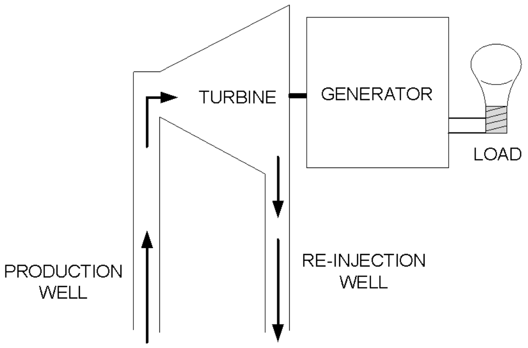

Fig. 2. Basic layout of a dry-steam geothermal power plant.

As of 2004 dry steam plants accounted for about 14% of all the geothermal plants. On average a dry steam unit in operation in 2004 had an electrical capacity of 39 MW. Globally, dry steam plants have an estimated electrical capacity of 2,460 MW and contribute approximately 28% of geothermal power generation [14]. Dry steam plants have higher capacities and efficiencies than other geothermal plant arrangements, with energy efficiencies typically between 10% and 17%.

The greatest barrier to greater use of dry steam plants is that they are restricted to few geographic areas around the world. Also, these systems require high temperature fluid with low concentrations of dissolved minerals; dissolved matter promotes corrosion, scaling, low plant efficiency and, possibly, harmful emissions. Reserves with such fluids exist in limited locations and for the most part are being exploited already [7], [15].

4.2 Flash Steam Power Plants

In flash steam plants are the most common type of geothermal power plant arrangements, due to the abundance of the resources it they utilize. Flash plants use liquid dominated wet steam from hydrothermal resources with temperatures in excess of 180°C. Hot fluid flows through a production well under its own pressure, which decreases as it approaches the surface; as the pressure decreases a portion of the fluid flashes into vapor [9]. At the plant the pressure is reduced through an expansion valve that flashes the fluid further. The vapor and liquid in the resulting vapor/liquid mixture are separated, and the vapor passes through a turbine (Fig. 3) [3], [4]. At turbine exit, the remaining vapor is condensed and either released to the environment or re-injected with the separated liquid into the reservoir. Re-injection is common in new plants as it reduces emissions significantly [9].

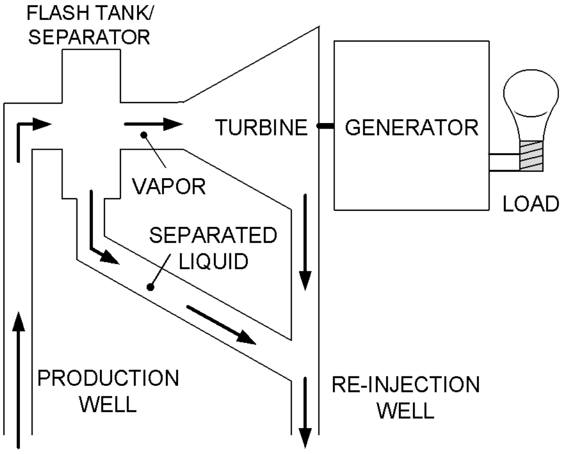

Fig. 3. Basic layout of a single flash-steam geothermal power plant

Approximately 135 flash steam units were in operation in 2004 in 18 countries. Unit capacities ranged from 3 MW to 90 MW, with an average of 28 MW globally. These plants account for 28% of all the geothermal power plants in operation and constitute 40% of the total installed geothermal power plant capacity worldwide [14].

A more complex version of the flash steam plant exists: the double-flash geothermal power plant. It is similar to the single flash plant, but the separated liquid is exposed to a second flashing and separation process, creating vapor at lower pressure to drive a low pressure turbine. Plant output generally increases by 15-25% when a plant is modified from single to a double flash, for the same geothermal resource and fluid conditions. Plant capacities range between 4.7 MW and 110 MW, with an average of 30 MW globally. As of 2004, 70 double flash units were operating in nine countries, comprising approximately 15% of all the geothermal plants worldwide [9], [14]. Although capacity increases with a double flash arrangement, complexity, maintenance and cost also increase. Triple-flash units are beginning to be implemented but require a substantial increase in plant output in order to be economic.

4.3 Binary Power Plants

Binary geothermal power plants are increasingly being utilized and operate on the binary cycle, also known as the organic Rankine cycle. The working fluids used in these systems have low boiling points; the organic fluid used depends on the temperature of the geothermal reservoir which must be sufficient for boiling the working fluid. Typical working fluids used with this application include propane, isobutene, isopentane and ammonia [7].

Binary power plants use fluid filled reservoirs with temperatures between 85°C and 150°C, where the fluid cannot produce sufficient vapor to operate a flash plant. The plant is essentially composed of two closed loops: one including the geothermal fluid flowing from the reservoir to a heat exchanger and the other including a working fluid that is boiled in the heat exchanger, drives a turbine, condenses and returns to the heat exchanger (Fig. 4) [4], [9].

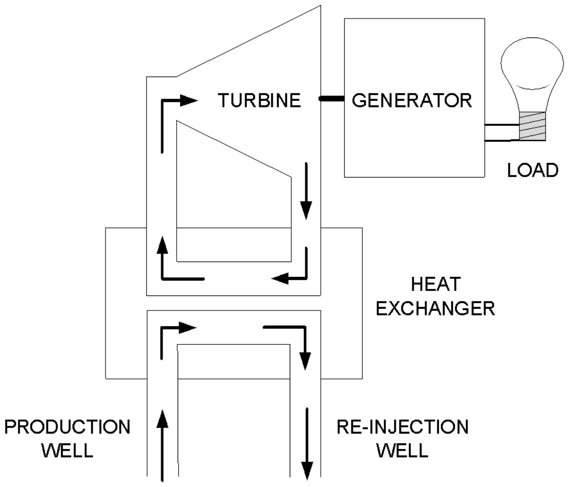

Fig. 4. Basic layout of a binary cycle geothermal power plant

As of 2004, 155 units were in operation worldwide, with an average unit size of 1.8 MW and a total generation capacity of 256 MW [14]. This total accounts for 33% of the installed geothermal power plants, but only 3% of the geothermal power capacity. These systems have low energy efficiencies (2.8%-5.5%), due to their low operating temperatures and indirect use of thermal energy.

Binary plant configurations could potentially contribute significantly to the world energy supply, as much larger quantities exist of low temperature rather than high temperature resources [9]. This resource abundance allows binary cycle plants to be used to generate power in smaller quantities, but at numerous locations.

An important advantage of binary power systems is that they have little to no emissions during operation. The two closed loops ensure that there is no interaction between the geothermal fluid and the working fluid; consequently the geothermal fluid is never exposed to the atmosphere using re-injection [4].

5 WORLD STATUS

Until 1939, Italy was the only country utilizing geothermal energy for power generation, but during the Second World War many of its plants were destroyed. After the war the plants at Larderello were rebuilt and many other countries began to recognize the advantages of using geothermal energy, largely because geothermal power was seen to be economically competitive compared to conventional power production methods and able to reduce energy imports [7], 16].

Since 1945, geothermal power use has grown slowly, with the highest annual growth rate being 11.6%, which occurred from 1979 to 1990. The current annual growth rate is about 3-4% [6], [9], [14].

Approximately 468 geothermal power generating units, spread between 24 countries, currently exist [16]. The plants have a combined net electrical output of roughly 9055 MW (Table 1). Their annual electrical energy production is approximately 79,300 GWh, which is less than 0.4% of the world's electricity supply [6], [7]. Though small in comparison with other power generation methods, the contribution of geothermal power generation in some countries is substantial, e.g., geothermal energy supplies 14% of the total energy use in Iceland, 14% in El Salvador, 13% in the Philippines and 11.2% Nicaragua[7], [13], [16].

. For developing countries geothermal energy could supply a large portion of the electricity required for further development

Table 1. Approximate installed geothermal generating capacities worldwide, in 2005 [6], [7], [15], [16]

Country	Number of Commercial Units	Power Production Capacity (MW$_e$)
U.S.A	187	2560
Philippines	57	1980
Mexico	37	953
Indonesia	15	810
Italy	33	795
Japan	22	537
New Zealand	33	453
Iceland	17	230
Costa Rica	6	163
El Salvador	5	160
Kenya	8	127
Russia	8	82
Nicaragua	4	78
China	13	32
Guatemala	8	29
Turkey	1	20
Portugal	5	16
France	2	15
Ethiopia	1	7
Papua New Guinea	2	6
Austria	1	1.3
Thailand	1	0.3
Germany	1	0.2
Australia	1	0.2
Total	468	9055

Although the prospects for geothermal power generation are good, it is noted that some of the main geothermal fields have decreasing resources, resulting in lowered plant capacity. Many nonetheless feel that geothermal electricity use will continue to increase worldwide, with the introduction of new exploratory and developmental technology, such as HDR resources and the development of EGS technology [6].

6 RECENT RESEARCH AND DEVELOPMENTS

Research and development into geothermal power generation technology and systems is ongoing and can be divided into two types: geothermal resources and geothermal generating plants. Selected examples of recent developments in both these categories are discussed here.

6.1 Geothermal Resource Developments

Enhanced Geothermal Systems

Enhanced Geothermal Systems (EGS), also known as Engineered Geothermal Systems, involve the creation of artificial reservoirs to exploit otherwise unusable geothermal resources. Conventional wells are drilled into naturally fractured and/or porous, high-temperature rock, but naturally occurring geothermal reservoirs are limited in size, quantity and lifetime [8]. EGS improves or expands current reservoirs and creates new ones through increasing rock permeability. The United States Department of Energy defines EGS as "engineered reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources" [11], [12].

Over time, minerals found in geothermal fluids can accumulate in reservoirs, collecting in fractures and reducing permeability. This phenomenon affects the amount fluid extractable and the heat transfer, especially in old reservoirs. To offset this challenge, cold chemically mixed water is injected into the reservoir under very high pressure. The process causes the fractures to (1) widen, returning plant production to normal or enhancing it, and/or (2) extend, substantially increasing their size so that more wells can utilize a single reservoir [11].

EGS is also being explored as a means to increase the utilization of HDR resources through creating new reservoirs. An EGS can be created in a hot dry rock reservoir in the following manner [3]:

1. A well is drilled into an expected reserve of HDR.
2. A mixture of cold water and corrosive

chemicals are injected into the well at very high pressure.

3. The combination of hydraulic, thermal and chemical processes causes the rock to fracture, and pre-existing fractures to widen and extend (ideally the fractures interconnect, creating a reservoir of adequate volume).
4. A second well is drilled to intercept the newly created fractures, allowing, if successful, water to be recovered via the second well after first being pumped down the first well and through the fractures where it is heated.
5. Once injection and production wells are in place, other wells tapping into the new reservoir can be added so that the optimum power generation can be generated from the reservoir.

Several successful tests of various EGS components have been performed, but currently no full scale EGS has been used to generate electricity for an extended period of time as several technical and economic issues remain unresolved [11]. An increasing number of government and private organizations have made EGS a priority and are working on developing the technology, including ongoing projects in the United States, Australia, France, Germany, Switzerland, the Czech Republic, the United Kingdom and elsewhere [12].

Supercritical Volcanic Geothermal

A supercritical fluid, which is a substance at a temperature and pressure above its thermodynamic critical point, behaves as both a liquid and a gas, allowing it to diffuse through solids like a gas but dissolve minerals like a fluid. Water is in a supercritical state when it reaches both a pressure of 218.3 atm and a temperature of 374.1°C [12]. Volcanic regions provide appropriate conditions for the existence of such fluids within reachable subsurface depths. When a reservoir of supercritical fluid is tapped, the fluid naturally moves up the well bore, providing a fluid for power production with an enthalpy much higher than that of fluids from conventional dry steam reserves. Most research on supercritical geothermal fluids has been conducted through the Iceland Deep Drilling Project (IDDP) [12], which has shown that a plant could deliver a minimum of an order of magnitude more power per well compared to other geothermal resources (Table 2). The main barriers to the development and commercialization are technological, similar to those limiting the use of magma reserves.

Oil/Gas Co-Production

During the extraction of oil and gas, hot contaminated water at temperatures between 120°C and 200°C often exits as waste. The disposal of this potential by-product is costly. But the fluid arriving at the surface, a mixture of hydrocarbons and water, could be separated and used as a thermal energy input to a binary cycle power plant. The major benefit of co-production is that geothermal energy can be harnessed at lower cost since the initial installation is shared with the oil and gas extraction operations. Also, such co-production could allow provide the increased revenue needed to make more fossil fuel reserves economical [12].

Table 2: Comparison of production features of conventional dry-steam and supercritical volcanic wells [13]

	Conventional Dry Steam Well	IDDP* Well
Downhole temperature (°C)	235	430-550
Downhole pressure (bar)	30	230-260
Input volumetric flow rate ($m^3 s^{-1}$)	0.67	0.67
Electric power output (MW_e)	~5	~50

* Iceland Deep Drilling Project

This process could potentially supply most oil extracting countries with a reasonable base load supply of electricity. In the United States the potential exists for the generation of tens of thousands of megawatts of power from the water coming from current oil and gas wells. These systems have not been commercialized and are in the early development phase. Test facilities exist and are under development, including a major one at the Naval Petroleum Reserve-3 within the Rocky Mountain Oilfield Testing Center in central Wyoming, U.S. [12].

6.2 Geothermal Power Plant Developments

Mixed Working Fluids (Binary Plants)

Studies have shown that using hydrocarbon fluid mixtures in binary-cycle power plants can reduce boiler and condenser inefficiencies. Typical working fluids for conventional binary cycles are propane, isobutene, isopentane and ammonia [7]. The same cycle arrangement could be used with a mixed working fluid such as ammonia and water (Kalina thermodynamic cycle). The main improvement is associated with the fact that, for a given pressure, boiling of a mixture occurs over a range of temperatures, unlike pure substances that boil at a single temperature, allowing for more efficient heat input. Testing is currently taking place in Iceland to explore the actual improvements in efficiency resulting from using a mixture [3], [7].

Equipment Lining

Geothermal fluids are normally highly corrosive because they contain dissolved minerals from reservoir rocks. This corrosiveness reduces the lifetimes of many of the components in geothermal power plants, necessitating the use of expensive corrosive resistant materials. To develop an economic alternative, research has been conducted on coatings for geothermal applications [3].

Research is currently ongoing into developing polymer-based coatings that can be applied to inexpensive carbon steel. For example, Brookhaven National Laboratory (NBL) and National Renewable Energy Laboratory (NREL) have developed a coating that has been commercially successful in refinery operations. Currently NBL and NREL are working on methods of application, lined heat exchanger design, and field tests. These results may be transferrable to geothermal power applications.

A substantial amount of scale usually builds up within geothermal plant equipment, reducing flow rates in pipes and components and fouling heat exchangers. The expensive materials used to provide corrosion protection do not always prevent scaling. Some coatings may help mitigate this problem.

Air-Cooled Condensers

Geothermal power generation has low operating temperatures compared to conventional fossil fueled or nuclear power plants. Because of their low operating temperatures, geothermal power plants must reject approximately 90 percent or more of the thermal energy in the geothermal fluid during operation and reduced heat rejection can have a considerable impact on overall plant performance [3].

Air cooled condensers are common to remote power plants without sufficient make-up water. With conventional air cooled condensers, the power output of a geothermal power plant varies about 1% for every degree Centigrade change in the condensing-air temperature. This effect is more significant in lower temperature plants, which are more sensitive to air and condensing temperature because of their large heat rejection requirements [3].

Large air flow rates are required for air cooled condensers, necessitating the use of large fans that consume up to 10% of the gross power output of the plant. Research is presently ongoing at the National Renewable Energy Laboratory and the Idaho National Engineering and Environmental Laboratory [3] into designs that improve performance, including efforts on fin design to enhance condenser heat transfer efficiency. Design concepts include perforated fins and the introduction of winglets on fins, and are aimed at lowering air flow rates and consequently power requirements as well as reducing the cost of the generated electricity.

Researchers also are examining ways to combine some degree of evaporative cooling with air cooling so as to provide constant heat removal and plant electrical output for hot weather applications when air-cooled condenser performance drops [3].

Alternative Non-Condensable Gas Removal Methods

In steam and other vapor cycles, it is important to remove the non-condensable gases that can accumulate in the system. Otherwise, turbine back pressure can increase, reducing turbine output. Also non-condensable gases can coat heat transfer surfaces, reducing heat transfer efficiency and increasing corrosion [3].

Researchers at Idaho National Engineering and Environment Laboratories are working on innovative separation technologies, such as selective membranes, for low energy removal of non-condensable gases from binary cycle power plants. These membranes should reduce the amount of fluid loss resulting from venting the gas, while allowing for continuous ventilation. Full scale testing is ongoing in commercial binary power plants [3].

Advanced Geothermal Energy Conversion Systems

Researchers around the world are seeking geothermal energy conversion systems with increased efficiency and output. New system arrangements are being developed, which often are variations and combinations of common geothermal plants. Several such systems under developed are described below.

Combined flash-binary system: This system combines a flash steam plant and a binary cycle, which results in reduced losses and increased power. In the flash system vapor and liquid are separated and the vapor is used in a turbine while the liquid is used to boil an organic fluid in a binary cycle to drive another turbine. An important advantage to this innovation is that it can be incorporated into pre-existing flash steam plants [8].

Integrated flash-binary system: Similar to the combined flash-binary system the separated liquid provides heat to drive a binary cycle in this integrated system. Further, the separated vapor passes first through a turbine and then through a series of heat exchangers connected to another binary cycle. The heat from the spent vapor is utilized by the second binary cycle and condenses (without the need for a conventional condenser). This system exhibits little material and thermal emissions to the environment [8].

Fossil fuel-superheat systems: This concept, which is applicable to flash-steam systems, involves the use of a supplemental fossil fueled superheater to superheat the vapor [8]. Turbine output increases as a consequence and the potential is created for additional conventional multistage turbines. However, emissions are also increased. Nonetheless, fossil-fuel super heating may increase the utilization of geothermal resources from smaller reservoirs, with increased efficiency and output [8].

7 CONCLUSIONS

Many approaches and options exist for enhancing the utilization of geothermal energy. Geothermal energy systems are diverse in terms of configuration and can accommodate a variety of resources at many locations globally. It is important to determine the most appropriate system for a given application, considering such factors as effectiveness, efficiency, economics and emissions. Geothermal energy technology and applications are growing modestly, in part because they provide an attractive alternative for meeting energy demands. Increasing attention to economic and environmental concerns will likely increase the contribution of geothermal energy to the future global energy supply.

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