TECHNOLOGICAL REVIEW OF GEOTHERMAL ENERGY UTILIZATION

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ABSTRACT

Although geothermal energy is acknowledged and well positioned within the renewables, the recent worldwide growth is rather slow. While wind and solar power production demonstrate exponential growth, geothermal energy utilization develops rather linearly. The universally deployable Enhanced Geothermal Systems technology could speed geothermal growth. To achieve this objective, substantial research and development efforts, technological and educational improvements are required all over the world to solve still open problems. Some possible approaches are and perspectives are reviewed and outlined in this conference paper.

INTRODUCTION

Geothermal energy is one of the contributors to any future energy mix. Many advantages of geothermal energy can be enumerated: great, still only marginally developed potential, available nearly everywhere, environmental friendly and economically rewarding energy ***(Rybach 2010)***. Technological developments like Enhanced Geothermal Systems are envisaged as the main key to accelerate increase on geothermal development. Geothermal direct use development is mainly governed by the increasing development of heat pump systems. In some countries such systems demonstrate exponential growth ***(Horne and Szucs 2007)***. The future prospects of geothermal energy in general will depend on the future pace of growth. If exponential growth is achieved, geothermal energy can become a more significant player in the future energy supply schemes.

Rock and groundwater temperatures play significant roles in the potential of geothermal energy (Bodvarsson, 1974). Based on the temperature distributions, identified hydrothermal systems are divided into three temperature classes: low temperature ($\leq 90\ ^0C$), moderate temperature (90 to 150 ^0C), and high temperature ($\geq 150\ ^0C$). The different temperature classes mean different opportunities in the practical utilization of geothermal resources.

GEOTHERMAL ENERGY

Geothermal energy is the internal energy of the Earth's crust. This geothermal energy originates from the original formation of the planet, from radioactive decay of minerals. Geothermal energy is cost effective, reliable, sustainable, and environmentally friendly, but has historically been limited to areas near tectonic plate boundaries. Recent technological advances have dramatically expanded the range and size of viable resources, especially for applications such as home heating, opening a potential for widespread exploitation. Geothermal wells release greenhouse gases trapped deep within the earth, but these emissions are much lower per energy unit than those of fossil fuels. As a result, geothermal power has the potential to help mitigate global warming if widely deployed in place of fossil fuels. The Earth's geothermal resources are theoretically more than adequate to supply humanity's energy needs, but only a very small fraction may be profitably exploited. Drilling and exploration for deep resources is very expensive. Forecasts for the future of geothermal power depend on assumptions about technology, energy prices, subsidies, and interest rates ***(Cataldi F. and Muffler P1976, Bobok E. 1987, Lorberer Á. 2005, Szanyi et al. 2009)***.

ELECTRICITY

The International Geothermal Association (IGA) has reported that 10715 megawatts (MW) of geothermal power in 24 countries is online in 2010. IGA projects growth to 18500 MW by 2015 ***(Bertani 2010)***, due to the projects presently under consideration, often in areas previously assumed to have little exploitable resource. In 2010, the United States led the world in geothermal electricity production with 3086 MW of installed capacity from 77 power plants. The largest group of geothermal power plants in the world is located at The Geysers, a geothermal field in California. The Philippines is the second highest producer, with 1904 MW of capacity online. Geothermal power makes up approximately 18% of the country's electricity generation.

Geothermal power plants were traditionally built exclusively on the edges of tectonic plates where high temperature geothermal resources are available near the surface. The development of binary cycle power plants and improvements in drilling and extraction technology enable enhanced geothermal systems over a much greater geographical range. Demonstration projects are operational in Landau-Pfalz, Germany, and Soultz-sous-Forêts, France, while an earlier effort in Basel, Switzerland was shut down after it triggered earthquakes. Other demonstration projects are under construction in Australia, the United Kingdom, and the United States of America.

Conventional binary geothermal power plants are a well-established technology to produce electricity from moderate-temperature resources between 93 °C and 149 °C. Hot water drawn up from underground reservoirs cycles through a heat exchanger, where it heats a working fluid that is kept physically separate. The working fluid, typically an organic chemical such as isopentane, boils at a lower temperature than water. As it vaporizes, the force of the expanding vapor spins a turbine that generates electricity. Supercritical binary plants use a similar setup. The only difference is that the working fluid is pumped up to a pressure above the fluid's "critical pressure" before it flows into the heat exchanger. At this supercritical pressure, the fluid does not vaporize at a specific temperature. Instead, it gradually transitions from a liquid to a high-density vapor that gets lighter and lighter as it heats up ***(Di Pippo R. 2004, Kovács and Szanyi 2005)***. This lets the working fluid extract more heat from the hot water, increasing the power plant's efficiency.

The thermal efficiency of geothermal electric plants is low, around 10-23%, because geothermal fluids do not reach the high temperatures of steam from boilers. The laws of thermodynamics limit the efficiency of heat engines in extracting useful energy. Exhaust heat is wasted, unless it can be used directly and locally, for example in greenhouses, timber mills, and district heating. Because geothermal power does not rely on variable sources of energy, unlike, for example, wind or solar, its capacity factor can be quite large – up to 96% has been demonstrated. The global average was 73% in 2005.

DIRECT APPLICATIONS

Direct use geothermal energy is one of the oldest, most versatile and also the most common form of utilization of geothermal energy. Lund et al. (2010) gave a detailed worldwide review about direct utilization of geothermal energy. Lund at al. (2010) reported 50583 MW capacity worldwide with a 0.27 capacity factor. Toth (2010) presented 654.6 MW direct-use capacity in Hungary with a 0.47 capacity factor. The growing awareness and popularity of geothermal heat pumps have headed the most significant impact on direct-use energy.

As it is written above, in the geothermal industry, low and moderate temperatures mean temperatures of 300 °F (149 °C) or less ***(Székely 1999)***. Low- and moderate-temperature geothermal resources are typically used in direct-use applications (Fig. 1.), such as district heating, greenhouses, agricultural drying, fisheries, mineral recovery, heat pumps, bathing and industrial process heating. However, some low-temperature resources can generate electricity using binary cycle electricity generating technology.

Fig. 1. Direct use geothermal energy utilization.

Approximately 70 countries made direct use of 270 PJ of geothermal heating in 2004. More than half went for space heating, and another third for heated pools. The remainder supported industrial and agricultural applications. Global installed capacity was 28 GW, but capacity factors tend to be low (30% on average) since heat is mostly needed in winter. The above figures are dominated by 88 PJ of space heating extracted by an estimated 1.3 million geothermal heat pumps with a total capacity of 15 GW. Heat pumps for home heating are the fastest-growing means of exploiting geothermal energy, with a global annual growth rate of 30% in energy production.

Direct heating is far more efficient than electricity generation and places less demanding temperature requirements on the heat resource. Heat may come from co-generation via a geothermal electrical plant or from smaller wells or heat exchangers buried in shallow ground. As a result, geothermal heating is economic at many more sites than geothermal electricity generation. Where natural hot springs are available, the heated water can be piped directly into radiators. If the ground is hot but dry, earth tubes or downhole heat exchangers can collect the heat. But even in areas where the ground is colder than room temperature, heat can still be extracted with a geothermal heat pump (Fig. 2.) more cost-effectively and cleanly than by conventional furnaces. These devices draw on much shallower and colder resources than traditional geothermal techniques, and they frequently combine a variety of functions, including air conditioning, seasonal energy storage, solar energy collection, and electric heating. Geothermal heat pumps can be used for space heating essentially anywhere ***(Rybach L.and Muffler L. 1981, Lund J. 1989, Szucs and Horne 2009)***.

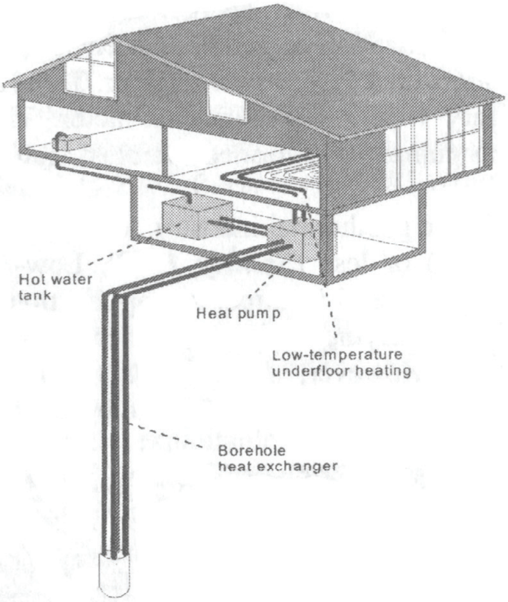

Fig. 2. The application of a heat pump systems for house heating (Lund J.W. 1989).

Geothermal heat supports many applications. District heating applications use networks of piped hot water to heat many buildings across entire communities. In Reykjavík, Iceland, spent water from the district heating system is piped below pavement and sidewalks to melt snow.

ENHANCED GEOTHERMAL SYSTEMS

Enhanced Geothermal Systems can play a significant role in the future of geothermal energy utilization ***(Tester et al.2006)***. EGS is an umbrella term for various other denotations such as Hot Dry Rock, Hot Wet Rock and Hot Fractured Rock. The EGS principle is simple (see Fig. 3). In the deep subsurface (150-200 Celsius) and extended fracture system is created or enlarged to act as a new fluid pathways and at the same time as a heat exchangers.

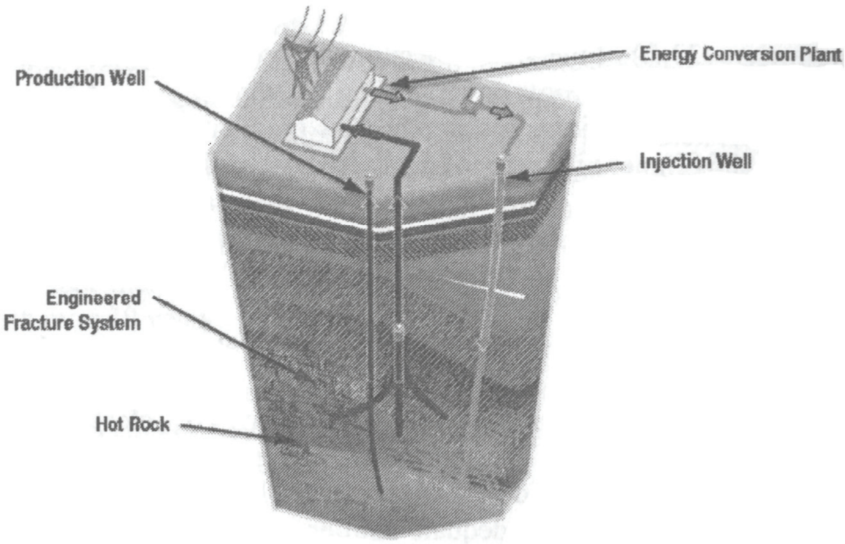

Fig. 3. The scheme of the EGS.

ENVIRONEMENTAL IMPACT

Fluids drawn from the deep earth carry a mixture of gases, notably carbon dioxide (CO_2), hydrogen sulfide (H_2S), methane (CH_4) and ammonia (NH_3). These pollutants contribute to global warming, acid rain, and noxious smells if released. Existing geothermal electric plants emit an average of 122 kilograms (269 lb) of CO_2 per megawatt-hour (MW·h) of electricity, a small fraction of the emission intensity of conventional fossil fuel plants.

In addition to dissolved gases, hot water from geothermal sources may hold in solution trace amounts of toxic chemicals such as mercury, arsenic, boron, antimony, and salt ***(Szűcs et al. 2009)***. These chemicals precipitate as the water cools, and can cause environmental damage if released. The modern practice of injecting cooled geothermal fluids back into the Earth to stimulate production has the side benefit of reducing this environmental risk (Fig. 4).

Direct geothermal heating systems contain pumps and compressors, which may consume energy from a polluting source. This parasitic load is normally a fraction of the heat output, so it is always less polluting than electric heating. However, if the electricity is produced by burning fossil fuels, then the net emissions of geothermal heating may be comparable to directly burning the fuel for heat.

Plant construction can adversely affect land stability. Subsidence has occurred in the Wairakei field in New Zealand and in Staufen im Breslau, Germany. Enhanced geothermal systems can trigger earthquakes as part of hydraulic fracturing. The project in Basel, Switzerland was suspended because more than 10,000 seismic events measuring up to 3.4 on the Richter Scale occurred over the first 6 days of water injection.

Geothermal has minimal land and freshwater requirements. Geothermal plants use 3.5 square kilometres (1.4 sq mi) per gigawatt of electrical production (not capacity) versus 32 and 12 square kilometres (4.6 sq mi) for coal facilities and wind farms respectively. They use 20 litres (5.3 US gal) of freshwater per MW·h versus over 1,000 litres (260 US gal) per MW·h for nuclear, coal, or oil.

AVAILABLE RESOURCES

The Earth's internal heat naturally flows to the surface by conduction at a rate of 44.2 terawatts (TW), and is replenished by radioactive decay of minerals at a rate of 30 TW. These power rates are more than double humanity's current energy consumption from all primary sources, but most of it is not recoverable. In addition to heat emanating from deep within the Earth, the top 10 meters (33 ft) of the ground accumulates solar energy (warms up) during the summer, and releases that energy (cools down) during the winter.

Beneath the seasonal variations, the geothermal gradient of temperatures through the crust is 25–30 °C (77–86 °F) per kilometer of depth in most of the world. The conductive heat flux is approximately 0.1 MW/km^2 on average. These values are much higher near tectonic plate boundaries where the crust is thinner. They may be further augmented by fluid circulation, either through magma conduits, hot springs, hydrothermal circulation or a combination of these.

A geothermal heat pump can extract enough heat from shallow ground anywhere in the world to provide home heating, but industrial applications need the higher temperatures of deep resources. The thermal efficiency and profitability of electricity generation is particularly sensitive to temperature. The more demanding applications receive the greatest benefit from a high natural heat flux, ideally from using a hot spring. The next best option is to drill a well into a hot aquifer. If no adequate aquifer is available, an artificial one may be built by injecting water to hydraulically fracture the bedrock. This last approach is called hot dry rock geothermal energy in Europe, or enhanced geothermal systems (see above) in North America. Much greater potential may be available from this approach than from conventional tapping of natural aquifers.

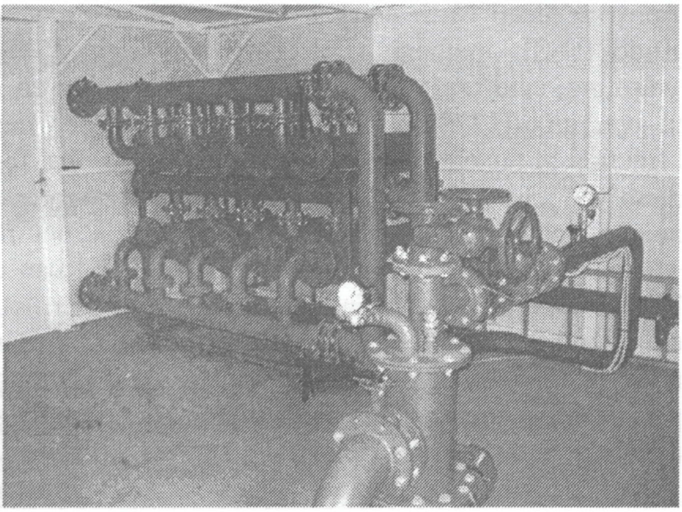

Fig. 4. An injection well for the cooled geothermal fluid.

SUSTAINABILITY

Geothermal power is considered to be sustainable because any projected heat extraction is small compared to the Earth's heat content. The Earth has an internal heat content of 10^{31} joules ($3 \cdot 10^{15}$ TW·hr). About 20% of this is residual heat from planetary accretion, and the remainder is attributed to higher radioactive decay rates that existed in the past. Natural heat flows are not in equilibrium, and the planet is slowly cooling down on geologic timescales. Human extraction taps a minute fraction of the natural outflow, often without accelerating it.

Even though geothermal power is globally sustainable, extraction must still be monitored to avoid local depletion ***(Bobok et al. 2010)***. Over the course of decades, individual wells draw down local temperatures and water levels until a new equilibrium is reached with natural flows ***(Tóth J.1999, Szucs et al. 2006)***. The three oldest sites, at Larderello, Wairakei, and the Geysers have experienced reduced output because of local depletion. Heat and water, in uncertain proportions, were extracted faster than they were replenished. If production is reduced and water is reinjected, these wells could theoretically recover their full potential.

Long term high or medium pressure reinjection into karstic and fissured rock formations performed at many locations at greater depth by both the petroleum and geothermal industry ***(Bobok et al. 1991, Tóth A. and Bobok E. 2008)***. The reinjection into porous layers seems to be a bigger technical challenge, therefore there are several projects running to investigate the clogging behavior of layers ***(Bálint et al., 2010; Papp – Vass, 2010; Kovács et al., 2010)***, despite the fact that there are sustainable operating doublet systems established on sandy formations with over 10 years of experience.

Such mitigation strategies have already been implemented at some sites. The long-term sustainability of geothermal energy has been demonstrated at the Lardarello field in Italy since 1913, at the Wairakei field in New Zealand since 1958, and at The Geysers field in California since 1960.

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