100 YEARS OF GEOTHERMAL POWER PRODUCTION

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INTRODUCTION

Electricity from geothermal energy had a modest start in 1904 at Larderello in the Tuscany region of northwestern Italy with an experimental 10 kW-generator. Today, this form of renewable energy has grown to 8771 MW in 25 countries producing an estimated 54,793 GWh/yr. These "earth-heat" units operate with an average capacity factor of 71%; though, many are "on-line" over 95% of the time, providing almost continuous base-load power. This electricity production is serving an equivalent 60 million people throughout the world, which is about one percent of our planet's population. The development of worldwide geothermal power production can been seen in Figure 1. The large downward spike in the production is the result of the destruction of the Italian field at the end of World War II–discussed later. Since WWII, geothermal power has grown at a rate of 7.0% annually. Electric power from geothermal energy, originally using steam from resources above 150°C, is now produced from resources down to 100°C using the organic Rankine cycle process in binary power units in combination with a district heating project.

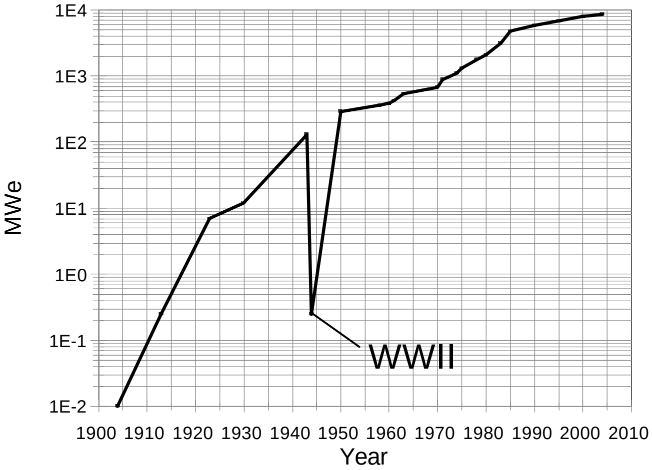

Figure 1. World geothermal power production 1904-2004.

THE EARLY YEARS – DRY STEAM DEVELOPMENT

Geothermal energy was not new to the Larderello area in 1904, as sulfur, vitriol, alum and boric acid was extracted from the hot spring areas, and marketed at least since the 11th century. In the late 18th century, boric acid was recognized as an important industry in Europe, as most was imported from Persia. Thus, by the early-1800s, it was extracted commercially from the local borate compound using geothermal heat to evaporate the borate waters in *lagoni* or *lagone coperto*--a brick covered dome (Figure 2). Wells were also drilled in the early-1800s in the vicinity of fumaroles and natural hot pools to access higher boron concentrations.

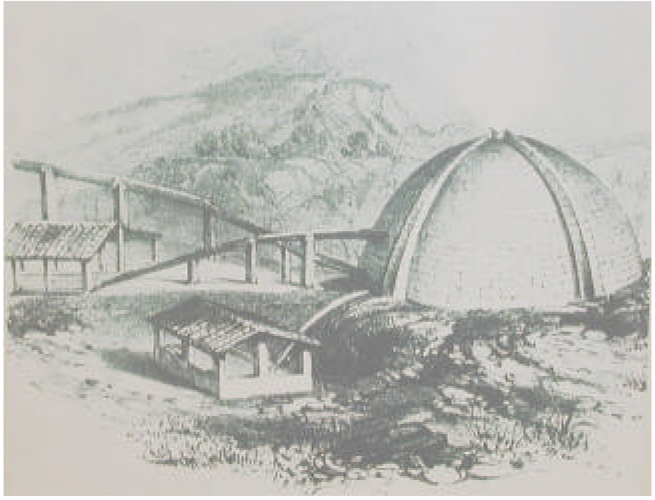

Figure 2. Covered lagoon ("lagone coperto"), Larderello, Italy, 1904 (courtsey of ENEL), 18th century.

In the beginning of the 19th century, the Larderello chemical industry came under the direction of Prince Piero Ginori Conti. He experimented with the use of geothermal steam as an energy source for electrical production. He carried out his investigations for several years and was rewarded with success in 1904, when five light bulbs were lighted using geothermal power. He used a piston engine coupled with a 10-kilowat dynamo; the engine was driven by pure steam produced in a small heat exchanger fed with wet steam from a well near Larderello (Figure 3). This engine used an "indirect cycle"–that is the geothermal fluid heated a secondary pure water to produce steam that moved the piston generator set. This was the first binary cycle–using a secondary working fluid. The "indirect cycle" protected the piston from the potential harmful affects of chemicals in the geothermal fluid.

Encouraged by the results from this "first" experiment, Prince Conti developed the "first" prototype of a geothermal power plant, which went into operation in 1905. This Cail reciprocating engine connected to a 20-kilowatt dynamo along with a Neville Reciprocating engine coupled to a second 20-kilowatt dynamo in 1908 enabled the electrification of Larderello's most important industrial plants and the main residential buildings. In 1913, the "first" commercial power plant, named Larderello 1, was equipped

Figure 3. ***Prince Ginori Conti and the 10-kW experimental power plant, Larderello, Italy, 1994 (courtesy of ENEL).***

with a turbine generating 250 kilowatts of electricity (Figure 4). It was designed and built by the Tosi Electromechanical Company to operate with wellhead fluid pressures of up to three atmospheres. The turbine was driven with pure steam obtained from a heat exchanger supplied by geothermal fluids from two wells at 200 to 250ºC. The energy from this plant was fed into a network serving all the chemical production plants and the main buildings of Larderello, and the villages of the region.

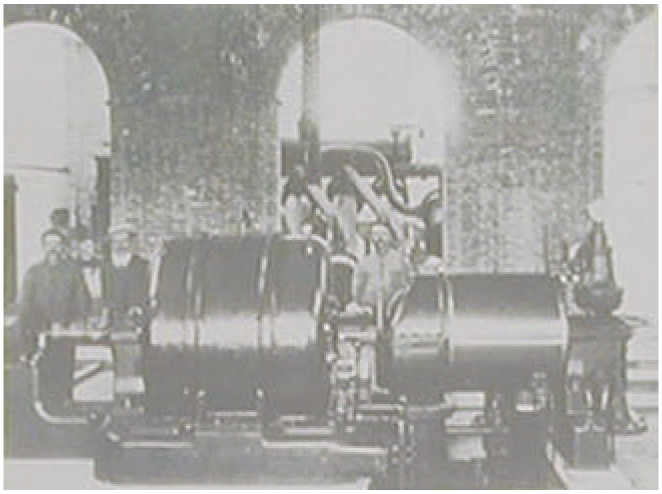

Figure 4. ***First commercial geothermal power plant, 250 kW, Larderello, Italy, 1913 (courtesy of ENEL).***

By 1923, two 3.5-megawatt turbo alternators units using the "indirect cycle" were installed, equaling most of the world's installed hydroelectric and thermal power plants of the time. The "first" pilot turbine fed directly with natural steam produced from the wells or "direct cycle," with a capacity of 23 kilowatts was installed at Serrazano in 1923 (Figure 5). Other "direct cycle" plants at Castelnouovo (600 and 800 kW) and at Larderello (3.5 MW) followed in the late-1920s. Thus by 1930, the installed capacity of this Boraciferous region was 12.15 MW of which 7.25 MW used the "indirect cycle" and 4.90 MW the "direct cycle." The "indirect cycle" plants remained popular, as the natural steam produced by the wells at Larderello was more valuable to extract valuable chemical by-products.

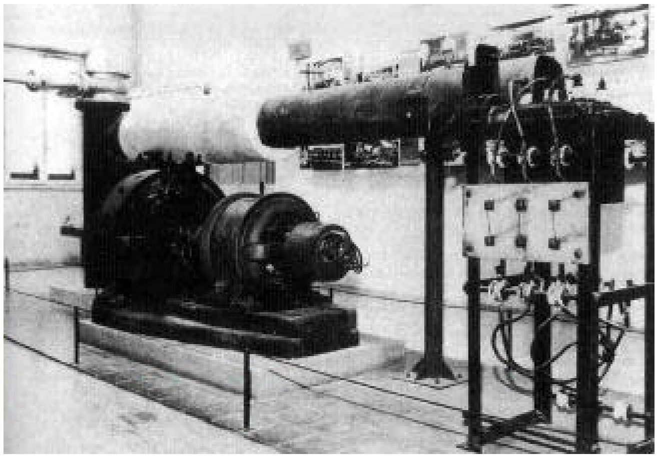

Figure 5. ***First "direct cycle" power plant, Serrazzano, Italy, 1923 (courtesy of ENEL).***

At the end of 1943, the total installed capacity in the Boraciferous region was 132 MW of which 107 MW used the "indirect cycle." The others were exhausting-to-atmosphere units or "direct cycle." Unfortunately in 1944, the Larderello region was directly involved in World War II. The Larderello power plants were strategically important because they provided electricity to the whole railway network of central Italy. In the spring of 1944, not far from Larderello, the retreating armies then in Italy formed the "Gothic Line' which separated the two warring groups. All the geothermal power stations and chemical plants in the area were heavily bombed and destroyed (Figure 6), and almost all the production wells were blown up by charges placed at the base of the master valve. Only the 23-kW "direct cycle" plant survived–which has been used at the company school to train technical personnel since 1925.

Figure 6. ***Geothermal plant at Larderello, destroyed in WWII, 1944 (courtesy of Ian Thain).***

With hard work, the capacity of the region was reconstructed and reached almost 300 MW by 1950, and has continued to increase over the years to the present installed capacity of 790.5 MW (699 MW operating capacity) producing 5.3 billion kWh in 2003. Many of these earlier plants have natural draft cooling towers that dominated the landscape. However, the newer plants are designed to have a low profile with forced draft cooling towers and are architecturally pleasing in appearance (Figure 7). Most of these plants are supplied by "dry steam" wells that produce only high-temperature steam–thus, eliminating the need to separate steam from water.

Figure 7. Geothermal power plant at Larderello today (courtesy of ENEL).

THE NEXT STAGE – WET STEAM DEVELOPMENT

A major geothermal resource with surface manifestations occurs at Wairakei, in the volcanic region of North Island of New Zealand. Thus, during World War II, New Zealand government scientists arranged for army engineers serving with the British 8th Army in the Italian campaign, to visit, inspect and report on the Larderello geothermal power development. Unfortunately, when they got to the plant in June 1944, it had been total destroyed.

Further interest in the development of the Wairakei field came in 1947 from severe electricity shortages following two dry years which restricted hydro generation and a desire by the government for the New Zealand electricity supply to be independent of imported fuel. Thus in 1948, New Zealand engineers were again sent to Larderello; where, they found rebuilt power plants producing over 140 MW and another 142-MW station under construction.

These observations of the power plants and geothermal use at Larderello were important; however, the New Zealand engineers faced a more complicated problem. Whereas, the Larderello resource was of the "dry steam" type, Wairakei was a "wet steam" resource. This meant that New Zealand technology had to be developed to separate the steam from the high-temperature hot water, produced at 13.5 barg (approximately 200°C). Thus, encouraged by the enthusiasm of the Italian engineers for geothermal power production, New Zealand decided to proceed with the development of Wairakei.

Drilling started in 1949, with some spectacular results (Figure 8), and 20 MW of power was proven by 1952. The initial plans for Wairakei was a combined power station and a heavy water plant. Conceptual designs in 1954 provided for a 47-MW power plant and production of 6 tonnes per year of heavy water. However, the heavy water plant idea was abandoned in 1956 and thus, the electric power station, Wairakei "A," was redesigned for two high pressure (HP) units of 6.5 MW, two intermediate pressure (IP) units of 11.2 MW, and three low pressure (LP) condensing units of 11.2 MW, giving a total installed capacity of 69 MW. The HP units used flashed steam at the wellhead of 13.5 barg, the IP units used 4.5 barg, and the LP units used a pressure of just above one barg. Due to increased output from the wells, two addition HP units of 11 MW and one LP unit of 11 MW were added to Wairakei "A" Station. Additional generating capacity was added through a "B" Station, which brought the entire development to 192.6 MW.

Figure 8. Drilling a Wairakei, New Zealand, 1950s (courtesy of Ian Thain).

In November of 1958, the first turbine-generator sets in "A" Station were synchronized to the national grid– the first geothermal electrical development in the world using "wet steam." High-temperature and pressure well water of five HP and two IP wells was fed into a flash plant; where, the pressure was reduced and a fraction of the water (15 to 20%) is flashed to steam in successive stages. The Wairakei Separator was developed for this task, which used a tangential entry bottom outlet tank. The center of the production field is approximately 3.5 km from the power station, and the steam is transmitted to the power station via three 760 mm and five 508 mm diameter pipelines (Figure 9). The power station is located adjacent to the Waikato River; where, the water is used for the direct contact condensers (Figure 10). Condensing the steam with river water exiting from the turbine reduces the pressure to a vacuum, thus increasing the pressure drop across the turbine, which in turn increases the output efficiency by as much as 100% compared to atmospheric exhaust plants.

With time, both double flash and triple flash turbines were installed to take advantage of the three-pressure levels of steam. Due to steam decline, the HP systems were derated and only IP and LP steam are only used today. Other fields at Ohaaki, Rotokawa, Mokai, Kawerau and Ngawha have been added to the geothermal power generating network with a total installed capacity of 453 MW (334 MW operational) of which 162 MW are at Wairakei. These plants operate with a capacity factor of 90 to 95%, providing the country with about 5% of its installed electricity capacity and 6% of the energy generated.

Figure 9. Wairakei, New Zealand geothermal field.

Figure 10. Wairakei power plant with Waikato River in background, New Zealand.

EARLY DEVELOPMENTS IN THE AMERICAS

United States

The surface geothermal manifestations at The Geysers geothermal field in northern California, was used by Indians who cooked with the steam and hot water at thermal features, and basked and bathed for pleasure and cures. In the mid-1880s, European settlers "discovered" the area and referred to them as the "Gates of Hades." The area was then developed for tourists with the construction of The Geysers Hotel. By the 1880s, the hotel had earned an international reputation as a resort and spa. By the early-1920s, the resource was being considered for electrical power generation. Well No. 1 was drilled in 1921 and at a shallow depth "…the well blew up like a volcano." A second well, also called No. 1, was drilled in 1922 and controlled, but not before it blew out "…mud, tools, rocks, and steam"--the world's first successful geothermal well drilled for electrical power generation outside of Larderello. Steam was found at about 60 meters–a second "dry steam" field. Well No. 2 was completed in 1923 to a depth of 97 m with a temperature of 153ºC and 4 barg pressure.

John Grant constructed the first power plant at The Geysers in the early 1930s near wells No. 1 and 2 (Figure 11). It was a 35-kilowatt power plant containing two reciprocating, steam-engine-driven turbine generators from General Electric. Various metal alloys were heated to determine the best composition for the turbine blades–as the steam was used directly in the turbine–unlike the early "indirect steam" plants at Larderello. A contract was signed to sell the energy to nearby Healdsburg City; however, an oil glut hitting the West Coast of the U.S., made electricity generated from this fuel more attractive. The contract was cancelled in 1934 and at least one of the two original generators was moved to The Geysers Resort. Here, electricity was generated for the hotel, cottages, bathouse and grounds into the 1950s.

Figure 11. First power plant at The Geysers, USA, early-1930s (courtesy of Geothermal Resources Council).

B.C. McCabe, who had created Magma Power Company, drilled the first modern well, Magma No. 1, in 1955. Dan McMillan Jr. created Thermal Power Company in 1956, and together these two companies began drilling five wells over the next two years--the deepest at 427 meters. In 1958, Pacific Gas & Electric Company (PG&E), a major public utility in Northern California, signed a contract to purchase steam from the Magma-Thermal venture, the first modern commercial agreement for geothermal electrical power generation in the United States. PG&E built power plant Unit 1 and began operating in 1960–the first modern power plant to generate electricity from geothermal steam in the U.S.

By 1968, the capacity of the field increased to 82 MW and wells reach to depths of 600 meters. In 1967, Union Oil Company of California became the field operator. By

1989, twenty-nine units had been constructed with an installed capacity of 2,098 MW. Today, Calpine Corporation and Northern California Power Agency (NCPA) operate the field with a gross capacity of 936 MW from 22 units (Figure 12). The reduction in capacity is due to the dismantling and retirement of a number of units, a reduction in steam production due to "too many straws sucking from the reservoir" and only about 20% of the produced fluid being injected back into the reservoir. This reduction is being reversed in several units by the Southeast Geysers effluent recycling system (SEGEP). This project and the more recent one from the city of Santa Rosa injects recycled wastewater into the reservoir to recover more steam for power production. A total of 820 liters/second is being injected through two large pipelines. To date, the inject water from SEGEP has brought back 77 MW and another 100 MW increase is expected from the Santa Rosa project.

Figure 12. Modern 110-MW plant at The Geysers, California.

The total installed capacity in the U.S. is now about 2400 MW (2020 operating) generating about 16,000 GWh/yr for a capacity factor of 90%.

Mexico

Another "dry steam" field was developed at Pathé in central Mexico. It was the first geothermal zone explored in the country between 1950 and 1955. In 1955, the first exploration well was drilled. Over 24 wells, to depths of 195 to 1288 meters, were drilled over the next four years, with three successful ones used to supply steam to a geothermal power plant of 3.5 MW in 1959. The geothermal plant, the first commercial one on the American Continent was operated until 1972, when it was abandoned and dismantled.

Later fields at Cerro Prieto, just over the U.S. border near Mexicali, and at Los Azufres, between Mexico City and Guadalajara were developed. They, with two other smaller fields, now have an installed capacity of 953 MW producing 6,282 GWh/yr (2003) for a capacity factor of 75%.

DEVELOPMENTS IN ASIA

Japan

Small geothermal test plants were made in Beppu (1925) and Otake (1926) geothermal fields on the southern island of Kyushu. These tests were based on the idea that "… volcanoes have enormous heat energy as seen in volcanic explosions." However, these trials were not successful.

The first commercial power plant was put online at Matsukawa on northern Honshu in 1966. This 23-MW condensing power plant uses a "dry steam" resource. Like Larderello and The Geysers, this is one of the few sites in the world where "dry steam" is available. This plant is the result of drilling in 1953 in the hope of discovering a source of hot water to supply a health spa. Instead, many of the wells produced steam at a depth of 160 to 300 meters. Before the power station was constructed, tests were run for 18 months on a 450-kW atmospheric exhaust (back-pressure) turbine to assess the corrosion effects on various materials from exposure to geothermal steam and its condensate. Five wells now provide superheated steam at a pressure of 4.4 barg and temperatures ranging from 153 to 190°C. A natural draft tower, the only one of its type in Japan, provides water for the direct-contact condenser (Figure 13).

Figure 13. First power plant in Japan, 23-MW "dry steam" at Matsukawa.

Japan now has an installed capacity of 535 MW with plants distributed over 14 fields producing 3470 GWh/yr (1999-2000) for a capacity factor of 74%.

Russia

The Paratunka geothermal power plant, located on the Kamchatka peninsula in eastern Siberia, was an attempt to provide cascaded energy for use in both electric power generation and direct-use. The power plant began operation in 1967 (Figure 14), and was the first to use an organic binary fluid in the power cycle, R-12 refrigerant, as the working fluid heated so that it vaporized by geothermal water at 81°C–which is the lowest geothermal fluid temperature recorded for electric power generation!

Figure 14. First binary plant using 81°C water at Paratunka, Kamchatka, Russia, 1967.

The power from the plant served a small village and several Soviet state farms. The geothermal water, after leaving the plant, was cooled to 45°C and used to heat the soil in a series of greenhouses. Finally, the cooling water leaving the condensers of the power plant was used to water the plants in the greenhouse, as the water from the local river was too cold to use. The power plant has since be shut down and dismantled, mainly due to leaks in the refrigerant piping.

A second plant at Pauzhetka in the same region was also put into production in 1967. This plant is a flash steam type using a cyclone separator, consisting of two units combining to 5 MW capacity. Nine wells are used to supply the plant, providing 2 to 4 barg pressure at 127°C. Another 11 MW have been added at Pauzhetka, along with 12 MW at the Severo-Mutnovka field. A 50-MW plant, consisting of two 25-MW units, at Mutnovsky was recently completed. Several smaller plants have been constructed on the Kuril Islands producing about 11 MW of power.

The total installed capacity of geothermal power plants in Russia, all located in the Kamchatka and Kuril Islands area, is 100 MW. These plants are critical, as all power in this area has to be produced for local plants. Due to heavy snowfalls in the area, the new plant at Mutnovsky, is designed to be remotely operated.

Peoples Republic of China

In the early-1970s, recognizing the importance of geothermal energy as an alternative source of electrical power, small experimental power units were established along the east coast of China at Fengshun in Guangdong Province in 1970 (0.3 MW flash steam), followed by small binary plants, around 0.3 MW capacity, using temperatures between 80 and 100°C at Wentang and Huailai in 1971, Huitang in 1975 and Yingkou in 1977. It was found that these units were too small and the efficiency too low due to the low temperature of the geothermal water, and all have been shut down. In 1977, a geothermal power plant was put online at Yangbaijing in Tibet supplying power to Lhasa. The installed capacity was 3 MW using 202°C fluid of which 5 to 20% was flashed to steam. Today, the installed capacity, all located in Tibet, is 32 MW supplying over 50% of the electric power to Lhasa.

ICELAND

The first geothermal power plant was placed online in 1969 at Namafjall in northern Iceland (also known as Kisilidjan). This 3-MW non-condensing (back-pressure) plant was purchased second-hand from England to reduce construction time (Figure 15). The energy is supplied to a diatomaceous earth drying plant located next to Lake Myvatn. Diatomaceous earth, with moisture contents at 80%, is dried in rotary drum driers and shipped to Germany to be used as a filter in beer production. Since it is a non-condensing plant, the efficiency is quite low, estimated around 14%; however, it is still in operation today.

Figure 15. First geothermal plant in Iceland at Namafjall, 1969, 3-MW non-condensing plant.

More recently, a combined heat and power plant has been built at Svartsengi in southwestern Iceland. The plant using 240°C fluid, provides 45 MW of electricity (8.4 MW of which is from binary units) and 200 MW of thermal energy to the surrounding community. The waste brine, high in silica content, is run into the adjacent lava field, sealing the bottom, thus providing a large heated pond. This pond today is famous as the Blue Lagoon, used by locals and tourists (Figure 16).

Figure 16. Combined heat and power plant at Svartsengi, Iceland–Blue Lagoon on right (courtesy of Haukur Snorrason, Reykjavik, Iceland).

RECENT DEVELOPMENTS

With the successes through the 1960s and early 1970s, geothermal power plant construction took off:

1975	– 30 MW at Ahuachapan, El Salvador
1980	-- plants in Indonesia, Kenya, Turkey, the Philippines and Portugal (Azores) were online.
1985	-- plants in Greece (Milos), France (Guadeloupe) and Nicaragua online.
1990	-- plants in Thailand, Argentina, Taiwan and Australia online – the plant in Greece shut down.
1995	-- plant in Costa Rica online.
2000	-- plants in Austria, Guatemala and Ethiopia online – the plant in Argentina shut down.
2004	-- plants in Germany and Papua New Guinea online.

Binary cycle plants using the organic Rankin cycle, became more popular–as they can use lower temperature water –down to 100°C. Since efficiencies are low and economics questionable (high parasitic loads) at these temperatures, these plants are often constructed in concert with a district heating system. These plants are also modular, generally in sizes less than one megawatt; thus, allowing for rapid installation. Examples of these new installations are as follows:

Austria

A one-megawatt binary unit at Altheim using 106°C fluid at 100 liters/second from a 2,270-meter deep well, also supplied 10 megawatts of thermal energy to the local district heating network (Figure 17). A second power plant-district heating project is at Bad Blumau in eastern Austria providing 250 kW of electric power from a binary plant using 110°C water, and then supplies 2.5 MW of thermal power with the waste 85°C water to the hotel and Spa Rogner.

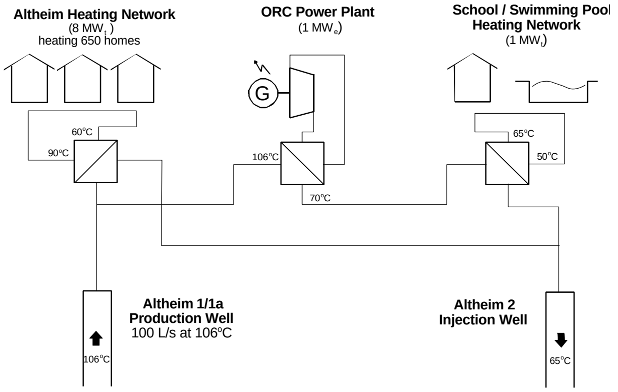

Figure 17. Combined heat and power plant at Atlheim, Austria.

Thailand

A 300-kW binary plant using 116°C water provides power to the remote village of Fang (Figure 18). In addition hot water is also used for refrigeration (cold storage), crop drying and a spa. The power plant provides electric energy at a rate of 6.3 to 8.6 US cents per kWhr, replacing a diesel generator that cost 22 to 25 US cents per kWhr.

Figure 18. Binary power plant, 300 kW, at Fang, Thailand (courtesy of ORMAT).

Germany

At Neustadt Glewe in north Germany, a well at 100°C provides energy for a 210-kW binary plant and 11 MW thermal to a district heating system (Figure 19). This is the lowest temperature binary plant operating in the world at present.

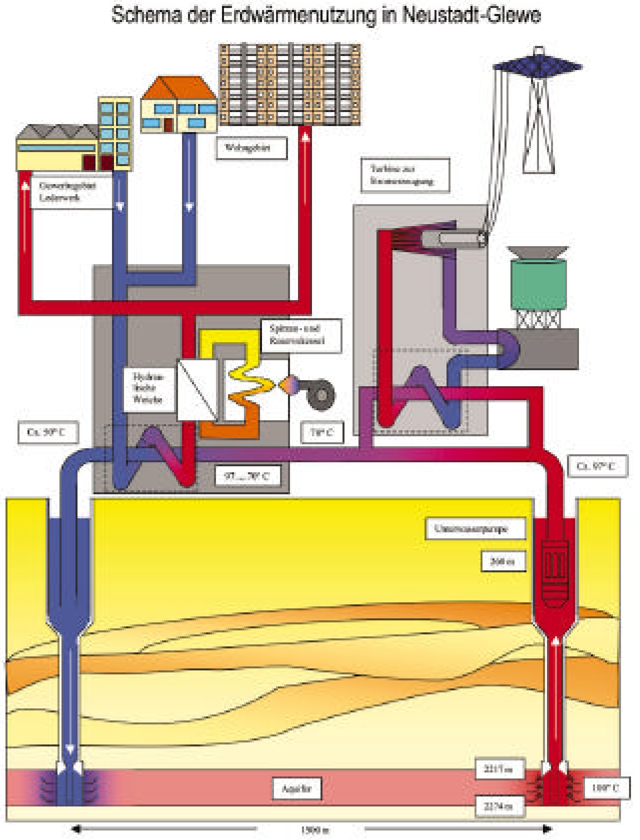

Figure 19. Combined heat and power plant at Neustadt Glewe, Germany.

Mexico

In the northern state of Chihuahua, an isolated village, Maguarichic, relied on a 90-kW diesel generator to provide electricity for only three hours in the evening. The villagers rarely had meat, cheese or milk, and they were not aware of national events since no television was available. The federal government in 1997 provided a 300-kW binary plant using 150°C water for US$3000/kW (Figure 20). The villagers now have street lights, refrigerators and have established a small cottage industry using electric sewing and tortilleria machines. Best of all, the children now have ice cream!

Figure 20. 300-kW binary plant at Maguarichic, Mexico (courtesy of CFE).

United States

Near Susanville in northern California, two 375-MW binary plants operated by Wineagle Developers provide a net power output of 600 kW (Figure 21). The plants used 63 liters per second of 110°C waters. The plant is completely automated. The entire plant, including the well pump, is controlled by either module. By pushing one button on the module control panel, the plant will start, synchronize to the power line and continue operation. If the power line goes down, the module and downhole pump immediately shut down, since no power is available for its operation. When the power line is re-energized, the modules restart the downhole pump, and then bring themselves on line. Operation can be monitored remotely, with a service person alerted by an alarm system.

Figure 21. Wineagle binary plant of 2x375 kW in northern California, USA.

SUMMARY

The following figures are based on reports from the World Geothermal Congress 2000 (Japan) and from preliminary reports for the World Geothermal Congress 2005 (Turkey). The figures for capacity is the installed number, as the operating capacity may be less, and the energy produced, in many cases are estimated, as little data are available.

CONCLUSIONS

With 100 years of experience, reservoir engineers, and plant operators have learned the importance of giving more attention to the resource, including the injection of spent fluids. With proper management, the resource can be sustained and operated for many years. Geothermal fields have been operated for over 50 years and probably can be for over 100 years. The cost of power has been declining and in many cases, is competitive with fossil fuel plants at 4 to 5 U.S. cents per kWh.

Table 1. Installed (gross) Geothermal Power Worldwide (2004).

Country	Installed MW	Est. Energy Produced (GWh/a)
Argentina	(1)	not operating
Australia	<1	3
Austria	<1	5
China	32	100
Costa Rica	162	1,170
El Salvador	105	550
Ethiopia	7	30
France (Guadalupe)	4	21
Germany	<1	2
Greece	(2)	not operating
Guatemala	29	180
Iceland	200	1,433
Indonesia	807	6,085
Italy	790	5,300
Japan	535	3,470
Kenya	127	1,100
Mexico	953	6,282
New Zealand	453	3,600
Nicaragua	78	308
Papua New Guinea	30	100
Philippines	1,931	8,630
Portugal (Azores)	8	42
Russia	100	275
Taiwan	3	15
Thailand	<1	2
Turkey	21	90
United States	2,395	16,000
TOTAL	**8,771**	**54,793**

Binary cycle plants are becoming more popular, as they can use lower temperatures–down to 100°C–and the economics of the system is improved if the wastewater is used in a direct-use project such as district heating. Modular units are available in both binary and flash steam models, which allows for rapid installation. This will allow geothermal power to be extended to many "low-temperature" geothermal resource countries. I predict, that in the next 20 years, we will see 25 new countries added to the list of geothermal power producers.

Finally, the importance of geothermal power production in some countries is significant in contributing to the electrical energy mix as presented in Table 2.

Table 2. National Geothermal Contribution to the Electric Power Utilization

Country	% of Natural Capacity (MW)	% of Natural Energy (GWh/yr)
Philippines	16.2	21.5
El Salvador	15.4	20.0
Kenya	15.0	20.0
Nicaragua	17.0	17.2
Iceland	13.0	14.7
Costa Rica	7.8	10.2
New Zealand	5.1	6.1
Indonesia	3.0	5.1

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