Geothermal power in Central America:

A case study of the Miravalles Project, Costa Rica

Central America. Courtesy Energy Information Administration.

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1. Abstract

As demand for electricity grows in Central America, geothermal power has the potential to be a clean, steady, local option for electricity generation. The abundance of high-grade hydrogeothermal reserves in the country have yet to be fully characterized or utilized to their full potential. One example of a successful geothermal power project is Miravalles in Costa Rica. Explorations around the Miravalles area, brought about as a result of the OPEC embargo of 1973, showed a high-grade geothermal reservoir. Even though well tests showed a tendency towards calcite scaling, full-scale development ensued, and eventually three operational plants were built. The most recent plant, Miravalles III, was the result of a new law designed to encourage private development into the public sector. This report looks at the Miravalles project as a case study to highlight some of the unique benefits, risks, and future trends in geothermal power development in Central America.

2. Introduction

Geothermal power has long been hailed as an environmentally preferable alternative to electricity derived from other sources. Unlike fossil fuel-based electricity, geothermal power emits only very small amounts of carbon dioxide, sulfur, and particulates. It uses a steady, renewable local resource rather than undependable, limited fossil fuel reserves imported from the Middle East or mined elsewhere. Geothermal energy is also much more constant than other renewable energy sources (sun, wind or surface water) which can vary in strength depending on the season or time of day (Fridleifsson, 1997).

However, there are some physical, technological and economic limitations to implementing geothermal power generation, especially hydrogeothermal power. Electricity generated from fossil fuels is fairly cheap nowadays. Any power generated from a geothermal plant has to be cost-competitive with other power options in the vicinity. In order to be cost-competitive, geothermal power has to have a local market, as well as a relatively high-grade hydrothermal reserve from which to draw heat. These high-grade thermal areas are fairly isolated and concentrated in certain geologically active regions, making widespread geothermal power relatively difficult to deploy at this time. Hot dry rock (HDR) technology would make geothermal power available from almost anywhere, but it is still being developed at this time (and cost-effectiveness has been a challenge).

Given the above requirements, Central America is an excellent candidate for geothermal power development. Central America is located along the geologically active region bordering the Pacific Ocean known as the “Ring of Fire.” Volcanic ranges, earthquakes, and other geological phenomena in Central America are caused by the subduction of the Cocos tectonic plate beneath the Caribbean plate. Because of this, Central America is the source of many high-grade hydrothermal areas. A study conducted in January and February 1999 by the Geothermal Energy Association, in conjunction with the U.S. Department of Energy, highlights the vast, untapped potential for geothermal power in Central America. The study included a range of expert estimates of potential geothermal power generation in MW, both using present available technology and future technology based on current technology trends. The average results for Central America (Figure 1) show the tenfold or greater geothermal power generation potential over the current installed capacity of each country.

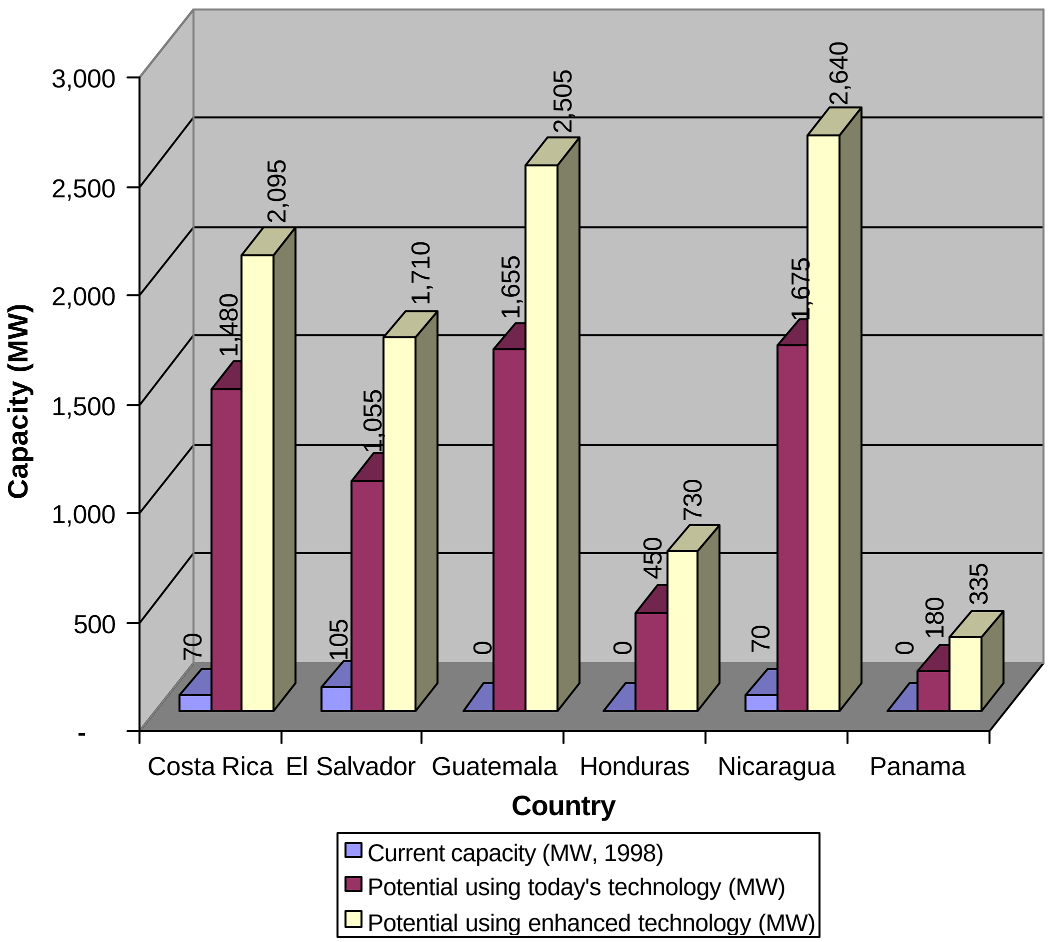

Figure 1. Current and potential geothermal power generation in Central America (Data from EIA, 1998).

In addition, much of Central America is still developing, from an economic and infrastructure perspective. Electricity is not available in certain rural areas, and demand for electricity in urban areas is growing. Figure 2 shows the growth of electricity demand in Central American countries from 1980 to 1998 (EIA, 1998).

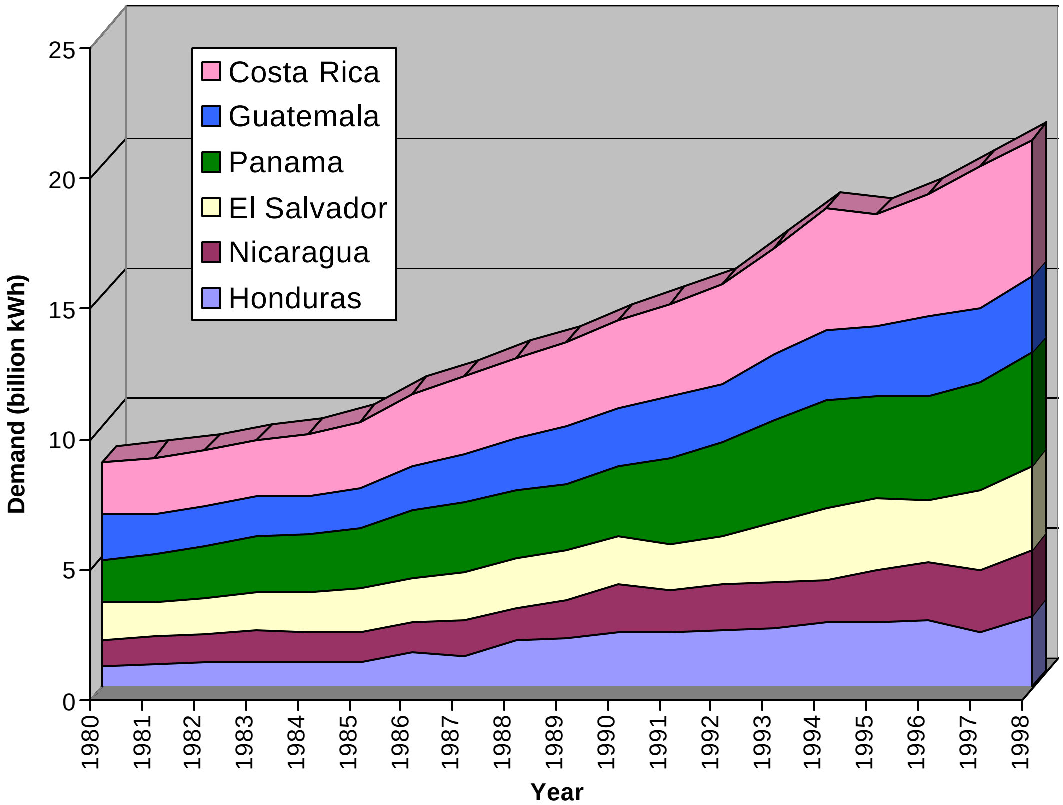

Figure 2. Growth of electricity demand from 1980 to 1998 in Central American countries in GWh (U.S. EIA, 1998).

In general, natural fossil fuel reserves are scarce in Central America, so any fossil fuel used for electricity, transportation, or any other purpose has to be imported at a high cost both economically and politically.

One of the options to decrease the use of fossil fuels has been to build high-capacity hydroelectric power plants. However, hydropower has fallen out of favor for several reasons. Several of the past hydro projects in Central America have been plagued with schedule and cost overruns, making those projects far more expensive than planned. Low or variable rainfalls in hydroelectric watersheds in the mid-1980s called into question the reliability of hydropower as a continuous source. Most of all, the environmental and social impacts of hydro dams have become a contentious issue. In particular, large hydropower dams have been faulted for displacing indigenous populations, flooding agricultural and ecologically sensitive lands, changing aquifer and watershed patterns, and increasing waterborne disease incidence (Trocki, 1985).

For these and other reasons, geothermal power has become increasingly popular as an energy alternative in Central America. This report looks at one example of a successful geothermal power project in Central America: Miravalles, Costa Rica. Examining the process of developing a geothermal power plant at Miravalles, from scientific characterization to testing to financing and deployment, highlights the unique benefits and challenges to developing geothermal power in Central America as a whole.

3. The country: Costa Rica, past and present

3.1 Economic conditions

Costa Rica is a Central American country of 3.8 million people (1998), bordered to the north by Nicaragua and to the south by Panama. Although not a wealthy country (GDP in 1998 was $10 billion), Costa Rica's economy has been growing, as seen by decreasing unemployment, increasing minimum wages, and a booming tourism industry. Inflation has decreased from 23% in 1995 to 10% today. Population growth has been steady at 2.1% over the past decade, and life expectancy, at 76.6 years, is higher than that of the U.S. (EIA, 1999). By all accounts, Costa Rica is a strong performer compared to its Central American neighbors as well.

However, such growth has put a strain on the current energy, transport, and communications infrastructure, and the government is trying to grapple with maintaining and expanding the infrastructure while managing the growing trade deficit and external debt of $4 trillion. One of the solutions to managing infrastructure upgrades in Central America has been the trend towards liberalization and privatization, and Costa Rica has joined in the trend. Over the past few years, the government has slowly relaxed the public monopoly on all of these sectors, allowing limited competition and private investment (Department of State). Indeed, the third phase of Miravalles is a perfect example of recent reforms allowing private investment into public infrastructure. The contracting and financing of Miravalles III will be explained later in greater detail.

3.2 Environment and society

Costa Rica is known for its lush and varied landscape and extremely high biodiversity; an estimated half million species reside in various wildlife reserves alone. Consequently, ecotourism has been a growing industry, and recent administrations have made environmental protection a priority. One of those priorities has been to decrease Costa Rica's greenhouse gas emissions by decreasing the use of fossil fuels and increasing development of other renewable energy sources. When President Jose Maria Figueres stepped into a four-year term in 1994, he established a carbon tax, doubled the size of Costa Rica's national parks and reserves, and pushed through the development of Miravalles at the expense of a planned oil-fired power plant (Tenenbaum, 1996). Current president Miguel Angel Rodriguez has been continuing the trend, encouraging the exploration of more geothermal resources as well as protecting wilderness areas. As of 1998, over 24 percent of Costa Rica's land area are protected as natural reserves. Culturally, Costa Rican citizens consider themselves conservation-minded, and strongly support environmental programs. As a society with a long democratic tradition, public opinion weighs heavily in Costa Rican decision making and policy (ESLAC, 1998). Other Central American countries have not been so open, but the trend towards liberalization of government agencies is pushing them towards that direction.

3.2 Energy output

Costa Rica, like most other Central American countries, relies heavily on hydropower for its electricity demand. Figure 3 shows the current installed generation capacity in Costa Rica by type, as of 1998.

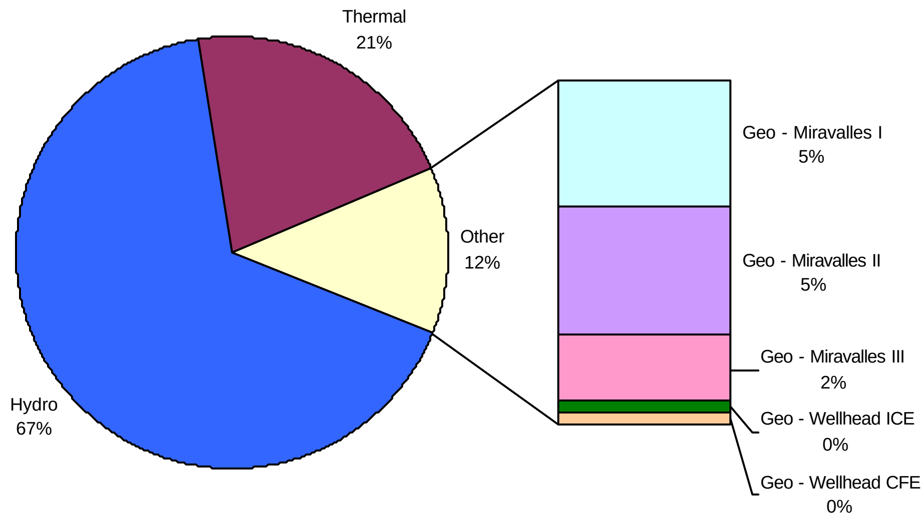

Figure 3. Installed electricity producing potential, by type of plant (data from ICE, 1998).

Unlike most other Central American countries, the electricity infrastructure is fairly widespread. Over 90% of the population have access to the electric grid. However, Costa Rica's energy usage has been growing by about 5 percent per year, as was seen in Figure 2.

Costa Rica had previously determined exploration of oil reserves to be unprofitable. Thus, all oil is imported from Mexico and Venezuela on preferential terms, and refined by the state-owned monopoly. The state may lose its monopoly, if the liberalization trend mentioned earlier reaches the fossil fuel sector. In addition, oil exploration has recently started again, this time offshore (EIU, 1999). However, more likely than not, environmental concerns will limit the use of hydrocarbon-based energy. Neither natural gas nor nuclear power is available as power options in Costa Rica at this time.

4. The resource: Miravalles hydrothermal field

4.1 History

There are two main volcanic ranges in Costa Rica, the Guanacaste Volcanic Range and the Central Volcanic Range. It had been known for some time (as early as the 1960s) that there may be geothermal reservoirs near these volcanic ranges, but there was no systematic investigation or testing of any of these areas until the world energy crisis of 1973-1974. High oil prices and limited fuel availability for thermal electric plants prompted the Costa Rican government to seriously examine geothermal alternatives for electricity production.

The Instituto Costarricense de Electricidad (ICE) is the government body in charge of developing and distributing electric power to Costa Rican citizens. In 1974, a group of ICE scientists and engineers began a general study around the slopes of two volcanoes, Miravalles and Rincon de la Vieja. Both are located in the Guanacaste range, which is approximately 80 km long and includes five different volcanic areas. Miravalles is currently inactive, with the last known volcanic activity dated at 5000 B.C. Figure 4 shows the location of Miravalles and several other volcanoes in the Guanacaste range.

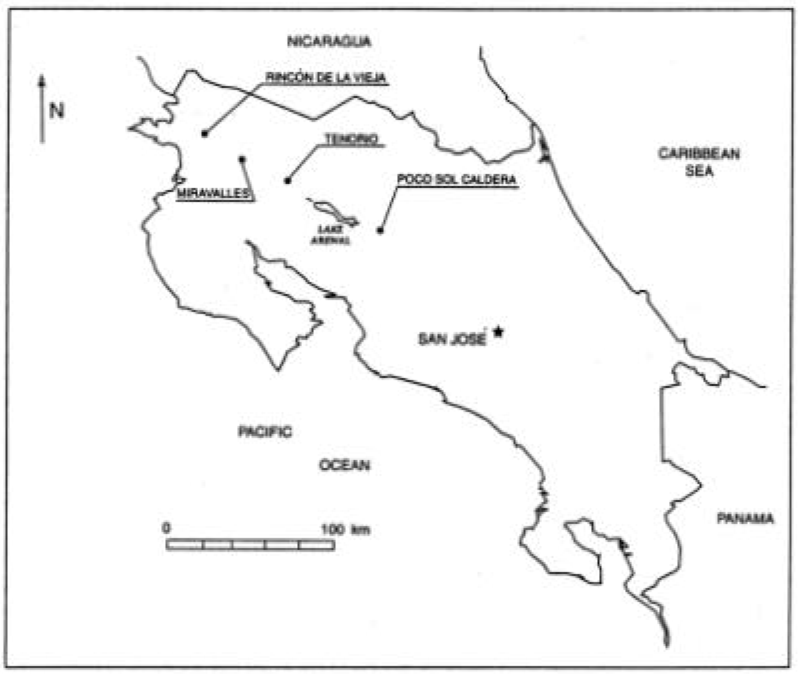

Figure 4. Location of Miravalles and other geothermal volcanoes in Costa Rica (Robles, 1998)

Since Rincon de la Vieja is in the middle of a national park, whereas Miravalles is located on dry grazing land, Miravalles was chosen as the location for further study. A prefeasibility report, produced by ICE and Rogers Engineering and Geotherm of California in 1976, showed the Miravalles field to be promising for further study and development, and recommended drilling three or four wells towards the southwestern side of the volcano (Corrales, 1985).

4.2 Exploration

In 1979 and 1980, three wells (labeled PGM-1, PGM-2 and PGM-3) were drilled in the area recommended by the prefeasibility report. They were drilled to 1300 m, which was the physical depth limit of the well rigs at the time. All three of the wells proved to be geothermally productive. The wells showed a water reservoir with flow rates of 70 to 90 kg/s of steam, temperatures exceeding 200°C at depths of 600 m (with maximum temperatures of 245°C), slightly alkaline pH and total dissolved solids of 7000 ppm (Mainieri, 1985). Figure 5 shows the high temperature gradients found in well PGM-1.

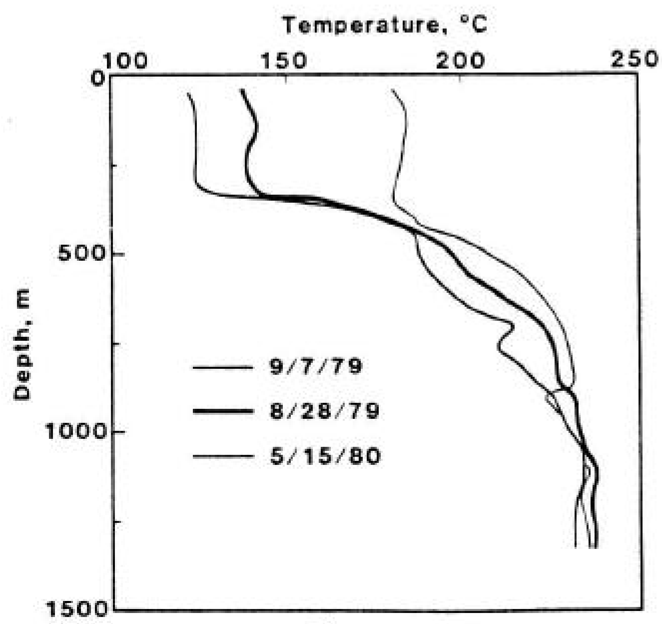

Figure 5. Plot of temperature vs. depth at three different dates for Well PGM-1 (Granados, 1985)

These statistics meet or exceed general requirements for cost-effective geothermal power extraction using water reservoirs (Armstead, 1983):

- Fluid temperatures of at least 180°C at the bottom of the well;
- Temperatures sustained at depths not exceeding 3 km;
- Steam flow rates (from a 9 5/8 in boring) at least 25 kg/s;
- Relatively neutral pH;
- Relatively low dissolved solids and salinity.

All of these requirements may vary, depending on the type of system to be installed and other surrounding conditions. As a general guideline, though, they demonstrated that the Miravalles reservoir was more than feasible for power production. The specific requirements and design parameters for the power systems used at Miravalles will be explored in more detail in Section 5.

4.3 Testing and results

With these promising initial results, ICE decided to continue exploration and testing, and between 1984 and 1985, three more wells (PGM-5, PGM-10 and PGM-11) were drilled north of the original wells to 2000 m depth, and PGM-2 was extended in depth from 1200 to 2000 m. However, several problems surfaced during this second phase of the project. Long-term testing of the initial three wells showed that they tended to develop calcium carbonate ($CaCO_3$) deposits within the wellbores at the flash point, or where the pressurized hot water converted to steam, at about 1000 m depth. This calcite scaling inside the well had grown over time such that it significantly decreased steam flow rates (Mainieri, 1985). Manual cleaning of the calcite buildup improved the situation, but it was clear that another solution had to be developed. Also, extending the depth of well PGM-2 proved successful in improving its flow rates, which were not as high as the other wells. However, the water produced from the deeper drilling turned out to be an extremely acid brine (pH=3). Fortunately, this low-pH water turned out to be a localized pocket, and did not affect any of the other wells (Corrales, 1985).

A third round of exploration and testing occurred between 1988 and 1989, to further determine the electricity producing potential of the field. Three more wells were drilled (PGM-5R, PGM-12, PGM-15), and more tests were conducted to try to alleviate the calcite problem and expand general knowledge of the reservoir. It turned out

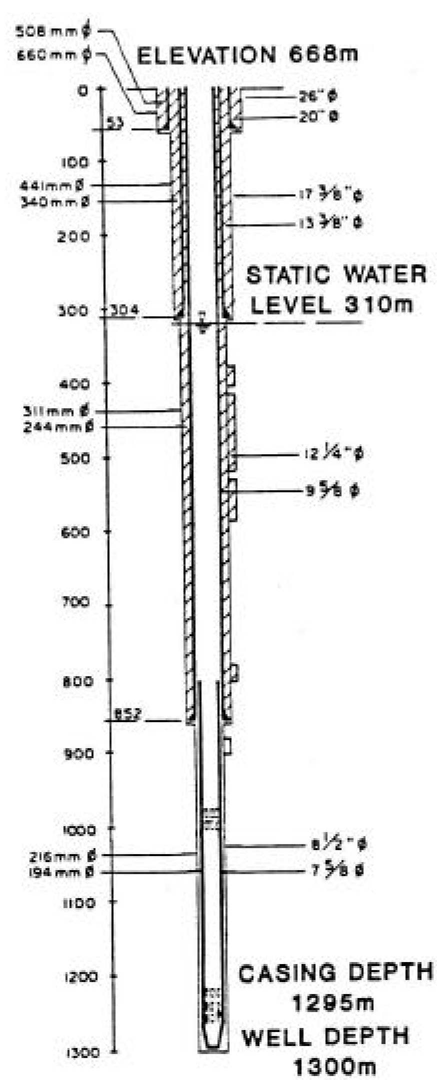

Figure 6. Well casing for PGM-1 (Granados, 1985)

that the new wells, drilled at 9 5/8 inches diameter rather than the 7 5/8 inches of previous wells, slowed the growth rate of the calcite twofold (Dennis, 1985). Figure 6 diagrams the well casing of these new wells.

An experiment was also conducted to examine the feasibility of using a chemical calcite inhibitor to prevent the scaling, rather than manual scaling removal. Unfortunately, the inhibitor, an organophosphate salt, degraded under the high temperatures of the well at flash point, leaving a corrosive, clogging residue behind (Mainieri, 1990).

Despite the calcite problem, the ICE scientists were optimistic about the electricity generating potential of Miravalles. With nine wells in place, there was enough data to model the whole reservoir, and to determine where and how production and reinjection would occur. Results from this modeling and testing were positive, and indicated that two 55-MW power plants could feasibly be built (Mainieri, 1985). With funding secured from the InterAmerican Development Bank (IDB) and government sources, the green light was given to build the two plants, and construction began in late 1989.

5. The results: Miravalles power plants

5.1 Miravalles I and II

On March 25, 1994, the first 60 MWe of geothermal power in Costa Rica was produced from the Miravalles reservoir. Two plants were built by Toshiba: one 55 MW single-flash unit and one 5 MW non-condensing backpressure unit. Figure 7 shows a schematic diagram of a flash steam power plant.

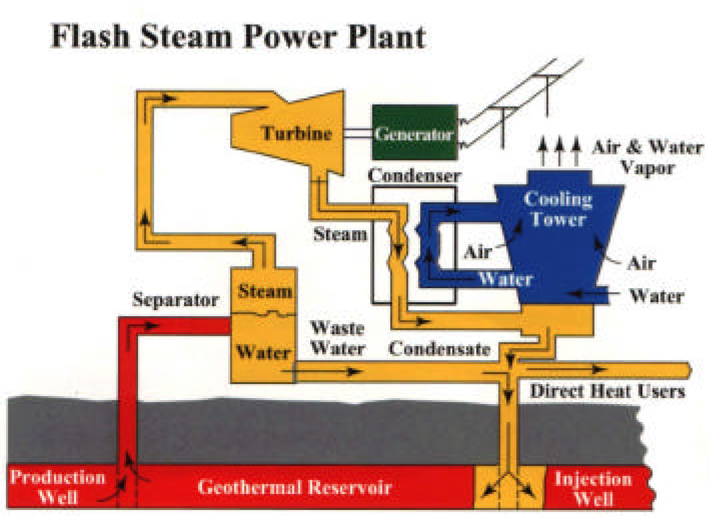

Figure 7. Diagram of a geothermal flash steam power plant (Energy and Geoscience Institute).

Hot steam, "flashed" or explosively boiled from the pressurized reservoir water, is brought up from eight production wells and sent at a rate of 114 kg/s at 6 bar pressure through a separator, where the steam is separated from minerals and other condensates left behind with the liquid water. The steam is sent to a turbine where it generates electricity in the same way as a steam turbine fueled by coal or petroleum. The spent steam is then condensed using a standard air-water exchange cooling tower, and the condensed steam joins the separated waste water, where it is reinjected back into the reservoir through six injection wells at a rate of 642 kg/s. Small amounts of non-condensable gases from the reservoir water, mostly CO2 and some H2S and CH4, are separated and released through the cooling tower along with waste heat.

The backpressure unit uses excess steam from the production wells to extract an additional 5 MW of power. Unlike the flash steam unit, the backpressure unit does not have a condensing cycle; the spent steam from the turbine is released directly into the atmosphere without condensation.

Two additional 5 MW backpressure units were installed and began operating in September 1996. However, one of the plants was subsequently shut down in order to leave some steam pressure for the second 55 MW plant that ICE was planning to build. Dubbed Miravalles II, this plant was built in the same housing location as Miravalles I, but by a different manufacturer (Ansaldo, an Italian company). Both Miravalles flash plants are single flash, meaning that the hot water produced from the wells is flashed once only. Dual flash plants have two flash vessels that send steam to the turbine. According to ICE, the plants were constructed as single flash plants to save money on capital costs.

As for the calcite scaling problem, additional studies found that a polyacrilate calcite inhibitor worked better than the organophosphate inhibitor tested earlier. A capillary tube running along the well and ending below the flash point level is used to inject the inhibitor and keep the calcite scaling under control (IGA, 1998). This system has been in place since the beginning of plant operation and has worked well since then, eliminating the need for manual scale removal. According to Dr. DiPippo of UMass Dartmouth, it is crucial that the system work flawlessly, since even the shortest outage can cause scaling to build up very rapidly and reduce well productivity.

Even while Miravalles II was being constructed, testing and planning was occurring for another 27.5 MW single-flash steam plant, Miravalles III. Construction began in late 1998, and was completed earlier this year. With Miravalles III in place, only one of the 5 MW backpressure units was needed, and the other unused turbines were sent to Mexico (Lippman and DiPippo). Figure 7 shows the location of the power plants as they stand today.

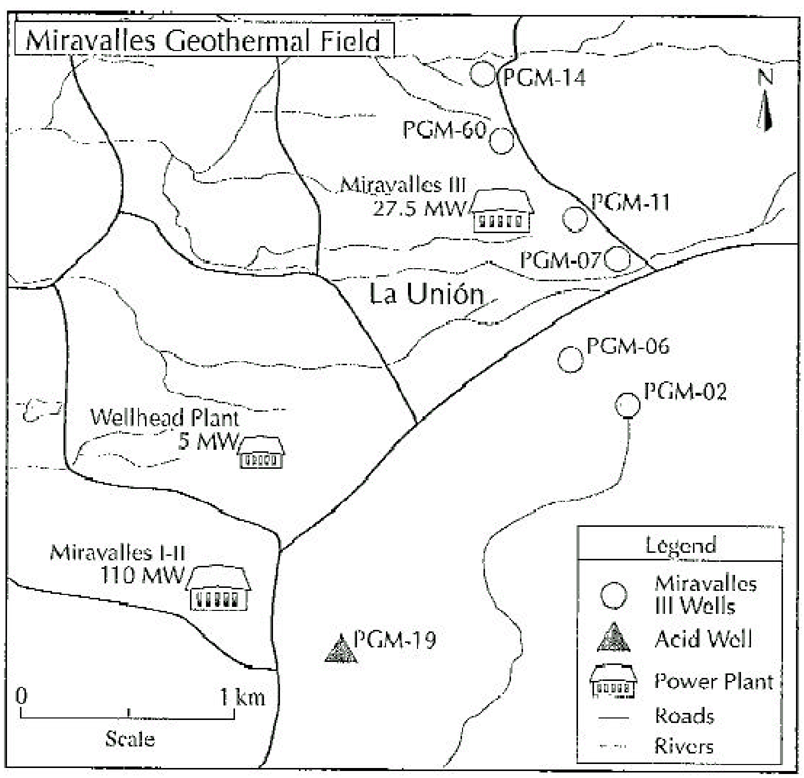

Figure 8. Location of Miravalles geothermal power plants and wells (facsimile courtesy M. Lippmann).

The complete system uses 44 wells (production and injection) at depths from 890 to 3200 m.

All of the process water brought up from the deep reservoir is currently reinjected back into the ground upgradient of the producing wells, at a final temperature of 150 to 160 degrees C. According to Lippmann and DiPippo, reservoir reinjection has many benefits. Reinjection helps sweeps the heat from the underlying hot rock, and keeps the reservoir pressure from getting too low. Deep-well reinjection also ensures that water quality of surface drinking water aquifers is maintained, and that any seismic and ground subsidence risk is minimized.

It has been shown that some of the heat from the reinjected water could be used, perhaps using a binary-cycle plant, to extract an additional 18 MW from the reservoir (Mainieri, 1998). However, ICE has no plans as of yet to implement this.

5.2 The financing of Miravalles III

In 1995, Costa Rica's Independent Power Generation Act was amended to allow private investment into the energy sector for the first time. In late 1996, ICE took advantage of this amendment, and put Miravalles III out for international bid. The winner of the bid, selected in the spring of 1997, is an international consortium of power companies that include Oxbow Power Services of Reno, Nevada and Marubeni Corporation of Tokyo. IDB coordinated a $49.5 million loan, underwritten in part by other foreign banks, to help finance this $70 million project. Under the contract, the consortium will build the plant, operate it for 15 years, sell the electricity output to ICE during this time, then transfer the plant to ICE at the end of 15 years. Known as a Build-Own-Transfer project (BOT), this is the first project of this kind in Costa Rica and the first geothermal BOT in Latin America to reach construction stage. It is also one of the largest privately financed power investments in Latin America at this time (GRC, 1999).

At the time of writing, construction of Miravalles III has been completed, and startup tests successfully run in March 2000. The plant is expected to begin commercial production very soon. This project is already considered a success, not only from a technical perspective, but also from a financing and management perspective. Under public management and financing, Miravalles I and II each took 9 years to complete (from planning to operation). Miravalles II, in particular, ran into difficulties with their equipment supplier Ansaldo, causing major delays in the construction (La Nacion Digital, 1998). Miravalles III, in contrast, took only 1.5 years, and was actually two months ahead of schedule (Garcia).

As deregulation becomes more widespread, and government-owned power agencies allow private investment and management of projects in Central America, Miravalles III can be used as an example of how privatization can work successfully, especially in the financing and management of future geothermal projects. Of course, there are risks and benefits inherent in private investment in projects such as Miravalles III; these are outlined in more detail in the next section.

6. Benefits and risks

Any public infrastructure project has risks and benefits associated with it, and it is up to the investor or government agency to decide whether or not the risks outweigh the benefits before deciding to commit to the project. The Miravalles project had (and still has) its own particular risks and unforeseen issues, many of which are common to geothermal projects, and some of which are common to Central American countries. However, it seems as though the benefits, both qualitative and quantitative, have outweighed the risks and problems to date. Some of the risks, issues and benefits associated with geothermal projects, especially as seen in the Miravalles project, are outlined below. These issues must be considered in the development of future geothermal projects in Central America.

6.1 Environmental and land issues

Geothermal power is not without its environmental challenges. There has been some concern over local water quality being affected by pumping hot mineralized water from the deep reservoir. This was one of the main challenges at Miravalles, since there are many sensitive waterways and aquifers in close proximity to the plant. To a great extent, this issue has been addressed through reinjection of the process water back into the deep reservoir from which it came. In this way, the production-reinjection loop occurs only through the deep reservoir and in the plant itself, bypassing the surface waterways and aquifers entirely. There are also some concerns regarding microclimate effects associated with direct heat exchange into atmosphere. Again, since Costa Rica is a fairly tropical climate to begin with, there haven't been any problems so far (Lippmann and DiPippo). Changes in local air quality and acid rain could also be a possible issue, due to the release of some SO_2 and methane, but that hasn't been much of a problem in the case of Miravalles, even after constant monitoring.

There is also a land use issue relating to the siting of the plants. One of the advantages of the land around Miravalles is that it is fairly isolated, and used mostly for grazing. There were some delays in negotiations for purchasing the land from the original landowners, but on the whole, land use has not been an issue at Miravalles. For most projects, the siting of a potential project is an extremely important consideration. Rincon de la Vieja, considered the most promising geothermal reserve in Costa Rica, has not been explored due to its location within a national park. Other siting concerns include visual impact, especially if it is located near an urban center or a sensitive area. To a certain extent, this can be addressed with careful camouflaging or landscaping. However, the issue of visual impact and siting is a difficult one, especially when trying to extract from a high-grade reserve in a highly sensitive or political area. This is one of the benefits of low-grade hydrothermal power, or HDR, as these technologies are much more flexible in their siting requirements.

Seismic risk is also an issue, but it has not been a significant problem in any of the geothermal projects to date (Trocki, 1988). It is always good to be aware of the fact that geothermal resources occur precisely because of geological instability, but careful monitoring and management of the reservoir should minimize this risk to an acceptable degree. Reservoir management becomes especially important considering that it is actually possible to deplete and overuse a reservoir if not careful (i.e. deplete too much of the heated water and aquifer pressure).

All of these issues and risks must be weighed against the environmental and land use benefits derived from geothermal power over other forms of electricity. Emissions-wise, geothermal emissions are negligible compared to any fossil fuel-based plant. Geothermal power is entirely local, and does not require imports or foreign labor to produce (Kurman, 1985). Geothermal projects have few of the environmental and social problems associated with large hydropower projects. They use much less land, disrupt much less of the surrounding surface waters and aquifers, do not displace any indigenous populations, and are not pathways for disease. In addition, hydropower is inherently unreliable, as the power output highly depends on the amount of rain received in a season. Even high rainfall is detrimental to hydropower in areas where deforestation causes silt runoff to clog the dams and shorten plant life (Trocki, 1988).

6.2 Financing and Investment

All power projects have financing risks, but in Central America, which is still considered to be a developing region, the perceived risk of a project falling through is even higher. There are particular technical risks associated with geothermal power development, including reservoir quality, reservoir depletion, seismic risk, deterioration through corrosion and mineral buildup. However, many of these can be mitigated through careful and thorough exploration, investigation, and operation/maintenance, as well as creative and persistent solution engineering. The calcite buildup problem at Miravalles was an unforeseen complication that required several different solutions before a suitable one was found.

Private investment can help with the operation and maintenance risk. Through a build-own-transfer project, the ICE is a guaranteed buyer of the electricity produced for 15 years at a guaranteed price, thus eliminating the risk to the investor of no market demand for the electricity. In addition, they are only responsible for those first 15 years, after which the ICE takes over. Thus, they do not need to worry about further depreciation, maintenance and operation beyond that time period. Also, in the case of Miravalles and many other Central American infrastructure projects, the InterAmerican Development Bank has helped with the financing structure. By underwriting the private loans for the project, IADB insures against financial risks such as currency exchange rate and interest rate fluctuations. In addition, having IADB on board a project has boosted investor confidence in a given project; knowing that the IADB is involved lends more security to banks who want to lend or developers who want to invest (IADB, Garcia). Recently, there have been other creative financing alternatives to IADB and other multi-national banks. The California Energy Commission’s Energy Technology Export Program has helped fund small- to mid-size California geothermal development firms for overseas projects, offsetting project startup risks with a package of pre-investment “seed” funding and assisting in project negotiations (GRC, 1998).

One of the main benefits of a build-own-transfer regime is that international private funds are successfully transferred into Central American infrastructure, without undue risk to the private investor. However, in the wake of the recent World Bank/IMF protests in Washington, it is also hoped that there is no undue harm or intrusion into the country’s best interests through these foreign investment projects. In the case of Miravalles, ICE and the government are heavily involved in every step of the process, making sure that the country’s best interests are served.

6.3 Technology and Cost

There are technology and cost risks as well. Capital costs for a geothermal exploration program can be high if there is uncertainty as to the viability of the resource. In other words, there is the risk that several million dollars will be spent on feasibility studies and exploratory drilling, only to find nothing. Several of the Miravalles wells turned out to be unproductive, or infeasible (e.g. the deep PGM-2 well, which hit a pocket of corrosive brine). However, Miravalles has proven to be an excellent and reliable producer overall, and there is already much data on the geothermal "hot spots" in Central America. Also, drilling and investigation costs have come down quite a bit, making exploration for geothermal areas less expensive than it used to be, especially for smaller projects (Vimmerstedt, 1998). It can be said that there are similar risks in searching for oil and gas reserves in other countries, and that there are similar high capital costs associated with hydro or thermal power plants. As for cost of generation, the average cost per kwh ranges from 3 to 6 cents, depending on the location and the size of the plant. This is competitive to the cost for hydropower, and lower than that for a thermal plant (Corrales, 1990).

One of the big technology advantages of geothermal power plants is their modularity and flexibility. Small units can be built and taken apart fairly easily according to changes in demand or aquifer conditions. At Miravalles, the 5 MW backpressure plants were used in this manner. They were quickly built, deployed, then shut down and sent to Mexico as necessary to keep the aquifer system and the load steady. The same cannot be said for hydroelectric projects or large thermal generators, where an extremely large capital expenditure is required in order to get even one MW, and the system is not flexible to handle changes in load or in fuel supply. This leads to another advantage of geothermal plants, which is the extreme reliability of the energy source. Both Miravalles I and II have consistently had availability factors of over 90 percent (ICE, 1999), and the industry average for geothermal plants ranges from 70 to 90 percent, whereas the availability of hydro and thermal projects tend to be much lower (Trocki, 1988). One suggestion has been to alternate loads between and among different plants. For instance, existing hydroelectric plants would be used during the rainy season, giving geothermal reservoirs a chance to recharge and replenish themselves. Once the rainy season ends, geothermal plants can be used to provide base load power while the hydroelectric reservoir recharges. This scheme would effectively lengthen the lifetimes of both plants (Fridleifsson, 1997).

The technology used in a typical geothermal power plant is transferable from other industries, such as drilling from oil and gas extraction, and turbines from coal- and gas-fired plants. Thus, the learning curve is very quick, as can be seen in the deployment schedules of the three Miravalles plants. Also, because construction and maintenance are relatively easy, local workers can and do get involved in the process, providing employment and a sense of local ownership in the project.

6.4 Social and Economic

Central America has had a history of economic problems, civil unrest and political instability, which has made some investors wary of getting involved and governments unable or unwilling to invest in building new infrastructure. However, the Central American situation has improved as of late, and several projects that had indefinitely been on hold have recently been successfully completed. One example is the 56 MW Berlin plant in El Salvador. Geothermal investigation had begun in Berlin as early as the 1960s, but El Salvador's civil war in the 1980s left the project abandoned for over 10 years. The end of the civil conflict in 1992 left the country with a 12% annual increase in electricity demand, thus renewing interest in the project. Deep well exploration revealed a high-quality aquifer of over 300^{o}C. The completed plant, financed by IADB, went online in July 1999 (Rodriguez, 2000).

If even half of the geothermal potential in Central America were utilized for electricity, they would end their reliance on imported fossil fuel for electricity, and become a net exporter of energy, thus helping to alleviate Central America's trade deficit issues (Olson, 1998). The rich natural resources, the growing economies and electricity demand in Central America, as well as the assistance and leeway given to investors under recent privatization trends, leaves no doubt as to the potential profitability of geothermal development in Central America at this time.

It is also important to mention the unquantifiable social benefits associated with geothermal power. Increased energy, especially clean electricity, helps a great deal in terms of helping a developing economy. Conversely, it is very difficult for an economy to grow without ample energy for manufacturing, transportation, business, tourism, and even agriculture. With increased energy supplies, quality of life improves as well.

7. The future of geothermal power in Costa Rica and Central America

Central American governments have already started to realize the need, as well as the feasibility, of increased geothermal power generation. Development has already occurred in the past two or three years at a quickened pace, and is likely to continue into the next decade.

7.1 Future geothermal projects in Costa Rica

As previously mentioned, another potentially high-grade geothermal area is at the base of another volcano in the Guanacaste province, Rincon de la Vieja. However, this volcano is located within a national park, so development is currently not allowed. As of this writing, legislation is currently being debated in the Costarrican Congress to allow limited development in the national parks, which would allow exploration of the Rincon de la Vieja field. However, this proposal has met with much controversy. Public resistance to the proposal has even incited demonstrations and strikes. Thus, this legislation is not expected to pass anytime soon (Lippmann and DiPippo).

Tenorio Volcano, located 25 km southeast of Miravalles in the Guanacaste volcanic range, is ICE's next target for geothermal exploration. Tenorio is located at the edge of a national park, but not directly inside as is Rincon de la Vieja. The private land surrounding the volcano has already been purchased by ICE, and feasibility studies are underway (Mainieri, 1998). However, drilling has stopped for now, since two deep exploratory wells drilled at the edge of the national park have produced temperatures too low for large-scale power generation (Lippmann and DiPippo). It is unclear what the future of Tenorio is at this point.

7.2 Current and future projects in Central America

As seen in Section 2, there is a great deal of geothermal electricity potential in Central America, and some of it has already been developed. The first geothermal plant was at Ahuachapan, El Salvador in the early 1980s, which is still running today despite some early problems resulting from aquifer mismanagement (Trocki, 1988). In Nicaragua, a 70-MW capacity plant at Momotombo has not been producing to capacity, so requests for additional recovery investment are being made (Zuniga, 1998). In addition, several other geothermal fields will be investigated in the near future. A 24-MW plant began operating in Zunil, Guatemala in mid-1999 after several rounds of investigation. All of the remaining countries are actively considering geothermal exploration in the near future.

7.3. Distributed geothermal power for rural areas

One option that has not yet been explored in Central America is that of small geothermal projects for rural areas (i.e. 1 to 5 MW). Earlier, there was mention of the difficulty in siting of large geothermal plants, due to the fact that high-grade geothermal resources are often located in environmentally or ecologically sensitive areas. However, low- to medium-grade geothermal resources are abundant in Central America (up to 150^{o}C). The advantage is that they are widely distributed, unlike the high-grade areas, making it an attractive option for bringing electric power to rural areas that have no or poor access to the national electric grid. Miravalles works for Costa Rica since the national grid is well developed there, but in Guatemala or Honduras, where the rural population is much higher and the infrastructure much less developed, small geothermal plants are an attractive option.

A report by L. Vimmerstedt of the National Renewable Energy Laboratory highlights the opportunities that abound in this market, especially considering the much lower cost of drilling "slim wells" for exploration and development, the much lower base loads required for a rural village and the lack of other cost-effective options. Kurman (1985), Trocki (1988), and Lippmann and DiPippo all agree that this is the next step towards truly widespread, effective use of Central America's geothermal resources.

8. Conclusion

Central America has an abundance of geothermal energy reserves, both high-grade "hot spots" where current exploration is taking place and widespread areas of low- to medium-grade thermal reservoirs. There are many arguments for increased development of these resources into electrical energy. Growing populations, expanding economies, increased tourism and decreased civil unrest all add up to a growing demand for electricity. Though hydropower, and to a lesser extent, thermal power, provides some of this demand, there has been some dissatisfaction with the reliability of hydropower, the environmental and social effects of large hydro dams, and the high cost and emissions associated with fossil fuel plants.

There are many risks and potential issues associated with geothermal power development in Central America. However, the Miravalles project in Costa Rica is an example of how environmental, economic, financial, social, and technical obstacles were all successfully overcome for a Central American geothermal project. Problems such as well productivity and calcite scaling, delays in scheduling, disagreements with suppliers, land use negotiations, environmental concerns, foreign investment, and various other issues that came up were all dealt with, and now the Miravalles project is providing over 115 MW of steady, clean power to Costa Rica.

The success of Miravalles over its 20-year history points to an optimistic future for continued geothermal power development in Costa Rica and Central America in the years to come.

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