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ASSESSMENT AND DEVELOPMENT OF THE GEOTHERMAL ENERGY RESOURCES OF COSTA RICA

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ABSTRACT

The assessment and development of geothermal energy resources in Costa Rica and their contribution to the electricity needs of the nation are reviewed. A national reconnaissance resource study, carried out during 1989 and 1991 (ICE, 1991), indicated that the possible total geothermal potential of the country was about 900 MWe.

The first deep geothermal exploratory wells in Costa Rica were drilled at the Miravalles geothermal field in 1979-1980. The good results obtained in these wells allowed ICE to proceed to study the possibility of installing a geothermal power plant of 55 MW (Unit 1). Electricity was first generated at the Miravalles field in early 1994. Since then, the installed capacity has grown from 55 MWe (1994) to 163 MWe (2007). The two undeveloped Costa Rican geothermal systems that have been studied the most are those associated with the Tenorio and Rincón de la Vieja volcanoes. In 2001, a deep exploratory drilling program was begun at the Las Pailas geothermal zone on the southern slope of the Rincón de la Vieja volcano. At the same volcano, but in another geothermal zone called Borinquen, geothermal wells have been drilled starting in 2003 and 2004. Preliminary results of those drilling programs are presented.

The contributions of different energy sources to the electricity system of Costa Rica are discussed. In 2006, geothermal energy contributed 1,214 GWh, representing more than 14% of the total electricity generated, even though it accounted for only 7.6 % of the country’s installed capacity.

1. INTRODUCTION

Costa Rica is located in the southern part of the Central American isthmus, between Nicaragua and Panama. The country extends over an area of approximately 51,000 km^2 and has a population of about 4.4 million. In the early 1970s, Costa Rica satisfied its electricity needs using hydro (70%) and thermal (30%)

energy sources. The continuous rise in oil prices, especially during the 1973 crisis, motivated the authorities of the national utility company, the Instituto Costarricense de Electricidad (ICE), to study the possibility of using other energy sources for generating electricity, including geothermal energy (Moya, 2006). Preliminary exploratory studies of the geothermal areas in the Cordillera Volcánica de Guanacaste (Figure 1) were performed in 1975.

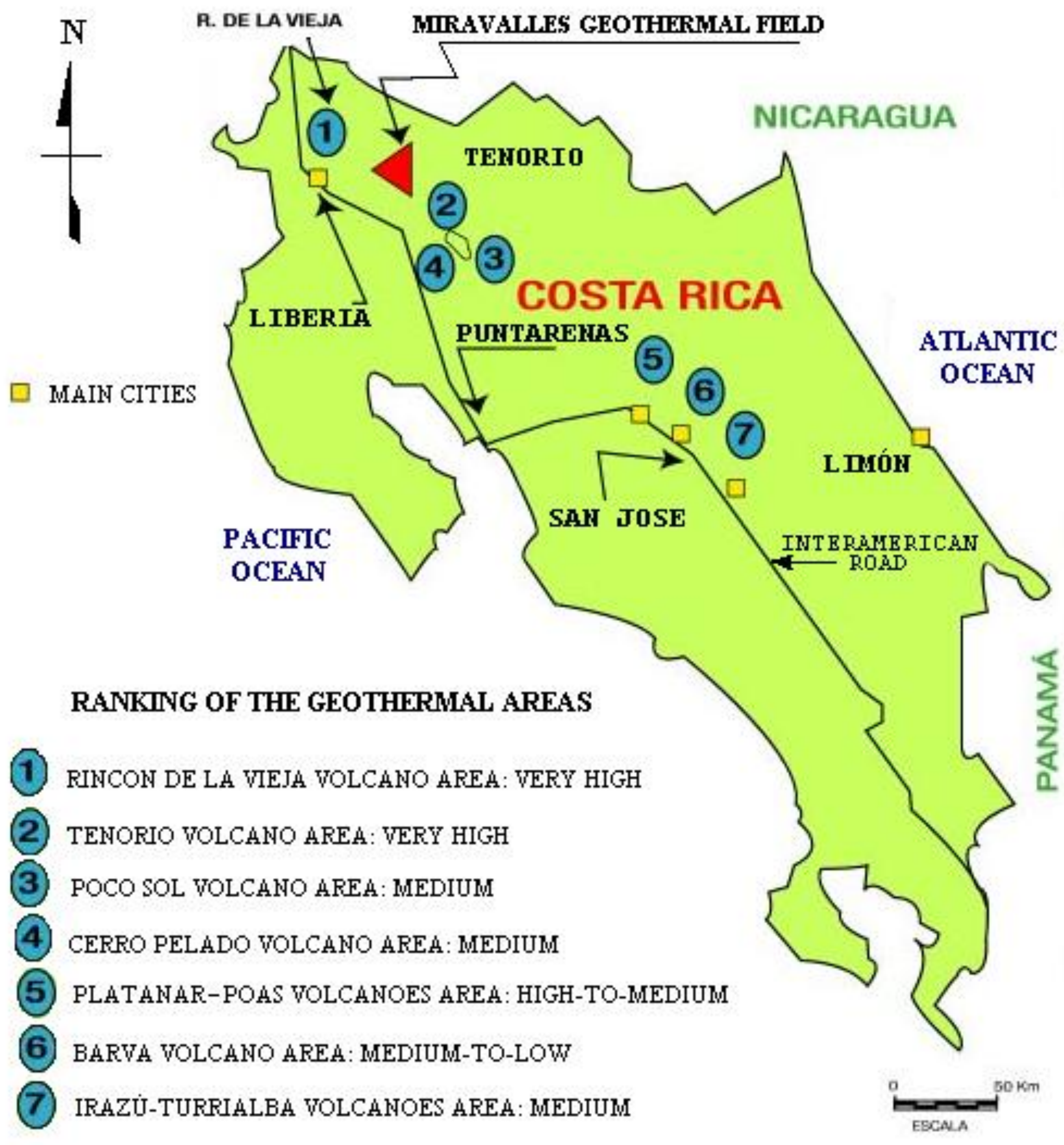

FIGURE 1: Location of geothermal areas in Costa Rica

One of the recommendations made was to investigate the areas on the slopes of the Rincón de la Vieja, Miravalles and Tenorio volcanoes in more detail. Thus, ICE began to collect geologic, hydrologic and geochemical data over a region of more than 500 km^2 between the volcanoes and the Interamerican Highway ("Carretera Interamericana"; Figure 1). The first technical report (a set of pre-feasibility studies) on the possibility of exploiting geothermal resources for generating electricity within the area mentioned above was completed in 1976 (ICE et al., 1976). The positive outcome of this work allowed ICE to proceed to apply for loans from the Interamerican Development Bank (IDB), which were needed to initiate the development of the Miravalles geothermal field (Figures 1 and 2).

Since this first report in 1976, many investigations, studies, pre-feasibility studies and feasibility studies have been carried out, primary at the Miravalles geothermal field, but also at the Tenorio and Rincón de la Vieja volcanoes, where areas of geothermal interest have been found.

Huge quantities of scientific documents have been prepared, including volcanological, geophysical, geologic, fluid geochemistry, soil geochemistry, petrography, and mineralogical studies. Also, temperature gradient wells as well as exploratory, production and injection wells have been drilled in the main geothermal areas (near the Miravalles, Tenorio, and Rincón de la Vieja volcanoes). Deliverability curves, production and injection tests, fall-off tests, transmissivity tests and interference tests have been carried out when possible in all these geothermal areas.

The assessment of resources and development of geothermal energy in Costa Rica are described in the following sections.

2. RESOURCE ASSESSMENT IN COSTA RICA

The first evaluations of the geothermal resources of Costa Rica were made during 1963-1964 when, at the request of ICE, a mission of experts from the United Nations recommended that a detailed study be carried out at Las Pailas (on the slope of the Rincón de la Vieja volcano) and at Las Hornillas (on the slope of the Miravalles volcano).

2.1 Miravalles Geothermal Field

Background: As mentioned before, during the oil crisis in 1973 and 1974, ICE decided to explore the possibility of producing geothermal energy. Therefore, three phases were established:

1. The pre-feasibility studies of Guanacaste Province (1975 - 1976)
2. Electric Power Generation and Resource Assessment (1977 - 1980)
3. Feasibility studies of the Miravalles Geothermal Field (1983 - 1986)

Loan: The Interamerican Development Bank (IDB) assigned a loan to fund all of these studies. Also, ICE invested some of its own funds to complete the studies.

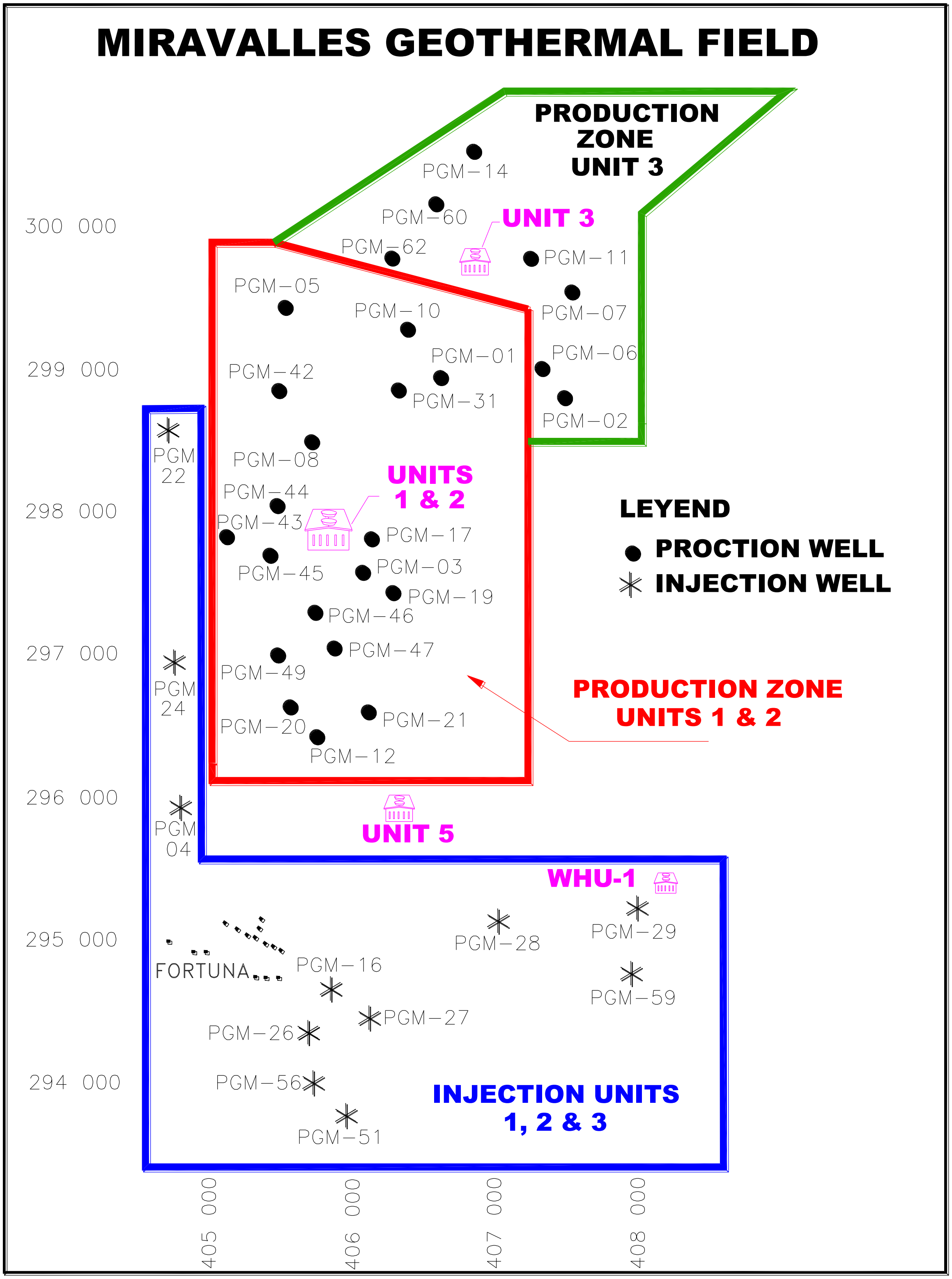

FIGURE 2: Miravalles geothermal field

2.1.1 Phase I: The pre-feasibility studies of Guanacaste Province (ICE et al., 1976)

Objective: To evaluate the geothermal potential of the selected area and to locate possible sites for drilling exploratory geothermal wells

Duration and Consultant: This phase was initiated on November 13th, 1975, when a contract was signed with Rogers Engineering Co., and was finished when the report on the pre-feasibility studies was presented in December 1976.

Study area: It was limited by the Miravalles, Rincón de la Vieja and Santa María volcanoes to the north, the Interamerican Highway to the south, the Tenorio river to the east and the Salitral river to the west.

Work performed:
Geovolcanological Studies: Prepare a geologic map covering 500 km^2 (scale 1:50,000) with emphasis on the stratigraphy, geologic history, regional and local structural geology and hydrothermal alteration details. This project included: petrographic analyses, chemical analyses and age determinations, photogeologic interpretation of geologic structures, evaluation of geologic formations outside of the area under study (important for a deep reservoir), and studies of rock cores from the temperature gradient wells. The primary products were maps, cross sections and tabulated data.

Geochemical Studies: Water was sampled from hot springs, cold springs, fumaroles and wells during the dry season and the rainy season, to determine the possible relationship between pluvial waters and the chemical quality of the surface and subsurface waters. Parts of the analyses were done in the field and the majority of them were carried out in the laboratory. The gases of the fumaroles were also evaluated. This information was used to determine the patterns of subsurface water circulation and to determine the possible reservoir temperatures and the chemical quality of the reservoir.

Regional and local climatology information was integrated as well as the superficial hydrology, to study the subsurface waters in the project area. This included the estimation of recharge areas, net affluence and effluence, upwelling zones and the outflow of deep circulation waters and the identification of potential aquifers.

Geophysical Studies: These included a gravimetric reconnaissance in an area of 500 km^2 (gravimetric information can be correlated to geological structures and helps to evaluate the conditions of the potential reservoir) and 60 Schlumberger soundings of electrical resistivity, which provided information about the apparent resistivity of the rocks to depths of 1 km (the resistivity of rock is controlled by the lithology, grade of clay alteration, primary and secondary porosity, permeability, grade of saturation, aqueous salinity and temperature).

Approximately 35 wells were drilled to measure temperature gradients and calculate the heat flow across the study area.

Conclusions:
The main conclusions of this report were:

- The most attractive zone in which to continue with geothermal investigations is the area located between La Unión and La Fortuna (Miravalles Volcano).
- A more detailed geoscientific exploration (geology, geophysics, geochemistry and hydrology) should be carried out in the rest of the study area, especially in other zones such as Las Pailas and

Borinquen which may be of interest, but were not studied with the same level of detail as Miravalles, due to the logistical difficulties of these areas.

- The selection of drilling sites for up to four production-sized test wells in the vicinity of the Las Hornillas-La Fortuna area.

2.1.2 Phase II: Electric Power Generation and Resource Assessment (ICE et al., 1980)

Objective: The objective of this phase was to investigate the most promising area proposed to test and confirm the existence of the geothermal reservoir hypothesized in the Phase I studies.

Duration and Consultants: This phase started in December of 1977 and finished with the presentation of a final report in December of 1980. The consulting companies for this study were Rogers Engineering Co, Inc. (ROGERS), GeothermEx and Foraky-Foramines, which was contracted for the drilling of three exploratory wells.

Work performed:
The operations that were carried out in this phase were the following:

- Geophysical studies: 43 Schlumberger soundings were made in an area of 50 km^2 as well as gravimetric and magnetometric studies in the priority zone.
- Wells PGM-01, PGM-02 and PGM-03 were drilled.
- Petrographic and mineralogical studies of the drill cuttings and rock cores from each borehole as well as the preparation of lithostratigraphic columns and cross sections.
- Production tests: to evaluate the potential of each well and support the optimal design of the geothermal power plant. In this phase, the only test that was done adequately (that is, for long enough to ensure that the well's production is stable and can be maintained) was that of well PGM-01, leaving wells PGM-02 and PGM-03 for the next phase due to lack of time and funding.
- Interference tests: to evaluate the extent of the reservoir and mathematically estimate the volume of hot water in the reservoir, a number of interference tests were performed using well PGM-01 as a production well and wells PGM-02 and PGM-03 as observation wells.
- Preliminary design of a 55 megawatt (MW) geothermal plant.

Conclusions:
The assessment concluded that:

- The Miravalles geothermal reserve has characteristics that are typical of "large commercial resource fields throughout the world"
- The flow conductivity is "very large" in comparison to other commercial geothermal fields.
- The fluid content will be adequate to supply steam to a 55 MW power plant for a period of 30 years. The calculations show that a surface area of 1.3 km^2 will supply the necessary steam for a 55 MW plant and the surface area containing the proven geothermal reservoir is 2 km^2.

2.1.3 Phase III: Feasibility Studies of the Miravalles Geothermal Field

Objective: The main objective of this study was to expand the knowledge of the geothermal system and extend the proven potential of the field with a series of deep wells and temperature gradient wells.

Duration and Consultant:
This phase consisted of two feasibility studies:

The feasibility study of the first 55 MW unit, which started at the beginning of 1983 and finished in 1986 with the presentation of the feasibility report of the first unit [5]. The feasibility study of the second 55 MW unit, which was a continuation of the previous study and finished in September of 1988 with the presentation of the feasibility of the second unit, also a 55 MW unit [6]. For this phase, ICE utilized the consulting services of ELC-Electroconsult.

Work performed: (ICE and ELC Electroconsult, 1986, ICE and ELC Electroconsult, 1988)
The activities carried out in this phase were the following:

- *Geovolcanology*
  - Geovolcanological study and photogeologic interpretation in an area of 250 km^2 (Caldera de Guayabo and surrounding areas, geologic map at a scale of 1:10000).
  - Geologic and detailed structural study in an area of 45 km^2 (central sector of the field, geologic map at a scale of 1:10000)
  - Chemical, petrographic and radiometric analyses of rock samples.
- *Fluid Geochemistry*
  - Sampling and chemical analysis of the fluids (aqueous and gaseous) from hot and cold springs, fumaroles and temperature gradient wells drilled within and outside of the Guayabo Caldera.
  - Sampling and chemical analysis of geothermal well fluids (aqueous and gaseous) in the previous and current phases.
  - Sampling and isotope analysis of water samples from wells, springs and superficial drainages, with the cooperation of the IAEA (International Atomic Energy Agency; Vienna, Austria), DSIR (Department of Scientific and Industrial Research; Petone, New Zealand) and the Los Alamos Technical Laboratory (USA).
- *Soil Geochemistry*
  - Determination of radon concentrations in 370 samples, and mercury concentrations in 120 samples, in an area of 35 km^2.
- *Geophysics*
  - 80 Vertical Electric Soundings (VES), in addition to the 60 VES done in the first phase, in an area of 50 km^2; Wenner soundings, regional gravimetric mapping in an area of 500 km^2; gravimetric prospecting (850 stations) and magnetometry (1200 stations) over an area of 100 km^2; determination of seismic and microseismic noise; detailed geoelectrical and seismic mapping at the plant location.
- *Temperature gradient wells*
  - Drilling of temperature gradient wells with continuous rock cores (44 total wells) in an area of approximately 80 km^2.
  - Petrographic and mineralogical logging of each well.
  - Temperature gradient profile for each well.
  - Temperature gradient maps at different depths
- *Deep Exploration Wells*
  - Drilling of 6 deep exploration wells (5, 5R, 10, 11, 12, 15) and deepening of well PGM-02.
  - Petrographic and mineralogical logging of each well.
  - Thermo-hydraulic evaluation of each well (injectivity tests, temperature recovery profiles, static and dynamic temperature and pressure profiles, characteristic production curves, and others)
  - Geochemical evaluation of reservoir fluids.

- *Field Production*
    - To determine the evolution of the reservoir and well productivities, mathematic models were used. For the definition of the geometry and the thermodynamic and physical characteristics of the models, a conceptual model of the field was developed. This model synthesizes all of the information obtained from analysis and interpretation of the available data, such as superficial studies and deep well studies. To make this kind of model it was necessary to know:
        - The hydrothermal circulation model, which takes into consideration the results of geo-scientific field and deep well investigations, such as the location of the heat source, recharge zones, the hydrogeologic system, aquifers, etc.
        - Characteristic reservoir parameters such as: the area of potential geothermal interest {which can be subdivided in four sectors: confirmed area (8.9 km^2), area of probable extension (13.6 km^2), area of possible extension (21.3 km^2) and the area of reinjection (10.3 km^2)}, the ceiling, the basement, porosity, temperature, pressure, natural flow and permeability of the reservoir.
- *General Characteristics of the System*
    - The design of a geothermal plant is a very complex procedure, in which it is necessary to take into consideration the: type of cycle to be used, location of the power plant, fluid transport system, optimization of the efficiency of exploitation of geothermal resources, optimization of the potential and definition of the characteristics of the main plant equipment, environmental impact evaluation, cost estimation and final economic evaluation.

2.1.4 Phase IV: Installation of the Generation Plants

Based on the results of the studies carried out, financing options were investigated for the construction of the proposed units. The first unit went online in March of 1994; the financing for this project was made through the Japanese Government and the IDB loans. The financing for the second unit was made through another loan provided by the IDB.

In order to use the steam available from geothermal wells already drilled for Unit 2 while Unit 2 was being constructed, a 5 MW wellhead unit was placed online at the end of November 1994. This plant was also financed by IDB. Additionally, two 5 MW back-pressure plants were rented from the Comisión Federal de Electricidad (Mexico) from September 1996 to April 1999, in order to utilize the steam from the geothermal wells already drilled for Unit 2 and also to obtain additional electric generation for the country.

2.2 Reconnaissance and Pre-feasibility Geothermal Studies in Costa Rica (ICE and ELC Electroconsult, 1989)

Once the financing was approved for the construction of the first 55 MW unit in Miravalles, ICE, using its own funds and those of the Italian government, carried out a national geothermal reconnaissance study and a pre-feasibility geothermal study.

These studies were divided into two phases. In the first phase, a reconnaissance study of the geothermal resources in Costa Rica was carried out, while in the second phase a pre-feasibility study was done in the area of the Tenorio volcano. These studies were financed with funds from the Italian government, which were managed by the United Nations Fund for Scientific and Technological Development (UNFSTD) through the United Nations Development Program (UNDP).

Participants:
Italy: The Ente Nazionale per l' Energía Elettrica (ENEL), which served as coordinator and general supervisor of the contracted companies: ELC-Electroconsult, Geotermica Italiana and Geosystem.
Costa Rica: The Instituto Costarricense de Electricidad (ICE).

2.2.1 Phase I: Reconnaissance Study (ICE and Electroconsult, 1989)

It was carried out from November 1987 to January 1989. The objective of this phase was to characterize the country into different zones of geothermal interest, delimit the most favorable areas and select one or two of the preferred areas in which a pre-feasibility study would be carried out in the next phase of the project.

Main Activities:
The main activities that were carried out in this investigation were:

- Bibliographic compilation and analysis (in order to define the areas of primary interest).
- Satellite imagery study, covering an area of approximately 28,000 km^2.
- Geovolcanological study.
- Hydrogeologic study.
- Geochemical study.

Conclusions:
The conclusions of this study were the following:

- High temperature resources:
  - High Priority: Rincón de la Vieja, Tenorio
  - Moderate to High Priority: Arenal-Pocosol, Platanar-Porvenir.
  - Moderate Priority: Orosí-Cacao.
  - Moderate to Low Priority: Cerro Pelado, Poás, Barva, Iraza-Turrialba.
- Moderate to low temperature resources:
  - Tilarán Cordillera.
  - Central Valley.
  - Some sectors of the Talamanca Cordillera.
- Among the areas classified as high priority, Rincón de la Vieja clearly stood out as the most favorable, particularly due to the abundance, extent and nature of its hydrothermal manifestations.
- The final report, issued in November 1991 and entitled "Evaluación del Potencial Geotérmico de Costa Rica" [1], ranked the various areas of geothermal interest in the country (Figure 1), and indicated that the possible total geothermal potential of Costa Rica was about 900 MWe.

Recommendations:
The recommendations were the following:

- Conduct pre-feasibility studies in the areas classified as high priority (Rincón de la Vieja and Tenorio) and Moderate to High Priority (Arenal-Pocosol, Platanar-Porvenir)
- Recommended activities for the study of each area would be.
  - Study satellite imagery (1,500 - 2,000 km^2)
  - Detailed geologic and volcanological studies (500 km^2)
  - Detailed hydrogeologic and geochemical prospecting (1,000 - 2,000 km^2).
  - Gravimetric prospecting (1,000 stations per 500 km^2)
  - Magnetometric prospecting (1,000 stations per 500 km^2)
  - Geoelectrical prospecting (100 - 150 stations per 100 - 150 km^2)

- Drilling of at least 10 small-diameter wells to determine the temperature gradients and heat flow in the area.

2.2.2 Phase II Pre-feasibility Study of the Tenorio Area (ICE and ELC Electrocunsult, 1990)

Objective: The objective of this phase was to evaluate the geothermal potential in one of the proposed areas from the reconnaissance study (the Tenorio volcano area) and to identify appropriate sites for exploration wells.

Duration and Consultant: This phase started in mid-1989 and finished with a final report in 1990. The consultant company for this phase was ELC- Electroconsult from Italy.

The activities carried out were:
Satellite imagery study (1,500 km^2)
Detailed geologic-volcanological study (500 km^2)
Prospecting for gases in soil (330 stations per 500 km^2)
Gravimetric prospecting (470 stations per 450 km^2)
Magnetometric prospecting (470 stations per 450 km^2)
76 Vertical Electric Soundings in 7 profiles
25 magnetotelluric soundings
Drilling of 9 small-diameter boreholes, to determine thermal gradients and heat flow in the area.

Conclusions:
In conclusion, the most interesting area studied was Cerro-Jilguero-Río San Lorenzo. In this area, the electrical conductive layer is at a shallow depth and the measured thermal gradient is 1.9 and 0.9 ºC/10 m.

Note: In 1999-2000**,** two deep wells were drilled in the margin of the area of interest (on the slope of the Tenorio volcano), but they had negative results. Investigations in this area were halted because the area of interest cannot be accessed, due to the fact that it is located within a National Park and also because it is of difficult access.

2.3 Feasibility Study of Units 3 and 4 in Miravalles (ICE and Electroconsult, 1995)

Objective: The objective of this study was to prove the feasibility of installing additional geothermoelectric units at the Miravalles geothermal field.

Duration and Consultant: This phase began at the end of 1994 and finished with a final report in 1995. The consulting company for this study was ELC-Electroconsult.

Work performed:
This study was done basically in two parts. The first part was a study of the evolution of the reservoir and well productivities, for which mathematical models were used. To do this modeling, all available geo-scientific information and the thermodynamic parameters obtained as a result of field exploitation since March 1994 were analyzed to improve the conceptual field model. The second part of the study consisted of developing the general specifications and characteristics of each power plant unit.

Conclusions:
The main conclusions of the study were:

- The installation of an additional 25-30 MW plant (Unit 3) in the Las Mesas area is feasible from the perspective of resource availability. However, this will provoke a noticeable drop in the reservoir pressure of this marginal zone of the field, making it necessary, in extreme cases, to lower operating pressures in the long term (15-20 years). The uncertainties about effective reservoir conditions, and particularly the extension of the reservoir towards the north, make it impossible to determine the feasibility of adding further units in this zone, regardless of the highly positive outlook.
- The Cuipilapa sector (Unit 4) is very promising as an area for future field expansion, regardless of the fact that it is very near the anticipated re-injection area in the southern part of the field. If the existing wells (PGM-50, PGM-51 and PGM-52) are found to be good injection wells, then it will be possible to use wells PGM-28 and PGM-29 for production and begin the development of this sector with a 25-30 MW plant. Even though the probable potential seems to be greater, the current state of knowledge suggests that the expansion of installed capacity should be limited for the moment, particularly since it is still necessary to define the content of non-condensable gases and the possible direct connection of this area with the planned re-injection zone.

2.4. Pre-feasibility Study at Las Pailas (ICE and GeothermEx, 2001)

Objectives: The objectives of this study were to:

- Describe and synthesize the exploration data and other pertinent technical information that has been collected to date within the project area.
- Using the available database, develop a conceptual model of the geothermal system(s) in the project area. This model will serve as a base for interpreting the geothermal resource potential in the area, as well as for planning future exploration and development activities.
- Make a preliminary estimate of the commercial geothermal energy reserves that could be present in the project area.
- Make recommendations and establish priorities for drilling sites.

Duration and Consultant: This study started in April of 1999 with a meeting of specialists from GeothermEx, Inc. and ICE, and finished with a final report in December 2001**.** The consulting company for this study was GeothermEx, Inc.

Work performed:

Analyze and synthesize the available information from the disciplines of Geology, Geophysics and Geochemistry.

Analyze and interpret the results of the temperature gradient wells in the project area, including an estimation of the temperature regime at depth, based on projection of the temperature gradients.

Construct a conceptual model of the geothermal system by integrating the available data, including the heat and fluid sources, the probable position and extent of the system, the possible patterns of fluid flow, and the geologic and structural controls that affect these characteristics.

Preliminary estimation of the recoverable geothermal heat reserves, based on the conceptual model.

Description of the sites recommended for the drilling and completion of deep wells to test and confirm the existence of the geothermal resource. Five sites were recommended in the Las Pailas area and five in the Borinquen area. For each area, four wells were programmed to confirm the existence of a geothermal reservoir that could produce commercially exploitable steam for electricity production, whereas the fifth

well was programmed as a development in the periphery of the field where residual geothermal fluids could be re-injected.
Based on the pre-feasibility report, ICE continued testing at Las Pailas to confirm the existence of a geothermal reservoir (with adequate temperature and permeability) in the area. To continue with its activities in this area, ICE needed to consider that currently, a great part of the area of known geothermal interest is within the limits of Rincón de la Vieja National Park, which was created as a result of the application of a national policy that protects and preserves the natural resources and the environment. Therefore, a large part of the area of geothermal interest is excluded from any possible future commercial development. The zone that is available in the Las Pailas geothermal area to carry out the investigation is a stretch of land oriented northeast-southwest (approximately 4 km long and 3 km wide).

The Instituto Costarricense de Electricidad drilled five wells in the available area at Las Pailas. Three of the four production wells yielded positive results, making it possible to confirm the existence of a geothermal reservoir capable of commercial electricity production, with temperatures of 240ºC, 13,000 ppm of total dissolved solids and a low content of non-condensable gases.

The fifth well proved to be unsuccessful, and therefore the existence of a zone where re-injection wells could be sited to dispose of residual geothermal waters has not been confirmed yet. However, better results are expected within the short term from a new injection well to be drilled in an area near the production zone.

While drilling the deep commercial-diameter wells, ICE continued to reinforce the pre-feasibility project studies with additional electric resistivity soundings, geological studies, geochemical studies and the drilling of various temperature gradient wells, all of which supported the conclusion that a geothermal anomaly exists at Las Pailas.

2.5 Las Pailas Feasibility Study (ICE and GeothermEx, 2005)

Objectives: Demonstrate the feasibility of installing a geothermal unit and its capacity. Prepare a report that could be used to seek funding for the project.

Duration and Consultants:
The study started in January 2000 with the signing of an assessment contract between ICE and the companies involved, and finished with a final report in September of 2005**.** The consultants for this study were: GeothermEx, Inc. of Richmond California, USA for the development of the geo-scientific part and coordinator of the study, and Power Engineers of Hailey, Idaho, USA for the pre-design of the field-plant system proposed for the exploitation of the field.

Work performed:

- Analyze the type of resource available (water-dominated, fluid enthalpy, temperature and chemical characterization of the fluids produced and injected).
- Evaluate the field’s potential from reservoir engineering data, including the creation of a numerical reservoir model.
- Design the power plant and field installations based on the synthesis of the previous results, taking into account the applicable environmental restrictions throughout the process.

Conclusion:
The main conclusion from the perspective of resource availability is that it is feasible to install a 35 MW power plant.

Under the Environmental Protecting Infrastructure for Economic Growth Utilizing Renewable Energy under the Puebla-Panamá Plan, the company West Japan Engineering Consultants, Inc, the Japan Bank for International Cooperation and ICE conducted a second feasibility study in the Las Pailas area. The activities of this study were very similar to the ones carried out by GeothermEx, and the conclusion was the same; namely, that "it is feasible to install a 35 MW power plant." (ICE and West Japan Engineering Consultants, 2003)

While financing was being sought for Unit I at Las Pailas, ICE drilled two deep wells in the Borinquen area, finding a temperature of 278.3ºC (Table 3) but low permeability. Drilling activities in this zone have been postponed until the logistics of the area are improved. Meanwhile, geo-scientific studies continue in the area.

In mid-2007, an agreement was signed between the Ministry of Environment and Energy (MINAE), the Costa Rican Institute of Electricity (ICE) and the Guanacaste Dry Forest (Non-Governmental Organization), to carry out geo-scientific studies in the in area called "Mundo Nuevo", which is a property of the Guanacaste Dry Forest, located between the Las Pailas and Borinquen geothermal areas. The investigations of this area are currently in progress.

3. COSTA RICAN GEOTHERMAL DEVELOPMENT

Commercial production of electricity using geothermal steam began at Miravalles in early 1994, when Unit 1, a 55-MW single-flash plant, was commissioned. The following year, ICE completed the installation of a 5-MW wellhead unit. Then, two temporary 5-MW wellhead plants came on line as part of an agreement between ICE and the Comisión Federal de Electricidad de México (CFE). The two temporary units were disassembled in April 1998 and April 1999 (Table 1) and returned to CFE. Unit 2, the second 55-MW plant, started production in August 1998. In March 2000, Unit 3, a 29-MW single-flash private plant, started delivering electricity to the national grid, and finally Unit 5, a 19 MWe binary plant, increased the total installed capacity at Miravalles to 163 MWe (Table 1) [2]. The history of the growth of capacity at the field is shown in Figure 3. The location of the power plants is shown in Figure 2.

4. RECENT EXPLORATION ACTIVITIES

The most-studied undeveloped geothermal systems in the country are those associated with the Tenorio and Rincón de la Vieja volcanoes. Pre-feasibility studies have already been concluded for both areas. In 1999-2000, two exploratory wells were drilled at Tenorio (to 1,345 m and 2,472 m depth). The results were disappointing, as they only encountered zones of low temperatures (less than 160 ºC) and low injectivity (less than 0.5 l/s/bar).

In January 2001, as part of a feasibility project, a deep exploratory well program was begun at the Las Pailas geothermal zone on the southern slope of the Rincón de la Vieja volcano. A total of five wells were drilled during the first phase of this project. Downhole measurements indicate temperatures near 240^{o}C. Some parameters of the wells are shown in Table 2. The Las Pailas feasibility study was completed in September 2005. (ICE and GeothermEx, 2005)

TABLE 1: Units at the Miravalles Geothermal Field

Plant Name	**Power (MW)**	**Owner**	**Start-up Date**	**Shut-down Date**
Unit 1	55	ICE	3/1994	
WHU-1	5	ICE	1/1995	
WHU-2	5	CFE	9/1996	4/1999
WHU-3	5	CFE	2/1997	4/1998
Unit 2	55	ICE	8/1998	
Unit 3	29	ICE (BOT)	3/2000	
Unit 5	19	ICE	1/2004	

In Table 1, the abbreviations stand for: ICE - Instituto Costarricense de Electricidad; CFE - Comisión Federal de Electricidad (México); WHU - Wellhead Unit; and BOT – build-operate-transfer.

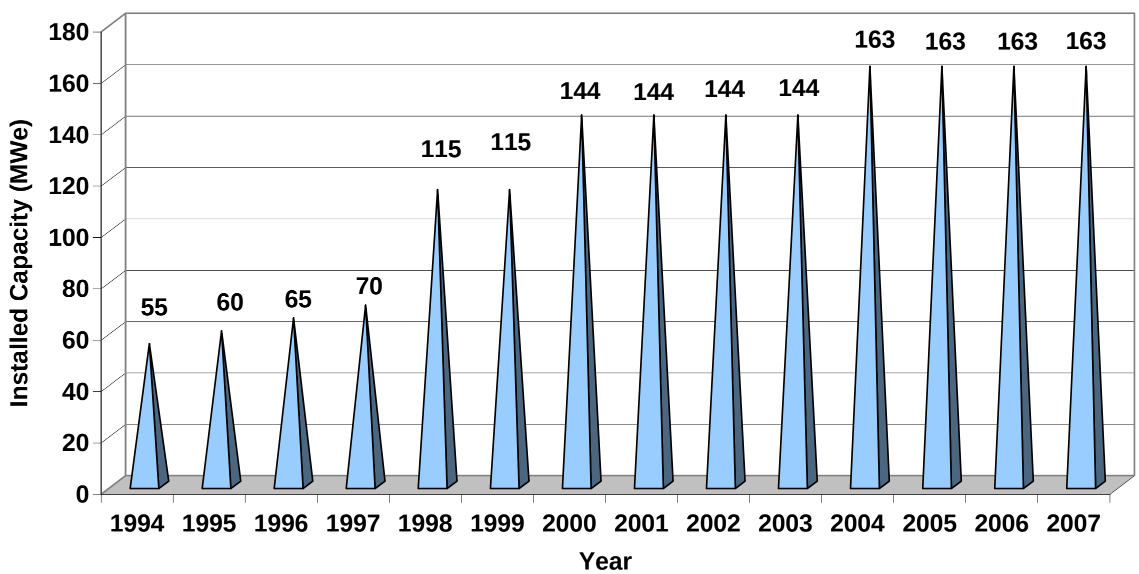

FIGURE 3: Costa Rica installed geothermal power capacity: 1994 – 2007

TABLE 2: Data on deep wells drilled at the Las Pailas geothermal area

Well No.	**Depth (m)**	**Max. T (°C)**	**Inj. Index (l/s/bar)**	**W.T. (m)**	**Enthalpy (kg/kJ)**	**Flow (kg/s)**	**Est. Output (MWe)**
PGP-01	1,418	245.4	8.3	380	1079	108.8	8.9
PGP-02	1,764	241.6	< 1.4	400	N. A.	N. A.	N. A.
PGP-03	1,767	249.8	4.7	440	1140	44.2	4.2
PGP-04	1,418	233.8	2.1	400	971	58	3.4
PGP-05	1,827	167.7	N. A.	260	N. A.	N. A.	N. A.

Notes:
W.T. = Depth of water table
N. A. = Not available

Borinquen is the name of another geothermal area at the Rincón de la Vieja volcano. In this area, the drilling of well PGB-01 was initiated in March 2003. The final depth of the well was 2,594.6 m, its maximum measured temperature was 278.5°C (at 1,276 m depth, 9/21/2005) and its injectivity index was less than 1.43 l/s/bar (Table 3). In summary, the well PGB-01 is very deep and very hot, but it has low permeability.

A new well (PGB-03) was drilled in the Borinquen geothermal area. Its final depth was 2,082 m and its maximum measured temperature (not stabilized) was 203.8ºC (at 1,995 m depth, 9/23/2005). Well PGB-03 so far demonstrates low temperature and low permeability. (Moya, 2006)

TABLE 3: Data on deep wells drilled at Borinquen geothermal area

Well No.	**Depth (m)**	**Max. T (°C)**	**Inj. Index (l/s/bar)**	**W.T. (m)**	**Enthalpy (kg/kJ)**	**Flow (kg/s)**	**Est. Output (MWe)**
PGB-01	2,594.6	278.5	<1.43	370	1079	31.3	N. A.
PGB-03	2,082	203.8*	N. A.	300	N. A.	N. A.	N. A.

Notes:
* = Temperature is not stabilized yet.
W.T. = Depth of water table
N. A. = Not available

5. THE IMPORTANCE OF GEOTHERMAL ELECTRICITY GENERATION FOR COSTA RICA

Most of the installed generation capacity in Costa Rica corresponds to hydropower and smaller amounts of fossil fuel (bunker and diesel), geothermal (all at Miravalles) and wind. Concurrently with the growth in installed capacity at Miravalles (Figure 3), there was an even more important increase in the amount of electricity generated (Figure 4). Between 1994 and 2006 the installed capacity at the field grew from 55 to 163 MWe (a 196% increase), while the generation grew from 341 to 1,214 GWh (a 256 % increase).

The high availability of geothermal plants is illustrated by Figure 5. Even though the installed capacity at Miravalles is only 7.6 percent of the country's total (year 2006), it produced more than 14 percent of the electricity generated. For Miravalles the load factor was 87.2% (year 2006), the highest of all types of power plants installed in the country.

The cost of the electricity produced by ICE for four types of energy sources (hydro, geothermal, wind and thermal) during 2000 and 2005 is shown in Figure 6. Hydro continues to be the cheapest source of energy for the generation of electricity in Costa Rica. The cost associated with geothermal is higher, but much lower than that for the thermal plants. The low load factor of the oil-burning plants – used only during a relatively few peak load periods – makes them very expensive to operate.

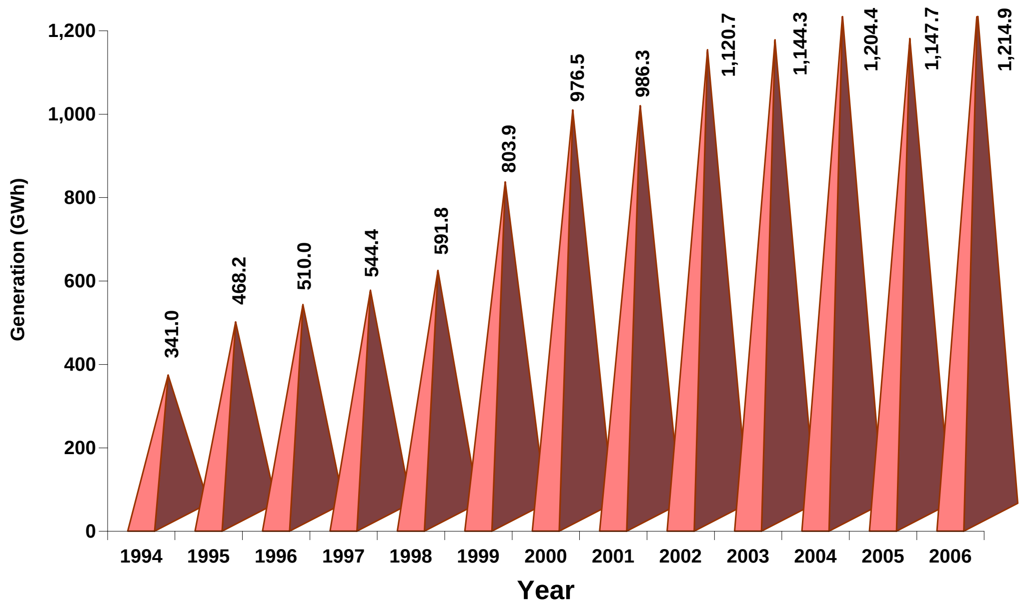

FIGURE 4: Geothermal energy generation in Costa Rica: 1994 – 2006

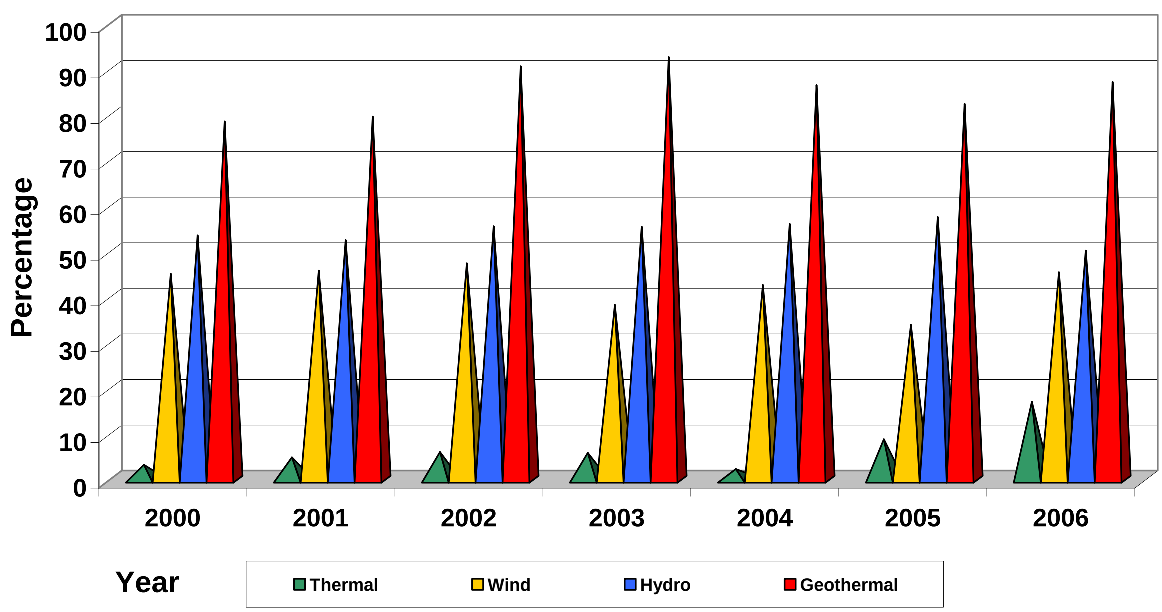

FIGURE 5: Load factors for different energy sources

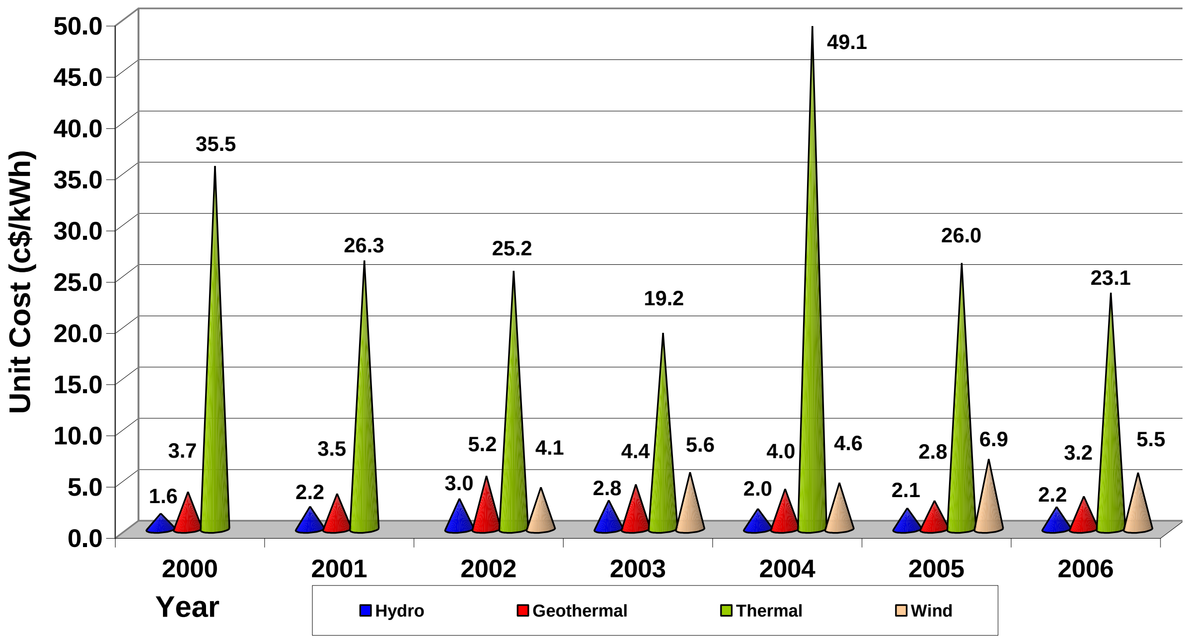

FIGURE 6: Electricity generation cost for different energy sources (2000-2006)

6. FINAL REMARKS

Huge quantities of scientific documents have been prepared pertaining to the geothermal resources of Costa Rica. These include geovolcanological, geophysical, geological, fluid geochemistry, soil geochemistry, petrographic, and mineralogical studies. Temperature gradient wells, and exploratory, production and injection wells have been also been drilled in the main geothermal areas (near the Miravalles, Tenorio, and Rincón de la Vieja volcanoes). Production and injection tests, fall-off tests, transmissivity tests and interference tests have been carried out when possible in all these geothermal areas.

Exploration for geothermal resources in Costa Rica began in earnest in 1979-80 when the first deep wells were drilled in the western foothills of the Miravalles volcano. The success of these wells and the results of subsequent studies led to the installation to date of five power plants at the Miravalles field with a total capacity of 163 MWe. The first was commissioned in 1994 (Unit 1, 55 MWe). It was followed in 1995 by a 5 MWe wellhead unit; then came Unit 2 (55 MWe) in 1998, Unit 3 (29 MWe) in 2000 and Unit 5 (19 MWe) in 2004.

Based on the success at Miravalles, ICE has been exploring other geothermal zones of the country. Wells drilled in the Las Pailas area, near the Rincón de la Vieja volcano, have shown promising results.

Even though the installed electrical generating capacity at Miravalles is only about 7.6 percent of the country's total, it produces approximately 14 percent of the electricity generated. The Miravalles geothermal plants have an average load factor of about 87.2 % (2006), the highest of all the energy sources used in the country.

The contribution of geothermal energy to the Costa Rican electrical system has been of great benefit to the country, not only because of the low cost of the electricity generated (significantly cheaper than thermal), but also due to its high availability and reliability (i.e., production is not affected by dry periods) and the indigenous nature of the resource (i.e., it has reduced the country's dependence on foreign sources of energy). Therefore, ICE plans to continue working on the development of this clean and renewable energy source.

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