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LATIN AMERICAN
ENERGY ORGANIZATION

INTER-AMERICAN
DEVELOPMENT BANK

PLANNERS' INFORMATION GUIDE ON GEOTHERMAL ENERGY

Quito, Ecuador
July 1994

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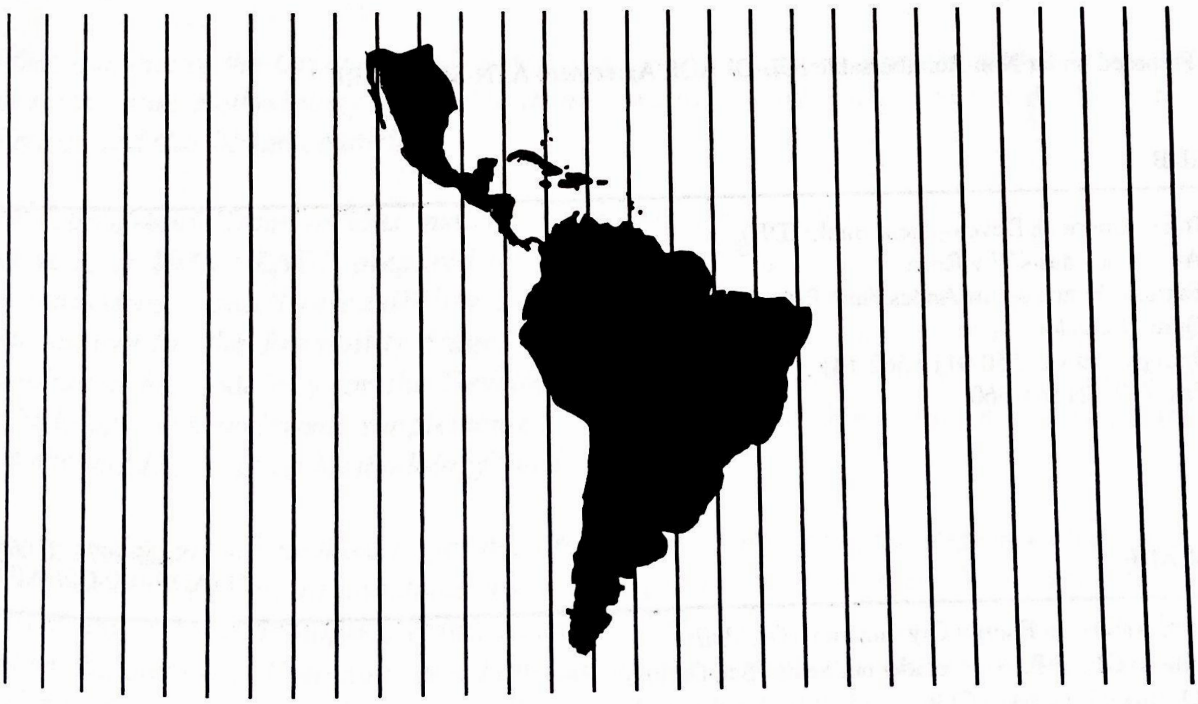

Quito, Ecuador
July 1994

Prepared under Non-Reimbursable IDB/OLADE Agreement ATN-SF-3603-RE.

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ISBN-9978-70-060-9
OLADE-010-GE/94 (En)

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PRESENTATION

In response to the oil crisis of the 1970s, in 1978 OLADE began a program of activities geared to fostering research on, and development of, geothermal energy as an alternative to conventional sources of energy. That program was framed within the Organization's objectives of a) promoting actions to develop, use and defend the natural resources of the OLADE Member Countries and the Region as a whole, and b) promoting a policy for the rational exploitation, transformation and marketing of energy resources.

To that end, one of the Organization's first actions was to compile a geothermal exploration and exploitation methodology adaptable to the conditions and characteristics of the Latin American and Caribbean countries.

With collaboration from various institutions and experts both from within the Region and outside it, in 1978 OLADE prepared the "Geothermal Exploration Methodology for the Reconnaissance and Prefeasibility Stages," in 1979 the "Geothermal Exploration Methodology for the Feasibility Stage," and in 1980 the "Geothermal Exploration and Exploitation Methodology for the Development and Production Stages." After the third methodology was reviewed, supplemented and updated, the Organization published the "Geothermal Exploitation Methodology" in 1986.

The availability of such methodologies has provided the countries of the Region with a useful, easy-to-apply tool to orient investigations of their geothermal resources. With support from OLADE and its methodologies, Haiti, Ecuador, Peru, the Dominican Republic, Grenada, Guatemala, Jamaica, Colombia and Panama, among others, carried out reconnaissance studies in their territories. Nicaragua, Panama, Ecuador-Colombia, Haiti and Guatemala, also with support from the Organization, developed prefeasibility studies in some thermal areas offering favorable conditions for the development of geothermal fields.

The application of the methodologies helped the countries of the Region to increase knowledge about their geothermal resources. By the end of the 1980s twenty of the twenty-six OLADE Member Countries had already done reconnaissance studies, 17 had carried out prefeasibility studies, 8 had conducted feasibility studies, and 4 were already generating electricity at some of their geothermal fields. Nonetheless, the rapid development of geothermal technologies made it necessary to once again update the methodologies.

Bearing in mind the fact that at different international forums the geothermal community had recognized the need to review, modernize and even supplement the OLADE documents, through Technical Cooperation Agreement ATN-SF-3603-RE the Organization and the Inter-American Development Bank (IDB) decided to review the existing geothermal exploration and exploitation guides and to prepare six new ones. Those guides, in response to the requirements of the technical groups of the Region, were to be on: Reconnaissance Studies, Prefeasibility Studies, Feasibility Studies, Evaluation of the Energy Potential (on the basis of information gathered in the reconnaissance and prefeasibility stages), Operation and Maintenance of Geothermal Fields and Plants, and Preparation of Geothermal Investment Projects.

The new documents on geothermal energy were prepared with assistance from seven international consultants and eight experts from the region with broad experience in geovolcanology, geochemistry, geophysics, drilling, reservoir engineering, operation and maintenance of geothermal fields and plants, and plant engineering and design.

The results of the efforts made by OLADE and the IDB to contribute to Latin American and Caribbean energy development are presented in this information guide for planners, for the purpose of providing the countries of the Region with an instrument apprising them of specific aspects of geothermal energy, related to the execution of geothermal power plants, which could be useful in national energy planning.

OLADE and the IDB especially acknowledge the work of Mr. Mauro Cozzini, who was in charge of the preparation of this document. They also thank Dr. Marcelo Lippmann, Dr. Jesús Rivera, Dr. Paolo Liguori, and Mr. Antonio Razo for their contributions to the guide.

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1. INTRODUCTION

A geothermal resource consists of underground energy stored in the form of heat in quantities and concentrations sufficient to justify its exploitation, particularly for electricity generation, with significant economic returns.

The use of geothermal energy for electricity generation began in Italy at the turn of this century, and it developed in other countries especially as of the 1960s. By 1990, installed capacity worldwide was almost 6000 MWe, and generation was more than 28,205 GWh/year (Table 1).

In Latin America, a study is currently underway on a possible increase in Nicaragua's installed capacity, and there are projects in the construction stage in Mexico, El Salvador, Costa Rica and Guatemala.

Table 1
Installed Geothermal Power Capacity
and Generation Worldwide in 1990

Country	Installed Capacity (MW)	Power Generation GWh/year	Geothermal Power % of natl. total
United States	2777	8000	0.3
Philippines	894	6730	23.7
Mexico	720	4660	4.4
Italy	545	3150	1.6
New Zealand	293	2000	6.9
Japan	215	1360	0.2
Indonesia	142	750	?
El Salvador	95	370	17.1
Nicaragua	70	410	37.0
Kenya	45	350	13.0
Iceland	45	260	5.8
China	21	50	< 0.1
Turkey	20	70	< 0.1
Soviet Union	11	25	< 0.1
France	4	20	< 0.1
Portugal	3	?	?
Taiwan	3	?	?
Greece	2	0	?
Argentina	0.6	?	?
Thailand	0.3	0	?

(Modified version of information from Gutiérrez, 1991)

Geothermal heat can also be used directly in heating systems and/or industrial processes. There are important examples of the direct use of geothermal heat in several countries, including relatively low-temperature resources.

A firm or utility that attempts to exploit this resource should, first and foremost, evaluate its economic significance and try to understand the problems that the geothermal project involves from exploration through final implementation.

The present guide is geared especially to those responsible for the economic assessment and strategic and operational planning of the firms interested in electricity generation. Its purpose is to familiarize them with particular aspects of geothermal energy, related to:

- the mining-related features of this energy resource, its approaches and the importance of its applications;

- the project development stages that are required to minimize risks and maximize results, and that condition planning, financing and final project implementation;

- technical aspects relating to the resource and the question of outfitting, which condition the project's technical and economic results;

- environmental aspects; and

- elements related to a geothermal project's costs, benefits and economic returns.

2. THE GEOTHERMAL RESOURCE

2.1 Geothermal Reservoirs

The formation of a high-temperature geothermal system potentially exploitable for electricity generation purposes is usually conditioned by the existence of:

- an important heat source, represented by a magmatic chamber (active or in the cooling phase) located at a relatively shallow depth (only a few kilometers deep), for which reason the geographical distribution of high-temperature resources (>200 C) is essentially limited to zones of recent volcanism;

- conduits (fractured zones) of deep fluid circulation, which permit the transport of endogenous heat to relatively deep upper levels;

- a volume of relatively porous and permeable rock, at a depth that would be economically accessible for wells and would permit the storage of hot fluids in a commercially significant amount (reservoir); and

- an essentially impermeable rock (cap rock) overlying the reservoir and confining it, although there are geothermal systems in which the reservoir is not totally confined.

The upsurge of fluids that have been heated at great depths and their circulation in the reservoir is part of the process that gives rise to a geothermal system. This process develops over very lengthy periods of time (thousands of years) and continues still.

A geothermal field is essentially of a dynamic nature, with continuous circulation and exchange of mass (fluid) and heat. In its natural state, without disturbances from exploitation, a geothermal reservoir is governed by a substantial equilibrium between system recharge (mass and energy) and the corresponding discharge. This can be seen particularly in the thermal manifestations (fumaroles, hot springs, etc.) that usually characterize geothermal areas. Its dynamic nature is what differentiates a geothermal field from other energy resources such as oil, coal and radioactive minerals.

A geothermal reservoir is thus the exploitable part of a broader circulation system, and it is constituted by rock saturated with hot fluids. The temperature of a high-enthalpy geothermal reservoir usually corresponds to a range of between 200°C and 350°C. Lower-temperature resources, which can also be exploited commercially, usually call for particular energy conversion technologies (binary-cycle plants, see Section 4.1) or direct use of the heat.

Two types of geothermal reservoirs can be distinguished as a function of the nature of the stored fluid:

- *water-dominated reservoirs*, where the fluid is essentially pressurized water in a liquid state, with possible localized boiling zones and/or small amounts of steam; and
- *steam-dominated reservoirs*, where the fluid is essentially steam, with a liquid phase possibly present in the reservoir in an immobile phase.

The geothermal fluid is the means of transporting energy to the surface through deep production wells. The commercial interest in the exploitation of a geothermal resource depends on the possibility of carrying out the extraction process at an economically attractive cost.

Heat can also be stored in hot dry rocks, and this is another type of geothermal resource that is potentially of interest. However, the technology for its exploitation, based on the artificial circulation of fluids with a "cold water injection - heating of rocks - recovery of hot water" scheme is still in the experimental state. This type of resource is therefore not considered in this guide.

Finally, it is worthwhile to point out that, in principle, a geothermal field cannot be considered a typically renewable resource; its formation has required geological time, and its intense exploitation at levels exceeding the net natural recharge of the hydrothermal system and affecting the energy stored in the reservoir will led to deterioration of its thermodynamic characteristics, ultimately reduce its production capacity and possibly lead to the definitive abandonment of the project for technical reasons (insufficient pressure) and/or economic ones (excessive steam production costs). Once the exploitation of a hydrothermal system is detained, the geothermal reservoir will be able to recharge slowly and naturally and could once again attain conditions favorable for its exploitation; however, such a recharge process could take several decades.

2.2 Potential Uses

The interest in a geothermal resource lies in the thermal energy contained in the rock and the subsurface fluid that can be exploited, mainly through its transformation into electrical energy and perhaps marginally in direct uses or through the extraction of minerals, in association with the main project.

The most economically profitable aspects of a geothermal project are noted below, without delving into depth regarding the technical and economic problems involved in direct uses of the heat, marginal uses and associated uses.

a. Conversion into Electricity

Based on the importance of the electricity market, as confirmed by projects implemented worldwide, this document considers only those geothermal projects devoted mainly to electricity generation.

In several countries the transformation of geothermal heat into electrical energy offers the great advantage of a demand sufficient to immediately tap the resource and permit the construction of a power plant nearby, with the electricity sent to consumption centers by means of a transmission system.

The elements necessary for the success of these geothermal power projects are:

- location of the resource at technically and economically accessible depths (<3000 m);
- high or medium fluid enthalpy (reservoir temperature >180°C);
- suitable potential to fuel units offering sufficient capacity to the power system, in principle over 15 MWe;
- low non-condensable gas content; and
- fluid-induced corrosion and scaling characteristics that are compatible with the process of electricity production.

b. Direct Use of Heat

There are a number of possible direct uses of geothermal heat: to heat buildings or greenhouses in regions with cold climates; to operate absorption-refrigeration units for industrial coldrooms or air-conditioning in urban centers; to dry agricultural, fishing or mining products; to provide heat for industrial processes; and to heat swimming pools and therapeutic hot springs.

It should also be noted that the cost of transporting and distributing heat is very high and it is difficult to find users near a potential geothermal field. Furthermore, only in very small areas of Latin America are there favorable climatic conditions for large-scale urban heating projects. These uses are therefore usually modest with respect to the total amount of energy that can be produced from a good geothermal field, and mining exploration projects for direct use of the resource are not justifiable.

Technical connections for the direct use of heat are less restrictive, and low-enthalpy fluids (<120°C) are particularly acceptable. These are sometimes discharged in the process of electricity production, and it is possible to identify small projects for direct uses of marginal interest associated with electricity production.

c. Extraction of Minerals

The extraction of minerals and chemical compounds has been of historical interest in Larderello for the production of boron, but currently it is almost non-existent. In Mexico, studies were done on the development and use of potassium and lithium salts; however, no such project has been implemented.

2.3 Stages of Geothermal Project Implementation

The development of a geothermal project is usually stimulated by expectations of benefits related to its ultimate success, but one must proceed with caution both in the mining and equipment selection components, in order to minimize the high risks of a partial or total mining failure and to plan activities rationally.

This calls for prudent, stagewise development characterized by continuous advances in gatehring data and gaining experience, so as to make it possible to reduce the risks of subsequent stages, which involve an exponential increase in investments.

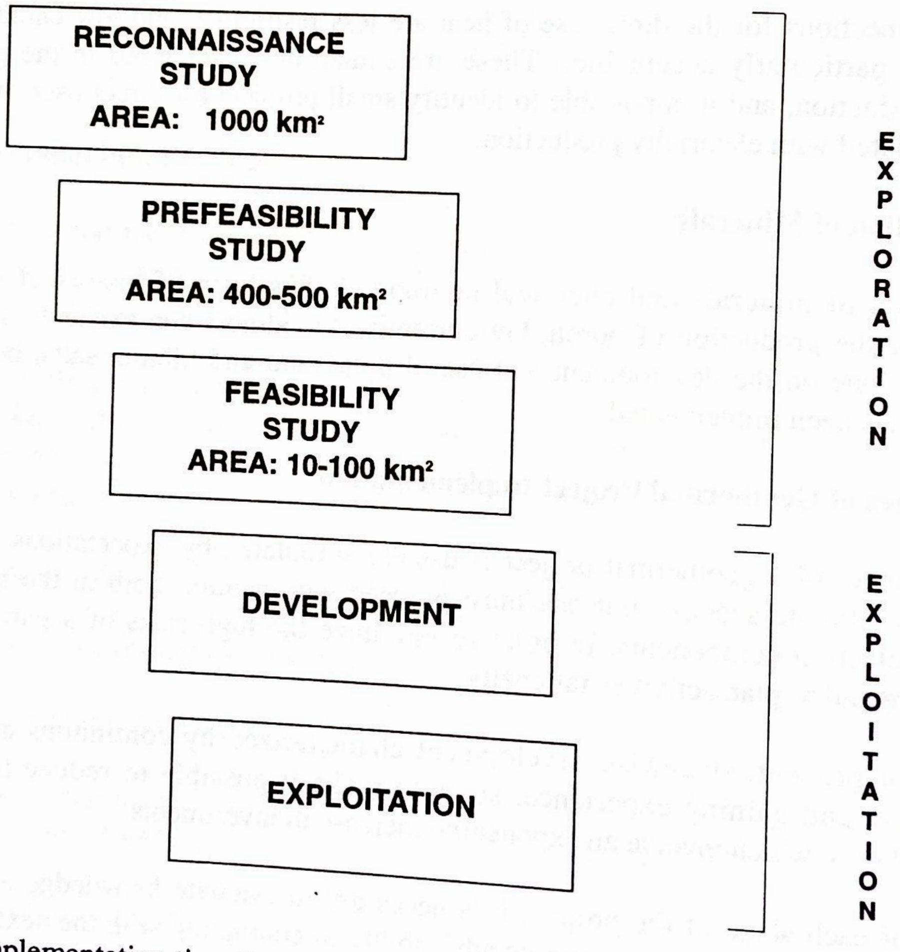
At the end of each stage of the project, it is necessary to evaluate knowledge and risks, in order to judge the technical and economic advisability of continuing with the next stage, plan accordingly, and assess financing for the work foreseen.

It is not possible to initially plan an entire project. The uncertainty surrounding ultimate success creates difficulties for power system planners, who must guarantee, well in advance, the date on which new power plants will be incorporated into the system. Such planning is only possible after feasibility studies have been completed.

The implementation of a geothermal project can be divided into five stages, of which the first three (reconnaissance, prefeasibility and feasibility) refer to project exploration. The other two (development and exploitation) refer to the preparation of the field to tap the geothermal fluid, systematic production of the fluid, its industrial utilization, and field management problem-solving. (See Figure 1.)

Figure 1

STAGES IN THE IMPLEMENTATION OF A GEOTHERMAL PROJECT



The total implementation time for a typical project, until the first power plant is completed, is approximately seven (7) years.

The methodology and objectives of each stage, as well as the most significant aspects of decisionmaking and planning, are described below.

2.3.1 Stage I: Reconnaissance Study

This corresponds to the first part of mining exploration, the purpose of which is to identify the areas where there is the most evidence of a geothermal resource. The study's objectives and methodology are described in the *Guide for Geothermal Reconnaissance and Prefeasibility Studies* (OLADE/IDB, 1994).

The studies are done in regions and/or specific areas, and they include: geology, hydrogeology, geochemistry and geophysics, as well as the identification of the energy demand that could be satisfied on the basis of the possible geothermal resource.

The findings should identify and classify the areas of geothermal interest and should establish priorities and the likelihood of success for more detailed exploration. Emphasis should also be placed on environmental aspects and the possible technical and economic utilization of the possible resource.

Bearing in mind the probability of success, a plan is then defined for the next (prefeasibility) stage, and its cost is estimated.

The time needed for a reconnaissance study is approximately one year, and the level of investment is relatively moderate: about US$500,000.

2.3.2 Stage II: Prefeasibility Study

The exploration begun during reconnaissance continues with more detailed geoscientific studies, concentrating on the area identified as the most promising or on two or more alternative areas, possibly with the drilling of gradient or multi-purpose wells. Its objective is to estimate in greater detail the existence of a geothermal reservoir, to define the area in which it might be found, tentatively determine the characteristics and possible potential of the resource and, finally, plan the successive deep exploratory wells foreseen for the feasibility stage. Details on the objectives and methodology to be followed in an investigation are described in the *Guide for Geothermal Prefeasibility Studies* (OLADE/IDB, 1994).

Prefeasibility includes: geological and volcanological studies to define a preliminary geological model of the geothermal system; geochemical studies with chemical and isotopic analyses of the hot and cold fluids (water and gas) outcropping at the surface and geothermometer readings of these to define a flow model and interpret the possible underground temperatures; hydrogeological studies to define the groundwater circulation model; and geophysical studies to locate the possible reservoir. The integration of all of this information will make it possible to prepare a preliminary geothermal model of the area of interest.

In the final phase of the prefeasibility study, prior to deep exploratory drilling during the feasibility stage, it will sometimes be advisable to drill shallow gradient wells to expand the information on the subsurface and reduce the economic risks of deep drilling. Gradient well drilling sometimes provides additional information that reinforces or rectifies the hypothesis of the presence of a significant underground geothermal anomaly.

In other cases, to obtain information permitting the confirmation or modification of a preliminary conceptual model of the geothermal system, the decision can be made to drill deeper, small-diameter exploratory wells, which offer the advantage of determining subsurface conditions at greater depths than those of the gradient wells.

The time needed for this study, excluding drilling, is approximately one year, and the level of investments, under normal conditions, is approximately US$1 million.

2.3.3 Stage III: Feasibility Study

This stage includes deep exploratory drilling of three to six wells, in order to have three or four production wells and at least one injection well. This stage is fundamental because the results and the information obtained from the drilling should provide more certainty as to the existence of the resource, and thus help focus the exploitation project. The objectives and methodologies of this study are described in the *Guide for Geothermal Feasibility Studies* (OLADE/IDB, 1994).

The time needed for the study is approximately two years, and the level of investment is quite a bit higher, given the number of deep wells to be drilled (US$10 to 15 million).

The activities corresponding to this stage can be divided into the following categories: field engineering, plant engineering and economic feasibility.

a. Field Engineering

This involves the execution of exploratory drilling, data collection and interpretation, activities and studies related to the reservoir, field development planning and fluid management. It includes drilling and completing the wells; conducting geological, geochemical and geophysical studies at the surface and in the wells, static and dynamic well measurements and production tests; refining the conceptual model of the field, by integrating the data that have been collected and evaluated; preparing a mathematical model for the reservoir and simulating its natural state; studying the fluids' chemistry and possibly testing scaling and corrosion; performing a resource assessment; and formulating a production/injection strategy through mathematical models.

The results should include: definition of the proven, probable and possible reservoir potential; definition of typical well productivity or injectibility, under initial exploitation conditions and the foreseen evolution during exploitation; determination of the energy, chemical and physical characteristics of the fluids; planning of the wells to be drilled for implementation of the project; definition of the fluid conduction and disposal scheme; and estimation of the probable investment costs for field development and production maintenance, with emphasis on the risks of variations in these costs.

b. **Plant Engineering**

This consists of preparing the proposal for the equipment needed to transform geothermal energy into electricity, and it involves: the study and optimization of the transformation process based on field productivity, the characteristics of the geothermal fluids, and the production/injection strategy, as well as the formulation of equipment designs based on modern construction technologies, economic objectives and environmental considerations.

The project should be defined in close collaboration with power system planning experts, particularly insofar as:

- the choice of power capacity, which must be coherent with the field's proven potential and with overall planning for power generation system development;

- the project completion date, which must permit the orderly execution of the works, with minimum interest accrual during construction and must guarantee start-up within the deadlines set by the power system's requirements; and

- economic parameters to be adopted to optimize the equipment, which should be coherent with the value of the electricity.

The results should include the following choices: the type of electricity production process (steam with single or dual flashing, binary cycle) and steam separation procedures, with the selection of process parameters and technical-economic optimization of the field-plant group; the strategy for implementing units, possibly beginning with the immediate installation of free-discharge (3-to-5-MW) wellhead units and developing by stages with modular sets of low power capacities (15 to 30 MW), or the rapid installation of large units (30 to 55 MW); power capacity, operating flexibility, and the features of the main equipment and auxiliary systems; plant site and the arrangement of the conduction system and the plant equipment; and ways to mitigate environmental impacts.

c. **Economic Feasibility**

The purpose here is to justify the large investments in project implementation, as compared with the benefits of electricity generation. Economic feasibility can be examined only if technical feasibility has been demonstrated and perhaps if the basic design has been prepared, once:

- the type and technology of resource utilization has been individualized;
- the field's capacity for supplying the plant has been proven;
- the fluid extraction system's basic design and utilization plant have been prepared; and
- the project has been shown to be environmentally sound.

Risks of serious technical noncompliance are not acceptable; there can only be uncertainty about the total amount of the project's costs and benefits, which should fall within a range of variation in which suitable rates of return can be maintained.

2.3.4 Stage IV: Project Development

Project construction should follow the technical and economic criteria and strategies defined in the feasibility study, The objectives and methodology for this stage are described in the *Guide for the Development Stage of a Geothermal Project* (OLADE/IDB, 1994).

Usually, development takes place in phases, following the strategies recommended in the feasibility study:

- drilling of production and injection wells, and sometimes immediately installing free-discharge (3 to 5 MW) wellhead units
- field development by stages, with modular sets of small power capacities (15 to 30 MW) or large units (55 MW).

The time required for drilling wells and building the power plant is approximately three years. The level of investment is very high, and it depends on the number of deep wells to be drilled and on the plant's power capacity (approximately US$2000/kW, in other words, US$100 million dollars for a 50-MW plant).

During well drilling and construction of the works, any new data available should be collected and the reservoir engineering and design studies should be continuously updated. Possible later increases or modifications in the works should be justified on the basis of specific feasibility studies.

2.3.5 Stage V: Operation and Maintenance

Operation and maintenance of the field-plant system should permit maximum equipment efficiency and continuity of energy production. See the *Guide for Geothermal Field and Plant Operation and Maintenance* (OLADE/IDB, 1994).

The evolution of the reservoir and of well production should be continuously monitored in order to detect significant variations and to update and adjust the mathematical model of the field. The correct application of the model is indispensable in interpreting changes and problems observed in the behavior of the reservoir, in order to predict its future evolution and make decisions regarding replacement drilling programs and the possible expansion of installed capacity.

2.4 Role of Geothermal Power

2.4.1 Technical Aspects

Geothermal power is fed into the local electricity grid, which is usually interconnected with the main national distribution networks and sometimes with those of neighboring countries, thus creating large electricity markets.

The planning of a given geothermal system's development should form part of the expansion plan for power system generation to cover the demand that normally accompanies a country's economic development. Geothermal generation should be technically compatible and coordinated with the generation from other system plants, in order to have reliable, low-cost supplies.

To achieve this objective, field-development and plant-construction activities should avoid technical risks and foresee implementation controls, in order to eliminate delays. This is only possible after feasibility studies.

The typical generation of a geothermal plant is continuous. In other words, there are no fluctuations in load and the unit is not shut down; so, baseload power is provided. This arrangement is an outgrowth of the advisability of not frequently modifying the wells' production regime (steady operation) and of the high cost of the field-plant system, which is only economically viable with a continuously high plant utilization factor.

However, specific situations may differ somewhat; for example:

- small isolated systems in which geothermal power can play a comprehensive role, providing baseload, modulating and peak generation. In this case, the design and operation of the field-plant system should be carefully optimized.

- surplus generation during the rainy season, when hydroenergy's temporary availability can satisfy demand and the geothermal plant can reduce its generation.

- surplus capacity of plant equipment due to partial drawdown of the reservoir. When generation can be decreased during periods of greater availability of energy from other plants, the reservoir could be allowed to recover its capacity for use during critical periods for the power generation system.

2.4.2 Economic Aspects

Thus, the design of a geothermal power plant should be in accord with the country's power generation system and should be economically competitive with non-geothermal plants, in order to be able to substitute for them in the long-term expansion plan for the power generation system.

Consequently, the benefit of geothermal power generation is represented in the savings on costs, in other words, in the "avoided costs" resulting from the fact that it is not necessary to build and operate alternative plants.

A geothermal plant usually substitutes for a plant run on fossil fuels, which would require lower investments but has the drawback of being subject to fluctuations in fuel costs. Section 5, which provides significant figures for comparison, shows that the elimination of the cost of fuel used in a thermoelectric plant is one of the major benefits generated by an investment in a geothermal field (which represents about 50% of the total cost of a geothermal power project).

The economic importance of this benefit is based on fuel costs calculated in foreign currency (whether imported or exportable) and the risks run when there are fuel availability crises and price increases exceeding inflation. This aspect should, above all, encourage investments in initial stages, when the project's success has not yet been proven by feasibility studies.

The economic justification of a project should demonstrate that its incorporation into the expansion plan is the least-cost solution for satisfying the power system's energy demand. If the project is only part of a broader program aimed at covering a given demand, it should be demonstrated that the overall program is the optimal solution.

Demonstration of the advantages of an economically viable geothermal power plant should include a comparative analysis of the project's monetary benefits and its costs, and the most significant econometric parameters should be calculated. Furthermore, there should be timely sensitivity and probabilistic analyses to evaluate the effects of possible results and costs other than those foreseen.

One very significant economic comparison parameter is the average cost of generation from alternative plants, defined as the ratio between total discounted costs and total discounted energy; this is the Long-Run Marginal Cost.

3. TYPICAL FIELD CHARACTERISTICS AND COSTS

3.1 Potential and Productivity

3.1.1 Stored Energy and Exploitable Potential

The amount of *stored thermal energy* in a geothermal reservoir is a function of its volume, its temperature and the thermodynamic state of the fluid contained in the rocks.

The exploitable potential is lower than the total amount of energy in the reservoir, and it is obtained by introducing the concept of the "recovery factor," which represents the fraction of the total stored energy that can actually be recovered/exploited and made available at the surface for its conversion into electricity.

In fact, most of the energy stored in the reservoir is contained in the rock itself, more than in the fluid. Therefore, this energy cannot be fully recovered, because it is limited by the possibility of exploiting the fluid stored in the reservoir itself, by drainage into surrounding areas as a result of system exploitation, and by the rock's capacity to transfer its heat to the fluid.

The value of the recovery factor involves physical and technical limits (the amount of energy that can be extracted in technical terms) as well as economic ones (the amount of energy that can be extracted for less than a given maximum cost).

The application of appropriate factors for the conversion of the energy available at the surface (which depend on the type of cycle adopted) ultimately leads to the definition of the *field potential* in terms of *installable power capacity*.

3.1.2 Evaluation Methods

Determination of a field's potential on the basis of knowledge about its geometric characteristics (volume), physical characteristics (pressure and temperature) and hydraulic characteristics (storage and permeability), and the evaluation of a reasonable recovery factor value is one of the main reservoir engineering tasks, particularly in the initial stages of a geothermal project.

In the evaluation of potential, basically two approaches can be distinguished:

- *volume methods*, which estimate the amount of heat and fluid stored in the reservoir and which, through the application of an empirical recovery value, provide a value for exploitable potential; and

- *simulation methods*, based on the application of mathematical models for the analysis of the dynamics of the thermal-fluid behavior of a reservoir under exploitation. Simulation permits the study of future reservoir evolution, especially the pressure and enthalpy of the fluids produced, as well as determination of the possibility of maintaining required extraction levels over a certain time period (from 15 to 30 years).

Through simulation, the recovery factor is not defined a priori, but rather is essentially the result of the simulation itself. Thus, this approach is more accurate than the volume method, although it also has its limitations, particularly in terms of the initial field conditions, since knowledge about the reservoir is still incomplete. The incomplete input data lead to a degree of uncertainty in the simulation results. To avoid the risk of overestimating, prudent-conservative hypotheses should be adopted for the still unknown reservoir parameters, and a reduction factor may have to be applied to the simulated capacity.

3.1.3 Categorization of Potential

In each stage of a geothermal project, an important difference should be kept in mind between:

- *proven potential,* which represents the energy capacity that is known with certainty to be available in the reservoir, based on technological and economic factors and knowledge about the resource already proven through deep wells, to guarantee the production of the steam necessary throughout the plant's useful lifetime. The risk of a mining failure should be absolutely marginal, with the only uncertainty being the level of exploitation costs.

- *probable/possible* potential, which represents the probable/possible energy capacity available in the future, from the entire resource, provided that technological and economic factors are taken into account. This is estimated on the basis of a hypothesis regarding the area and nature of the field, not yet confirmed by direct exploration.

It is evident that, before beginning the project's *feasibility* stage, there will only be estimates of possible potential, and only successful deep drilling during the feasibility stage will make it possible to define proven potential, which can prove to be substantially lower than the real resource potential. However, to avoid the risk of overoutfitting, it can only be decided in this stage whether a capacity no larger than the proven potential should be installed. During field development and operation, the evolution of the *probable/possible* potential will make a substantial contribution towards defining plans for expanding installed capacity in the future.

3.1.4 Productivity

Resource *productivity* is defined as the level of energy extraction efficiency that can be attained, particularly in economic terms. The essential factor here is average productivity of production wells, or rather the average drilling cost per MW(e) produced. In fact, it is evident that a high rate of steam production will lead to a reduction in unit costs of steam supplies to the plant and will therefore make the project more interesting.

Well productivity is essentially a function of the nature of the reservoir, particularly its permeability and temperature. However, production costs are affected by other factors such as well depth, the need for injection wells, etc.

Well productivity does not usually remain constant. It can be affected negatively by the evolution of the reservoir's thermodynamic characteristics (particularly drops in pressure). Therefore, the progressive decline of productivity over the lifetime of the project, and the consequent need for drilling additional (replacement) wells, must be taken into account. Individual well and overall field productivity, and its evolution over time, also depend on the resource exploitation scheme (location and density of wells, flows, spacing between production/injection wells, etc.). Since the exploitation scheme may have to be adapted to the reservoir's evolution during its useful lifetime, resource exploitation should be properly controlled on the basis of continuous reservoir monitoring and the application of mathematical simulation models in order to predict reservoir evolution.

3.1.5 Economic Aspects

The concept of well productivity and its variation over time clarifies which economic factors are the main ones to be kept in mind in defining resource potential, which is simply the amount of energy that can be produced at an economically competitive cost.

In a resource development process implemented by stages, which is typical for geothermal energy, the installed capacity can be increased until the marginal cost of the expansion ceases to be economic.

3.2 Characteristics of the Fluids Produced

As a function of reservoir type, the fluid produced by the wells of geothermal field may be either:

- *dry, saturated or superheated steam*, which can be sent directly to the power plant; or

- *a mixture of water and steam*, with a varying proportion of steam, according to the type of well feed and the wellhead pressure. In this case the two phases must be separated using suitable equipment (cyclone separators); the steam is then sent to the turbine and a usually sizable amount of hot liquid must be disposed of or used for subsequent evaporation at a lower pressure (second flashing).

In water-dominated fields, the separated steam is usually 15% to 30% of the total mass. However, the massive exploitation of the resource can modify the proportion of steam to water, creating either higher values (reservoir boiling) or lower ones (reservoir cooling).

The chemical composition of the extracted fluids may affect resource exploitability, and in extreme and rare cases make it technically or economically impossible or unadvisable (when the fluids that are extracted produce a great deal of corrosion or scaling).

The fluid (steam or mixture) normally contains a certain amount of non-condensable gases, composed mainly of CO_2, smaller percentages of H_2S, and traces of other gases.

The concentration of non-condensable gases varies from field to field; however, it usually does not exceed 5% of the total amount of steam (produced or separated). In extreme cases of very high gas contents, it may not be advisable to install condensation plants, in which cases the applicable cycles would be limited to those with free discharge; or else, gas separation equipment would need to be installed before the turbine's steam intake.

The composition of non-condensable gases, especially the H_2S content, determines the corrosive characteristics of the steam. This has a bearing on the selection of the materials to be used in the equipment and on the environmental protection measures needed because of gas released into the atmosphere.

As for the separated water in water-dominated fields, this is usually brine with a quite variable content of dissolved salts, between a few thousand ppm and in extreme cases, 200,000 to 300,000 ppm (seawater has a salt concentration of 35,000 ppm). This salinity, and particularly the content of toxic elements such as boron and arsenic, call for careful control of the disposal system (Section 3.3).

One particular problem is related to the dissolved silica content. Abundant deposits of this mineral can be created when fluid temperatures drop, with the consequent difficulties for disposing of the fluid. In some cases, the risk of silica deposit formation, directly related to temperature reductions, is the main constraint for more complete exploitation of the energy contained in the extracted fluid; for example, through the adoption of a second evaporation (flashing) stage.

3.3 Fluid Transportation and Disposal

The steam produced by wells scattered over a relatively large area must be transported by a conduction system to the power plant.

In the case of dry-steam production, the system simply consists of connecting the wellhead to the plant's steam collector. In the case of a mixture, the water and steam phases must be separated, with conduction system arrangements selected on the basis of the characteristics of the wells and the fluids produced (especially the steam portion), the distance from the plant, and the terrain.

The disposal of separated water is an important aspect in selecting the exploitation regime for a water-dominated field.

The discharge of residual fluids at the surface has sometimes been adopted: for example, in Cerro Prieto, Mexico, in evaporation lagoons; and in Ahuchapán, El Salvador, in the ocean by means of a canal. However, it can be affirmed that usually the characteristics of the residual fluids call for their injection at great depth (see Section 3.2.), particularly in the geothermal reservoir itself, in order to avoid any contamination of shallow aquifers, surface water, soil, etc.

Furthermore, the adoption of large-scale injection, if done in the reservoir itself, will affect the reservoir and will have a positive impact on reservoir pressure (reduction of the net mass extracted) and partial cooling of the formation. It will then be necessary to do a careful evaluation of the location of injection wells and continuously monitor the field in order to avoid the possibility of accelerated deterioration of the producing areas.

Injection can also be used in steam-dominated field, to eliminate condensation water from cooling towers and to recharge the reservoir.

3.4 Environmental Aspects

The potential environmental impacts of a geothermal plant are mainly related to:

- the disposal of wastewater and
- the discharge of non-condensable gases into the atmosphere.

In general, the adoption of total water injection at depth (into the reservoir) provides suitable protection for soils and surface water during normal plant operation.

As for the discharge of gases, a suitable dispersion system must be adopted, primarily as a function of the H_2S content, which, at ground level, should not exceed established values. If necessary, this is done by building a stack that will permit gas dispersion at an appropriate height. Alternatively, H_2S-reduction systems may be installed; however, this would entail a sizable investment and a loss of plant efficiency. It is interesting to note that the emissions of CO_2, which is the principal component of geothermal gas (usually more than 90% of the total) are far lower (per kWh generated) than those of any type of conventional thermoelectric plant run on fossil fuels.

Other potential secondary impacts are:

- land occupation and use;
- visual impacts due to buildings, excavations, wellheads, fluid conduction equipment and drilling equipment during field development;
- noise from the wells and the powerhouse;
- pollution in the event of an accidental blowout;
- subsidence caused by geothermal fluid extraction; and
- seismicity due to subsidence or to fluid injection (microseismicity). The intensity of this induced seismicity is usually of the same order of magnitude as natural seismicity, especially in volcanic areas in which the latter is significant and has already been considered in the plant design.

In conclusion, it can be affirmed that, with the adoption of suitable environmental protection measures, the impact of a geothermal project can be kept within absolutely acceptable limits, and it can compare favorably to the impact of alternative plants.

3.5 Typical Investments

The typical investments in geothermal exploration and field development, until commissioning of a power plant, can be broken down as follows:

- **Preliminary/Surface Exploration Costs**: US$1.5 to 2 million (reconnaissance and prefeasibility stages, see Section 2.3)

- **Drilling Costs**: US$1-2 million per well.

  The actual cost of a well depends on its depth, diameter, type of completion (vertical, deviated, with or without slotted liners, etc.), drilling time, type of formation encountered, etc.

  For wells in the feasibility stage, the estimated cost is approximately 20% higher than for development wells due to their exploratory nature, the scant knowledge about subsurface conditions, and the need for more investigation (tests, drill core sampling, etc.).

  The impact of drilling costs on overall project costs varies a great deal and is primarily affected by:

  . the average productivity of successful wells (typical value: 5 MW)

  . the drilling success factor, or ratio of failures to productive wells (typical values: 1 to 3 in the exploration stage and 1 to 5 during the development of proven areas)

  . the need for injection wells (in water-dominated fields) and their injectibility (typical value: 1 injection well for every 3 production wells).

  With the typical values indicated above, drilling costs average US$500/kW.

  The costs of replacement wells are usually included in operation and maintenance costs (see Section 3.6).

- **Separation/Conduction System Costs**: US$200,000 to 500,00 per production well in steam-dominated fields and US$500,000-900,000 per production well in water-dominated fields.

Actual costs depend on well productivity, the separation/conduction layout adopted, and the distance from the wells to the plant.

Water-dominated fields involve larger investments because they require separators, water lines to injection wells, etc.

Considering an average of 5 MW per well, in water-dominated fields, typical costs under this item average US$150/kW.

- **Costs of Land or Clearance Purchases, Access Roads and Platforms**: The typical value is US$200,000 per well (US$50/kW).

  The actual cost of building accesses and platforms depends particularly on local the topography and the type of terrain (stability, rock alterations, etc.).

- **Engineering and Administration Costs**: These are on the order of 10 to 15% of direct investments.

- **Contingency Costs**: These are estimated as approximately 10% of the total.

As can be discerned from the above-mentioned amounts, the investment costs for the "field" part of a geothermal project depends on many factors, particularly the nature of the resource, its productivity, size and location. A typical value could be established as about US$900/kW, without including interest accrued during construction.

It is worthwhile to point out the importance of project economics and the need to ensure continuity in the various stages (feasibility-development-commercial operation), avoiding delays or interruptions. In fact, due to the importance of field investments, postponement of plant commissioning negatively affects project costs because of high interest rates that have to be paid during construction.

In the case of optimal development (four years from the start of the feasibility stage), interest is approximately 25%, which increases investment costs to US$1000 or US$1200 per kW.

3.6 Typical Operation and Maintenance Expenses

Annual operation and maintenance expenses for a geothermal field include:

- **Costs of drilling replacement wells**, which compensate for the other wells' progressive loss of productivity or shutdown, for different reasons. The reduction in productivity varies from case to case as a function of the type of reservoir, the exploitation regime, and particularly production intensity (ratio between installed capacity and the field's effective potential). The reported reduction rates range from 1 to 10% per year, with normal values of about 3% per year. So, the average annual cost for new wells should be taken as 3% of the initial investment in drilling (typical value: US$15/year/kW).

- **Field operation and maintenance costs,** with possible modifications in the conduction system. These can be estimated as approximately 1.5% annually of the total initial cost (typical value: US$15/year/kW).

In conclusion, the total cost of field operation and maintenance is on the order of US$30/year/kW. Considering the average annual generation of a geothermal plant (7.5 GWh/MW), the cost of field operation and maintenance is approximately US$4 mills/kWh.

4. PLANT CHARACTERISTICS AND TYPICAL COSTS

4.1 Energy Conversion Cycles

The geothermal fluids used to produce electricity must be transported to the area of the plant where geothermal heat is converted into electrical energy. The plant should be located on a wide, flat piece of land (150 m wide and 150 to 300 m long, depending on the installed power capacity and number of units), and it should be inside the field in order to reduce fluid-transportation costs.

In determining the optimal efficiency of the conversion cycle, the field-plant system should be considered as a whole. This will call for analyzing a number of parameters (for example, well productivity characteristics and their evolution; field costs; layout, efficiency and cost of the fluid conduction and injection system; and type of cycle, efficiency and plant costs). The costs corresponding to each increase in field production and each increase in plant efficiency should be lower than the economic value of the increase in electricity production.

In general, steam cycles and binary cycles are used in geothermal power plants.

a. Steam Cycles

Steam turbines are the most commonly used type of equipment in the energy conversion process. The fluid used is therefore steam, which can be produced directly from dry-steam wells (see Sections 3.2 and 3.3.) or obtained from water-steam mixtures by means of a first steam separation, and possibly a second one. Wastewater should usually be injected.

The turbines can be:

- counterpressure turbines that discharge steam directly into the atmosphere; or

- condensation turbines, where the steam is discharged to a condenser for vacuum condensation in contact with water, which is recycled in cooling towers. The vacuum in the condenser is maintained by machines (steam ejectors, mechanical compressors, etc.) that extract non-condensable gases.

The pressure of the steam, the pressure of the discharge (atmospheric or in a vacuum) and the non-condensable gas content are the main parameters governing the efficiency of the plant and of the field-plant system.

The parameters that summarize system efficiency are:

- *plant efficiency*, given by specific steam consumption and expressed in kg of steam per kWh of gross electricity production (in other words, production at the alternator terminals) or per kWh of net electricity supplied to the power transmission and distribution system after the plant's own consumption has been deducted.

- *field-plant system efficiency*, given by the specific consumption of the total mixture extracted from the wells, expressed in kg of fluid per kWh of gross electricity production.

b. Binary Cycles

When the geothermal fluid temperature is low (approximately 150°C), because there are low-enthalpy resources or wastewater after steam separation, or large amounts of non-condensable gases, it can be more effective and more economically advisable to transfer heat to a second fluid, a working fluid that is usually organic and formed by complex molecules. A binary-cycle unit is composed of a heat exchanger-evaporator located between the geothermal fluid and the organic fluid; a turbine; an organic fluid condenser; and a cooling tower.

Just as in the case of the previously described steam cycle, overall field-plant system efficiency is expressed in kg of fluid per kWh.

The following paragraphs will discuss only the case of the steam cycle, which is usually the target of geothermal exploration. The binary cycle can merely be a solution if the fluids encountered during exploration have only moderate temperatures or if there is to be marginal exploitation of the thermal energy contained in wastewater.

4.2 Equipment Technology

Plant construction should consider technologies, equipment and materials that have been tested and proven suitable in other fields and that meet the standards set by the best manufacturers.

Every geothermal project has specific conditions and problems that require analysis and special solutions to optimize the power and flexibility of the machines and adapt them to each field's characteristics and evolution.

There may be problems that still require experimental procedures; for example:

- new methods for eliminating or reducing possible scaling and corrosion;

- improvements such as the possibility of injecting wastewater at temperatures lower than that of the silica saturation temperature, which would make it possible to increase the system's overall energy efficiency; and

- new treatments for non-condensable gases, to eliminate contaminants such as H_2S.

It is particularly interesting for planners to compare the alternative types of plants available for strategic field-plant planning. They are as follows:

- **Wellhead units**, made up of turbines of the atmospheric-discharge type with a limited (3-5 MW) capacity. These units are characterized by low efficiency (due to the fact that they do not have a steam condenser) and by low investment costs. It is advisable for them to be installed immediately after the production wells have been tested, to tap their production, obtain rapid economic returns, and at the same time permit field evaluation and the adjustment of the mathematical model for the reservoir— which are necessary measures in reducing the risks associated with future project development.

- **Modular units**, made up of single-flow steam-condensation turbines and a connection to the condenser, with a capacity of 15 to 30 MW. The turbine makes it possible to direct the discharge of steam upward, to place the group at ground level, to install the condenser outside the powerhouse, to prefabricate a great deal, and to reduce the volume of the buildings and civil works. The equipment for a large-potential field can be installed in several modular units located at one same site or scattered around the field. The field-plant system is developed by stages with diminished risks, and each unit can be installed after the operation of a previous unit has been evaluated and the corresponding field assessment has been done.

- **Large-capacity units**, made up of dual-flow steam-condensation turbines and dual discharges and connections to the condenser, with a capacity of 30 to 60 MW. Arrangements of four discharges make it possible to increase the capacity of these units up to 120 MW. This large capacity usually involves a significant portion of a field's total potential. Several units could be installed in a single powerhouse. A large amount of civil works are needed; the powerhouse includes a turbine, a condenser, and pumps; and its floor is located approximately 8 m above ground level. The turbine is located on a reinforced concrete pedestal, and the condenser is under the pedestal. The plant's large capacity makes it possible to lower specific investment and operating costs and to achieve high levels of efficiency. However, there are some disadvantages, such as: the need to plan a large number of wells; greater mining risks and delays; high costs of the total structures and difficulties with the corresponding financing; and less flexibility in the operation of the field-plant system with respect to systems having several modular units, given the small number of units.

4.3 Marginal Heat Utilization

Projects of this type, which are small-scale by nature with respect to the resource potential, offer poor rates of return on project development investments. This utilization is interesting when it can be done with the wastewater resulting from electricity production based on steam cycles.

When there are conditions for carrying out a feasibility study on the marginal utilization of heat, this will include an economic evaluation to supplement the one done for the electricity generation project.

4.4 Typical Costs and Investments

This section considers the steam cycles that use "modular units" and "large-scale power units," which are the most important alternative solutions for a geothermal field with good potential.

Table 2 indicates the characteristics, typical investments, general costs and average operating and maintenance costs for these alternatives, considering 7500 hours of use per year.

Table 2
Typical Costs of Steam-Driven
Geothermal Power Plants

Type of Unit		Modular	Modular	Large-Capacity
Gross capacity	MW	15	25	55
Net capacity	MW	14.3	24	53.5
Net specific investment				
. Electromechanical equipment and substation	US$/kW	1100	950	780
. Civil works	US$/kW	130	100	140
. Mounting	US$/kW	200	150	130
Interest during construction	%	5	9	12
Engineering and administration	%	7	7	7
Total net specific investment	US$/kW	1600	1400	1260
Operating and maintenance expenses	US$/MWh	5	4	3

5. ECONOMIC EVALUATION CRITERIA

5.1 Economic and Financial Evaluation

The economic justification of a feasibility study must be based on a comparison between the benefits produced by the project and the costs associated with its execution and operation.

The costs and benefits must be assessed in economic terms, from the standpoint of the national economy. When there are factors that distort the ratio between local market prices and the true value of the resources (taxes, monopolies, prices set by the government, etc.), *shadow prices* should be used instead of local market prices. In the case of commodities traded internationally (such as the fuel saved by the geothermal power plant), the international market price should be used.

The figure for the economic rate of return should be accompanied by a financial viability value, which will reflect the perspective of the company that is the owner. Financial rates of return take into consideration the financial values of costs and benefits, in other words, the result of the company's disbursements and net earnings, as well as the availability of financial resources.

The main interest of government and international financial agencies lies in economic aspects, whose viability would justify funding the project. Whereas financial aspects can be improved by the government through a suitable fiscal policy, the company can also improve them through changes in energy tariffs. Economic aspects are thus considered to be more of a priority.

5.2 Identification of Benefits

The benefits of a geothermal power plant are represented by the savings in costs (in other words, the "avoided" costs) resulting from the plant's incorporation into the Long-Range Power Generation Expansion Plan (see Section 2.5.2).

The economic justification of a geothermal project will therefore have to be based on a comparison of the optimal plan in which the project is included and the optimal plan in which it is not included.

Each generation system expansion plan must foresee the incorporation of new plants in such a way as to handle increases in energy demand without the occurrence of generating deficits.

The technical and economic analysis of generation system expansion should be done using mathematical simulation models for operation and cost analyses, among which the most well-known is the WASP model. These models enable optimal programming of the plants available for operation with a view to obtaining least-cost generation; they also make it possible to analyze service quality and possible deficits in power generation and, thus, to foresee the need for the incorporation of new plants. These programs are usually available in the planning offices of the institutions in charge of power generation.

A specific, simplified case can be seen when a given plant, for example a thermoelectric plant, plays an identical baseload-generating role as a geothermal power plant (see Section 2.5.1) which can fully substitute for the thermal plant. In this case, the fuel costs saved constitute geothermal project "benefits."

5.3 Typical Alternative Plant Costs

It is not possible to define typical costs for hydropower plant alternatives to geothermal plants since these costs are variable and must be analyzed for each case.

For many medium-power systems (500-2000 MW of peak load), the alternative plant is constituted by a thermoelectric plant with a power capacity of 80 to 170 MW; the fuel can be fuel oil or coal.

The case of a plant run on fuel oil will be considered below. Under the present conditions of low petroleum prices, it can be assumed to be very similar to a coal-fired plant.

To point out the importance of environmental aspects, two hypotheses can be considered for plants run on fuel oil with a sulfur content of approximately 3% and with 7000 hours of use per year:

a. High-efficiency group, with modern burners having a low NOx output and a filter for the dust contained in the smoke; and

b. The same type of group but with SO2-removal equipment.

Table 3 indicates the typical features of the alternative thermal plants, average generating costs, and long-run marginal costs (LRMC).

The approximate value of US$56/MWh for LRMC represents the upper limit for considering a geothermal plant to be economically interesting.

The approximate value of US$64/MWh for LRMC would be more indicative if the thermoelectric solution having environmental impacts similar to those of a geothermal power plant were considered.

5.4 Economic Comparison

Simplified economic considerations are based on the comparison of average LRMC generating costs for the various geothermal and thermoelectric alternatives.

In the case of modular geothermal solutions, field costs are lower because the operation start-up time for the most immediate wells would decrease the amount of interest paid during field construction.

Table 3
Typical Features of Alternative Thermal Plants

		Group a	Group b
Power capacity	MW	80-170	80-170
Specific investment, including interest during construction	US$/kW	1350	1600
Engineering and administration (7%)	US$/kW	95	110
Cost of capital (7000 hrs/yr; 25 yrs.; 12%/year)	US$/MWh	26.3	31.1
Fuel cost (fuel)	US$/ton	100	100
Net specific consumption	kcal/kWh	2400	2500
Fuel cost	US$/MWh	24	25
Operation and maintenance	US$/MWh	6	8
Average energy cost or LRMC	US$/MWh	56.3	64.1

Table 4 compares the costs of geothermal power generation to those of thermoelectric generation under hypotheses a and b, with different environmental emissions intensities.

Table 4
Economic Comparison between Geothermal and Thermoelectric Plants

Alternative		Modular	Modular	Large-Capacity
Gross capacity	MW	15	25	55
Investment in the field,including interest during construction	US$/kW	1000	1100	1200
Capital cost of energy (7000 hrs/yr; 25 yrs.; 12%/year)	US$/MWh	17.0	18.7	20.4
Field operation and maintenance expenses	US$/MWh	4	4	4
Plant investment	US$	1600	1400	1260
Capital cost of energy	US$/MWh	27.2	23.8	21.4
Plant operation and maintenance expenses	US$/MWh	5	4	3
Total geothermal energy cost (LRMCgeo)	US$/MWh	53.2	50.5	48.8
Total thermoelec. energy cost (LRMCtherm)	US$/MWh	56.3	56.3	56.3
Least-cost geothermal	US$/MWh	3.1	5.8	7.5
Discounted least-cost value	US$/kW	180	340	440

The cost of generation from a geothermal power plant proves to be notably lower than the cost of generation from a thermoelectric plant, even with current low fuel costs.

The difference in costs between thermoelectric energy and geothermal energy increases still further (US$7-8/MWh) if very low limits for gas emissions are set for thermoelectric plants.

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