Evolution of Technical and Economical Decision Making in Geothermal Energy Projects

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ABSTRACT

The aim of this study is to review the evolution of geothermal energy project evaluation techniques. Both power generation and heating (excluding heat pumps) projects and their evaluation techniques are reviewed. Although geothermal power generation projects have more extensive literature than the direct use applications in terms of project evaluation, inferences of this study can be generalized for all geothermal energy utilization types. The literature was investigated under two main subtitles deterministic studies and stochastic studies. Evolution of both techniques are presented with their advantages and disadvantages.

Introduction

Compared to conventional energy (fossil fuel) sources, *renewable energy* sources have numerous advantages. They are environmentally friendly, sustainable, home grown and cheap to operate. On the other hand renewable energy projects require huge initial investment cost and they contain technical and economical risks due to the use of new technologies, lack of expertise and know-how. In spite of the benefits of renewable energy sources, it is not always possible to realize renewable energy projects. Potential investors of the renewable energy are discouraged by many uncertainities, which are not encountered in non-renewable energy sources and they finally tend to view renewable energy projects as riskier. To provide the competitiveness of renewable energy among other types of energy sources and achieve technical and economical goals projects should be planned, designed and evaluated by considering all of the existing uncertainties in the projects. Exposure of all hidden risks in renewable energy sector provides more realistic feasibility studies and can attract more investors to this area.

When we look at the geothermal energy literature, most of the risk assesment studies belong to the late 1970's or early 1980's, when the geothermal boom occured in the USA. Considering the advances in the computer technology during last 30 years, these studies can be improved in a great detail and precision.

This article briefly reviews the past work done on the risk assessment of geothermal energy projects. The main goal is to present the evolution of geothermal energy project evaluation techniques and point out the need for the standardized and improved methods in evaluation of geothermal energy projects.

Deterministic Approaches in Geothermal Energy Decision Making

The word "deterministic" is defined as referring to events that have no random or probabilistic aspects but proceed in a fixed predictable fashion. Use of deterministic simulation techniques was common especially in the early ages of the personal computers. The main disadvantage of the deterministic models is that they do not respond many factors that influence the actual risk. This disadvantage is generally overcome by employing sensitivity analysis. Today deterministic simulation techniques are still being used at the phase of decision making in many projects. Although they provide relative benefits compared to methods other than stochastic ones, deterministic approaches cannot capture all risk factors in the geothermal projects in an appropriate way.

Geothermal Power Production Analysis with Deterministic Approaches

The first extensive study done on this area is "*Economic Analysis of Geothermal Energy Costs*" by Bloomster, C.H. (1975). To the best of our knowledge it is one of the first studies - if not the first - published in the area of geothermal energy assessment. Even today the study remains as one of the most detailed studies in this area. In this section, we mostly focus on this study since it has been referred and followed by many other later studies in the literature. The study describes the idea behind the GEOCOST software, which was developed to meet the need for *rapid and systematic calculations of* *the potential costs of geothermal power.* The study combines the both technical and economic factors into one systematic cost accounting framework in geothermal energy area for the first time.

The study doesn't use any stochastic approach to analyze uncertainties and concentrate on geothermal power plant economics and excludes any other geothermal energy utilization type. Perhaps the most interesting part of the study is sensitivity analyses of the main parameters like, plant size, wellhead flow rate, average annual capacity factor, heat exchanger coefficient and water temperature. The authors of the study divide study into two phases' reservoir model and power plant model.

Figure 1 presents the flow diagram followed by the study. The diagram covers the most major cost elements of the geothermal energy projects.

Each box (sub-model) in Figure 1 contains several steps. At this point it is important to show these steps to present the detail level of the Bloomster's study.

Reservoir exploration sub-model is composed of seven steps.

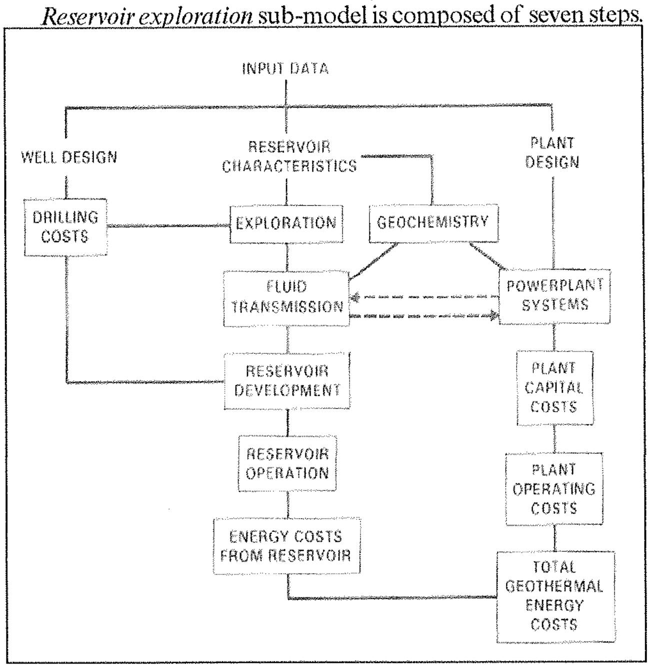

Figure 1. Flow Diagram For GEOCOST.

Each step has a time function, assigned cost, decision point and success ratio based on industry estimates.

i. Identification of target areas.
ii. Preliminary land check.
iii. Preliminary geologic reconnaissance.
iv. Detailed land check and geologic reconnaissance.
v. Identification of drillable sites.
vi. Exploratory drilling.
vii. Identification of the producible resource.

Reservoir development sub-model also contains the cost associated with drilling and well design.

i. The percentage of non producing wells.
ii. Capacity of injection wells.
iii. Geometry of the well field.
iv. Fraction of the excess producing wells.
v. Drilling depth.
vi. Bottom hole diameter.
vii. Bottom hole temperature.
viii. Fraction case.
ix. Average rock hardness.
x. Drilling cost (may be specified independently).

Fluid transmission sub-model calculates the conduction of the geothermal fluid, either water or steam. Pipeline diameter, length, pipe schedule, number of producing wells required, the well field layout, pumping requirements, and the costs of the transmission piping system, insulation, pumps and associated equipment is determined by this routine.

The steps of the *reservoir operation* sub-model can be summarized as:

i. Royalty payments.
ii. Replacement well drilling.
iii. Taxes.
iv. Overhead and management.
v. Well maintenance.
vi. Maintenance costs for the transmission system.
vii. Well re-drilling costs.

The effects of geothermal fluid composition on cost are modeled in *geochemistry* sub-model.

i. Water temperature.
ii. Steam/water ratio.
iii. PH.
iv. Silica.
v. H2 S.
vi. Salinity.
vii. CO2.
viii. Calcite ($CaCO_3$).

Based on the thermodynamic state of the geothermal fluid delivered to the power plant *power plant model* predicts the mass flow rate required for a specified electrical output. It also determines the physical and thermodynamic properties of the working fluids, the state points in the thermodynamic cycle being used, the size of various power plant components, the in-house electrical consumption, and the design performance of the power plant. This sub-model can simulate the generation of electricity from different power cycles. The main steps are:

i. Water temperature.
ii. Average flow rate per well.
iii. Average well spacing.
iv. Average well replacement rate.
v. Power plant capacity.
vi. Power cycle.
vii. Annual plant capacity.

The main inputs of the calculation procedure are wellhead conditions of the geothermal fluid, power plant design and the capacity, cost of the wells and annual power production.

First the total geothermal fluid flow rate requirement for the given input is calculated. Then the fluid transmission system is designed. Finally reservoir submodel calculates the capital costs and operating expenses for exploration, development, and operation of the reservoir. Based on this information cash flow and energy supplied and the unit cost of energy is found. The results of the study show that geothermal fluid temperature, well flow rate, well drilling and fluid extraction costs are the main determinants of the geothermal power costs.

Discounted cash flow analysis is used for economic analysis of the project. The procedure employs pure economic analysis without looking at additional advantages of geothermal energy.

"The Economics of Geothermal Electricity Generation From Hydrothermal Resources, 1989" by Bloomster and Knutsen is the continuation of the first study. While most of the effort in the first study was dedicated to a formation of the model, in the second study authors utilize the model for detailed sensitivity analysis. Advances in computers allow authors to conduct more detailed analysis by using GEOCOST software. By extending the sensitivity analysis to a greater detail, the authors endeavor to capture most of the uncertainties in the geothermal power investments. Together with the first study these two studies constitutes the fundamentals of deterministic geothermal power cost modeling efforts. On the other hand these two studies do not consider the additional benefits of the geothermal energy in the economic analysis part. Reduction in greenhouse gas emissions, contribution to the employment and contribution to a national economy as a result of using home grown energy is not being considered in this study.

In his recent study Sanyal (2005) analyses the variation of power cost and presents a formula to calculate the levelized power cost of geothermal energy projects. The study focuses on power cost rather than a power price to avoid involving extra uncertainties such as financing mechanisms, local market forces and government policies. Therefore power cost in the study includes a) capital cost, b) operation & maintenance (O&M) cost and, c) make-up well drilling cost. The study is presented in a deterministic format with most likely values and detailed sensitivity analysis. The results of the study show that the power cost is most sensitive to unit O&M cost. This inference deserves the further attention of the researchers in the area. Majority of the geothermal power plants were built in the 1970s and 1980s. The studies done on those times had mostly focused on capital cost estimations and paid little attention to O&M costs. Today some of these plants completed their economic lives and it is possible to re-evaluate economics of these projects with actual data and experiences. Starting from 1990s with aging geothermal power plants O&M improvement studies (Plant performance improvement, advanced thermodynamic cycles, turbine efficiency, condenser types and efficiencies, non-condensable gas removal systems, corrosion and scaling problems) became popular. Sanyal's study clearly indicates the new trend in geothermal energy evaluation projects. Based on the past experience O&M cost models may provide more accurate financial models for geothermal projects.

Geothermal Heating Analysis

In the literature cost analysis of geothermal energy direct use and power production have been considered as separate subjects of study and the studies conducted in this area usually include only one type of utilization. On the other hand the use of geothermal energy can be more profitable if it is utilized in more than one way. Cascaded use of geothermal energy provides the extraction of greater amount of energy from the geothermal fluid.

One of the most extensive studies in the area of geothermal energy direct use cost modeling is "Geothermal Heating, A Handbook of Engineering Economics, 1990". The study begins with the patterns of heat demand and covers the every element of cost in geothermal heating projects. The outline of the study can be summarized as:

i. Patterns of the Heat Demand.
ii. Heat exchangers and room heaters.
iii. Fluid transmission systems.
iv. Well drilling.
v. Geothermal Fluid Production.
vi. Case Studies.

The study also gives valuable technical information for each phase of a geothermal heating project. Detailed cost models for every stage are presented. The use of these models requires high technical knowledge in the area. Case studies provide valuable information on different heating schemes. The study does not offer a general procedure but presents sub-models for every stage of geothermal heating projects. A software would be really good complementary as a product for this study. The study deserves great appreciation since it gives great importance to technical details and for the first time sheds a light on the area which lays between technical and economical standpoints.

In the literature the first serious attempt to create project evaluation algorithms for geothermal heating applications was done by Pacific Northwest Laboratories as in the case of geothermal power production. GEOCITY software (1978), created by Pacific Northwest Laboratories is based on GEOCOST software and utilizes the same approaches where it is possible. Just after 4 years the model is improved to include cooling applications. Simpler approach, Geothermal Internal Rate of Return Algorithm (GIRORA), was proposed by McDevitt and Nowotny (1979) in a less detail in terms of reservoir modeling. Finally HEATMAP software by Bloomquist, has been continuously evolving since 1988. This software utilizes the advances in computer technology and provides economic and technical features for geothermal analysis, including:

- The ability to assess thermal distribution opportunities of produced energy that will be available for sale to various space heating and cooling, greenhouse, industrial processing, and industrial distribution consumers.
- The design of direct use geothermal applications in conjunction with fossil fuel peaking and thermal storage.
- Integration of geothermal energy with the production and sale of electricity (e.g., cogeneration).

- Integration of geothermal with cooling applications.
- Integration of various economic alternatives including well pumping and disposal with district energy provided from a geothermal or geothermal/fossil fuel peaking source.
- The capacity to quantify and provide graphical analysis of actual greenhouse gas emission reduction for specific geothermal site applications.
- Enhanced economic analysis capability optimized for geothermal operation and maintenance to ensure reliability of service and long term economic system life.

The HEATMAP has four main modules 1) Analysis of heat demand pattern, 2) Production module, which allows geographical placement of all production and injection wells as well as central heat exchangers and integral peaking, back up or storage facilities, 3) Analysis of fluid transmission and 4) Economical module. The software is capable of working with AutoCAD and GIS systems and has a library to store different information like climate data and economical data (tax tables etc.). HEATMAP is mainly based on conventional district heating system feasibility methods, and it provides wide range of options in terms of district heating modeling.

Probably the most ignored part of the geothermal district heating feasibility analysis is the demand for geothermal energy in the region. Especially in the areas where the individual heating systems are common, geothermal energy needs to be competitive compared to other types of heat sources. On the other hand set up (initial) cost of geothermal energy heating prevents important number of potential customers from subscribing to the geothermal district heating system. The demand should be forecasted to determine the size of the geothermal system. The information on climate and heat energy bills of the buildings are certainly useful on the other hand they do not have any use to forecast the number of customers (or subscription rate) in the area. Experiences form recent geothermal district heating projects in Turkey show that subscription rate vary between 25%-89% in the first year. Although the subscription ratio can change region to region, cash flow assumptions should be conducted by paying extreme attention to this matter.

Stochastic Approaches in Geothermal Energy Risk Assessment

A word "stochastic" refers to patterns or processes resulting from random factors. Most of the real life processes involve series of random events.

Utilization of stochastic approaches to model the risk in geothermal energy projects begins with Juul-Dam and Dunlap (1975). The approach mainly orginates from the conventional oil and gas development studies. The required durations for the activities are modeled as triangular distributions (Table 1).

Some of the chance factors assigned in the study of Juul-Dam and Dunlap are given in Table 2. Authors tried to build very detailed economic model to capture all possible uncertainties in the geothermal projects.

Since authors focused on estimating present value of geothermal projects, they use city-gate power cost value. This approach provides the comparison of geothermal energy with other competitive energy sources. Factors influencing city-gate power cost such as length of tranmission lines, were not modeled in the study. City-gate power cost is treated as input and detailed sensitivity analysis of the variable is presented in the study. Based on 1975 prices the break even city-gate power cost was calculated as 16 mills/kWh. The study also presents the detailed sensitivity analysis of the results based on 1975 prices. The study is certainly the pioneer of the geothermal energy risk assessment studies and deserves appreciation for introducing Monte Carlo simulation technique to the geothermal energy project evaluation area.

Table 1. Activity Durations and Cost (Taken from Juul-Dam and Dunlap, 1975).

	Duration (Years)			Cost (Thousand Dollars)	
	Min	Mode	Max	Time Dependent ($/year)	Time Independent ($)
Geological, geochemical and geophysical work	0.5	1.0	2.0	120	200
Exploratory and appraisal drilling	0.5	0.9	1.8	2 exploratory and four appraisal wells	
Reservoir testing and evaluation	0.5	0.8	1.3	350	250
Delineation drilling	0.4	1.0	1.5	4 delineation producers	
Contract negotiation and litigation	0.2	0.5	1.2	300	200

Table 2. Base Chance Factors and Parameter Values (Taken from Juul-Dam and Dunlap, 1975).

Conditional Event	Probability
Drillable prospect / geophysics and geochemistry	1
Land rights / drillable prospect on hand	0.625
Geothermal fluid discovered / drilling initiated	0.5
Environmental impact litigation / profitable venture	0.33
Project cleared / litigation	1
Making sales contract / dry steam discovered	0.9
Making sales contract / hot water discovered	0.8
Parameter Values	
Probability of discovered fluid being dry steam / a geothermal fluid reservoir has been discovered	0.1
Probability of discovered fluid being flashable / a geothermal fluid reservoir has been discovered	0.3

Hirakawa et. al. in Japan follows the same pattern in their study in 1981. The studies conduct economic risk analysis by using Monte Carlo simulation model. In the study uncertainties were modeled as triangular distribution or single valued (binomial) chance factor. Activity durations for each geothermal activity were modelled by using triangular distribution. Table 1 presents the assumptions of Hirakawa et. al. in their model. Geothermal power projects are divided into 4 phases and the duration of these 4 phases were modeled by triangular distribution. Each phase has also associated time dependent cost function.

Other activities such as chance of geothermal fluid discovery (p=0.7) were modeled as binomial process in the study. Figure 2 shows the flow diagram of the Hirakawa's study.

Table 3. Geothermal Activity Durations (Taken from Hirakawa et. al., 1985).

Activity	Min (Years)	Mode (Years)	Max (Years)
Geological, geochemical and geophysical work.	2	3	4
Exploratory drilling.	0.5	0.9	1.8
Reservoir testing and delineation drilling.	0.9	1.75	2.75
Time between the initiation of development well drilling and the start of commercial operation.	4.0	4.5	5.5

Compared to GEOCOST, mentioned in the deterministic approaches section the level of detail is rather low. Only the main aspects of the geothermal energy development were modeled in this study. Results were presented as a function present worth in the conclusion section (Figure 3). Finally present worth versus frequency histogram (Figure 4) for the base case is presented in the study. Figure 3 is certainly more informative than the single number outcome, which is the case in deterministic approaches.

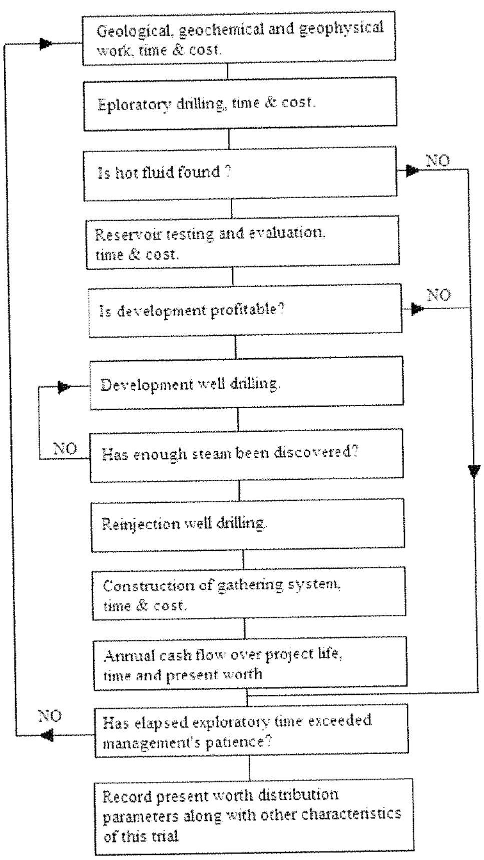

Figure 2. Geothermal Venture Analysis Flow Diagram by Hirakawa et. al.

On the other hand GEOCOST model, which utilizes deterministic approach captures much more detail than, stochastic model presented in Hirakawa's study.

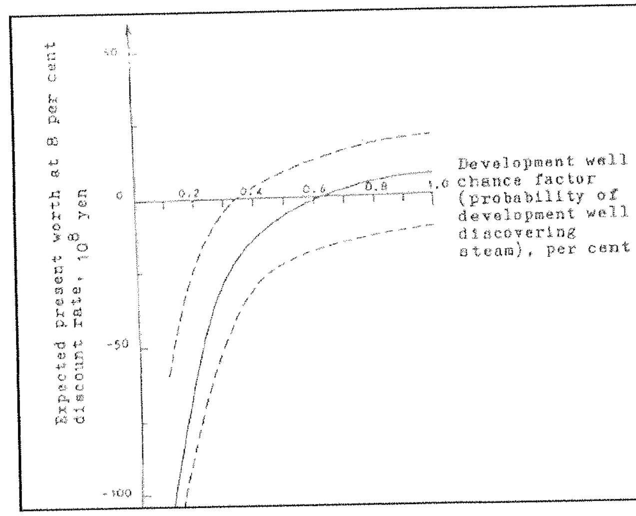

Figure 3. Development well chance factor versus present worth plot by Hirakawa.

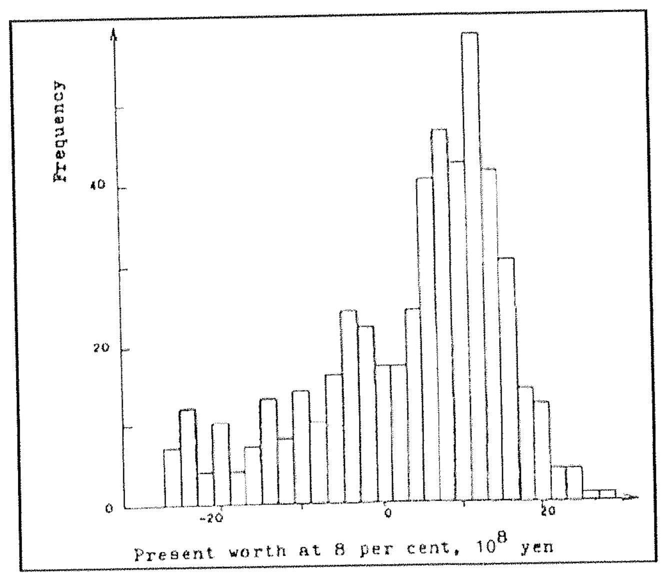

Figure 4. Histogram of present worth distribution of a geothermal exploration and production venture by Hirakawa.

A more detailed and improved stochastic approach is proposed by Parker in 1987. The proposed method "Geothermal Electricity Venture Analysis Model (GEVA)" uses triangular distribution and single valued chance factor in the modeling of uncertainties like the older methods. However GEVA models geothermal projects in a greater detail and uses higher number of sample simulations (200 samples) than the older models.

The input variables to be assigned probabilistic distributions were selected among most critical factors, which were found as a result of sensitivity analysis. These are, plant capacity factor, project lifetime, well replacement rate, energy produced per well, drilling risk and drilling depth. At this point author hints the necessity of further studies to improve the level of detail by stating that "*some of these factors must incorporate knowledge (or lack of knowledge) on associated topics. For example, the range estimates for the energy produced for a well must embody uncertainty in future well fluid temperatures and prodcution rates. Well replacement rate can be influenced by a host of factors, including reservoir transmissivity and porosity, increase in non-condensible gas content, scaling and corrosion of boreholes and loss of injectivity of injection wells.*"

The study compares the single point estimate (deterministic study) results with the results of Monte Carlo simulation results for the sample geothermal energy projects and emphasizes on the advantages of having probabilistic distributions. It is probably the first study stressing the advantages of the stochastic evaluation techniques over single point estimate (deterministic) techniques. Although it uses the similar techniques with Hirakawa et. al. Parker's work is an obvious advancement in geothermal energy risk assessment research.

Goumas et. al. (1998) improves the Parker's study in terms of decision analysis. In addition to the Parker's work this study employs multicriteria decision methods to optimize the exploitation of a low enthalpy geothermal resources. Unlike other studies in this study decisons are not only based on economics. Different evaluation criteria measure of the substitution of fossil fuel by renewable energy and creation of new jobs were also used to evaluate projects. The study definetely improves the geothermal energy evaluation techniques by including different evaluation techniques other than economics.

The study of Serpen et. al. only considers the geothermal potential estimation from a field and employs stochastic approaches to improve conventional reservoir engineering assessment approach. The study basically takes the well-known accessible geothermal energy estimation equation of Muffler and Cataldi (1979) and assigns triangular distribution for the independent variables in the equation. Aerial extension, reservoir temperature, formation thickness, porosity, formation rock density, specific heat and formation fluid specific heat are assigned minimum, maximum and mod values and modeled as triangular distributions in the equation. Considering the poor detail level of reservoir uncertainty models in the geothermal energy evaluation algorithms, this study models the reservoir uncertainty in a greater detail and can be a complementary part of more general evaluation study.

To the best of our knowledge there is no stochastic study in the literature to evaluate the geothermal direct use applications in a sufficient detail. Evolution of stochastic approaches to evaluate geothermal energy projects is obvious but not sufficient. Frontier studies presented in this article are not followed by the other. Despite the obvious superiority of stochastic methods deterministic methods seems to stay as a first choice of project managers.

Discussions and Conclusion

Compared to deterministic methods, stochastic methods are superior in terms of providing greater degree of detail on outcomes of the projects. For geothermal resources most of the uncertainty is related with the geothermal reservoir. Today reservoir simulation softwares provide detailed information on the situation of the reservoir. Combination of these softwares with the geothermal energy project evaluation methods utilizing Monte Carlo simulation technique can provide a great tool for the decision makers.

In general geothermal energy evaluation techniques do not pay enough attention to other advantages of geothermal energy such as reduction in greenhouse gas emissions, job creation, contribution to a national economy. Considering the increasing international enforcements on the greenhouse emission amounts, and world wide increasing oil prices, it will be advisable to find a way of including these factors in further studies. The difficulty in quantization of the benefits of the geothermal energy is a well known fact. On the other hand geothermal energy sector should find an objective way of including all benefits of geothermal energy while evaluating projects. Competitiveness of geothermal energy with other energy sources is highly related with this issue.

Absence of standard project evaluation methods for geothermal energy projects seems to be one of the main reasons for its failures. Because of the uncertainties related with resource, geothermal energy projects require different treatment than the other energy projects. The world wide acceptance of standard geothermal energy project evaluation techniques is possible if international funding agencies such as World Bank, United Nations Development Program enforce such techniques in the project proposals. On the other hand most of the studies in the literature needs further improvements to be accepted as a standard approach in this area.

World Bank, one of the biggest supporters of geothermal energy projects in the World, draws attention to the need for the systematic approach for the identification, preparation and implementation of renewable energy projects in one of its recent reports.

"*The World Bank and Global Environmental Facility have recognized that a systematic approach in the support of developing strategies for renewable energy is essential. Mechanisms need to be developed to systematically support the identification, preparation, and implementation of renewable energy projects. This is even more important when considering the typically high up-front costs of renewable energy projects on the one hand and the major beneficial externalities of use of renewable energy on the other, which present energy markets typically do not recognize. Indeed, the first order of business is the identification and removal of barriers relevant in the context of different renewable energies.*"

One of the goals of this study was to scan the geothermal energy project evaluation techniques in the literature and present the evolution of these techniques in a systematic way and emphasize the need for further studies in this area. Since most of the geothermal energy literature on this subject belongs to a late 1970's or early 1980's, most of the articles do not exist in a electronic form. We have experienced many difficulties in reaching some of the older articles. It is our hope that this study can guide to geothermal researchers working on geothermal energy evaluation techniques.

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