Geothermal Development Potential for Small Island Nations Situated Along the Pacific "Ring of Fire"

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ABSTRACT

Geothermal energy has a great potential for meeting a major portion of the electrical and thermal energy requirements for many of the Pacific island nations, that form volcanic island arcs that have been active since the early Tertiary along the southwestern portion of the Pacific "Ring of Fire."

Energy requirements of these small, scattered island nations preclude development of conventional generating facilities of sufficient size to incorporate any economies of scale. By attempting to discover and develop shallow, relatively low temperature, geothermal reservoirs, exploration expenditures and risks and problems associated with the development of high temperature resources can be reduced. Exploration and development drilling for these resources can be accomplished with truck mounted rotary drilling rigs that are less costly and more suitable for operation within the island infrastructures than the conventional oil and gas rigs normally used in the drilling of deep, high temperature geothermal resources.

Experience over the past decade with the discovery and development of small, moderate temperature geothermal resources indicates that geothermal energy can provide a reliable source of baseload electricity in the amounts required for the Pacific island nations at a cost of approximately $4,000per installed kW and annual operation, maintenance, and well replacement costs of between $170 and $180/kW. These costs are more than competitive with other available alternative energy sources and would provide island nations with access to an indigenous source of clean, environmentally benign energy. Development of shallow, moderate temperature, geothermal resources with small, modular binary-cycle generating units can provide an ideal energy source for many of the Pacific island nations within the framework of their island economies.

INTRODUCTION

Since the development of geothermal resources for electrical generation first began in the 20th century, high temperature (175^{o}-200^{o}C) hydrothermal fluids from the earth in the form of steam, hot water, or a mixture of both have been used to drive turbines to produce electricity. During this time, the most important factors hindering the widespread use of geothermal energy have been the uncertainty of geothermal reservoir discovery and reservoir productivity. In comparing geothermal generation costs with alternative resource generation costs, it has not been possible to factor in real fuel costs except in instances of known reservoir discovery and production. For geothermal to achieve widespread acceptance and utilization, further reductions in exploration risks and the cost of geothermal wells will improve the competitiveness of geothermal energy resources in relation to other conventional, alternative, and renewable energy sources. Research in reservoir analysis techniques will improve industry's ability to predict size, performance, and longevity. Improved conversion technologies will make it possible to use lower temperature liquids more effectively for electrical generation. Moreover, these needed improvements in geothermal generation are solutions to basic engineering problems that can be solved within the parameters of existing technology.

Lower temperature fluids traditionally have been used for direct applications, but during the last decade they have been utilized increasingly for binary (Rankine) cycle electrical generation. Moreover, new applications in existing technology for electrical generation from lower temperature hydrothermal fluids have been on-line a sufficient length of time to obtain reliable and meaningful operational data and costs.

Today's geothermal industry contributes to the world's energy supply more than 5,000 MW of electrical power, or approximately the same quantity of electricity as five nuclear power plants (DiPippo, 1988). Furthermore, current geothermal technology can produce this power as baseload electricity that is on-line greater than 95% of the time, at costs ranging between six and seven cents/kW hour! These costs are competitive with coal and nuclear electrical generation costs (USDOE, 1987) and compare favorably with oil generation costs.

Currently, the main sources of electrical energy in the Pacific Basin are diesel generation, hydropower, and biomass combustion. Diesel generation has all the disadvantages of disruption of supply, fuel import costs, and price uncertainty, causing balance-of-trade problems in countries lacking oil production. Hydropower potential is an obvious solution to increased energy requirement of some of the larger islands but is insignificant or nonexistent on most of the smaller volcanic islands. Biomass is in ample supply on many islands, but is lacking on many islands as well. On islands that currently have sufficient biomass supplies for present demand, increased usage could result in rapid depletion of the resource and could result in future restrictions because of possible greenhouse warming or other environmental considerations. Wind and photovoltaic generation is gaining general acceptance, but is interruptible, requires storage, and has not proved suitable for baseload service. Moreover, for wind and solar, most Pacific island nations do not have a sufficient land area to ensure that favorable conditions for electrical generation will occur on an uninterruptable basis. Nevertheless, in scattered dwellings, villages, and remote towns, wind and photovoltaic electricity currently is commonly the most practical, economical, and only source of electrical energy available.

Geothermal energy is not universally distributed throughout the Pacific Basin and is absent throughout most of the eastern islands and the central and western equatorial atolls. Geothermal resources, however, are abundant on the island of Hawaii, and on many Pacific volcanic islands along the "Pacific Ring of Fire" in tectonically active zones at or near crustal plate boundaries. Geothermal energy provides baseload generation with a high (95%+) availability at a price that is competitive with alternative energy resources. Although geothermal energy is a viable, mature technology with a long history of successful production, the initial risk of resource discovery and uncertain development cost are perceived disadvantages that have hindered development of the resource. Nevertheless, on many of these islands, geothermal energy represents the ideal solution for an economical, reliable, and non-polluting energy supply.

With the exception of the large island nations, such as Japan, the Philippines, Taiwan, Indonesia, and New Zealand, many of the island populations in the Pacific Basin are either small in number or scattered, or both. Locally, electrical utilization is minimal to nonexistent. Throughout large portions of the Pacific Basin, large-scale electrical generation is measured in tens of megawatts, with generation plant sizes more commonly measured in hundreds of kilowatts rather than in megawatts. In most instances, oil generation presently meets this demand most efficiently and economically, as is shown in Table I, which lists power generation facilities on Fiji, Tonga, and American Samoa (PICHTR, 1986). Table II gives the land area, population, and average price and cost of several Pacific Islands with geothermal potential. (Rizer and Hansen, 1992). Much of this electricity is highly subsidized by the island governments although hydro and bagasse are used where applicable. To successfully compete against oil generation in the Pacific Basin, an energy source must be indigenous to the islands, highly reliable, reasonably competitive in price with available diesel, hydropower, and biomass generation, within acceptable pollution and waste product limitations, and, perhaps most importantly, be suitable to the scale of the islandeconomies.

Table **I.** Power Plant Data for American Samoa, Fiji, and Tonga

Plant Location Power Plant		1986 Installed Capacity *(MW)*	Energy Source
AMERICAN SAMOA			
Satala	Island of Tutuila	7.0	Diesel
Tafuna	" " "	18.0	
Faleasao	" " Ta'u	0.5	
Ofu	" " Ofu	0.5	
		26.0	
FIJI			
Wailoa		83.20	Hydropower
Kinoya		26.00	Diesel
Vuda		11.86	
Nadi		8.00	
Suva		4.80	
Labasa		3.97	
Lautoka		3.35	
Sigatoka		3.35	
Deuba		2.20	
Levuka		0.84	
Savusavu		0.84	"
Rakiraki		0.68	Bagasse
		149.09	
TONGA			
Tongatapu		5.85	Diesel
Vava'u		0.60	
Ha'apai		0.11	
'Eua		0.11	
		6.67	

TABLE II. Land Area, Population, and Average Electrical Price and Cost of Several Pacific Islands with Geothermal Potential

Island	Land Area Km^2	Population* 1990	Average US$/kWh Revenue	Cost
American Samoa	197	39,600	0.14	0.13
Fiji	18,272	725,000	0.15	0.12
Hawaii	16,641	1,137,200	0.09	na
Northern Marianas	471	22,990	0.09	na
Papua New Guinea	462,243	3,910,000	0.16	0.13
Solomon Islands	27,556	318,700	0.18	0.17
Tonga	699	96,000	0.21	0.20
Vanuatu	1,880	142,600	0.25	na
Western Samoa	2,935	158,000	0.13	0.13

(1989 Data Except Where Indicated*)

POTENTIAL FOR GEOTHERMAL DEVELOPMENT

The Pacific Ocean is rimmed in large part by the "Ring of Fire," a tectonically active zone of earthquakes and volcanism, which truly represents the greatest zone of geothermal activity and potential on earth. Of the 5,003 MW of electricity generated by geothermal energy at the end of 1987, approximately 4,376 MW, or more than 87% were generated from the Circum-Pacific and Pacific Basin areas (USDOE, 1987). Moreover, most of the new geothermal plants subsequently brought on line since that time have been along this zone.

Although electricity is generated geothermally in Hawaii, and geothermal potential exists at other sites in the eastern Pacific, such as the Galapagos, Tahiti, and the Chile Islands, these locations represent special geological conditions and are distant from the main island arc zones of volcanism, tectonism, and geothermal activity. The Philippines, New Zealand, Indonesia, and Japan have extensive geothermal developments, and lie along these major zones of tectonism. The area of geothermal and volcanic activity specifically covered in this discussion is the southwestern and western Pacific along the western marginal zone of the Pacific crustal plate. An excellent summary of the geology and volcanism of this area, as well as the occurrence of geothermal activity, is given by Cox, 1980). This area, as shown in Figure I (Olson, 1988), is a region of diverse tectonic features that include continental land masses and oceanic crust, crustal subduction and associated island-arc formation, backarc basins, and elevated areas of sea floor in which new crust is being formed. The zone **is** characterized by belts of intense seismic activity with shallow earthquakes that are related to zones of crustal consumption or formation and large-scale crustal faulting, occurring below many land masses and adjacent shallow basins.

The Pacific island nations encompass a wide range of geographic, demographic, linguistic, cultural, and economic characteristics. Although the islands have relatively small land areas, they are scattered over enormous expanses of the Pacific Ocean, and through their Exclusive Economic Zones control large oceanic areas with their associated resources. Many of these islands with geothermal potential are experiencing rapid population growth as shown in Table III (Entingh et al., 1994) and will require additional electrical power supplies in the coming years. Currently, petroleum is the dominant energy source for transportation, commerce, and electricity in the

Table III. Potential for Geothermal Electrical Power in Developing Countries (MW for 30 Years)

Country	Megawatts
Fiji	50
Indonesia	16,400
Papua New Guinea	300
Philippines	8,000
Solomon Islands	50
Taiwan	200
Tonga	50
Vanuatu	100
Total	25,150

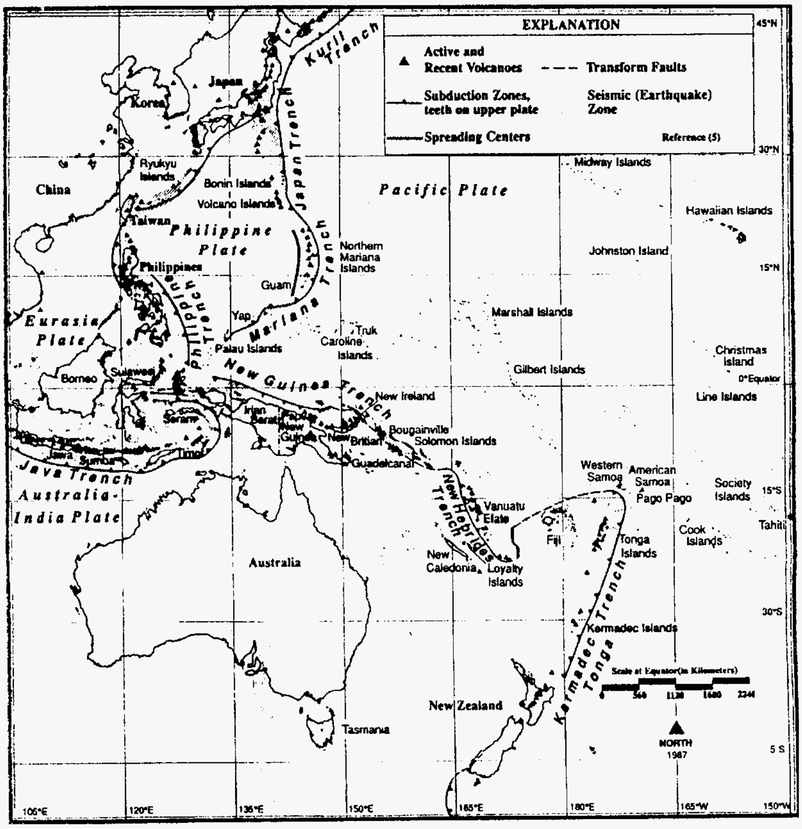

Figure 1. Recent Volcanism and Tectonic Features of a Portion of the Pacific Ocean Basin

Pacific island nations, and most island communities depend almost exclusively on diesel-powered generators for electrical energy. As such, these countries have become increasingly vulnerable to supply and price fluctuations of imported oil. Their governments are concerned that future energy costs will cause the loss of valuable foreign exchange, disrupt economic management and growth, and undermine or limit the region's potential for future development. These island nations are anxious to secure economically competitive energy sources that are not vulnerable to natural disasters, unreliable fuel supplies, political uncertainties, and unpredictable costs.

Many of the Pacific island nations currently are investigating alternative energy sources such as wind, solar, and biomass, but have been unable to proceed because of lack of funds or reliable technology, the need for small incremental sources of electrical power, and lack of experience and expertise in developing their indigenous energy sources. Geothermal energy may have an important role to play in fulfilling the energy needs of this area of the Pacific. Geothermal resources, as discussed in this paper, have wide distribution throughout countries such as Tonga, Fiji, Vanuatu, the Solomons, and Papua New Guinea, to name a few, which have an obvious potential for resource development. Moreover, geothermal energy has many advantages in fitting into the island economies. Besides being cost-effective and economically competitive with alternate energy sources, geothermal energy is relatively non-polluting and can be developed in a relatively small area. Operating histories have shown it to be able to provide reliable baseload power. With the recent availability of modular binary cycle generating units and other well-head generating facilities, small-scale power plants can now be ordered on an "off-the-shelf" basis and installed or expanded in a timely manner in relatively small incremental generating sizes.

Techniques for geothermal resource discovery and evaluation are now well known and explorationists with extensive experience are readily available. By scaling exploration objectives to those suitable for the island economies, costs can be kept within reason. By developing lower temperature geothermal reservoirs, the risk of exploration failure can be reduced, and production complications and expenses resulting from high temperatures minimized. As lower temperature reservoirs are usually found at shallower depths than higher temperature reservoirs, it should be possible to drill shallow exploration and production wells with truck-mounted equipment that is available locally or can be off-loaded onto existing port facilities. Truck-mounted equipment could traverse existing roads or do so with minimal road upgrading. Drilling supplies would be less than required for drills used for production drilling on the U.S. mainland, further reducing logistical problems and costs. Modular binary cycle or other well-head generating equipment can be ordered in the 100 to 1,000 kW plus sizes needed for island power requirements and can be expanded quickly and at reasonable cost by drilling additional wells and adding modular units. These units can be skid mounted and are available in sizes that fit in standard shipping containers. By injecting waste brine back into the reservoir, reservoir properties can be maintained, reservoir life extended, and the cost of expensive surface abatement equipment avoided.

GEOTHERMAL EXPLORATION AND DEVELOPMENT COSTS

Exploration Costs

Exploration techniques for geothermal resources are well developed, but as exploration success cannot be predicted with certainty, costs can vary widely, and risk, no matter how well represented by explorationists or quantitatively required by management, always will be essentially unknown! Exploration costs, however, can be controlled, and risk can be minimized by carefully selecting exploration targets and lowering the criteria for successful economic discovery.

Exploration results over the past two decades have confirmed that low temperature (<150°C) resources are more numerous than high temperature (>200°C) resources. Small geothermal reservoirs are more numerous than large reservoirs, and, generally speaking, higher temperature resources usually are deeper than lower temperature resources. As drilling costs tend to increase geometrically with depth, drilling costs can be minimized and multi-million dollar drilling projects or exploration failures avoided if exploration is confined to relatively shallow depths of 750 m or less. Geothermal wells to depths of 750 m or deeper can be drilled by truck-mounted rotary drills. These relatively small drilling rigs can be unloaded onto marginal dock facilities and moved on unimproved road systems much easier and less expensively than the deep (3,000 to 6,000 m), oil-field type rigs normally used for geothermal exploration and production programs.

A generalized geothermal exploration program for islands in the Pacific Basin normally would involve five phases, each generally increasing in cost and contingent upon positive results of the preceding phases. If a specific survey or exploration technique is not applicable in a particular situation, or fails to give reliable results, it should be eliminated from the program or another applicable survey used instead. As in all exploration programs, costs should be kept in line with a realistic risk/reward ratio, and as the island nations usually have relatively small electrical demands, only small power plants should be needed. The small demand for power and relatively small income potential will preclude numerous and expensive exploration surveys and should result in programs designed to discover and develop relatively obvious targets at relatively shallow depths.

Phase 1: Reconnaissance

The first phase of an exploration program generally involves a literature search of the geology, geography, and geothermal indications in the study area. If sufficient potential or interest is indicated in the literature search, a reconnaissance visit is scheduled to the area of interest to determine the general geology, access, availability of supplies, services, and land status and to discuss needs, regulations, permits, costs, and working conditions with the regulatory authorities and local service providers. During this phase hydrogeochemical samples should be taken and analyzed if any thermal springs or features are visited to determine if the hydrogeochemistry is anomalous.

Phase 2: Geology and Geophysics

If all conditions of the first phase are generally positive, a second exploration phase is initiated that involves geologic mapping and geochemical and geophysical surveys designed to define the geologic and hydrologic conditions and areas of geothermal potential. During this phase, maximum use is made of geochemistry, as water chemistry is a powerful geothermal exploration tool. Water sampling and analysis are relatively inexpensive, and ratios of dissolved elements in the groundwater can be used to predict with considerable accuracy minimum reservoir temperatures and the potential for scaling, corrosion, or possible abatement problems. Geophysical surveys such as self-potential (SP) can give indications of faulting and flowing groundwater, and electrical resistivity surveys can give indications of rock alteration, structure, and possible reservoir conditions. Induced Polarization (IP) usually can be obtained with active electrical resistivity surveys at nominal additional cost and should be utilized if possible, as IP can identify sulfide mineralization which usually occurs with gold and other epithermal minerals that are often associated with geothermal resources. Remote sensing surveys such as black and white, color, or infra-red aerial photography, and other geophysical surveys such as magnetics or gravity, should be acquired and interpreted for geothermal potential, only if available at nominal cost. High-cost surveys providing indirect evidence of geothermal resources should be minimized or avoided. All the surveys incorporated in second phase exploration should serve to define drilling targets for the next exploration phase.

Phase *3:* Exploratory Drilling

If the geology, geochemistry, and geophysical surveys indicate that the geothermal potential remains encouraging, the third exploration phase should involve drilling shallow temperature-observation holes to depths of 3 to 50 m, depending upon the geological conditions. Optimum drilling depths can be established by experience and the results of several of the initial drill holes. These holes will give direct evidence of subsurface rock types, temperature, geology, hydrology, and drilling conditions and will serve to delineate deep drilling targets for the next exploration phase.

Phase 4: Target Drilling

If conditions continue to remain favorable after the shallow-temperature surveys, deeper temperature-observation holes of ~150 m should be drilled during the fourth exploration phase to further define deeper geologic and hydrologic conditions and to provide drilling targets for production wells. These holes may be drilled with local water well drill rigs; however, if suitable rigs are not available, off-island rigs will have to be mobilized for subsequent drilling.

Phase *5:* Production Drilling

If a viable exploration drilling target is defined by the two preceding temperature surveys, a fifth exploration phase of development drilling is warranted to test for possible discovery of producible geothermal fluids. Nominally for the development of a one-megawatt facility, at least four wells would be needed: the test-for-discovery well which could be used for production; a second production or stand-by well; an injection well; and a contingency for a "dry" well with little or no production value. If the initial test-for-discovery well is an outstanding success, and subsequent wells are also successful, all four wells need not be drilled, substantially reducing exploration costs. A "dry" well drilled after one or more successes can generally be used as an injection well. On the other hand, if neither of the first two wells are successful for any number of reasons, such as lack of permeability or decreasing temperature with depth, serious consideration should be given to drilling elsewhere or to discontinuing the drilling program altogether. As exploration is a contingency undertaking, an exploration program always should remain completely flexible. If the evidence suggests that the program can be condensed, or that different surveys should be used, the program should be modified to test the new conditions as soon as they are identified and understood.

The number of wells required to supply a one megawatt binary-cycle generating facility will depend upon the flow capability of the geothermal fluids that are discovered. As shown in Figure 2, approximately 1,000 (–63 lps) gal/min (gpm) of 250°F (~120°C) fluid or 500 gpm (31.5 lps) of 300°F (~150°C) fluid are required to produce one net megawatt of electricity after accounting for parasitic losses (Nichols, 1986). If wells in the geothermal reservoir are capable of producing 500 gpm (31.5 lps) of 250°F (–120°C) fluids, two wells would be required to support the generating unit. If the well produces at a rate of 1,000 gpm *(63* lps), only one production well would be required. The binary-cycle units are adjusted to differences in geothermal fluids by adjusting working fluid composition and mixture.

Costs for this generalized exploration program are summarized in Table **IV.** (Olson, 1988). These are ball park costs and should be used only as a guide or "rule of thumb" as to the order of magnitude of the cost of an exploration program starting from scratch. As such, exploration costs can be expected to vary widely, from essentially the cost of drilling the production well(s) if geothermal resources have been identified at the prospect site, to the full estimated cost of the exploration program if only a general area or island with geothermal potential is specified. By the very nature of the resource, cost to discover and develop each specific property will be different and will vary due to location, transportation requirements, fluid quantity, quality, and temperature, well depth, institutional compliance requirements, infrastructure, supplier availability and so forth. If any of the assumptions described above or given in the table should vary, costs could vary also. If more wells, or deeper drilling are required, costs would increase as it would if lower temperatures than assumed were developed. If exploration failed to discover a resource or reservoir, all monies expended in the unsuccessful exploration effort would be lost. A more detailed and comprehensive treatment of geothermal costs, especially relating to generating facilities, is given by Entingh, et al. (1994).

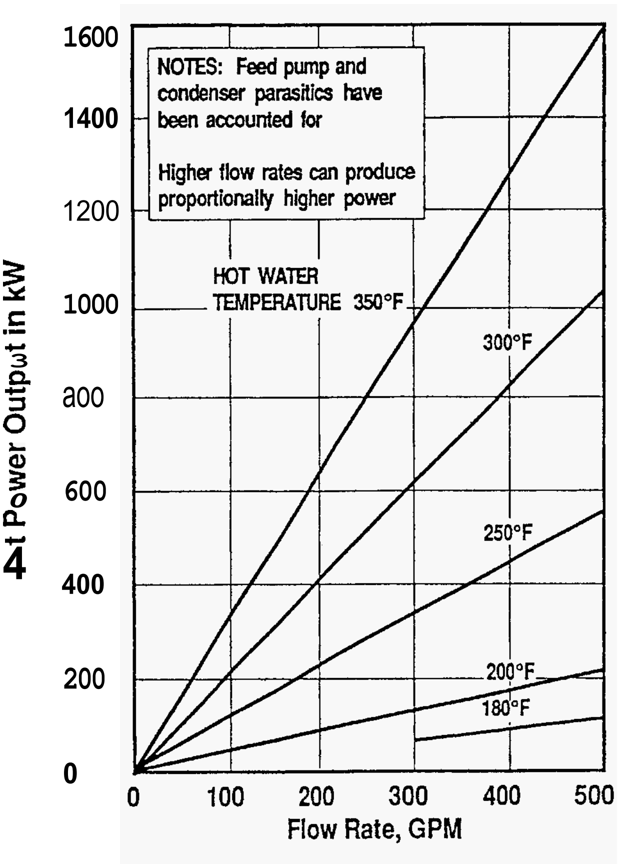

FIGURE 2. Power Generation Potential of a Geothermal Resource

Table IV. Estimated Cost to Discover and Develop a Geothermal Reservoir Capable of Producing One Megawatt for 30 Years

PHASE	ACTIVITY	EST. TIME (months)	EST. COST ($000) Project	Total
I.	Reconnaissance			
	Literature Search	1/2	5	
	Site Examination	1/2	9	
				14
II.	Geology and Geophysics			
	Geology & Geochemistry	3	55	
	Geophysical Surveys	I	77	
	General & Administration		10	
				142
III.	Exploratory Drilling			
	180 - 3 meter Temperature Observation Holes	1	22	
	36 - 50 Meter Temperature Observation Holes	1	54	
	General & Administration		20	
				96
IV.	Target Drilling			
	12 - 150 Meter Temperature Observation Holes	1	120	
	General & Administration		16	
				136
V.	Development Drilling			
	4 - 600 Meter Production Wells @ $350,000 to $400,000 each	2	1400-1600	
	General & Administration		92	
	Decision Making	2	20	
				1512-1712
TOTAL				1900-2100

Plant Costs

Sufficient binary-cycle generating plants have been installed worldwide, so that costs for plants in various locations even for remote pacific island sites can be estimated with some degree of confidence. These estimates can be expected to vary widely depending on location, weather conditions, and cooling requirements, and can vary anywhere from approximately $1,500/installed kW for a water-cooled facility in a cool climate located near a well developed service infrastructure, to $2,500/installed kW for a remote, air- cooled plant in a warm climate (Burch, Campbell, Nichols, and Schochet, 1994 person. comm.). A nominal cost of $2,000/installed kW should be sufficient for preliminary planning purposes.

As many of the modular binary generating units are designed to operate in remote locations, operation and maintenance costs probably will run about $100/installed kW annually (Campbell, Nichols, and Schochet, 1994 person. comm.). Daily maintenance by part-time local staff should be limited to reading gauges, checking lubrication and fluid levels, and making minor adjustments. Major repairs would involve trained, local technicians, if available, or temporary duty factory staff. Parts not kept in inventory would be air freighted in for specific repairs.

Conservatively assuming individual wells will slowly deplete and a five-year average life for production wells, replacement well drilling at $350,000 to $400,000 per well would add between $70 to $80/kW annually for a I-MW generation unit.

To summarize, estimated exploration costs leading to the discovery and development of a reservoir capable of producing 1 MW of electrical power for 30 years would be approximately $2,000/kW. Adding $2,000/kW as the cost of an installed modular binary generating unit, gives a total program cost of $4,000/kW of capacity for exploration development, and delivery of electricity to the system. Annual cost for operation and maintenance of the facility should be approximately $100/installed kW, and well replacement for a 1-MW electrical development should be about $70 to $80/kW of capacity.

At sites of active volcanism, reservoirs capable of supporting production rates much larger than 1 MW could be discovered and ultimately developed. If a reservoir capable of supporting at least 10 MW of electrical generation for 30 years is discovered, and if subsequent development of an additional 9 MW requires an average of only three wells to supply a 1-MW generating unit, then development cost for the additional generating units would be approximately $1050 to $1200/kW of capacity -- 60% or less than the cost of the postulated initial 1 MW development. Moreover, if the government or a private producer controlled both the geothermal wells and the generating units, the producer should be able to capitalize the wells together with the plant, thus, in effect, capitalizing fuel cost, which would bring current costs more in line with those of diesel generation.

If reservoirs with temperatures of $165^{\circ}C$ or greater are discovered, the possibility also exists of developing the resource utilizing existing, small 5 to 10 MW single-flash, condensing, generating units capable of being installed at the well-head in less than a year after being ordered. Depending upon the amount of power produced, these units could be installed at costs ranging between $1,000 and $1,500/kW of capacity (Shulman, 1994 person. comm.). Small non-condensing units of the same size could probably be brought on line for about $700/installed kW to start up the field and bring power on line quickly. These units, however, may not be suitable for small, isolated applications lacking infrastructure and skilled labor.

In addition to electrical generation, fluids from the binary cycle heat exchanger could supply process heat for such direct uses as fish canning, produce drying, refrigeration for food storage, and air conditioning. Utilization of the waste heat from the binary heat exchangers, ultimately, is limited only by imagination and economics. Moreover, in the final analysis, the overriding factor for the development of indigenous geothermal energy in the Pacific island nations may not be economics, but may be strategic in nature, in providing a highly reliable, environmentally benign, baseload source of energy that is not dependent on outside forces beyond the control of the island nations and their economies.

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