DEVELOPMENT OVERVIEW OF GEOTHERMAL RESOURCES IN KĪLAUEA EAST RIFT ZONE

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ABSTRACT

This study reviews the geothermal resources associated with the Kīlauea East Rift Zone (KERZ) of Hawaii island by focusing on a holistic development strategy for additional geothermal production. A review of existing literature in the fields of geology, drilling, power production and policy challenges, highlights critical issues for geothermal enterprises. A geological assessment of the hydrology, geochemistry, and structural features that characterize the region is discussed. Available data are interpreted including geology, geochemistry, well depth and temperature. A power plant design is proposed and options for electric power and direct use are discussed. Changes in regulations, policy and cultural barriers, made relevant by a 1991 well blowout are discussed. A stakeholder engagement process based on environmental and cultural metrics is proposed in order to benefit the neighboring community.

SUMMARY

In this overview, it is assumed that near term geothermal development on the island of Hawaii will occur in the Puna district. The research group is a multi-disciplinary systems integrator and consulting partnership. Core skills are in drilling, mining engineering, geology, geophysics, power plant engineering, direct use, permitting, and community development.

Geothermal exploration operations will most likely be costlier in the future thus more robust drilling operations will be necessary. With magma flows continuing from the caldera at Kīlauea, and a comprehensive geophysic research capacity at the University of Hawaii, the basaltic geology and geochemistry are fairly well understood. Geothermal plant siting will continue to rely on a sensitive cultural and environmental balance. Thus, policy, compliance, CSR, and power plant operations must become more transparent and community focused. A sustainable development strategic approach is recommended to guide further development.

This paper summarizes the technical response to a request for proposals (RFP) from an investment group considering a second power plant in the Puna district where Ormat already has a functioning 38 MWe grid connected operation.

BACKGROUND

There is a history of direct use of geothermal energy in the Hawaiian islands going back at least to the 1800's that certainly preceded historical accounts. Soaking in warm pools or steam baths are common remedies Hawaiian healers have recommended for their important therapeutic benefits. Some historical accounts also mention King Kalākaua, who wanted to produce power in the 19th century from geothermal energy sources.

Today, the state of Hawaii has significant developable conventional hydrothermal resources, yet the possibility of significant barriers to resource development should not be ignored. Conventional resources, related to Kīlauea volcano on the island of Hawaii alone, are estimated to be around 750 MWe. If EGS is included, this capacity is increased to 1,396 MWe. There are also significant developable resources on Maui estimated to be ~130 MWe. Peak demand for electricity on the islands of Maui and Hawaii is ~200 MWe, and for Oahu, the most populated island, ~1,200 MWe (GeothermEx, 2005). An ocean floor power transmission cable has been discussed for a number of years and despite the relatively low technical risk, the politics, costs and the natural cultural independence of these islands has hindered cable construction between the natural supply and the population demand.

GEOLOGY

The geologic overview considers the tectonic setting that has led to the development of the highly-productive geothermal system in the East Rift Zone of Hawaii. This section considers the processes that contribute to the three main components of the geothermal system: heat, permeability, and water. The hydrothermal system is largely blind, with minimal surface alteration (Iovenitti & D'Olier, 1985), but extensive geophysical and geochemical surveys, combined with drilling logs from the Puna Geothermal Venture (PGV) plant have helped characterize the hydrothermal system. Due to the proprietary nature of PGV, current well-log data is limited, so this section primarily summarizes findings from the 1970s to early 2000s.

Tectonic Setting, Lithology, Heat Flow, Temperature

The Hawaiian island chains are formed by the movement of the Pacific plate at a rate of 9-10 cm/yr over a stationary hotspot magmatic plume. Unlike subduction zone stratovolcanoes, shield volcanoes have shallower slopes formed by eruptions of low-viscosity mafic basalts (<52%SiO_2) that flow more slowly and in a non-explosive manner. Kīlauea is currently in the shield-building phase of the volcanic life-cycle, during which 95-98% of the volume is formed. During this phase, magma composition is primarily tholeiitic basalt, which is relatively higher in silica than ordinary alakali basalt. In 2005, the Puna Geothermal Venture well KS-13 drilled into dacitic magma at a depth of ~2400 m, with a considerably enriched SiO_2 content of 67wt% (Teplow et al., 2008).

Average heat flux for mid-ocean ridges basalts is between 270-290 mW/m^2, which corresponds to a thermal gradient of 93-100˚C/km (using an average basaltic thermal conductivity value of 2.9 W/m˚C). Teplow et al. calculated heat flux from dacitic melt to be ~1,300˚C/km, or 3,830 mW/m^2, which is over 10 times average values for the KERZ. Bottom-hole temperatures from wells drilled between 1976 & 2005 range from >200-360˚C at depths between 500-2,700 m, and reservoir temperatures are estimated to exceed 360˚C (Thomas & Conrad, 1997). Well temperature logs show modest temperatures (<50˚C) until depths of 1,000-1,500 m, at which point temperature increases rapidly and roughly follows the boiling-point to depth curve (indicating saturated steam). This pattern is demonstrated clearly in the well-studied HGP-A research well drilled in 1977 (Figure 1).

Porosity and Permeability

Unaltered surficial basalt flows at Kīlauea have relatively large permeability values of > 10-10 m^2, but this increases to <10-15 m^2 at 1-2 km deep within the rift zone (Ingebritsen & Sanford, 2006). Convective circulation is largely absent at depth, indicating low permeability within the hydrothermal system outside of fracture zones. This decreased permeability with depth is typical of most settings due to increased confining pressure that reduces porosity, along with diagenetic and metamorphic alteration that seals pore spaces. High

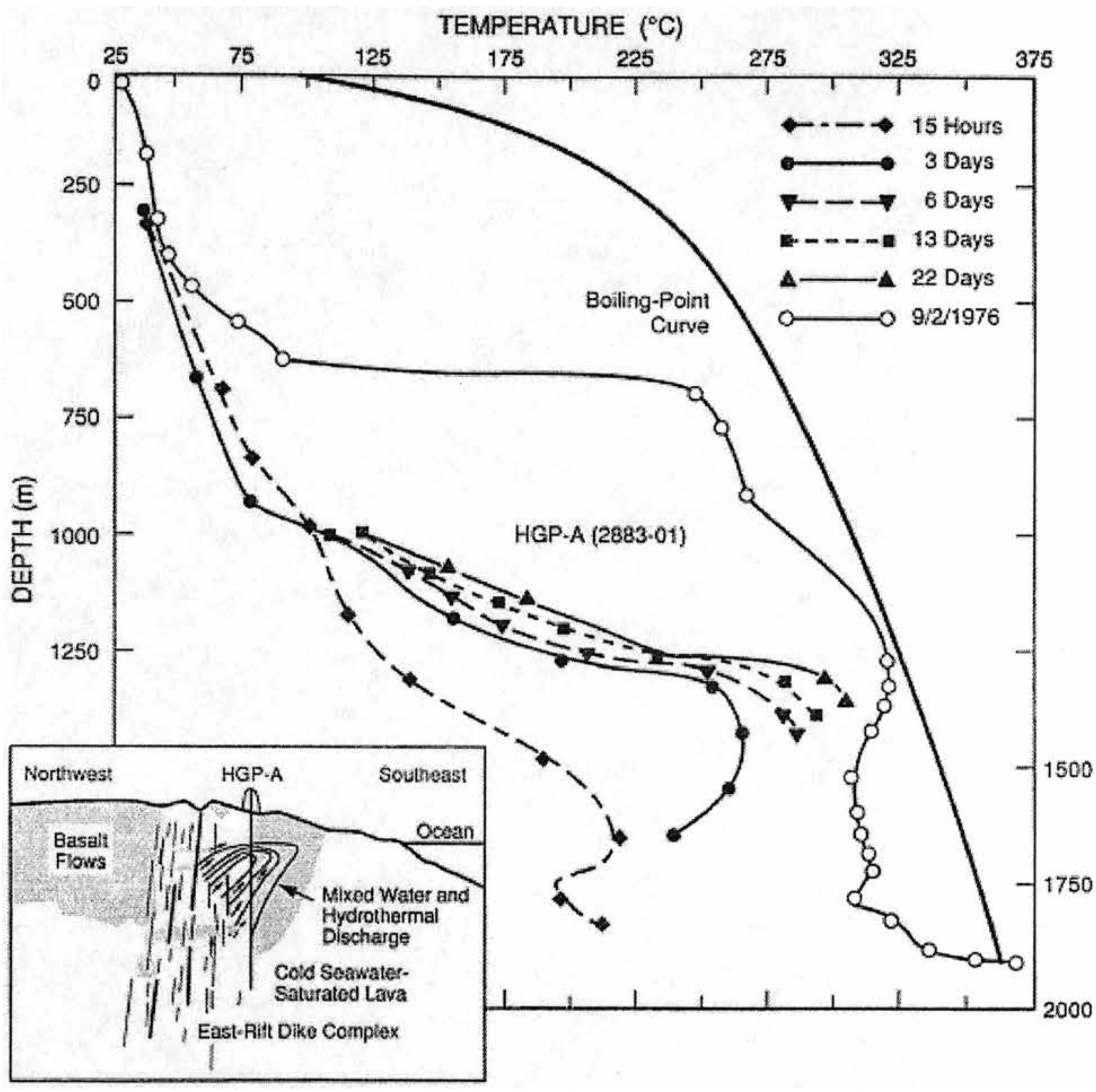

Figure 1. Temperature-Depth profile of research well HGP-A (1976)(Wohletz and Heiken, 1992).

density, low-porosity dike intrusions also compartmentalize permeability. Faults and fractures are the dominant mechanism for hydrothermal circulation.

Rift Zone Fractures and Fissures

The Kīlauea East Rift Zone is characterized by a series of linear fissures that result from spreading during shield volcano formation. As the volcano accumulates material, it starts to subside under the influence of gravity, and the surface ruptures forming step-over "en-echelon" fissures. Magma flows laterally from the summit through these fractures under the influence of gravity, forming steeply dipping dike complexes. These are fairly wide (1.5-4.6 m) and range from 1,067-2,286 m deep (Spielman et al., 2006). The faults and fractures of the KERZ are rift-parallel, NE-striking and SE-dipping, as a result of seaward slumping of Kīlauea's flank as increased mass accumulation subsides under the effect of gravity. The Puna Hydrothermal System is located in a step between two large normal faults, in a "relay ramp" setting, with a fracture system at depth that enables fluid flow (Kenedi et al., 2010). Geothermal reservoir temperatures are highest in the middle of the dike complex and drop off moving north or south away from the rift zone.

Hydrogeology

Groundwater hydrology in islands is commonly described by the Ghyben-Herzberg model, which predicts that basal waters will consist of a fresh-water lens floating above sea water due to the difference in density between the two fluids (Gingerich and Oki, 2000). The thickness of the lens is determined by the amount of rainfall that recharges the system and the rock permeability, and is predicted to be ~70 m in the KERZ (Thomas, 1987). In rift-zone settings, dike-impounded water systems form as low-permeability dikes intrude into the parent rock, compartmentalizing the water (Figure 2).

Well data, particularly HGP-A, show low salinities at depth (~5% that of seawater), contrary to what would be expected with the Ghyben-Herzberg lens. This anomalous finding indicates a meteoric source for the hydrothermal fluids, which has been explained by several theories. Firstly, the presence of a heat source in the Puna geothermal system could invert this typical density-layered lens since heated seawater becomes buoyant and rises above the cold freshwater. Second, the structure of the east-west trending fractures in the KERZ increases vertical and lateral permeability for fresh-water recharge. Freshwater recharge is predicted to come predominately from subsurface inflow off the flanks of Mauna Loa. Finally, the presence of dikes, along with hydrothermal alteration of seaward facing rock, inhibit seawater intrusion from the south rift flanks (Thomas, 1987).

Geochemistry

Recharge to basal ground water comes from four main sources: 1. cold meteoric fresh water (rainfall), 2. cold sea water, 3. hydrothermally altered meteoric water, and 4. hydrothermally altered sea water (Thomas, 1987). Seawater that has undergone hydrothermal alteration typically exhibits depleted magnesium, sulfate and carbonate ions. The Cl:Mg ratio is used as the primary indicator of the degree of hydrothermal alteration since Cl is insoluble while Mg is incorporated into secondary alteration minerals in high-temperature settings. Sorey and Colvard (1994) categorized fluids based off salinity and temperature into six main types based off of spring and well geochemical data compiled between 1975 and 1992 (Janik et al., 1994). These findings are summarized in Table 1 and shown in Figure 2.

Table 1. Geochemical Data

Type I: Cold, Dilute T≤25˚C, Cl ≤10 mg/L N of KERZ Basal freshwater lens	Type II: Cold, Brackish T≤25˚C, Cl ~75-300 mg/L Near-coastal Mixing zone b/w basal fresh & salt water	Type III: Warm, Dilute T~40˚C, Cl ~20 mg/L N of PGV Wells Hydrothermally heated freshwater
Type IV: Warm, Brackish T~40˚C, Cl ~100-800 mg/L E of PGV lease & S of LERZ Hydrothermally heated transition water	Type V: Hot, Saline T~50-100˚C, Cl ≥1000 mg/L PGV Lease & South Geothermal waters	Type VI: Warm, Saline T~30-40˚C, Cl≥1000 mg/L Warm springs on S coast ; Heated seawater

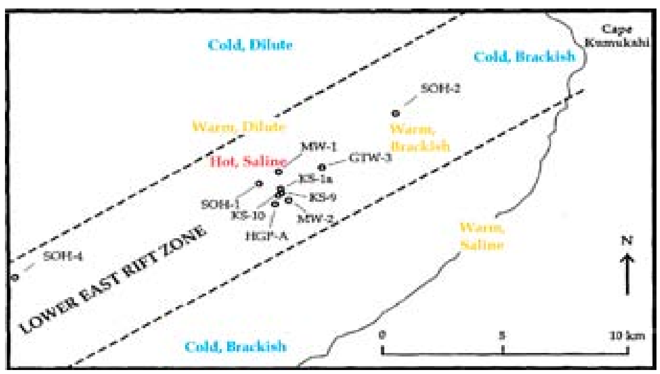

Figure 2. Geochemical Data modified from Thomas & Conrad, 1997

These data were plotted in a ternary C^{l}-HCO_3-SO_4 diagram using the Powell-Stanford 2010 GW Liquid Geochemistry Spreadsheet (provided by Joe Moore in NGA 2012 Module 2). As is expected, type IV, V, & VI (warm-hot, brackish-saline) plot in the mature waters region, while type I (cold-dilute) plot in the peripheral region and type III (warm-dilute) plot in the steam-heated waters region. The presence of seawater slightly complicates this analysis, as its high Cl content also plots cold seawater near the mature-waters region. The Na-K-Mg cation ternary diagram appears to be a better tool for determining the mineral-fluid equilibrium. This diagram uses the temperature-dependent nature of ion-exchange reactions to determine the degree of equilibrium between water and rock. Note that all the geothermal wells are largely depleted of magnesium.

Hydrothermal Alteration

Alteration mineralogy in wells follows the same general pattern, with low-temperature deposition of montmorillonite clays, anhydrite and calcite in shallow portions of the well, grading into chlorite, albite, and finally epidote in the highest temperature regions. Due to the fracture-controlled permeability and fluid-circulation, alteration is intermittent and varies in degree throughout a section.

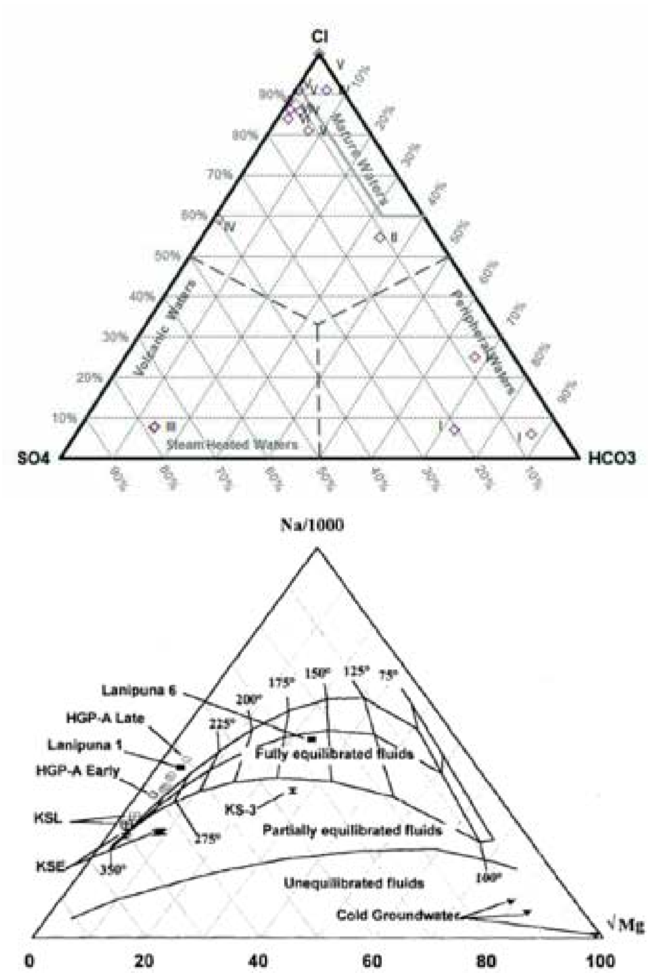

Figure 3. Ternary Cl-HCO_3-SO_4 diagram (top) and Na-K-Mg cation ternary diagram (bottom)

Geothermal Reservoir

In a nutshell, the geothermal reservoir within the KERZ is characterized as a high-temperature, two-phase, liquid-dominated system with a variable steam fraction (Iovenitti & D'Olier, 1985). The major components of the system are summarized below:

1. *Heat Source:* Kīlauea East Rift Zone basaltic magmatic intrusions. Magma rises buoyantly along rifts, pooling in a shallow crustal environment between 2-7 km deep in areas of neutral buoyancy between the fractured crustal rock and magma. Reservoir temperatures are highest (>360°C) in the center of the rift.
2. *Permeability:* Largely controlled by rift-parallel, NE-trending, SE-dipping step-over faults & fissures in the rift zone. Low-permeability dikes compartmentalize the flow of water and define the boundaries of the system. Shear-wave splitting analysis predicts that the most concentrated fractures are located south of the Puna Hydrothermal System at 1.5-2 km deep, in the step of the rift (Kenedi et al., 2010).
3. *Water:* Production fluids are derived from both seawater and freshwater from subsurface inflow off of Mauna Loa. Lower than expected salinities at depth indicate an inversion of the typical Ghyben-Herzberg lens, which predicts that denser saltwater underlies freshwater. Seawater influx may be blocked by the presence of impermeable dikes and by self-sealing hydrothermal alteration.

DRILLING

From early drilling experience near KERZ, wellbore complications (e.g. hostile environment, obstructions, interzonal flow, etc) have prohibited complete definition of the wells and reservoir performance both with time and varying wellhead pressures. Technical challenges and higher costs are indicated both for exploration and development wells. A revised well program with upgraded casing, cementing and completion procedures has been prepared to best fit the unique characteristics of the Puna geothermal system. An improved well test program to minimize flow interruptions and maximize data recovery has been similarly designed.

Problems discovered in early drilling experiences can be tackled which can optimize drilling operations. This optimization process will reduce costs and increase safety. Early drilling operations encountered fractures and faults at high temperatures and high pressures. When fractures and faults in the KERZ are encountered by drilling, they rapidly transfer their high temperature and pressure fluids upward to the nearest low temperature and pressure region. Rapid mineralization within open spaces of the formation can seal the new fluid location and create a hot overpressure section in the formation. This is a challenge in existing and new wells; blowouts or well collapse can result because of this. For these reasons, development of an appropriate site-specific drilling plan is required (Patterson et al., 1994a).

In 1991 during the drilling of KS-8 and KS-7, a blowout occurred. This created uncontrolled flowing of H_2S steam and fluids at the surface. Consequently, the surrounding community reaction was negative which has continued to present. In response, the State of Hawaii Department of Land and Natural Resources (DLNR) published a Geothermal Drilling Guide and Blowout Prevention Manual (Patterson et al., 1994a and b).

During the drilling it has been observed that the pH of the production fluid was around 4.5, which implies that the fluid is acidic in nature. Due to the presence of acidic corrosive fluid, lower grade casing will not last long. Corrosive fluids, such as CO_2 and H_2S and high temperature regimes of up to

350°C can result in burst or collapse of well-bore casings. Presence of dissolved solids can cause scaling in the pipe and which may reduce the power production. For example, KS-10 production was dropped significantly due to scaling. To overcome this scaling problem, the well was re-drilled. After the re-drilling of KS-10 it started producing 7.5 MWe of steam. KS-6 produced 8.3 MWe worth of steam when drilled (Spielman, et. al., 2006). Thus, all casings and well structures should be able to withstand corrosion and be thermally stress resistant. For example, steel with ~1% chrome can provide enhanced corrosion resistance and adding ~0.5% molybdenum increases steel resistance degradation at high temperatures (Spielman, et. al., 2006). Casing weight, grade and joint threads should be sized on tension, burst and collapse pressures. According to the DLNR drilling guide, common safety factors in use are 1.125 for collapse, 1.50 for burst and 1.75 for tension (Patterson, 1994b).

In wells KS-6, KS-10, and KS-13 innovative procedures were used to overcome the difficulties which were previously encountered while drilling. Parted casing was repaired using a casing patch. Foam cement is used for intermediate casing as well as for reverse circulation for production casing (Spielman, et. al., 2006). Hydrostatic pressure can increase due to the conventionally circulated cement, but intense planning is required due to the complexities involved in reverse circulation cementing jobs (Spielman, et. al., 2006). Occurrence of dog legs and saving of time can be achieved by MWD (measurement while drilling). Bit RPM (revolutions per minute) is important while drilling in the formation. A 100% increase in rate of penetration can be achieved by rotation while drilling. As discussed before, shallow formations in KERZ are unstable and permeability is very high. Because of this, loss circulation can be encountered at shallow zones. To avoid this issue micronized cellulose (Spielman, et. al., 2006) was used. Partial to full circulation, without mud system clogging can be maintained, which was not possible with conventional LCM (loss circulation material) [Rickard, et al., 2011].

To achieve fast and economical drilling operation use of proper and technologically advance drilling bit is very important. According to the report presented by Baker Hughes Inc. (2011) the Kymera Hybrid bit is twice as fast as premium roller-cone bit. This was proved by experimental drilling operation in Iceland which has basaltic formation more or less similar to the formation in Hawaii. Kymera drill bit is a combination of roller cone and polycrystalline diamond compact (PDC)(Figure 4). It provides high durability and cutting efficiency in tough and hostile subsurface formations. Some of the advantages of the Kymera drill bit technology are listed below (Baker Hughes, Inc., 2012):

- Excellent directional drilling performance
- Extremely stable drilling foundation which reduces vibratio
- Efficient torque control is provided in transition zones, which helps in smooth and fast drilling performance

COMBINED HEAT AND POWER PLANT

The design of a proposed power plant is based on available data from the existing power plant operated by Puna Geothermal Venture (PGV), a subsidiary of Ormat Technologies Inc. Through analyzing the reservoir characteristics and incorporating wellhead data from the area, a design of a power plant with direct use applications is recommended. RefPropmini was used to calculate the various stages of the geo-fluid as it goes through the steam power plant. Incorporating direct use applications was an important factor in determining the exiting temperature of the power plant and was designed to be 125°C to provide adequate heat for further uses.

Figure 4. Kymera Drill-bit (Baker Hughes, Inc. 2012).

The wellhead conditions are a saturated liquid of 310°C under 98.6 bara (Bronicki, 1995) that flows 45.36 kg/s to the separator (Schochet, 1996). For simplicity in scope, any pressure losses due to flow through pipelines has been neglected. Due to the resource temperature, as well as the chemical composition, a single flash plant is the first recommendation (DiPippo, 2012). The reason a double flash plant is not recommended is to try and reduce the scaling, or precipitation of amorphous silica and other minerals, in the well or any pipelines. To determine the optimum flash temperature, the equal temperature split rule was applied (DiPippo, 2012). Once the steam is flashed from the brine, the brine will be used in a bottoming binary cycle to produce more electricity. Figure 5 depicts the flow diagram of the proposed power plant with numbers indicating the various state calculations performed in RefPropmini.

Single Flash Plant

Using a cyclone single flash separator (CS) at 195°C and pressure of 14 bara, the geo-fluid is separated into steam flowing at 13.25 kg/s, and brine flowing at 32.1 kg/s. The steam will enter a steam turbine (ST) with outlet conditions of 125°C and 2.3 bara (predetermined for direct use applications). The steam will be condensed in a heat exchanger (C) with cold water provided from a water cooling tower with makeup water coming from a shallow well on site.

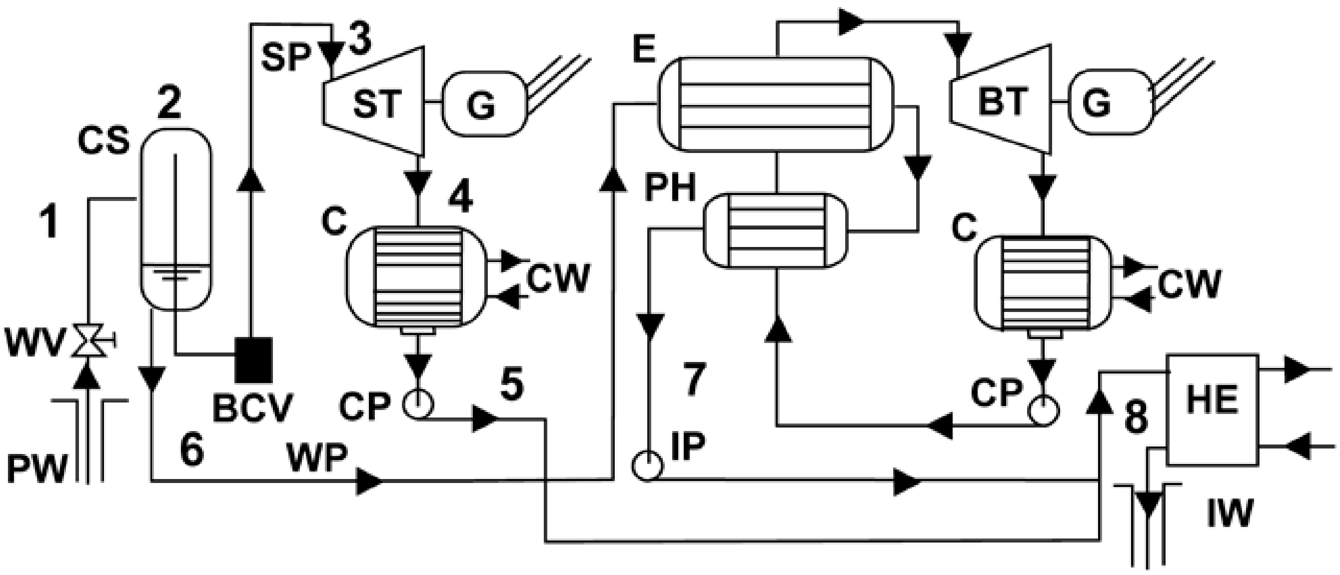

Figure 5. Single Flash plant bottoming Binary cycle. Modified from DiPippo, 2012.

The steam will then be recombined with the exiting brine from the binary plant, and they will both feed the direct use heat exchanger. Overall, the steam plant will produce roughly 3.4 MWe. Table 2 includes the RefPropmini state data, and the relevant calculations are included below.

Table 2: RefPropmini Results

Corresponding	Temp	Pressure	Density	Enthalpy	Entropy	Quality
State #	(°C)	(MPa)	(kg/m³)	(kJ/kg)	(kJ/kg-K)	(kg/kg)
1	310.00	9.8651	690.67	1402.2	3.3510	0.00000
2	195.00	1.3988	23.821	1402.2	3.5059	0.29219
3	195.00	1.3988	7.0976	2788.8	6.4678	1.0000
6	195.00	1.3988	870.43	829.79	2.2832	0.00000
4s	125.00	0.23224	1.4603	2470.5	6.4678	0.88914
4	125.0	0.232	1.41	2529	6.61	0.916

Calculations

Using the Baumann rule, assuming a dry turbine efficiency of 85%, the enthalpy of the steam exiting the turbine can be determined as follows:

$$h_4 = \frac{h_3 - A\left[1 - \dfrac{h_{liq}}{h_{vap} - h_{liq}}\right]}{1 + \dfrac{A}{h_{vap} - h_{liq}}}$$

$$A = 0.425(h_3 - h_{4s})$$

This equation results in an enthalpy of 2,529.6 kJ/kg and quality (found using RefPropmini) of 91.6%. To determine the electrical output of the turbine, the equation below was applied:

$$\dot{W} = \chi_{steam}\,\dot{m}(h_3 - h_4)$$

This results in 3.4 MWe of output from the steam turbine.

Equipment

Separator (CS) - A cyclone vertical separator allows for the pressurized geo-fluid to drop pressure, thus expanding and producing separate brine and steam flows. At this pressure about 30% of the mass of the reservoir fluid is converted to steam that goes to the steam turbine: the brine will be used to transfer heat to the binary power plant.

Turbine and Generator (ST and G) - The selection of the turbine will be done through a request for proposal (RFP) process where various turbine designing companies will submit price and size estimates for the given entering and exiting parameters.

Condenser and Cooling (C and CW) - With the availability of water rights in Hawaii, a water-cooled condenser provides a more efficient cooling of steam from the geo-fluid, and working fluid from the binary plant. A water well on-site will provide sufficient makeup water at a dead-state temperature of 25°C. Using a water cooling tower allows for 100% reinjection of the geo-fluid (not including NCGs).

Chemical abatement and treatment - The high concentration of H_2S relative to other geothermal reservoirs requires an abatement plant to be included in the power plant design. Venting the CO_2 at these concentrations to the air will have very little environmental impact; however, venting H_2S to the atmosphere at these concentrations could have detrimental impacts to the local community. There is also a requirement to chemically treat the fluid to prevent scaling from silica precipitation in the injection well.

Binary Power Plant

Currently, PGV uses a dual pressure Ormat Energy Converter (OEC) that are rated at 3 MWe each (Sinclair Knight Merz, 2007). Although there are other manufacturers of binary power plants, Ormat provides a case specific power plant using existing products. The dual pressure OEC with the given resource temperature has a utilization efficiency of 55% (DiPippo, 2012) and the exergy loss can be calculated using the dead state conditions in Hawaii:

$$\dot{E} = \dot{m}(h_1 - h_0 - T_0(s_1 - s_0))$$

$$\dot{W}_{net} = \eta_u \times \dot{E}$$

These equations result in a net power output of 2.7 MWe. This capacity corresponds with the current OECs used at PGV, and would likely be similar in design. These type of hybrid power plants increase the power generation from a given resource and are the most installed types of geothermal power plants (James, 1990).

Direct Use

Direct use applications are the most efficient way to utilize heat from a geothermal resource. Using the exhaust from the power plants, 14.3 MWt of useable heat can be extracted for various direct use applications before injection of the geo-fluid. This value is calculated using the equation below:

$$Energy = \dot{m} C_p (T_{in} - T_{out})$$

A plate heat exchanger will take the heat from the geo-fluid and transfer it to a district loop where the community will be able to utilize the heat. This application of geothermal provides the community with visible uses of the resource and has the potential to create many jobs (Fox et al., 2011). Traditionally, the cost of geothermal heat is 80% that of the cost same amount of heat provided from natural gas. In Hawaii, the savings could be even larger due to no transportation costs of the native resource. Ultimately, direct use will provide the community with hands-on applications of geothermal that will generate jobs, and increase the acceptance of using the resource.

Figure 6 depicts a suggested cascading program that will seek to accomplish the previously stated goals.

The recommended single flash with a bottoming dual pressure binary cycle power plant will provide in excess of 6 MWe from a single well. The focus of using direct use will provide the community with an avenue to stimulate the local economy and become more familiar and accepting of geothermal utilization. This preference is shown numerically as 14.3 MWt of the well's potential is directed to direct use. The KERZ has the ability to help Hawaii Island become a self-sustaining island that would relinquish the dependence of fossil fuels.

COMMUNITY ENGAGEMENT

Hawaii has not issued a geothermal development permit in decades. However, the potential of geothermal power is recognized in the Hawaii Clean Energy Initiative (HCEI 2008) as a significant contributor to the 2030 mandate of 70% renewable energy portfolio. Due to the 1991 well blowout in Hawaii and some high profile international investment failures of geothermal projects, it seems reasonable to recommend two paths forward.

1. Clarify state and federal permitting processes, and
2. Initiate a participative stakeholder engagement process.

Concurrent to this legislative mandate, there has been a strong statewide signal from the citizens of Hawaii that human and environmental issues are important considerations in permitting and siting industrial renewable energy projects. Project developers are expected to be partners alongside communities and government to facilitate energy security statewide. Therefore, any future geothermal development enterprise should expect a rigorous review process that includes the affected communities.

Achieving buy-in from the community is as important as getting approval from government or political jurisdictions. In order to be successful, the stakeholder analysis and engagement must be concurrent with or considered part of the permitting process. This comprehensive stakeholder analysis and engagement process will reduce investment risk due to community resistance. As part of the engagement process, a community benefit agreement (CBA) could be used to ameliorate community concerns, especially if the CBA were a condition of permit approval (Reed, 2008).

Geothermal Resource Permitting in Hawaii

Every renewable project in Hawaii requires several resource-specific federal and state permits and a number of county permits. Permitting for geothermal developers is complicated by the fact that currently there are potentially 16 Hawaii county permits, 51 state permits and 15 federal permits. Because there is no flow-chart describing geothermal permitting either at the federal or state level, it requires years of effort to receive both levels of permits. Hawaii has

Figure 6. Cascaded Direct use applications.

attempted to clarify the permitting process by publishing online guidebooks to the renewable energy approval process (DBEDT, 2012). However, the process is still cumbersome.

In 2012, there has been a coordinated effort to streamline geothermal permitting processes at federal and state levels. In an attempt to simplify the state process, the Hawaii state legislature through Act 97 (2012) eliminated the county geothermal sub-zones permits (GRPs). Because of this both Maui and Hawaii counties permitting processes are temporarily on hold. However, the GRPs should be reinstated in the 2013 legislative session.

At the federal level, the goal of the USDOE's NREL's Geothermal Regulatory Roadmap program is to create and publish a flowchart and document the regulatory processes for geothermal development in Alaska, California, Hawaii, Idaho, Montana, Nevada, Oregon, Utah and at three levels (federal, state, county). The Hawaii working group has met to clarify the flow of permits in the state Department of Land and Natural Resources (DLNR) and Department of Health (DOH), as well as the process of permit facilitation for which Department of Business and Economic Development and Tourism (DBEDT) is authorized. These efforts are ongoing (USDOE, 2012).

In summary, geothermal power is an enormously promising source of base load energy and if incentivized through CBAs and transparent permitting processes, could rapidly become a significant contributor to Hawaii's clean energy future.

CONCLUSION

It would seem that geothermal power production would have a bright future out in the middle of the blue continent. On the island of Hawaii, the potential of industrial base-load geothermal development is increased by the near magmatic zone which produces high borehole temperatures and convective heat flows conducive to geothermal power production in the Kīlauea East Rift Zone (KERZ). However, the islands with the highest potential for geothermal heat are separated by miles of oceans from the demand of the populated older islands. Due to missteps by both governments and developers in past geothermal endeavors, affected communities have a negative perception of the geothermal enterprise.

Further, the regulatory and permitting regimes, while well intentioned, are difficult to interpret without the organizational memory of first generation geothermal regulators. The current developer, by some accounts, has responded in a protective manner thus alienating the community in which it is embedded. There is a need for a comprehensive stakeholder analysis and engagement process if further geothermal development is to occur.

Recommendations

While the Puna Geothermal System has been well-studied since the first research well was sunk in 1976, new well drilling locations are highly dependent on sub-surface fracture networks. Further geophysical exploration and drill tests of a potentially high-density fracture network south of the PGV plant at a depth of 1.5-2km should be conducted.

- Further investigation of the extent of the dacitic intrusion (discovered during drilling of KS-13 in 2005) may provide useful information about higher heat-flow (possibly steam-dominated) areas. It would be useful to map this in order to avoid future problems of drilling into magma.
- Previous drilling experiences provided important lessons about high temperature, pressure and corrosive environments in KERZ. Incorporating lessons learned into regulations can make future geothermal drilling operations safer and efficient.
- A single flash power plant with a bottoming binary cycle could generate about 6 MWe per well. There could be 14.3 MWt provided from the same fluid for community direct use.
- Use of direct use should be integrated with geothermal electrical power production. Doing this will create green jobs and directly benefit stakeholder communities. Thus reducing risk for investors in geothermal development in Hawaii.
- A state roadmap for geothermal projects permitting should be developed. Federal and state regulatory processes should be transparent for both project developers and affected communities.
- A robust stakeholder engagement process should be implemented immediately in affected communities in order to reduce risk to investors, developers and the state.

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