Geothermics 70 (2017) 406–413

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Play fairway analysis of geothermal resources across the state of Hawaii: 3. Use of development viability criterion to prioritize future exploration targets

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ARTICLE INFO

Keywords:
Hawaii
Play fairway
Development viability
Geothermal
Exploration

ABSTRACT

A recent Play Fairway Analysis of geothermal prospects in Hawaii identified and compiled data relevant to subsurface heat, fluid, and permeability, and developed and applied a statistical method to integrate the compiled data to produce a map of resource probability across the state. As a final screening of prospective geothermal resources, we considered the *viability of development* in areas showing an elevated resource probability. This screening was intended to prioritize prospects that have a greater likelihood of proceeding through regulatory review to production in a timely and cost-effective manner. Development viability was determined to be high, medium, or low based on four factors: i) grid accessibility, ii) vulnerability to natural hazards, iii) current and probable future land uses; and iv) community sentiment and acceptance. Development viability was assessed in > 10 areas of interest that were selected based on the results of the probability and confidence mapping, and was a guiding criterion used to develop a prioritized roadmap for the next phase of exploration activity in Hawaii. Planned activities include a groundwater sampling and analysis campaign in ~10 broad areas, and the collection of magnetotelluric and gravity data in 2–5 locations statewide.

1. Introduction

Play Fairway Analysis (PFA) refers to an integration of individually weighted quantitative datasets that individually and collectively indicate the potential for a subsurface resource (a Play) in a given geographic area (a Fairway). This is the third paper in a series describing a recent PFA of geothermal resource potential in Hawaii. The papers describe the three main goals of the project:

1) ***Data.*** Identify the critical data types that are relevant to geothermal resource prospecting in a volcanic ocean island environment, rank the datasets in order of their relevance to the essential characteristics of a geothermal prospect (heat, fluid, and permeability), and compile all the accessible relevant data. These activities are described in the first paper in this series (Lautze et al., 2017);
2) ***Model Resource Probability.*** Develop a Bayesian statistical method to produce maps of geothermal resource probability across the state using the data collected in step one; and develop a method to assess confidence in the probability maps. These modeling activities are described in our second paper (Ito et al., 2016).
3) ***Exploration Plan.*** Devise a prioritized roadmap for future exploration (investment/effort/activities). To best construct this plan, we first considered the plausibility of development, or development viability, in areas of interest that resulted from steps one and two.

The purpose of this development viability assessment was to prioritize exploration activities in resource prospects most likely to contribute to Hawaii's renewable energy portfolio in the foreseeable future; and to defer additional investment in prospects that currently have low or no likelihood of development to a time when economic and/or technological conditions may be more favorable. Specifically this analysis asked the question: If an elevated temperature, permeable, and fluid-rich resource is identified, what is the likelihood that it could be developed to produce electrical power for the local grid in a realistic, timely, and cost effective manner? The development viability analysis considered four factors: i) ease of access to the existing grid; ii) vulnerability to natural hazards; iii) current and prospective land use; and iv) the surrounding community perception and acceptance of geothermal power production.

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http://dx.doi.org/10.1016/j.geothermics.2017.07.005
Received 9 April 2016; Received in revised form 22 November 2016; Accepted 11 July 2017
Available online 14 August 2017
0375-6505/

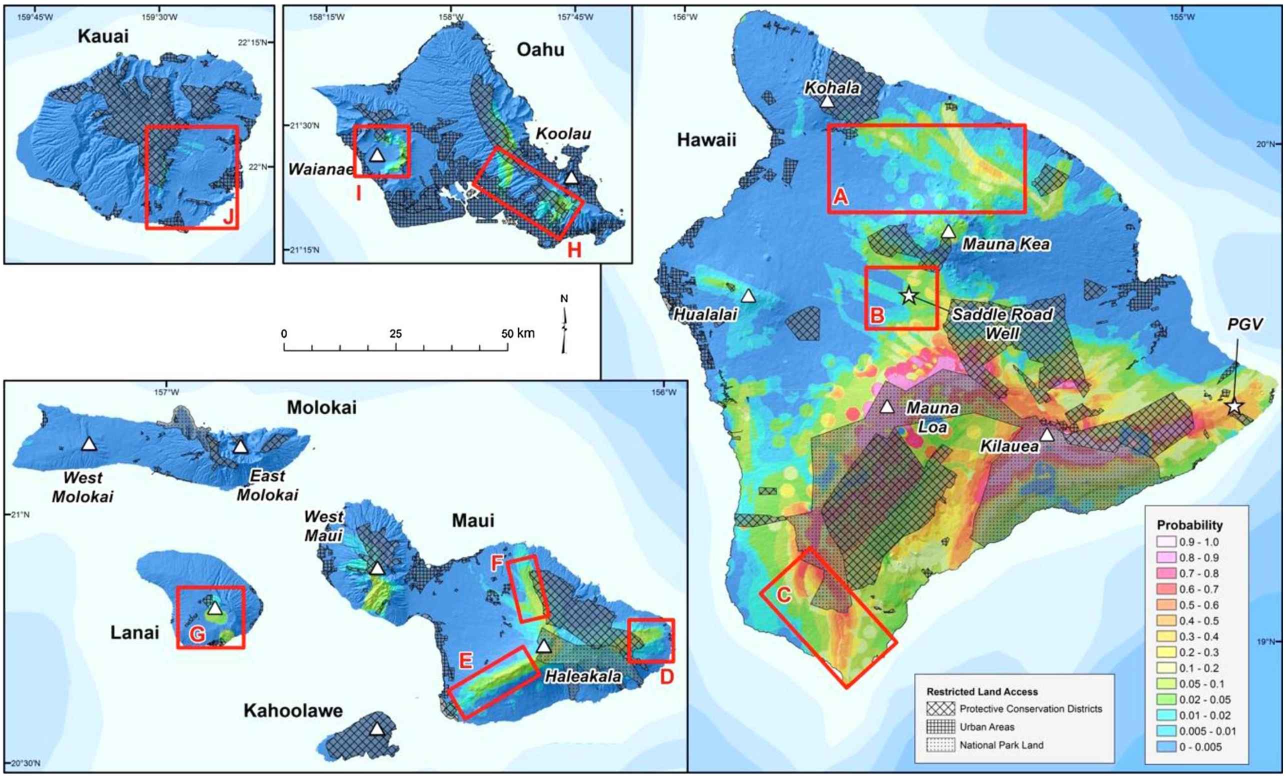

Fig. 1. Results of the DOE Phase 1 geothermal play fairway probability analysis for the State of Hawaii. Probabilities of a geothermal resource are colored. Areas with restricted land access are shown in stippled and crosshatch patterns (e.g., National Park lands, protective conservation districts, and urban areas). Red boxes outline areas proposed for Phase 2 study. White triangles indicate the calderas of the main shield volcanoes. White stars mark the locations of the Saddle Road well and Puna Geothermal Ventures (PGV). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Background

2.1. Probability and confidence results

Fig. 1 shows the results of the probability analysis described in detail in paper two (Ito et al., 2016). The probability of a geothermal resource is the joint probability of the three key qualities: elevated subsurface heat, permeability, and fluid, as supported by datasets described in paper one (Lautze et al., 2017). Not surprisingly, locations with the highest resource probability occur along the rift zones and at the calderas of the active shield volcanoes, Kilauea and Mauna Loa. However, results show some elevated probability on each island. Fig. 1 also shows areas with restricted land access in shaded patterns. These are areas in which further exploration and/or resource development would be challenging to impossible; such regions were excluded from our consideration for future work. The areas in red boxes are included in our recommendation for future (Phase 2) exploration based on results from probability modeling, our confidence in those results, and development viability. Other locations that were considered, but not included, in the Phase 2 targets, due to low development viability (as discussed below), are Kilauea's lower east rift zone, Hualālai, and the southern segment of West Maui (Fig. 1).

Fig. 2 shows results of the confidence analysis. This analysis provides a measure of confidence in the probability results, and is based on the number of datasets available at a given location, the quality of the data, and the relative importance of each dataset for the probability (Ito et al., 2016). In considering future exploration recommendations, areas of elevated resource probability, and areas with low to high confidence, were considered for future work, subject to viability as noted above. For example the confidence value south of Mauna Loa and north of Mauna Kea is moderate. South of Mauna Kea it is high (due to findings of the Saddle Road well), and in target areas on the other islands it is moderate to low. Areas with moderate and low confidence are in need of more data to better ascertain resource probability.

2.2. Criteria for ranking development viability

2.2.1. Grid integration potential and access to market

For an otherwise viable play, how difficult would it be to integrate the power into that island's electricity transmission grid? In 2015 the Hawaii legislature passed a bill mandating that 100% of the state's electricity come from renewable sources by 2045; the political climate for geothermal development is therefore extremely favorable. However one of the unique challenges of Hawaii's electric utility system is that the islands are separated by large stretches of ocean, and each island's grid is autonomous. Therefore, in the absence of an interisland cable, each island must meet the 2045 policy mandate individually.

Our first consideration is the simple engineering issue of whether the prospect is physically near a transmission line, and whether that transmission line has the necessary capacity. Transmission capacity may be more easily upgradeable than construction of new line. Although transmission distances in Hawaii are generally short compared to those in North America, the relatively small increments in power production for Hawaii's market, coupled with anticipated high costs and challenging regulatory review incurred by installation of new transmission lines, could render development of a resource in remote locations impractical or uneconomic.

Our second consideration is the sufficiency of "head-room" in the utility's mix of power sources. Headroom is the difference between total energy sales and energy produced from renewable sources for each island. This gap must be filled by 2045 to meet the policy mandate. Table 1 shows renewable energy production values from 2014. The gap is minimal for Kauai (total sales exceed renewable energy production by 354,722 MWh), larger for Hawaii Island (546,474 MWh), still larger for Maui (734,798 MWh), and extremely large for Oahu (5,594,454 MWh). Moreover, for those islands with diminished

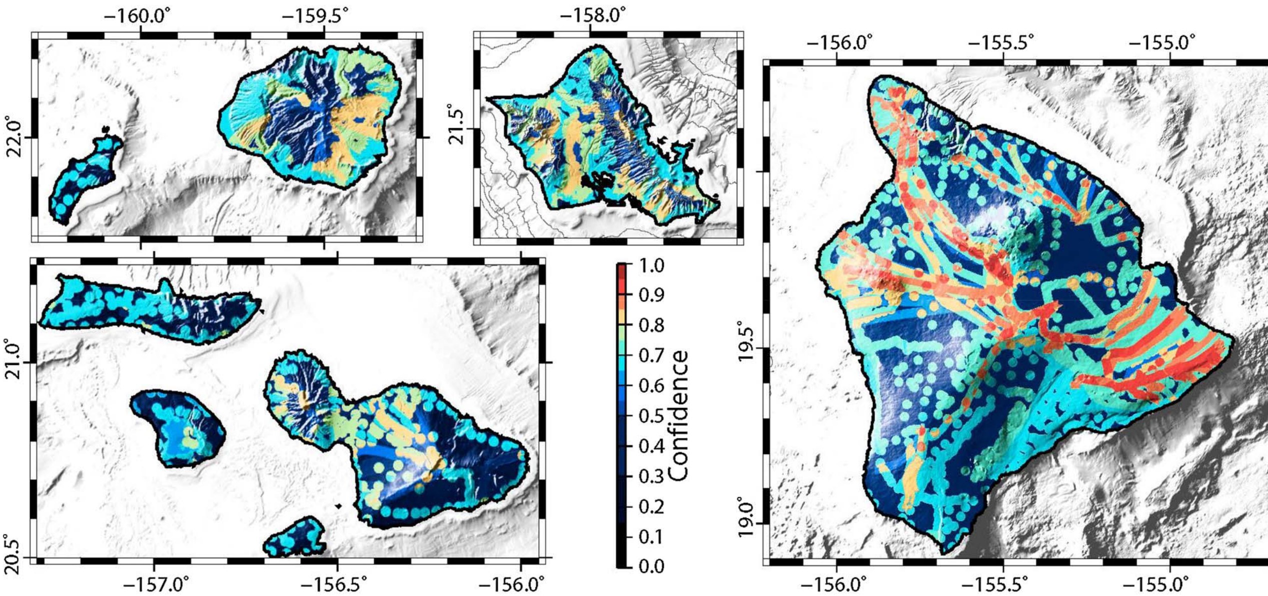

Fig. 2. Results of the Phase 1 geothermal play fairway confidence analysis for the State of Hawaii. Color indicates confidence in the probability values shown in Fig. 1. Confidence is a function of the number and quality of datasets at each location as well as their relative weight on influencing probability.

headroom, curtailment of geothermal production may be necessary when available renewable energy exceeds the electrical energy required by the grid. Such curtailment can adversely impact a project's economic feasibility.

2.2.2. Vulnerability to natural hazards

How vulnerable would a developed resource be to substantial loss from natural hazards? The Hawaiian Islands are at risk of volcanic eruptions, earthquakes, tsunamis and hurricanes, among other natural hazards. These natural hazards create additional financial risk for a capital-intensive power source such as geothermal, as well as a regulatory risk in the context of the public utilities commission (PUC) review. Geothermal development should be prioritized in areas of less risk to natural hazards in order to avoid substantial loss (e.g., Witter, 2012). Natural hazards vary in relative magnitude from island to island.

On Hawaii Island, volcanic hazards are the most significant, especially the threat of eruptive activity to transmission lines. In 2014, lava flowed 21 miles from its eruptive source on Kīlauea volcano (Hawaii Island) and nearly isolated a geothermal power source from the grid by impacting the transmission lines (Fig. 3). Several villages on Hawaii Island have been destroyed by lava flows in historical time. Hawaii Volcano Observatory publishes a lava-flow hazard zone map for Hawaii Island (http://hvo.wr.usgs.gov/hazards/lavazones/main.html), but not for the other islands, where the risk is much lower.

Earthquake risk is also greater on Hawaii Island than on other islands (USGS, 1997), and any geothermal plant on that island must be constructed in a way that is robust to such quakes. Similar to lava-flow hazard, earthquake hazard is higher near rift zones (USGS, 1997).

Tsunami risk is relatively low at most Hawaii geothermal prospects because they are located far from shorelines (Fig. 1). However, the Kawai Nui prospect on O'ahu is the exception: Butler (2014) found that a Mw9+ event in the Aleutians would completely inundate the Kawai Nui area, as well as the nearby town of Kailua; and Butler et al. (2016) estimate the 50-year probability of such an event in the range 6.5–12%. On the island of O'ahu, the existing Hawaiian Electric Kahe Power Plant, an oil burning plant that supplies 651 MW of power, may be inundated by such an event (Butler, 2014); hence a geothermal plant located far from the ocean would lower the risk of tsunamis to Oahu"s power supply.

On most islands, hurricane risk is thought to be low. Since 1950, only five hurricanes have caused significant damage in Hawaii and the only two that made landfall (Dot, in 1959 and Iniki in 1992) did so on the island of Kauai (Kodama and Businger 1998). However, on all islands the concentration of hurricane-related rainfall at higher elevations creates a risk of flash flooding. Most geothermal plants are industrial structures that are unlikely to sustain the type of damage to which the lightly built suburban residential structures of Hawaii are prone. Even on Kauai, a well-built geothermal facility ought to be safe

Table 1
Renewable energy output (in green) in MWh compared with total electricity sales (in blue) for larger utility systems in Hawaii. Quantities in parentheses are percentages of total sales. Sources: Hawaii Electric Company, 2016 Renewable Portfolio Standard Status Report; Kauai Island Utility Cooperative 2015 Annual Renewable Portfolio Standards Status Report.

	Hawaii Island	Maui	Oahu	Kauai
Wind	132,293 (12.4%)	264,291 (23.2%)	216,197 (3.2%)	
Solar (Connected)	2557 (0.2%)	7904 (0.7%)	40,750 (0.6%)	16,810 (3.9%)
Solar(Customer Sited)	89,691 (8.4%)	88,956 (7.9%)	464,412 (6.9%)	24,101 (5.6%)
Hydro (Run of River)	63,275 (6.0%)	9823 (0.9%)	0	34,291 (8.0%)
Biomass	0	30,870 (2.7%)*	385,846 (5.7%)	
Biofuel	0	988 (0.1%)	52,424 (0.8%)	
Geothermal	230,495 (21.7%)	0	0	0
Renewable Total (MWh)	518,311 (48.7%)	402,832 (35.4%)	1,159,629 (17.2%)	75,202 (17.5%)
Total Sales (MWh)	1,064,785	1,137,630	6,754,083	429,924
Gap to fill by 2045	546,474 (51.3%)	734,798 (64.5%)	5,594,454 (82.8%)	354,722 (82.5%)

* This biomass power was largely derived from excess power generated by sugar production on Maui that has recently announced an upcoming cessation of operations. Accordingly, this contribution to Maui's grid will decline.

Fig. 3. Top left: Photo of active pahoehoe lava flows encircling a utility pole that had been lifted and buffered with cinder blocks as a preventative action (Photo credit: Hawaiian Electric Light Company). Top right and bottom: Photos of utility pole roughly one year after lava had passed through (Photo credit: Nicole Lautze).

from hurricane damage if it is situated well above riparian flood plains.

A further element considered here was the magnitude of resource development that is likely to be at risk. Whereas a single power plant of moderate capacity in a high hazard area may be an acceptable risk, multiple facilities located within a footprint that could be impacted by a single volcanic event, or a single large facility in a high-risk area, creates a risk that might be deemed unacceptable by utility planners or the public utility regulatory process. This because the loss of a significant fraction of an island's generation capacity would adversely impact the economy of the entire island.

2.2.3. Land use

Is there adequate land area on which to place the necessary infrastructure to develop the geothermal resource and generate power? Is that development compatible with surrounding land uses? Large land parcels in regions of sparse residential or rural development were considered to have a high to very high viability for development. Prospective resources in more urbanized regions were considered to have moderate-to-low viability, as were regions of adverse topography, where development would likely be economically infeasible. Because Hawaii's economy depends heavily on tourism, geothermal prospects proximal to or on the following land designations were considered to have low to zero-development viability: National Park lands, State and County Parks, and land designated as State Conservation with Preservation sub-zoning (Fig. 1). Likewise, urbanized districts and lands having high cultural significance were considered to be poor prospects.

2.2.4. Community perception

What level of community acceptance is necessary for a proposed geothermal production facility? Largely due to its isolation, Hawaii is easily the most vulnerable state in the U.S. to energy supply disruption, and its residents suffer the highest utility rates in the nation. It is also, by far, the state most dependent upon imported petroleum for its electrical power generation. Until recently, public acceptance of utility-scale development of renewable energy, whether wind, solar, or geothermal, has been uneven, but this now appears to be changing (Hawaii Clean Energy Initiative, 2016; Hawaii News Now, 2015).

The earlier negative perception of geothermal energy was due in part to the history of early geothermal research and development in a single area of the state. The first proven geothermal prospect in Hawaii, in the Lower Puna District of Hawaii Island, was in an area in which large tracts of agriculturally unproductive lands were subdivided for speculative rural residential development. At the time of resource discovery in 1976, those subdivisions were largely unoccupied. During the subsequent decades, they became progressively more densely developed and populated, largely by people from the U.S. mainland. An early technology research and demonstration project, started in 1980, installed a 3 MWe wellhead generator to test the capacity of the resource and to investigate technical and engineering challenges to its utilization at the smallest realistic scale possible. Power generation was extended well beyond the facility's intended operational life of only two years. However, the plant's noise and odor nuisances led to ardent and vocal opposition to further development by the nearest neighboring residents.

Commercial-scale geothermal development nonetheless proceeded in proximity to the increasingly populous subdivisions, and occasional operational upsets (or abnormal) conditions at the commercial power plant resulted in vocal complaints as well as fines levied by the Hawaii Department of Health. Hence, the local public perception of electrical power production from geothermal resources in the Puna district is often negative, even as the broader public realizes Hawaii's potential for geothermal.

This analysis recognizes that communities in urbanized and densely populated regions are likely to oppose all but the most benign resource development, while development in more remote areas is expected to be more socially acceptable Similarly, installation of a second or third increment of resource development near a single community (e.g., Puna) can be expected to engender questions as to why that community should bear a majority of impacts associated with power generation for the island—especially if a resource exists in other parts of the island. In this case, even though a resource might exist and be economically viable, the cost of regulatory delays and extraordinary emission restrictions could render it economically infeasible to develop.

3. Development viability results

The development viability criteria were considered in the 10 locations (A-J) boxed in red in Fig. 1 as well as Puna, Hualālai, the southern segment of West Maui, and the areas adjacent to National Park and Conservation lands on Kilauea and Mauna Loa. Each location was deemed to have an overall development viability 'score' between 1 (low viability) and 20 (extreme viability) as shown in Table 2. The results are summarized more generally as high, medium or low viability in Table 3 below.

3.1. High to very high development viability

3.1.1. Haleakalā southwest rift (E)

This region includes several large land parcels that are quite rural, and owners of both parcels have expressed their willingness to host geothermal development if a viable resource is identified. Further, this location would not require substantial changes to the existing transmission system on the island. This area has experienced significant development of wind energy; less obtrusive geothermal production could be viewed in the community as a positive alternative to additional wind energy production. The headroom for renewables on Maui is significant at ~70%, and as the last eruption of this rift zone occurred ~270 years ago (Chen et al., 1991) we regard it as only a minor additional risk over the expected economic life of a power generation facility.

3.1.2 Lānaʻi (G)

Lānaʻi is a dominantly rural island that hosts a small population and a small grid; as a result, energy costs are very high. Lānaʻi's eruptive activity ceased in its shield building stage, with the last eruption ~ 1 Ma (Bonhommet et al., 1977), so the prospect located there is likely to be low to medium temperature. On the plus side, most land on this island is owned by a single individual who has expressed strong interest in pursuing sustainable development. Even with the relatively small demand and high costs, development of a small binary installation of an accessible resource could be a desirable alternative to petroleum-driven generation.

3.1.3. South shore Koʻolau, Oahu (H)

Oahu is the main population center for the state. It has the highest energy demand, and with the most headroom (82.8%) in the state, it has a great capacity to displace fossil fuel with geothermal energy (Table 1). Should there be a viable resource on Koʻolau volcano, it would likely be of moderate temperature. Development of the resource in a closed-cycle binary power generation design is expected to be acceptable to the surrounding community. Koʻolau experienced a significant amount of rejuvenation phase volcanism, with the last eruption ~80–100 ka (Lautze et al., 2017 and references therein).

3.1.4. Waiʻanae Oahu (I)

Similar to Koʻolau volcano, a viable low- to intermediate- temperature resource identified in the region of Waiʻanae volcano's caldera would be easy to integrate into Oahu's electrical grid. Furthermore, much land in this area is owned by the US Department of Defense (DOD), and development would fit within the DOD's sustainability initiatives. Waiʻanae has experienced no rejuvenation activity, and its post-shield volcanism ended ~3 Ma.

3.2. Medium development viability

3.2.1. Mauna kea north flank (A)

This region is largely rural with several large land parcels under single ownership. One of the major landowners is actively pursuing strategies to develop an alternative energy supply in order to facilitate infrastructure development, and would likely be receptive to development of geothermal power. However, the headroom for addition of base load renewable energy on Hawaii Island is limited (~50%, Table 1). An advantage here would be that development would occur on the major landowner's largely rural private land. Mauna Kea last erupted ~4 ka and is within the lowest volcanic hazard areas of the island.

3.2.2. Haleakalā east rift zone (D)

This region has some large parcels where limited development could occur, and the Maui grid can accept additional renewable energy. There has been significant development of wind power on the island, and some communities there view geothermal as a preferable alternative. However, this region is quite remote, and would require significant upgrades to its transmission line capability in order to integrate geothermal power. The last eruption at Haleakalā occurred ~400 years ago.

Table 2
Summarizes criteria used to evaluate 'Overall Development Viability' in Phase 2 Target locations.

Site	Grid Integration	Natural Hazards	Land Use	Community Perception	Overall Development Viability
(A) N MKea	3	5	4	3	15
(B) W Saddle	5	3	2	2	12
(C) SW MLoa	1	1	4	3	9
(D) E Haleakala	2	2	4	3	11
(E) SW Haleakala	4	5	4	3	16
(F) N Haleakala	3	4	2	1	10
(G) Lanai	5	5	4	4	18
(H) S Koolau	5	5	2	3	15
(I) Waianae	4	5	4	3	16
(J) Kauai	4	4	3	2	13

Table 3
Summary of Results. Probabilities in column 2 have been scaled by the probabilities at PGV, the only operating geothermal facility in Hawaii. Some scaled probabilities exceed 100% because PGV is not the highest probability location, an expected result given that siting decisions are affected to some extent by factors other than resource availability.

Site	Rankings			Phase 2 Activities	
See Fig. 1 for locations	Probability, % of PGV	Confidence, % of maximum	Development Viability	Water Surveys Priority	Geophysical Surveys Priority
(A) N MKea (Hawaii)	48–95% (high)	65–90% (high)	medium-high	high	medium
(B) W Saddle (Hawaii)	12–60% (low to medium)	65–95% (high)	medium	medium	medium-low
(C) SW MLoa (Hawaii)	50–170% (high)	60–85% (medium)	medium-low	medium	medium-low
(D) E. Haleakala (Maui)	10–24% (low)	25–65% (low to medium)	medium	high	medium-low
(E) SW Haleakalā (Maui)	7–17% (low)	25–75% (low to medium)	high	high	high
(F) N Haleakalā (Maui)	7–19% (low)	55%–85% (medium to high)	low	medium	low
(G) Lana'i	5–24% (low)	55–80% (medium)	very high	high	high
(H) S Ko'olau (Oahu)	1–10% (low)	65–85% (medium to high)	medium-high	medium	low
(I) Wai'anae (Oahu)	2–7% (low)	65–85% (medium to high)	very high	me	low
(J) Kauai	1–2% (low)	50–85% (medium to high)	medium	high	low

3.2.3. Kauai (J)

Of the five main Hawaiian Islands, Kauai has the lowest energy demand (Table 1). Current renewable supplies are not base-load, so there is some opportunity to displace petroleum-generated power with geothermal. But geothermal may be faced with capacity limitations for significant portions of the daily demand cycle. Kauai therefore has medium development viability at best.

3.3. Low development viability

3.3.1. West saddle (B)

This region shows significant resource potential, but the land-owner does not wish to develop the resource at this time.

3.3.2. Mauna loa SW rift (C)

This location has a relatively high geologic probability of a resource, however, most of the SW rift is located within Hawaii Volcanoes National Park, and previous proposals for geothermal development in proximity to their boundaries have drawn strong opposition from the National Park Service as well as community support groups. Furthermore, development of the resource would require significant upgrading of the transmission line in order to convey power to the island's primary markets to the NW and NE. Both corridors run parallel to the Mauna Loa southwest rift and, hence, would be exposed to lava flow threat along most of their length. Mauna Loa last erupted in 1984, and had a pattern of frequent (every ~5 yrs.) eruptive activity prior to 1950.

3.3.3. Haleakalā north rift (F)

This region is dominated by small landholders, and ecotourism is a significant industry; many of its residents relocated there for the natural environment. Based on the lawsuit filed by residents of a similarly rural area near Hualalai (see below), who sought to prevent geothermal exploration, we expect strong opposition to any industrial development in this region.

3.3.4. Kīlauea's lower east rift zone

Most geothermal exploration in the state has been concentrated in this region, and the state's one producing facility, the Puna Geothermal Venture (PGV) exists here. However, for the reasons explained above, there is ardent community opposition to current or expanded geothermal power generation in this area [CITE Star-Advertiser,]. It is also an area where exposure to natural hazards is extreme. The last volcanic eruption to threaten the area occurred in 2014 and a hurricane in 2014 caused extensive damage to transmission lines connecting the facility to the island grid.

3.3.5. Hualālai west rift

The west flank of Hualālai is developing as a high-end residential district with many small rural parcels. The area has attracted well-to-do retirees who have relocated there because of its proximity to year-round golfing, beaches, and resorts. In October 2015, six residents of the area filed suit to require an environmental assessment for a geothermal exploration project that would have involved only minimally invasive magnetotelluric measurements [http://hawaiitribune-herald.com/news/local-news/lawsuit-challenges-hualalai-geothermal-survey], citing concern for "Hualalai's sensitive natural and cultural environment.". Also located in the region are culturally important resources that would remove some of the larger parcels from consideration as development sites. Given the resource uncertainty, combined with an expectation of community resistance from land owners concerned about property values, we designated this area as low viability.

3.3.6. West maui, southern segment

Extreme topography in this area makes development practically unfeasible.

3.3.7. Areas adjacent to conservation and national park land on Mauna loa and Kilauea volcanoes

It can be expected that resource development adjacent to National Park lands will be challenged, such that we did not propose further exploration along the areas bordering National Park land that encompasses Mauna Loa's and Kilauea's SW rift zones. A small segment of land between conservation districts near Kilauea's caldera is known as Volcano Village, where it is expected that community opposition to geothermal development would be high (D. Thomas, personal communication). The block of land to the north of the easternmost extent of Conservation District land along Kilauea's east rift is divided into small residential parcels (zoned as agriculture lands), which would make resource development difficult.

We note that public perceptions of geothermal may change in the future. It may be recommended that some of the locations excluded here are considered for exploration in the future.

4. Future exploration recommendations

The results of the probability and confidence modeling and the development viability analysis are summarized in Table 2, along with a list of our recommended sites for future exploration. Our overarching goal in choosing such sites was to *balance* ***resource probability*** *and* ***development viability*** *in selecting and prioritizing locations that warrant improved confidence. Our next goal is* to identify the most cost-effective exploration activities to increase confidence at each location.

4.1. Summary of phase 2 objectives

Based on the combined results of the Play Fairway Analysis we recommend (1) a groundwater sampling and analysis campaign in locations A through J (Fig. 1) and (2) audiomagnetotelluric (AMT), magnetotelluric (MT), and gravity surveys in locations as prioritized in Table 3 and stated below.

The two main activities and their rationale are as follows:

(1) Conduct a ***groundwater sampling and analysis*** campaign. Use newly acquired chemical and isotopic data to validate existing groundwater indications of geothermal activity and to better define inferred groundwater flow paths. Circulation of groundwater through a geothermal reservoir imparts a temperature and chemical signature that is carried with the groundwater as it flows down the hydraulic gradient. In Phase 1 of the project, a groundwater temperature and chemistry database was compiled from multiple sources (Lautze et al., 2017). In order to evaluate the origin of the water exhibiting elevated temperatures and/or the characteristics of geothermal alteration, trajectories of groundwater flow were projected upgradient (models produced by the Hawaii Department of Health's Source Water Assessment Program) The groundwater data used in this PFA demonstrate their value to the assessment of Hawaii's geothermal resources.

Some drawbacks of the existing Hawaii groundwater data are that: a) the chemistry data are limited, and some valuable chemical indicators, e.g., trace metals and isotopes, are lacking; b) many of the samples were collected prior to 1980, and analysis techniques have greatly improved since then; c) the geographic availability of data is far from comprehensive; several of the modeled areas of interest (e.g., Haleakalā's rift zones) have very sparse groundwater data; and d) the groundwater flow paths are not well established.

The goal of this task is to remedy these shortcomings. Sampling and analyzing groundwater is relatively low cost, low risk, and straightforward to do, making it a logical next step in Hawaii's geothermal resource assessment program. New samples and analyses of groundwater are proposed for all prospect areas listed in Table 2, which identifies regions where further, more detailed, exploration would be informative.

(2) Explore for heated fluid and intrusives with ***new MT/AMT and gravity surveys***. Geothermal systems are often detected and delineated using electromagnetic geophysical methods (Spichak and Manzella, 2009; Munoz, 2014). Magnetotellurics (MT) and audiomagnetotellurics (AMT) provide estimates of electrical resistivity laterally and with depth. With their range of depth scales, MT and AMT surveys often delineate not only the resource itself but also the causative heat source (Munoz, 2014).

In conducting MT and AMT surveys for groundwater exploration and subsequent drilling, UH researchers identified a previously unrecognized geothermal resource in the saddle between Mauna Kea and Mauna Loa on Hawaii Island (Thomas et al., 2014; Thomas and Haskins, 2015). Not surprisingly, it was subsequently noted to have an elevated gravity signature (Flinders et al., 2013), an attribute often associated with intrusives/heat in Hawaii (Lautze et al., 2017; Ito et al., 2016). Gravity data exists for much of the state, but substantial MT data exist only on Hawaii Island. Additional geophysical data in prospective regions on other islands will aid in detecting and characterizing prospective resources.

The associated higher costs and greater personnel time required to conduct these surveys restricts the number of prospect areas that can be surveyed in the near future. The priority ranking for these surveys (below) is based on locally elevated resource probability and development viability, as well as the extent to which such surveys will improve our confidence in the presence and extent of a resource.

4.1.1. Highest priority

Lānaʻi (G) and *Haleakalā Southwest Rift (E)*. No AMT/MT data is currently available in either area. Both have elevated probability and high development viability.

4.1.2. Moderate priority

North Flank of Mauna Kea (A) is an area in which limited geophysical data were recently obtained via funding from the state. A modest amount of additional data will provide regional coverage and enable verification of a tentatively identified resistivity low, which suggests the possibility of heated fluids in a permeable subsurface. Abundant data exist in the *West Saddle* region between Mauna Kea and Mauna Loa *(B)*, which is currently being processed. It is expected that a small amount of additional data will enable us to arrive at more robust conclusions. No AMT/MT data currently exist at *Mauna Loa Southwest Rift (C)*; such data would be valuable in determining the presence of a resource. However, the development viability is low due to the area's remote location, relatively high volcanic hazard, and the high costs associated with integrating a power source at this location into the grid. New AMT/MT data along *Haleakalā East Rift (D)* would help determine subsurface resistivity variations, but development viability is reduced due to its remote location and potential sociopolitical issues.

4.1.3. Not prioritized for geophysical surveying

The *Haleakalā North rift zone (F)*; *South Oahu (H) and Waiʻanae Oahu (I)*; *Kauai (J)*. In addition to considerations of resource probability and development viability, other concerns include land access issues, as well as greatly degraded quality of MT/AMT data due to electrical noise in areas with high populations. We expect the lower cost, less risky groundwater results to determine whether additional exploration in these areas is warranted.

5. Conclusions

A comprehensive PFA for the entire State of Hawaii was recently completed. This project identified and compiled existing data relevant to Hawaii's geothermal resource, and developed a statistical method to incorporate such data into a prospect probability map. In constructing a plan for Phase 2 exploration activities, we considered the viability of resource development in locations with an elevated probability. This development viability analysis considered i) ability to connect power to the grid, ii) natural hazards, iii) land use, and iv) anticipated community acceptance. Development viability was deemed to be high in parts of Maui and Oahu, and on Lānaʻi due to a high energy demand and a need to increase renewables, as well as relatively low natural hazards, and anticipated community acceptance.

Phase 2 exploration recommendations were based on the sum of the probability results, a calculation of confidence in this probability, and the development viability assessment. For the next phase of exploration, we recommend collecting data through 1) a groundwater sampling and analysis campaign in ten locations across the state including Kauai, Lānaʻi, two locations on Oahu, and three locations on both Maui and Hawaii Island, and 2) MT, AMT and gravity surveys initially on Lānaʻi, and Haleakalā's SW rift (Maui) and, should time and funding allow, Haleakalā's E rift (Maui), Mauna Loa's SW rift, and North and South of Mauna Kea's summit.

These as well as other new data will be incorporated into the PFA in order for Hawaii to improve its geothermal inventory. In view of the age of the last comprehensive resource assessment (Thomas, 1985) and recent new discoveries, there is a powerful incentive to expand Hawaii's geothermal knowledge base, an essential first step for development. Given Hawaii's excessive dependence on imported petroleum, extreme electricity prices, and policy objective of becoming 100% renewable by 2045, the cost-benefit ratio of this work is very high.

Acknowledgements

We thank the U.S. Department of Energy's Geothermal Technologies Office for providing funding and management of this project, under award number DE-EE0006729. Local expert researchers, including John Sinton, James Foster, Stephen Martel, Robert Whittier, and Ormat geologists, willingly shared their knowledge throughout this project. We also thank thesis students Hannah Schuchmann, and Mahany

Lindquist for their enthusiastic participation.

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