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Power Density in Geothermal Fields, 2020 Update

Maxwell Wilmarth, James Stimac and Gugi Ganefianto

PT Jacobs, 15th Floor Talavera Tower, Jakarta Selatan, Indonesia 12430

max.wilmarth@jacobs.com

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ABSTRACT

We estimated and updated the power densities of 103 geothermal fields around the world. Power density follows a log-normal probability distribution. The mean power density of the population is 12.4 MW/km^2 and the median is 10.1 MW/km^2. Power density is a function of average reservoir temperature and correlates strongly with tectonic setting. Fault-based systems tend to be low to moderate-temperature and have low power density, volcanic arc systems tend to be moderate to high-temperature and have moderate to high power density, and rift systems tend to be high-temperature and have high power density. The one major deviation from these trends is that some high-temperature volcanic arc systems tend to have moderate to low power density which appears to be anti-correlated with temperature. One important reason for this may be that these volcanic arc-hosted systems tend to be found in more purely compressional settings which may have limited permeability. Area is very important to consider when estimating power capacity in exploration-stage fields. Areas should be chosen based on appropriate conceptual models with reference to analog fields and to the distribution of areas in operating fields.

1. INTRODUCTION

1.1. Resource Capacity Estimates

Resource capacity estimates are critical components at every stage of a geothermal project. A project must at all times have a potential capacity that justifies the expenditure of resources to explore, develop or continue to operate it. Resource capacity estimates are commonly made using power density, natural heat loss, stored heat, and numerical modeling (Benoit, 2013; Grant and Bixley, 2011). The most robust resource capacity estimates are made using a 3D numerical model of the reservoir, coupled to well bore models of the production and injection wells, and informed by extensive and detailed geoscientific data. However, in the exploration and development stages of a geothermal project, and even into the early production phase, these data and models are generally not available. Geothermal professionals commonly use power density for first-order estimates of resource capacity, and as checks on other methods, usually expressed in terms of MW/km^2. The benefit of an estimate using power density is that it instantly returns a reasonable value, while stored heat estimates may be in error by orders of magnitude, and numerical models require significant time and effort to build but may not be any more accurate than power density unless well-calibrated.

Historically, there have been only a few publications describing how to assess power density and how it might vary as a function of resource type and temperature. Grant (2000) suggested that power density increases with reservoir temperature, indicated 10-20 MW/km2 was a suitable range in early exploration and observed that "…power density for most fields ranges from 8 MW/km2 at 230°C to up to 30 MW/km2 at 300°C" (Figure 1). Grant and Bixley (2011) suggested that typical power density estimates used during exploration are 10-15 MW/km2. Power density was discussed as a metric for calculating reserves by Atkinson (2012) with the additional suggestion that an analogue field should be chosen first based on reservoir temperature and production characteristics. Bertani (2005) calculated power density for 69 geothermal fields and found an average value of 7.4 ± 6.0 MW/km^2. Sarmiento and Björnsson (2007) quoted power density for some of the geothermal fields in the Philippines. Benoit (2013) presented linear power density for a number of structurally controlled Basin and Range systems as MW/mile of fault length.

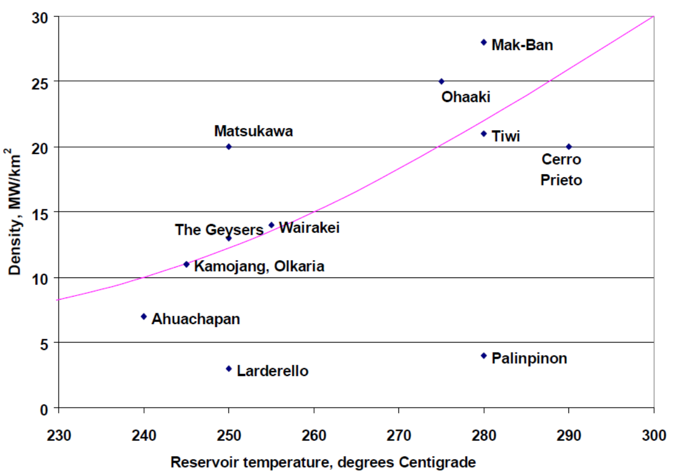

Figure 1: Power Density vs Reservoir Temperature (after Grant, 2000)

Wilmarth and Stimac (2015) presented statistics for 71 operating geothermal fields with more than 10 MW_{net} output and 5 years of production history, representing the majority of fields worldwide. The main finding was that for most fields power density is a function of reservoir temperature and increases in an exponential relationship (Figure 2). This major trend was termed the "Main Sequence" and contains at least three coherent groups of fields that have similar structural or tectonic setting: Fault-based, Arcs, and Rifts. Generally the fault-based group is lower temperature, the volcanic arc-based group is higher temperature, and the rift-based group dominates the highest temperature part of the Main Sequence. Additionally, a group of high-temperature, volcanic arc-based fields was identified that have an apparently constant power density of ~10 MW/km^2 regardless of reservoir temperature.

Wilmarth and Stimac (2015) also presented population statistics for the database of fields including an important measure of field area with a mean calculated to be 5.2 km^2 for the entire population. It has become apparent that many people have used this paper to guide them in making power capacity estimates using power density, but that the areas the density is applied to are often far too large. This paper will attempt to establish guidelines for appropriate areas used in power capacity estimates.

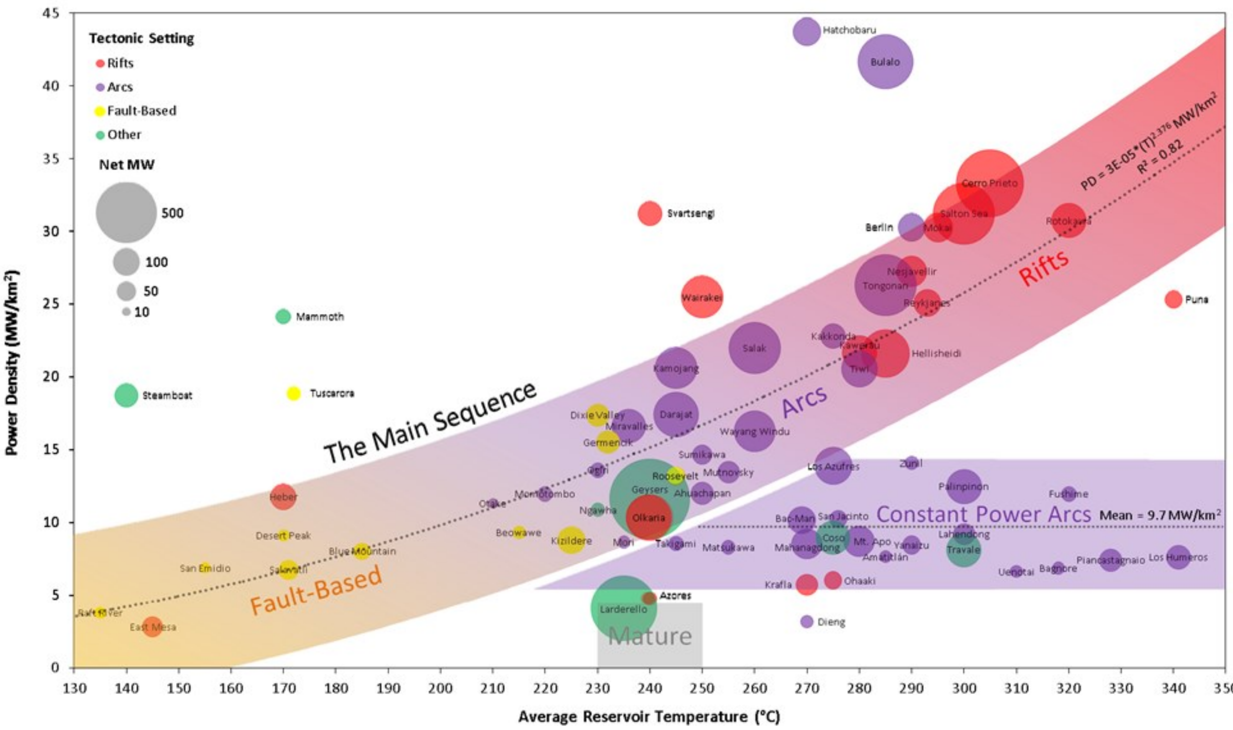

Figure 2: Power Density vs Reservoir Temperature with tectonic relationships (after Wilmarth and Stimac, 2015).

2. METHODOLOGY OF THIS STUDY

This study of power density examined the published literature of 103 operating geothermal fields representing the majority of fields worldwide. To be included in the study the field must have recent reliable published data on production well locations and power output, or reliable numbers had to have been received from the respective operating companies. This group includes new fields that were not yet online in 2015 and also expands the study to include fields with less than 5 years of operating history and with less than 10 MW of net capacity. This allows for a fuller picture of power density in geothermal fields to be presented.

Many fields that were included in the 2015 study have been updated with new power capacity numbers, reservoir temperature numbers, and areas based on updated production wellfield configurations. In some cases these changes are correction to previously erroneous data, but many represent new conditions in the field's evolution. Many liquid-dominated fault-based reservoirs decline measurably in average reservoir temperature on an annual basis.

2.1. Power Estimate

Net power output was estimated for each field. In many cases there were recent published values available, but in some cases the estimates were older, or it was unclear if the quoted value was net or gross. In fields with long histories, recent estimates were used, e.g. The Geysers was estimated at the current 850 MW rather than the peak output of ~2000 MW. This was considered more practical than estimating the lifetime-average power output because the current output can be readily paired with the current wellfield configuration. Fields with net power capacities as low as 0.45 MW (Chena Hot Springs) are included and demonstrate that the relationship between temperature and power density holds for even very small fields. Power density estimates for small fields are clearly more susceptible to error because a small uncertainty in output can be a large fraction of the output of a small field. Special attention was given to small fields to obtain precise output estimates.

In some cases a substantial amount of production is devoted to direct-use rather than electrical generation, which may reduce the power estimate (e.g. Nesjavellir, Kawerau). This should be noted when studying the plot.

2.2. Area Estimate

Production area was estimated as a merged 500 m buffer around all current production well tracks (Figure 2). This method remains unchanged from the 2015 study. While this method has potential pitfalls, it provides a common basis for comparison and can be consistently applied to a statistically significant number of cases. The literature includes many mapped estimates of production area, but it is often not clear how it has been defined. Often workers will include the entire area of thermal features, or an arbitrary boundary for a low-resistivity anomaly. These areas are invariably far too large to be a proxy for production area. The methodology used in this review introduces error because it makes no allowances for isolated, extended-reach deviated production wells (e.g. Ohaaki-Broadlands, Krafla) which may have dead legs. Generally these errors are small. Some fields may have deviated wells but only published locations of wellheads. In some cases production well locations were ascertained by analysis of publicly available air photos (e.g. Google Earth).

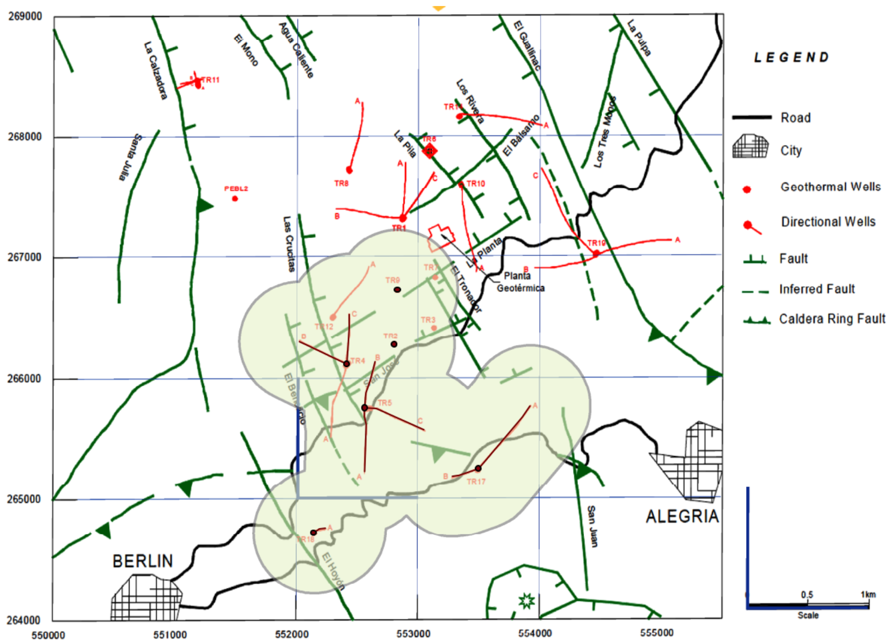

Figure 3: Berlin geothermal field with merged 500 m buffer around active production wells.

2.3. Temperature Estimate

Average reservoir temperature was the most difficult parameter to estimate. Many fields have consistent, authoritative published values for reservoir temperature. However, all fields have a range of reservoir temperatures and many fields have a very wide range of exploited temperatures corresponding to reservoir compartmentalization or the existence of multiple vertically separated reservoirs. Additionally, most fields experience temperature declines over time, and so recent values were used. The best estimates were made based on the available published data, but uncertainty on the order of 5-10°C is common and is occasionally up to 25°C or more.

2.4. Other Sources of Uncertainty

There are many other sources of uncertainty in this methodology. Net output was used rather than gross because these values are much more commonly available, but this means power plant efficiencies are not considered. Therefore some fields may appear to have anomalously low power density due to an inefficient power plant. Wells that are labeled as producers on maps and located on the edge of reservoirs, but are not actually currently producing to the station, could significantly alter the area estimate. Fields that have been recently expanded may have an unsustainably high power output. Some fields could expand their production area by moving injection from zones of possible production, or through step-out exploration into higher-power density areas of reservoir. Some fields have wells that produce acid fluids or high gas in otherwise good reservoir area (e.g. Mahanagdong), which limits power output.

3. RESULTS

The distribution of the 103 power densities is log-normal (Figure 3) with a range from 0.6 (Chena Hot Springs) to 41.8 MW/km2 (Silangkitang). The mean value of the population is 12.4 MW/km2, the median is 10.1 MW/km2, slightly lower than in the previous study due to the inclusion of more lower temperature fields. Compare this to the distribution calculated by Bertani (2005) which is also log-normal (Figure 4).

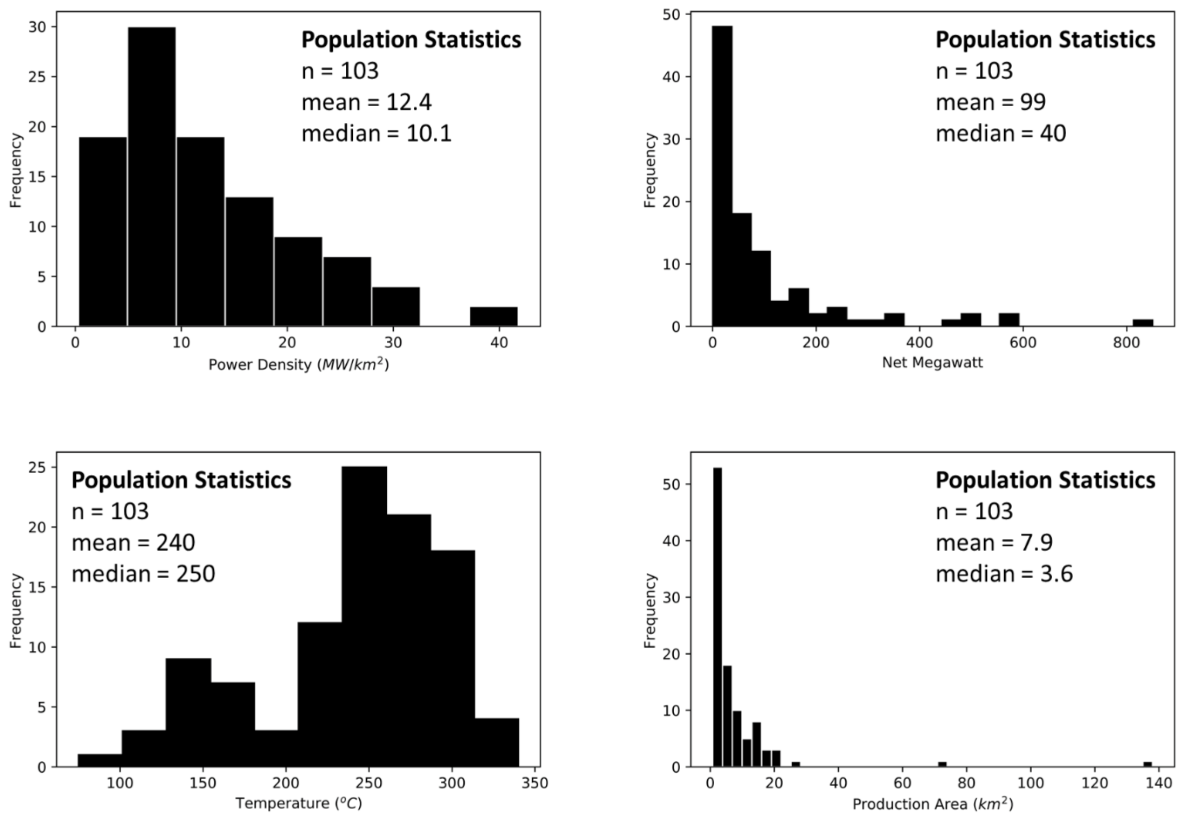

Figure 4: Histogram of power density for 103 operating geothermal fields. The distribution is log-normal.

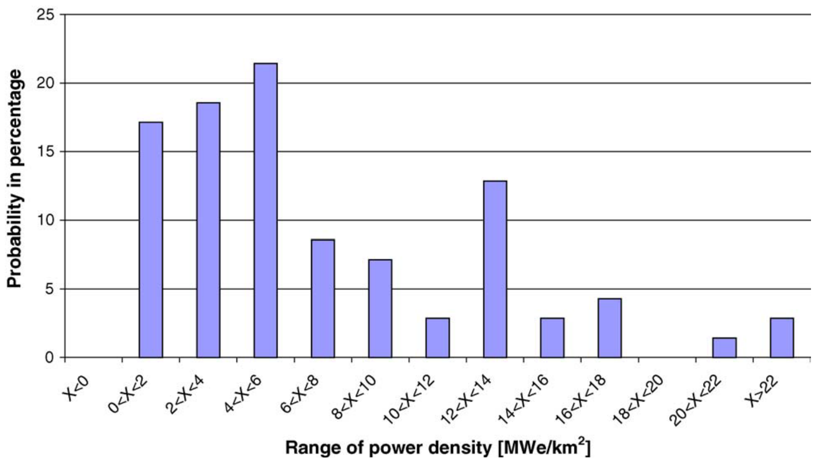

Figure 4: Power density distribution of developed geothermal fields (after Bertani, 2005).

The plot of power density vs average reservoir temperature is displayed in Figure 5. This plot is very similar to that from Wilmarth and Stimac (2015) and features the same structural/tectonic groupings.

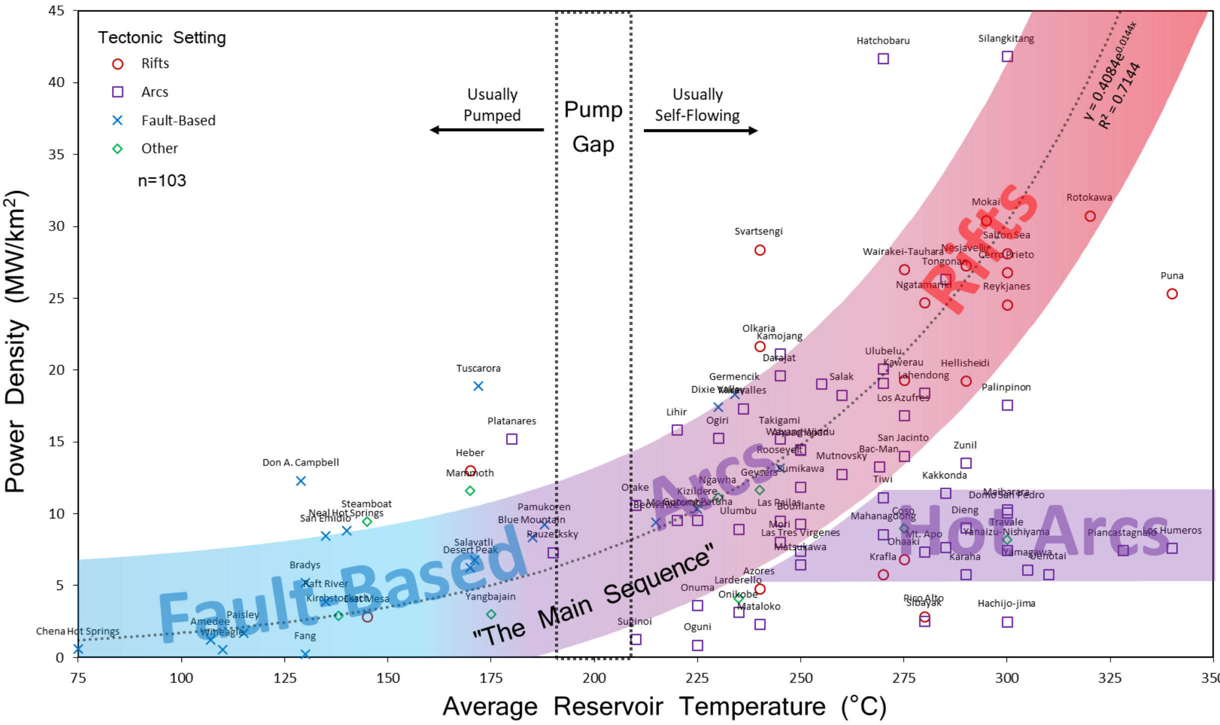

Figure 5: Power Density vs. Average Reservoir Temperature for 103 operating geothermal fields.

3.1. The Main Sequence

Fields on the Main Sequence are located in a variety of tectonic settings, including fault-based Basin and Range fields like Dixie Valley, arc volcanoes like Momotombo, arc volcanoes in complex tectonic settings like Tongonan, and fields in extensional rifting settings like the Salton Sea. Fields on the Main Sequence are mostly associated with three tectonic settings, moving from moderate-temperature fault-based systems, through high-temperature volcanic arc systems, to very-high temperature rift systems. There is considerable overlap between the three groups.

3.2. Fault-Based

Deep fault circulation systems are common in areas of thinned and extended crust and most appear to lack an immediate igneous heat source. The Fault-Based group lies entirely within the Main Sequence and these fields generally have moderate temperatures of 130-200°C with power densities below 10 MW/km^2. All are in the Basin and Range province of the western United States except Kizildere in Turkey. Dixie Valley is a clear outlier from this group and is widely regarded as the best of the Basin and Range systems. Roosevelt is also unusual in that it has an average reservoir temperature above 240°C. While these systems are considered fault-based, the producing fault zones are not perfectly linear and have some areal extent. The power densities found here are consistent with the linear power densities calculated in Benoit (2013).

3.3. Arcs

The Arcs group are generally fields associated with volcanoes located in broadly compressive tectonic environments along subduction zones. This group is strongly bi-modal with an upper arm that lies within the Main Sequence and consists of fields with high temperatures of 200-300°C and power densities of 10-30 MW/km^2, and another lower arm that diverges from the Main Sequence and consists of fields with temperatures up to 350°C and power densities slightly decreasing with greater temperature. All the fields in the lower arm have power densities below 10 MW/km^2. The main difference between the two arms seems to be that fields in the upper arm have complicated structural settings despite the broadly compressive tectonic regime, while fields in the lower arm seem to be in more purely compressional settings. Three arc-related geothermal fields lie above and below these two arms – Hatchobaru, Bulalo (Mak-Ban) and Dieng. Hatchobaru is a ~100 MW system limited by an adjacent national park, suggesting the system is benefitting from uncounted reservoir area. Bulalo is located in the extensional Macolod Corridor, is hosted by rapidly accumulated volcanic and volcaniclastic sequences with relatively high porosity, has great reservoir thickness, and a large adjacent area used for injection that provides hot recharge to the drilled production area.

3.4. Rifts

The Rifts group is variable but generally contains very high-temperature (>270°C), large fields located in rifts and rift-like extensional tectonic environments like the Reykjanes Ridge (Nesjavellir, Reykjanes, Hellisheidi), the Salton Trough (Cerro Prieto and Salton Sea), and the Taupo Volcanic Zone (Rotokawa, Mokai and Kawerau). Some of the other rift-based fields have specific reasons limiting their exploitation: Ohaaki suffers from calcite formation scaling. Puna has regulatory restrictions limiting utilization of reserves within the current wellfield.

It is worth noting that the largest rift system in the world is poorly represented in the data. The main East African Rift (e.g. Tanzania, Kenya, Ethiopia) and Afar Rift (e.g. Ethiopia) have high geothermal potential, but only a handful of the most promising systems have been drilled, and only Olkaria is included in our review. Thus it is difficult to know to what extent these identified trends in rift-based fields will be supported by further development and long-term production from this region.

3.5. Other

Seven fields do not fit neatly into any of the above categories. Coso, The Geysers, Larderello, Travale, Mammoth, Steamboat, and Ngawha are all unusual tectonic or structural cases. Most of these are volcanic but don't obviously belong to any particular volcanic arc. Larderello and Travale could be considered to be at the northern extreme of the Campanian Arc, but aren't associated with a proper volcano (rather phreatic eruption craters) and are unusual in that their reservoirs are developed in fractured carbonates. Mammoth and Steamboat both could be considered Basin and Range systems but the production at Mammoth comes from a fractured outflow and Steamboat has a significant volcanic component. Ngawha has deep circulation in distributed fracture permeability.

3.6. Mature Fields

One might expect that fields operated for many decades would tend toward vapour-dominated conditions, temperatures near that of the maximum enthalpy of steam (~240°C), lower reservoir pressure and lower power density. Only one long-produced field, Larderello, plots in this area between 230-250°C and below 5 MW/km^2. The Geysers would plot here as well if not for two municipal wastewater injection systems built in the early 1990s which succeeded in mitigating the reservoir pressure decline and stabilizing output.

Table 1: Statistics for the various groups identified.

Group	n	Median Temperature (°C)	Median Area (km^2)	Median Power (MW_{net})	Median Power Density (MW/km^2)
Total Population	103	250	3.6	40	10.1
Main Sequence	65	240	3.9	56	12.8
"Rifts"	19	280	6.6	95	8.4
Arc Volcanoes	55	260	3.7	40	10.3
Fault Based	20	155	2.3	16	8.4

4. DISCUSSION

The groups of fields identified above suggest that tectonic environment has at least as big an impact on power density as temperature. Fields in extensional environments that are regional like rifts, or local like a releasing bend of a strike-slip fault, may maintain distributed permeability over geologic time better than fields in more purely compressional environments like subduction arcs. The implication for development is that a high-temperature field in a volcanic arc may have lower than expected power density unless there is a structural feature which provides for local extension (e.g. Salak). This does not mean these fields are poor development targets, as many of these fields have high total power outputs.

Other reasons high-temperature fields located in volcanic arcs may have lower power density are the occurrence of acid fluids and high gas, which can limit production from otherwise hot, permeable reservoir (e.g. Mahangdong, Mt. Amiata).

Large fields with very long production histories tend toward lower power densities while fields with limited production histories may have unusually high or low power densities due to unusual economic or regulatory constraints.

5. POWER CAPACITY ESTIMATES BASED ON POWER DENSITY

Since the publication of Wilmarth and Stimac (2015) maybe power capacity estimates have been made for geothermal fields using the methodology and ranges included in that paper. This has resulted in more regularized power capacity estimates with a baseline reference to real-world data. In the case of exploration-stage projects, however, the authors have found that reasonable power density estimates have been applied to too-large areas, resulting in unreasonably large power capacity estimates.

5.1. The importance of area

Wilmarth and Stimac (2015) presented population statistics for the database of fields including an important measure of field area with a mean calculated to be 5.2 km^2 for the entire population. The methodology for calculating area is that study and the present study is the same: a 500 m merged buffer around all active production wells in map view. This means a single vertical production well would have a buffered area consisting of a circle of radius 500 m centered on the well, with an area of ~0.8 km^2. While there are drawbacks to this methodology as discussed above, using this consistent metric across fields allows them to be directly compared and we find it to be the most reasonable calculation of production area in use.

When making power capacity estimates for exploration projects using power density, careful consideration must be given to the area estimates. Often estimates are made based on reference to resistivity contour anomalies (e.g. areas with <10 ohm-m resistivity in the upper 500 to 1000 m) or to an area of thermal features. As discussed in Cumming (2016), "The area of low resistivity detected by an MT survey is not usually directly comparable to the area of the reservoir and is often several times larger". Reasonable areas should be selected based on reference to the population of operating geothermal fields. Histograms of operating geothermal field size using the Wilmarth and Stimac (2015) metric are provided below. While there are some very large fields with areas several times above the mean (e.g. The Geysers, Larderello) the population is lognormally distributed with most fields in a relatively narrow band. This can be seen even more clearly for the various structural/tectonic groupings (Figure 6).

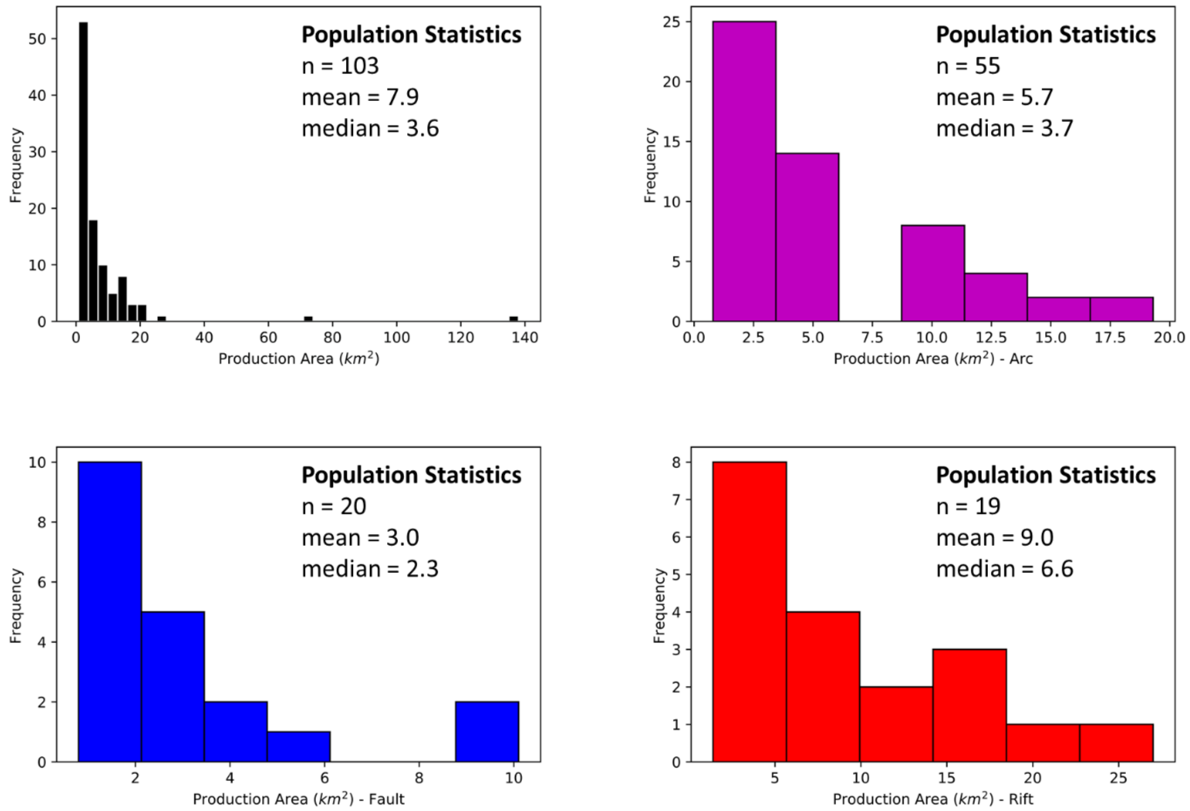

Figure 6. Histograms of production area for the entire population of fields and for the three structural/tectonic settings.

6. CONCLUSIONS

In general, power density is a function of average reservoir temperature and may increase in an exponential fashion. However, tectonic setting and field history are also very important. Fault-Based systems tend to be lower temperature and have lower power density while Rift-based systems tend to be high-temperature and have high power densities. Arc volcano hosted systems are strongly bi-modal with one arm having high temperature and high-power density while the other arm has very-high temperature but power density is not correlated with temperature. The main difference between the two arms seems to be that fields in the upper arm have complicated structural settings despite the broadly compressive tectonic regime, while fields in the lower arm seem to be located in more purely compressional settings. Area is very important to consider when estimating power capacity in exploration-stage fields. Areas should be chosen based on appropriate conceptual models with reference to analog fields and to the distribution of areas in operating fields.

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