Power Density in Geothermal Fields

Maxwell Wilmarth[1] and James Stimac[2]

[1]Mighty River Power, 283 Vaughan Rd, PO Box 245, Rotorua 3040, New Zealand

maxwell.wilmarth@mightyriver.co.nz

[2]Stimac Geothermal Consulting, 4210 Chaparral Rd, Santa Rosa, USA 95409

Keywords: Power density, capacity estimate, MW/km^2, resource assessment

ABSTRACT

We estimated the power densities of 66 geothermal fields above 10 MW_{net} with more than 5 years of production history. Power density follows a log-normal probability distribution. The mean power density of the population is 15.4 MW/km^2, the median is 12.0 MW/km^2 and the standard deviation is 9.5 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.

1. INTRODUCTION

Resource Capacity Estimates

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 may not be available. Inevitably, geothermal professionals invoke power density for first-order estimates of resource capacity, 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.

While many geothermal professionals make resource capacity estimates using power density, there are 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/km^2 was a suitable range in early exploration and observed that "…power density for most fields ranges from 8 MW/km^2 at 230°C to up to 30 MW/km^2 at 300°C" (**Figure 1**). Grant and Bixley (2011) suggested that typical power density estimates used during exploration are 10-15 MW/km^2. 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.

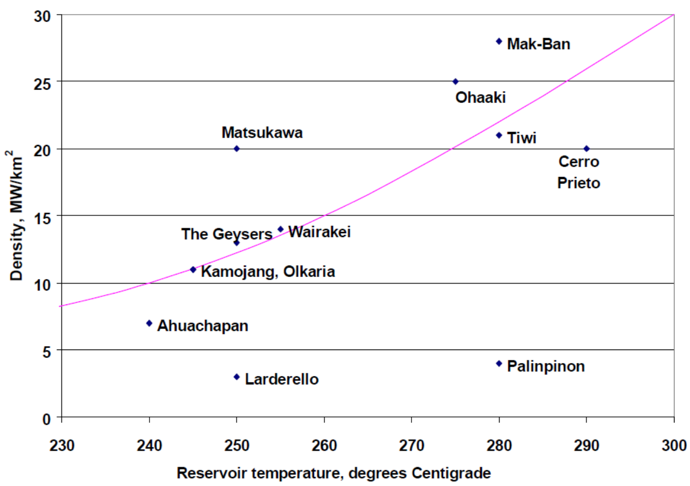

Figure 1: Power Density vs Reservoir Temperature (after Grant, 2000).

An earlier version of this paper (Wilmarth and Stimac, 2014) surveyed power density of 53 high-temperature (>200°C) geothermal fields around the world with more than 15 MW_{net} output and at least 10 years of production history and concluded that power density increases with average reservoir temperature in a manner similar to that proposed by Grant (2000), but that tectonic setting also plays an important role, especially in the power densities of very high-temperature volcanic arc systems (>270°C), which are anti-correlated with increasing temperature. This paper expands the study to lower temperature systems (>130°C), to smaller fields with more than 10 MW_{net} output, and to newer fields with at least 5 years of production history. Additionally, the present paper updates estimates for many fields based on recent declines and expansions (e.g. Olkaria), includes 13 additional fields (e.g. Mutnovsky), and corrects errors (e.g. Puna).

2. METHODOLOGY OF THIS STUDY

This study of power density examined the published literature of 66 operating geothermal fields with more than 10 MW_{net} output and 5 years of production history, 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.

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.

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). 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.

2.2 Area Estimate

Production area was estimated as a merged 500 m buffer around all current production well tracks (**Figure 2**). While this method has potential pitfalls, it provides a common basis for comparison and could 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 is defined. 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. Some fields may have deviated wells but only published locations of wellheads. In some cases production well locations were ascertained by analysis of publically available air photos (e.g. Google Earth).

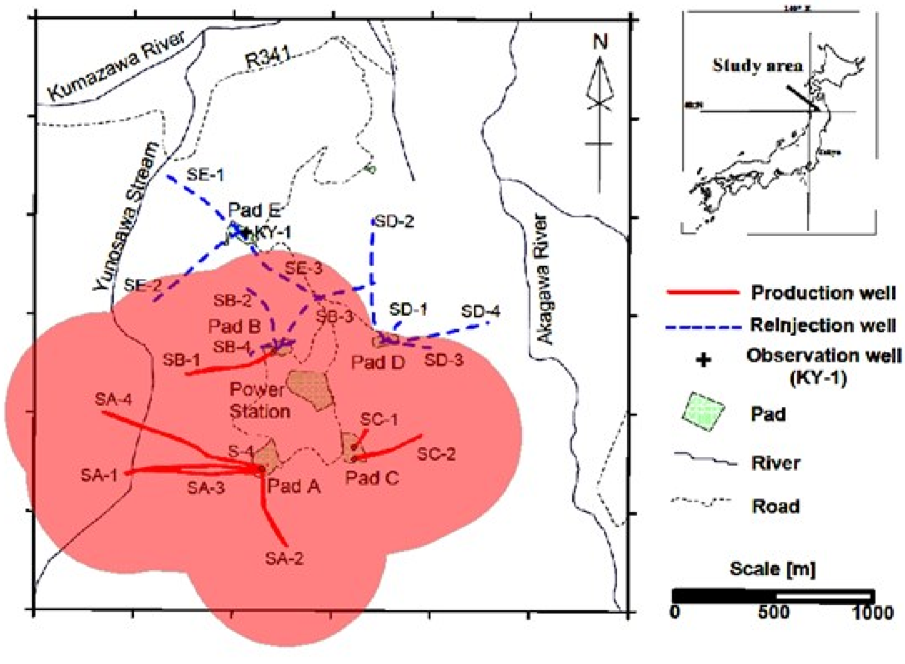

Figure 2: Sumikawa geothermal field with merged 500 m buffer around active production wells (after Nakao et al,, 2005).

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. 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 producing for more than 5 years but have only recently expanded may have an unsustainable power output. Some fields could expand their production area by moving injection from zones of possible production (e.g. Salak), or through stepout 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 66 power densities is log-normal (**Figure 3**) with a range from 2.8 (East Mesa) to 43.8 MW/km^2 (Hatchobaru). The mean value of the population is 15.4 MW/km^2, the median is 12.0 MW/km^2, and the standard deviation is 9.5 MW/km^2. Compare this to the distribution calculated by Bertani (2005) which is also log-normal (**Figure 4**).

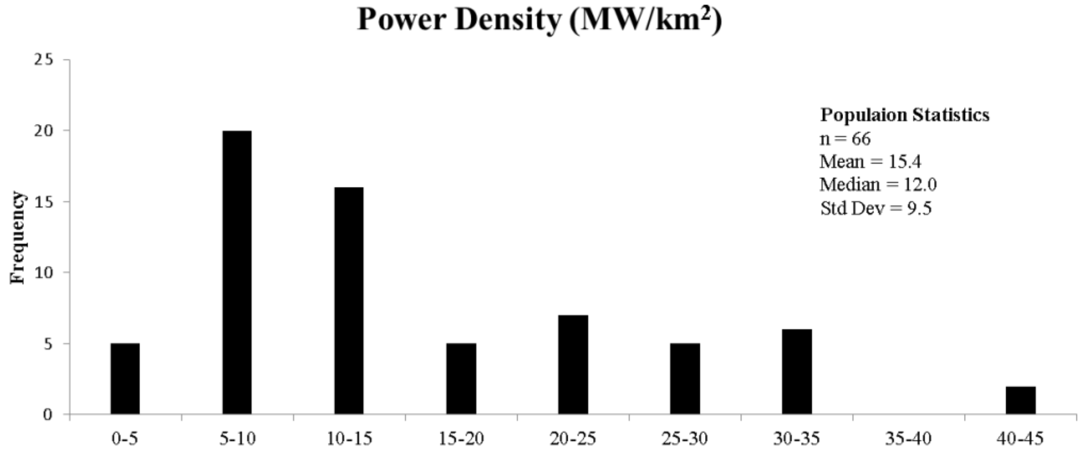

Figure 3: Histogram of power density for 66 geothermal fields. The distribution is log-normal.

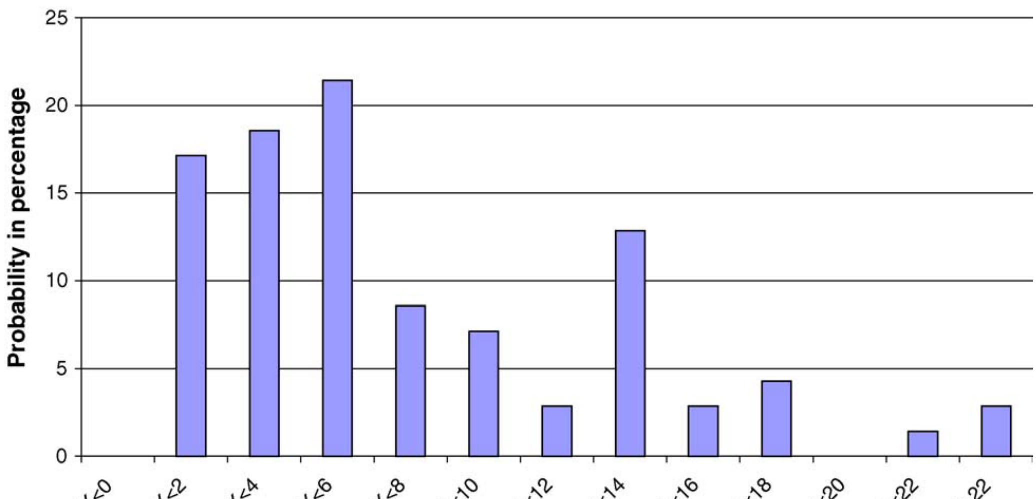

Figure 4: Power density distribution of developed geothermal fields (after Bertani, 2005).

3.1 Relationship to Temperature

Hot water and rock has greater enthalpy than cold water and rock, so it is reasonable to assume that higher temperature geothermal fields will have higher power densities. Indeed, plotting power density versus average reservoir temperature yields a scatter of data with a weak positive correlation (**Figure 5**), similar to that presented by Grant (2000). Most fields plot in the lower-left and upper-right quadrants as expected, and there are very few fields which plot in the top-left quadrant, also as expected. However, there are many fields which plot in the bottom-right quadrant, suggesting surprisingly an anti-correlation between temperature and power density for these fields.

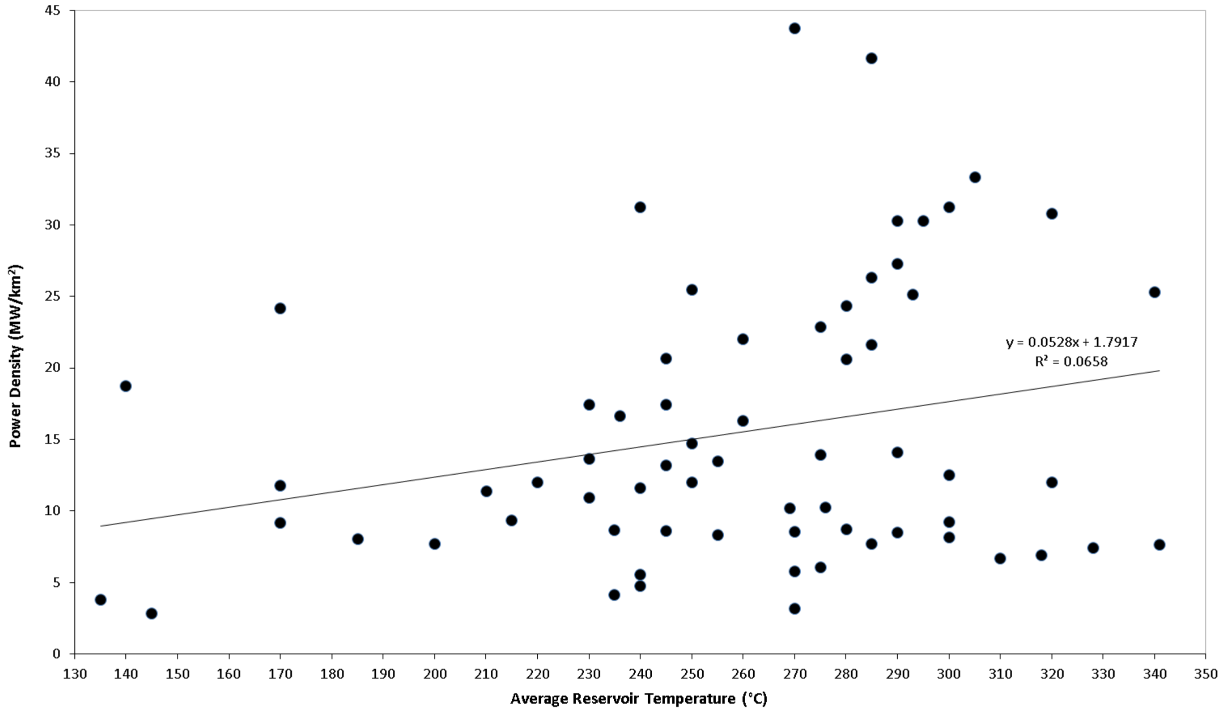

Figure 5: Power Density vs. Temperature for 66 geothermal fields.

4. INTERPRETED RELATIONSHIPS

Useful patterns emerge when the plot in **Figure 5** is interpreted in terms of tectonic setting and production history (**Figure 6**). Approximately half of the fields lie in a relatively narrow band that increases with temperature in a vaguely exponential manner ("the Main Sequence", grey band in figure). These fields are found in a variety of tectonic settings, but there is a clear sequence of overlapping tectonic affiliations from the bottom-left to upper-right quadrants. The first group are dominantly fault-based systems at moderate temperatures of 130-200°C with power densities below 10 MW/km^2. From 200-280°C and 10-25 MW/km^2 the fields are mostly associated with volcanic arcs in broadly compressional settings. Above 280°C and 25 MW/km^2 the fields are mostly associated with rifts and extensional rift-like provinces such as the Taupo Volcanic Zone. Another possible natural grouping is "Mature Fields". These are fields that have been under production for many decades, have average reservoir temperature near the maximum enthalpy of steam (~240°C) and have power densities below 5 MW/km^2. Additionally, fields tend to get bigger as one moves higher on the Main Sequence.

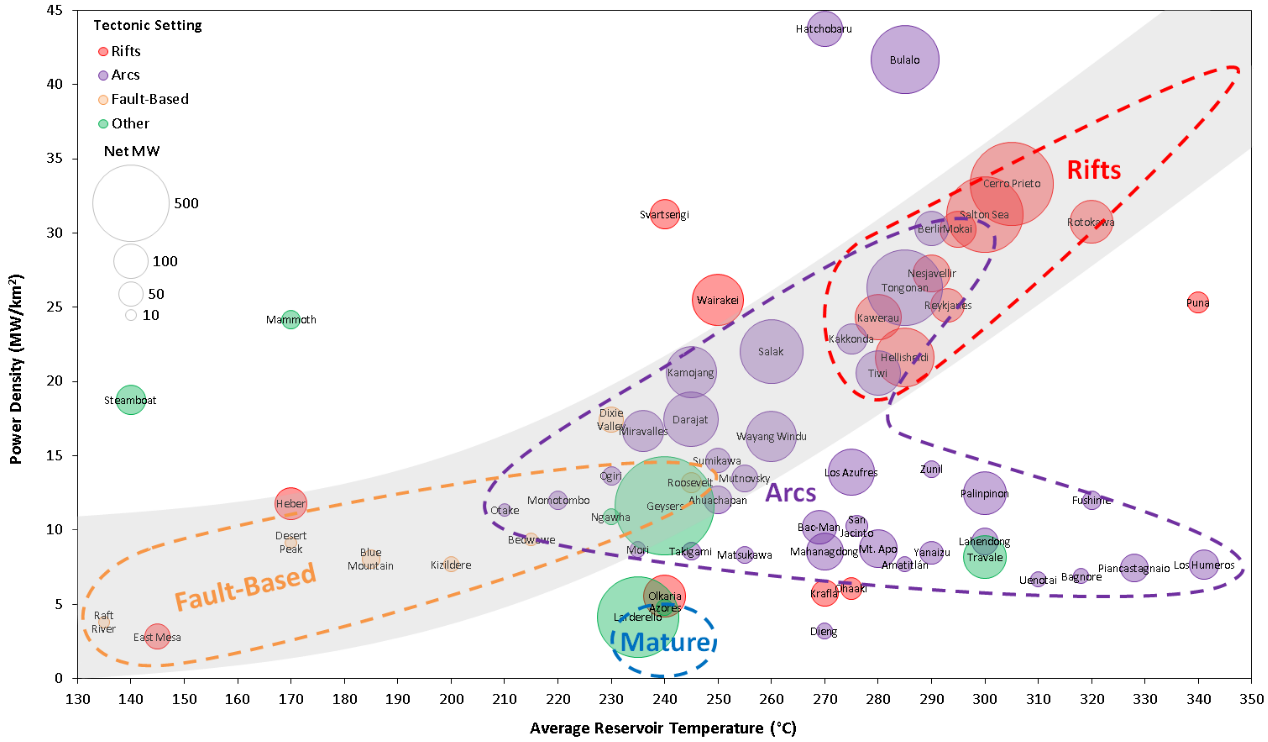

Figure 6: Power Density vs. Temperature for 66 geothermal fields with interpreted affiliations.

4.1 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. All these Main Sequence fields lie within a band of about ±5 MW/km^2.

4.2 Fault-Based

By fault-based systems, we refer to geothermal systems that are largely restricted to one or more major structures, with little distributed fracture permeability away from faults. 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). The median power output of the Fault-Based group is 20 MW.

4.4 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 15 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. Dieng has high non-condensable gas and major silica scaling problems (Tokyo Electric Power Corp., 2006).

A plot of net output vs average reservoir temperature (**Figure 7**) also indicates that increasing temperature does not result in larger fields above ~280°C. Although these fields have lower power density than might be expected from their temperatures, they are not necessarily small fields. Six of the fields have power outputs above 100 MW and three are above 150 MW. The median power output of the Arc Volcanoes group is 68 MW.

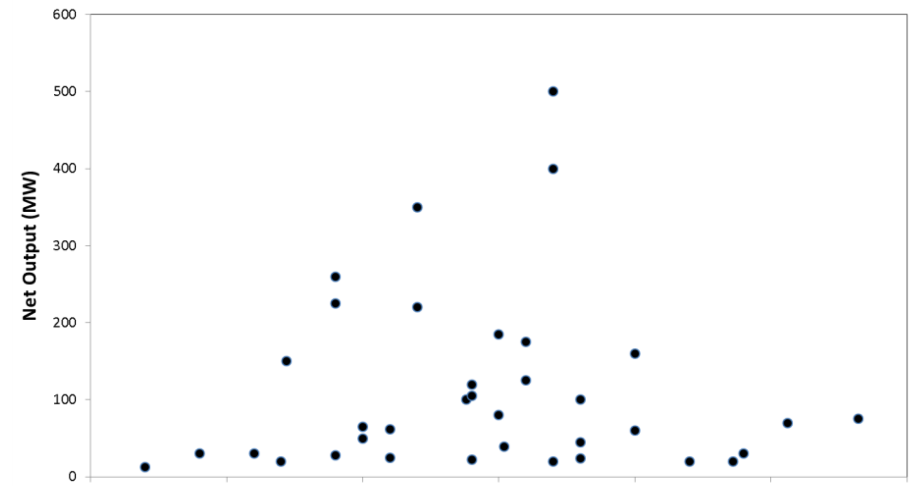

Figure 7: Net output vs average reservoir temperature for the 36 geothermal systems associated with arc volcanoes.

4.3 Rifts

The Rifts group contains generally 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). This group lies within the Main Sequence and contains half of the rift-based fields included in the study (8 of 16). Some of the other rift-based fields have specific reasons limiting their exploitation: Olkaria has long been underdeveloped and is in the process of expanding from 150 to 430 MW (Axelsson et al, 2013). Ohaaki suffers from calcite formation scaling. Puna has regulatory restrictions limiting utilization of reserves within the current wellfield. The median power output of the Rifts group is 116 MW.

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.

4.5 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.

5. 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.

5.1 Test of Methodology

The present study makes use a large number of assumptions. An excellent comprehensive data set of geothermal field statistics including Drilled Area, Reservoir Temperature, and Running Capacity (MW$_e$) is presented in Bertani (2005). As a "reality check", we subjected this independently prepared data set to the same analysis and compared it to ours. Ranges of Drilled Area and Reservoir Temperature are given for some fields in Bertani (2005). A simple average was computed for these values and the data was plotted (**Figure 8**). The resulting plot is similar to **Figure 5**, although the power densities are lower overall and the Rifts group is less coherent in this plot, which is partially due to major expansions of Iceland and New Zealand fields since 2005.

It was not explained how Drilling Area was calculated, but if this parameter includes injection areas, it would be a significant difference from the methodology used in this paper and provide an explanation for the lower average power density calculated from the Bertani (2005) data. Our methodology pairs a net power output directly with the wells that are producing that output. Injection areas can both help (e.g. pressure support) and hurt (e.g. thermal breakthrough) production, and sometimes have no effect (e.g. not connected to main reservoir). We feel that it is more straight-forward to use only the production area for the purpose of calculating power density.

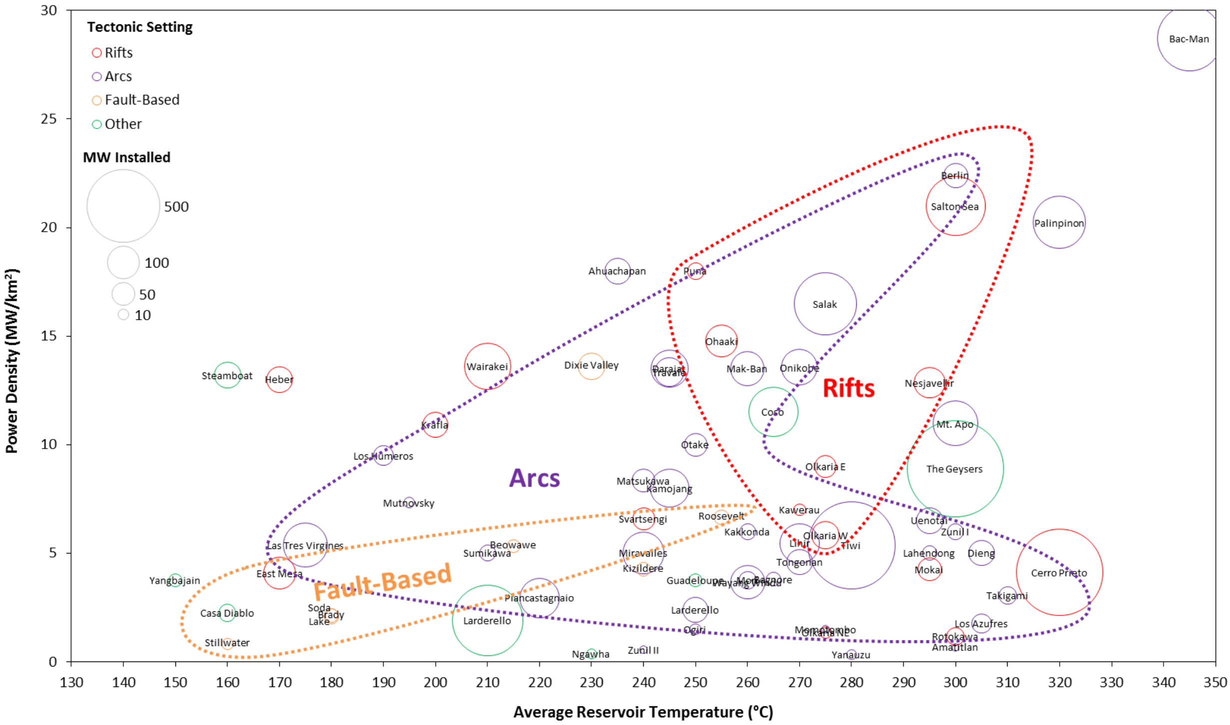

Figure 8: Power Density vs. Temperature for 69 geothermal fields with interpreted affiliations (data from Bertani, 2005).

5.2 Applying power density to undrilled prospects

Applying power density to undrilled prospects should be done with caution. Power output estimates critically depend on the area the power density estimate is applied to. Reservoir areas estimated at the exploration stage typically rely on the locations of low resistivity anomalies (e.g. areas with <10 ohm-m resistivity in the upper 500 to 1000 m), and boiling thermal features. Since most geothermal systems are the products of multiple episodes of hydrothermal convection over a period of roughly 50 to 500 ka, the area including the entire region of low resistivity and all boiling thermal features is likely to be significantly larger than the current productive reservoir. Estimates based primarily on thermal areas of unknown affinity scattered over the areas of young calderas or stratocones are even more suspect.

Specifically, the areas used in this study (500 m merged buffer around production wells) cannot reasonably be expected to apply to the entire area of a geothermal anomaly identified during exploration. The fraction of the geothermal anomaly determined from low resistivity and thermal area that may eventually be developed is typically on the order of 0.5, but may range from 0 to more than 1 (W. Cumming pers. comm., 2014). We advocate that a wide variety of geoscience data be integrated into one or more conceptual models, and a range of possible reservoir sizes be estimated that are consistent with the available data and models. The most likely area of the system will fall somewhere toward the middle of this range.

6. CONCLUSIONS

In general, power density increases with average reservoir temperature. However, tectonic setting and field history are important factors as well. 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 anti-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.

ACKNOWLEDGEMENTS

The authors wish to thank Mighty River Power for supporting this work. The authors benefitted from thoughtful discussion with Rich Gunderson, Tom Powell, Glenn Melosh, Bill Cumming, Dick Benoit, Novi Ganefianto and Mike Barnes, among others.

REFERENCES

Axelsson, G.; Arnaldsson, A.; Armannsson, H.; Arnason, K.; Einarsson, G.; Franzson, H.; Fridriksson, T.; Gudmundsson, G.; Gylfadottir, S.; Halldorsdottir, S.; Hersir, G.; Mortensen, A.; Thordarson, S.; Johannesson, S.; Bore, C.; Karingithi, C.; et al.: Updated Conceptual Model and Capacity Estimates for the Greater Olkaria Geothermal System, Kenya, *Proceedings*, Stanford Geothermal Workshop (2013).

Atkinson, P.: Proved Geothermal Reserves - Framework and Methodology, New Zealand Geothermal Workshop 2012 Proceedings, Auckland, New Zealand, **34**, (2012).

Bertani, R.: World geothermal power generation in the period 2001–2005, Geothermics **34** (2005), 651–690.

Benoit, D.: An Empirical Injection Limitation in Fault-Hosted Basin and Range Geothermal Systems, Geothermal Resource Council *Transactions*, **37**, (2013), 887-894.

Grant, M. A.: Geothermal Resource Management, *Proceedings*, World Geothermal Congress 2000, Kyushu-Tohoku, Japan (2000).

Grant, M. A., and Bixley, P.F.: Geothermal Reservoir Engineering 2nd Edition, Elsevier, Amsterdam, (2011), 359.

Nakao, S., Ishido, T., Hatakeyama, K. and Ariki, K.: Analysis of Pulse Tests in a Fractured Geothermal Reservoir - A Case Study at the Sumikawa Field in Japan, *Proceedings,* World Geothermal Congress 2005, Antalya, Turkey (2005).

Sarmiento, Z.F., and Björnsson, G.: Reliability of early modeling studies for high-temperature reservoirs in Iceland and the Philippines. *Proceedings*, Thirty-Second Workshop on Geothermal Reservoir Engineering, (2007), 221-232.

Wilmarth, M. and Stimac, J.: Worldwide Power Density Review, *Proceedings*, Stanford Geothermal Workshop (2014).

Tohoku Electric Power Co.: Preventions and Solutions for the Scale Problem at the Geothermal Power Plant and CDM Study in Indonesia (2006).