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Worldwide Power Density Review

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ABSTRACT

We estimated the power densities of 53 high-temperature (>200°C) geothermal fields above 15 MW_{net} with more than 10 years of production history. The mean power density of the population is 16.2 MW/km^2, the median is 12.0 MW/km^2 and the standard deviation is 9.9 MW/km^2. Additionally, power density was plotted vs. average reservoir temperature and several trends were identified. Most of the fields fall on a line with a slope of ~2 MW/km^2 per 10°C. Fields not on this trend are generally very high-temperature fields (>270°C) that form two very different groups. The first group are typically fields in extensional environments and have high power densities (>20 MW/km^2). The second group are typically fields in compressional environments and have lower power densities (<15 MW/km^2).

1. INTRODUCTION

Estimations of resource capacity in geothermal fields are best 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.

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". 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. 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.

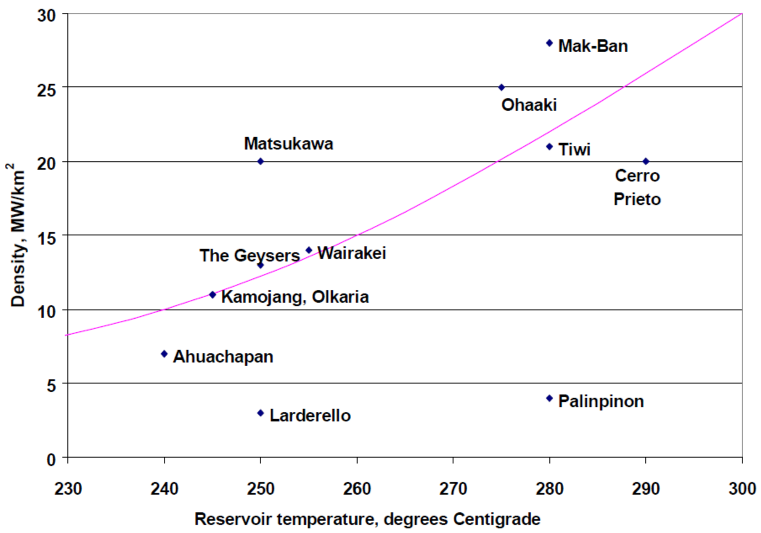

Figure 1: Power Density vs Reservoir Temperature after Grant (2000).

2. METHODOLOGY OF THIS REVIEW

This review of power density examined the published literature of 53 high-temperature (>200°C) operating geothermal fields, representing the majority of such fields worldwide. Fields were required to have a minimum of 10 years of production history and a minimum net power output of 15 MW_e.

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. In some cases a substantial amount of production is devoted to direct use rather than electrical generation, *e.g.* Svartsengi, which may reduce the power estimate.

2.2 Area Estimate

Production area was estimated as a merged 500 m buffer around all current production well tracks. While this method has potential pitfalls, it provides a common basis for comparison and could be easily 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. However this methodology matches the current production area to the current power output (*e.g.* West Tiwi) and is considered an objective and practical way of calculating area in the absence of detailed knowledge of each field.

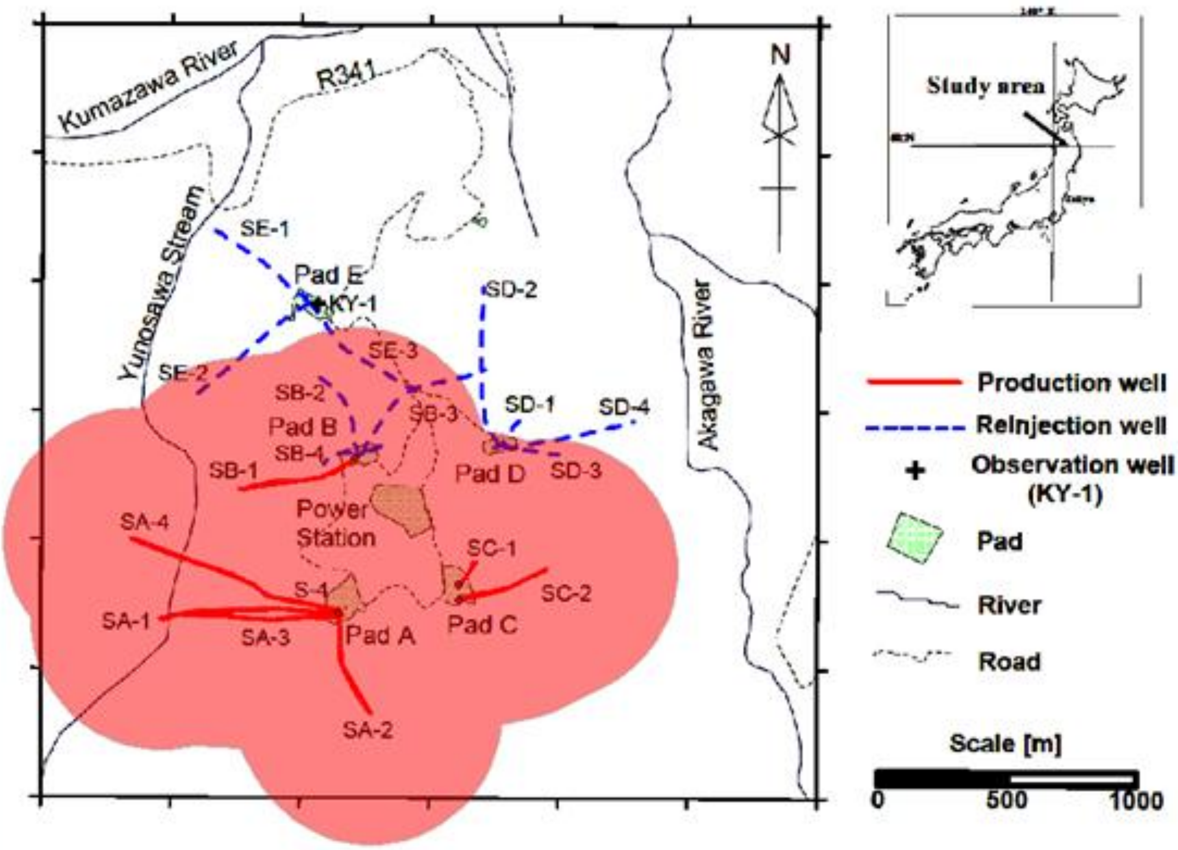

Figure 2: Sumikawa geothermal field with merged 500 m buffer around production wells after Nakao *et al* (2005).

2.3 Temperature Estimate

Average reservoir temperature was the most difficult parameter to estimate. Many fields have consistent, authoritative published values for average reservoir temperature. However many other fields have a relatively wide range of temperatures from productive well entries corresponding to reservoir compartmentalization or the existence of multiple vertically separated reservoirs possibly with different phase conditions and well enthalpies. The best estimates were made based on the available published data, but an average error of ±10°C could be assumed for each field.

2.4 Other Sources of Error

There are many other possible sources of error in this methodology. Power plant efficiencies are not considered. Wells that are labeled as producers 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 10 years but have been 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 high-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 may reduce power output.

3. RESULTS

The distribution of the 53 power densities is log-normal with a range of 4.1 to 48.3 MW/km^2. The mean value of the population is 16.2 MW/km^2, the median is 12.0 MW/km^2, and the standard deviation is 9.9 MW/km^2.

A log-normal model of the distribution has a most likely value of 8.3 MW/km^2, a mean value of 16.5 MW/km^2, and P10-P50-P90 values of 3.9, 13.0 and 27.8 MW/km^2.

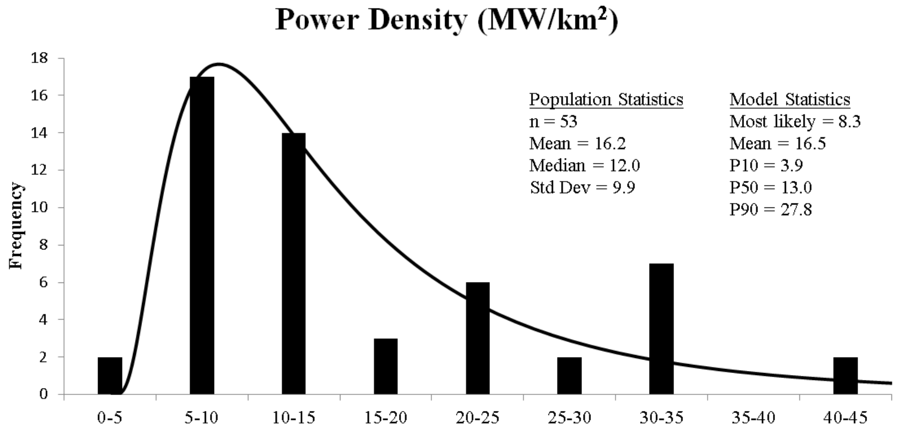

Figure 3: Histogram and modeled log-normal distribution of power density for 53 high-temperature fields.

3.1 Relationship to Temperature

Plotting power density versus average reservoir temperature yields a scatter of data with a weak positive correlation, similar to that presented by Grant (2000).

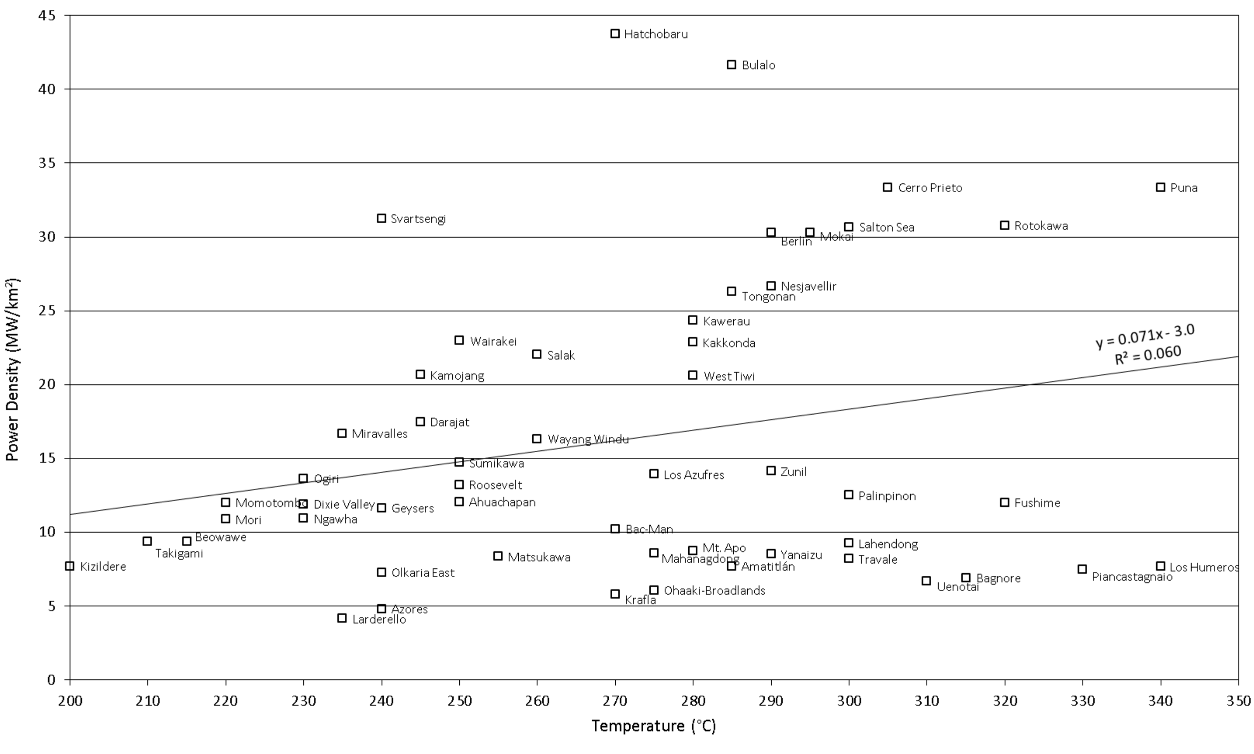

Figure 4: Power Density vs. Temperature for 53 high-temperature geothermal fields.

4. INTERPRETED RELATIONSHIPS

Useful patterns emerge when the plot above is interpreted in terms of tectonic setting and production history. By analogy to the Hertzsprung-Russell diagram which plots stars' luminosities against their effective temperatures, a "Main Sequence" may be identified which includes 31 of the 53 fields located in a band running from Kizildere at 200°C and 7.7 MW/km^2 to Puna at 340°C and 33.3 MW/km^2.

Above ~270°C the population forms two broad groups. The first group consists mostly of fields in extensional settings such as rifts, transtensional basins or broad rift-like features such as the Taupo Volcanic Zone and has power densities above 20 MW/km^2. Eleven of the 29 fields above 270°C fall into this group. The second group of fields is mostly associated with arc volcanoes in broadly compressional settings and has power densities below 15 MW/km^2. Fifteen of the 29 fields above 270°C fall into this group.

Another possible 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 under 5 MW/km^2.

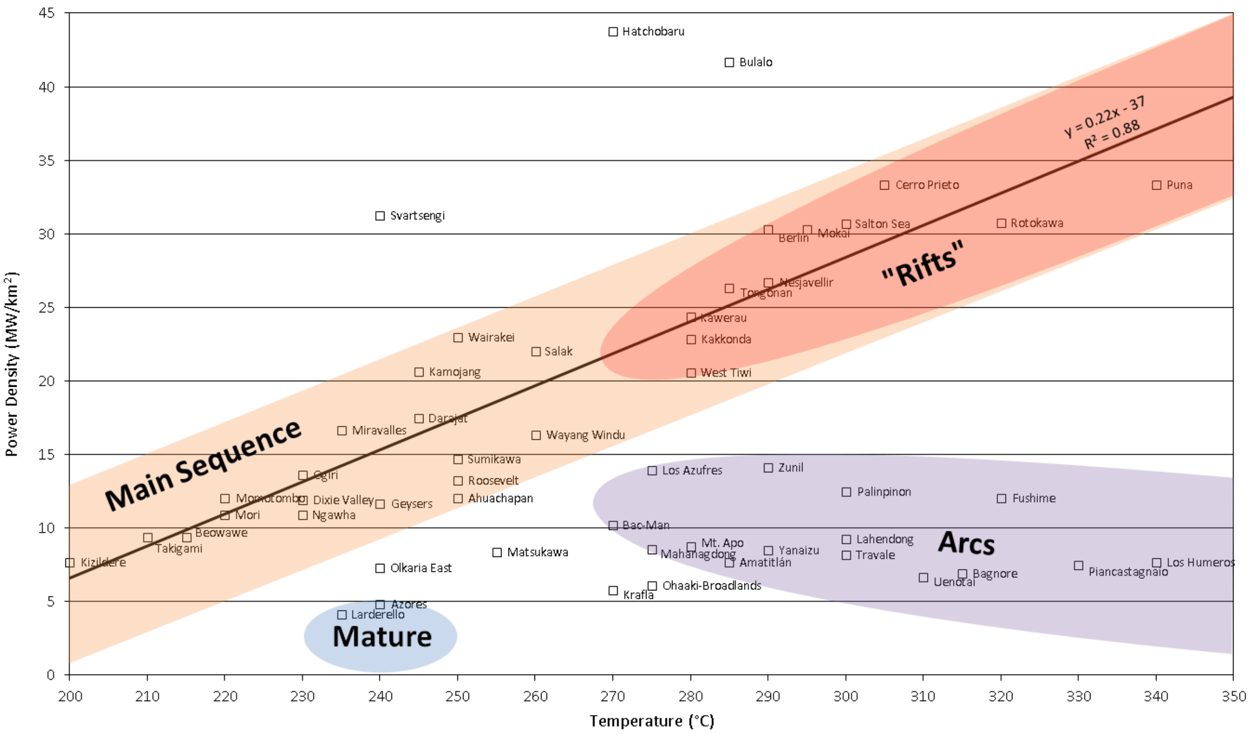

Figure 5: Power Density vs. Temperature for 53 high-temperature geothermal field with interpreted affiliations.

4.1 The Main Sequence

Fields on the Main Sequence are located in a variety of different tectonic and structural settings, including fault-based, extensional 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. What these fields all seem to have in common is an extensional structural setting, either regional like a rift or local like a releasing bend in a strike-slip fault. The trendline for the Main Sequence has a slope of ~2 MW/km^2 per 10°C of reservoir temperature and all the fields lie within a band of about ±5 MW/km^2 width.

The median power output of fields on the Main Sequence is 112 MW, but only 70 MW for those fields not in the Rifts subset.

4.2 Rifts

The Rifts group are generally very high-temperature (>270°C) and located in extensional tectonic environments like the East Kilauea Rift Zone (Puna), The Reykjanes Ridge (Nesjavellir), the Salton Trough (Cerro Prieto and Salton Sea), and the Taupo Volcanic Zone (Rotokawa, Mokai and Kawerau). This group continues the trend of the Main Sequence to higher temperatures with power densities above 20 MW/km^2. Berlin, Kakkonda, Tiwi and Tongonan do not fit this profile, but are located in structural environments which allow for local extension, such as the complicated Philippine Fault System.

The median power output of the Rifts group is 160 MW.

4.3 Arc Volcanoes

The Arc Volcanoes group are generally very high-temperature (>270°C) and located in compressive tectonic environments like volcanic arcs along subduction zones. This group does not have a positive correlation between power density and temperature and may in fact have a weak negative correlation. All the fields have power densities less than 15 MW/km^2. 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 70 MW, identical to those Main Sequence fields not located in the Rifts subset.

4.4 Mature Fields

One might expect that fields operated for many decades would tend toward vapor-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, inhabits this area of the plot between 230-250°C and below 5 MW/km^2. The Geysers would also plot in this area if not for two municipal wastewater injection systems that were built in the early 1990s which succeeded in mitigating the reservoir pressure decline and stabilizing output at ~850 MW. The Azores does not fit this profile, but consists of two underdeveloped well fields in the same reservoir. If this field were fully developed it may have a significantly higher power density.

4.5 The Exception that Proves the Rule

Other than the Azores, seven other fields do not fit nicely into the above groups. Some of these are underdeveloped for idiosyncratic economic or regulatory reasons, *e.g.* Hatchobaru is constrained by a national park and the production area is limited to the best part of the reservoir, which may artificially enhance the power density estimate. Olkaria East has been underdeveloped until very recently when the installed capacity was greatly expanded, which may raise the power density significantly. Of course, natural variability in geothermal reservoirs is high and these fields may simply have disparate physical reasons for why they diverge from the identified trends.

5. DISCUSSION

The groups of fields identified above suggest that tectonic environment and field production history have 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 due to unusual economic or regulatory constraints may have unusually high or low power densities.

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. Exploration resource area estimates typically rely on the locations of resistivity anomalies and thermal features and can vary widely from the ultimate drilled production areas of operating fields.

6. CONCLUSIONS

In general, power density increases linearly with average reservoir temperature at a rate of ~2 MW/km^2 per 10°C. However, above ~270°C fields either continue this trend to ever higher power densities or plateau and do not yield greater power densities. The first group is generally comprised of fields in extensional environments whereas the second group of fields is generally in more compressional environments.

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