Global-Scale Performance of Geothermal Fields using Power Density and Volumetric Stored Heat Methods

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Abstract – *The capacity of a geothermal power plant is generally based on the available geothermal resource. In this study, worldwide geothermal power production is examined in terms of installed capacity and total energy produced. Historical energy production data was used to assess the power density method and the stored heat method for resource estimation. The power density method was tested on 40 geothermal fields while for the stored heat method 14 geothermal power plants were considered to determine the 'actual' recovered energy that has been converted into useable electricity. All information used in this work used publically available data.*

It was found that most geothermal fields have a power density of less than 10 MW/km^2. It was observed a recovery factor of at least 11% was applicable in most fields with an average power output of at least 90 MW.

Keywords—geothermal fields, geothermal power plants, resource assessment, power density method, volumetric stored heat calculation, recovery factor, power output, installed MW capacity

I. INTRODUCTION

The design electrical power output of a geothermal power plant for electricity generation depends on the available geothermal resource. Typically, this is based on some standard values and assumptions about the characteristics of the geothermal resource [1]. For early estimates of power plant potential the nature of the geothermal systems might not be accounted for in the process or the size of the inferred productive region might have been overestimated [2]. Such uncertainties that leads to inaccurate estimates of power potential create various problems [3] and accurate assessment of the capacity of a geothermal field for long term energy production is very important. Two commonly used methods for geothermal resource assessment are the power density method ([4]–[6]) and volumetric stored heat calculation ([4], [5], [7]). Power density, or aerial method calculates the ratio of electrical output to the area of the productive region of the geothermal reservoir. This value is affected by average reservoir temperature, tectonic environment and production history of the geothermal fields ([4], [6]). Several works ([4]–[6], [8]) have studied important trends using this method in a number of geothermal fields worldwide and an appropriate level of power density has been suggested ([4], [9]). Table I-1 presents a review of power density levels from different sources [9].

Table I-1 Appropriate level of power density from various authors, after [9].

Power density (MW/km^2)	Comment	Reference
10 to 11	Wairakei, based on total field area	[10], [11]
60	Water-dominated fields, based on borefield area	[12]
10	Flash steam plants	[13]
8 to 30	Flash steam plants, with varieties of technology used	[4]
10 to 20	Early stage of exploration for field capacity estimates	
20	Liquid-dominated systems	[9]
25	High-enthalpy two-phase or steam dominated fields with good permeability	[9]

For volumetric stored heat method, some works ([5], [7]) have noted that although the method is not as accurate as numerical modelling, it provides the most practical way of estimating the size of the geothermal resource and is best suited to green fields assessment [14]. In many cases, however, the results of the stored heat calculation can often lead to overestimates of the geothermal resource due to arbitrary assumptions about various parameters ([4], [11], [14]–[16]). Among these parameters, the recovery factor, which is the amount of stored heat energy that can be recovered from the geothermal resource over the economic life time of a power plant, has the greatest influence on the design MW capacity for any type of geothermal resource ([15], [16]). Williams [17] mentioned that new adjustments are being suggested for recovery factors for geothermal fields with "heterogeneous characteristics" and for untapped reservoirs.

In general, early geothermal resource assessments do not account for the actual field performance [5]. While the result of the initial power potential estimates provides reasonable guide to what can be expected from the inferred geothermal resource from geothermal field survey explorations, it is also necessary to incorporate the actual power plant operation and energy generation history to assess the status of the geothermal field [4]. Because geothermal resources vary with respect to time, economics and technological advancement, Muffler [18] and Grant [4] suggested that a review of the current geothermal field performance should be made periodically, particularly those with an increasing level of energy utilization [18]. Some works ([2], [19], [20]) have reviewed the experience with geothermal field developments after several years of operation. However, Grant [4] remarked that there has been no resource assessment method that has been appropriately adjusted to account for actual field performances.

First, this study determines power density of 40 developed geothermal fields worldwide using the computed average long-term electrical power output from published available historical energy totals. The power density is classified in terms of the nature of the geothermal system and general permeability of the geothermal system. Secondly, a comparison between the design MW electrical capacity based on the volumetric stored heat method (using standard values for various parameters including recovery factor) and actual average long-term MW capacity of several geothermal fields is presented. Lastly, the 'actual' recovered heat-in-place that has been used for electricity production of some geothermal fields worldwide is determined in terms of actual field performance and is classified in terms of of the nature of the geothermal system and general permeability of the geothermal system.

II. WORLDWIDE GEOTHERMAL ENERGY FOR ELECTRIC POWER GENERATION

Previous works ([21], [22]) have looked at the worldwide geothermal development in terms of MW installed capacity. For the five-year term 2010-2015, a global increase of approximately 1,700 MW was observed. Moreover, linear trends of about 350 MW/year from 2010 to 2015 and 200 MW/year from 2005 to 2010 of installed capacity worldwide was noted [21]. For this present work, the information used for the installed net MW power output capacity and energy production was obtained from available published references including recent country updates from top producing countries ([23]–[30]). Only countries with at least 100 MW installed capacity were considered. Global, as well as per region average annual growth rates for both installed capacity and energy generated are determined over a 25-year period.

The average annual growth rate (AAGR) has been 3% for both worldwide total net MW installed geothermal capacity and total energy production for electricity generation since 1990. In addition, the average annual increment in MW power capacity, over 25 years, has been 231 MW/year. This corresponds to about a 15 percent rate of increase for the five-year period 2010 to 2015. In addition, an average annual rate of increase of 1,493 GWh/year has been observed in the worldwide total geothermal energy production since 1990. Figure II-1 shows the geothermal energy for electricity production share per continent in 2015 based on data from [31].

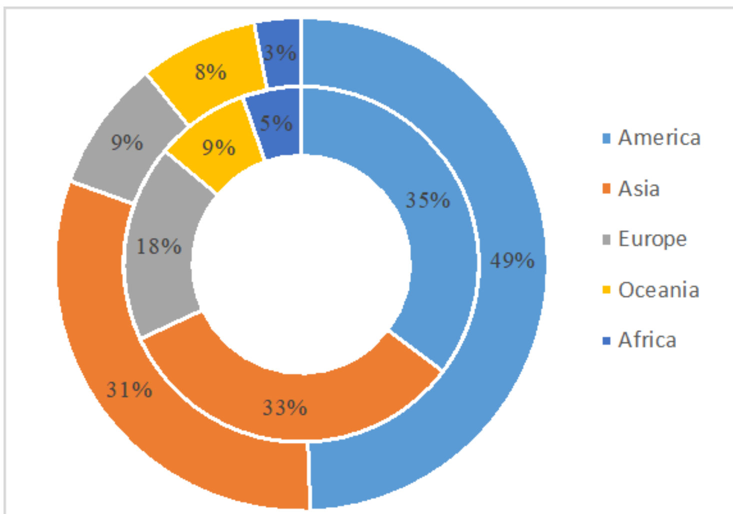


Figure II-1. Geothermal Energy GWh Production (outer) and Net MWe Installed Capacity (inner) to Worldwide Geothermal Total, 2015

America and Asia made the most significant contribution in terms of the geothermal energy generation at a global-scale in 2015. They comprised about 80% of the worldwide geothermal energy for electricity production, both in terms of installed MW capacity and energy generation. Africa, on the other hand, contributes to less than 5% of its electrical energy production from geothermal resources. Figure II-2 and Figure II-3 show the annual growth rate in terms of net MW installed capacity and total energy production since 1990 for each continent and producing regions worldwide, based on data from [31].

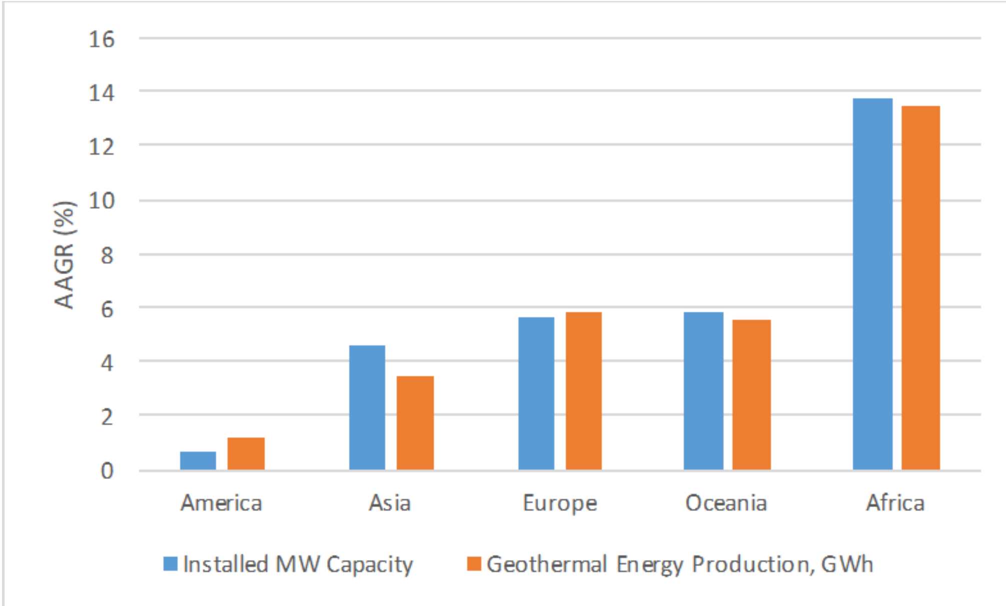


Figure II-2 Average Annual Growth Rate for each continent, 1990 to 2015

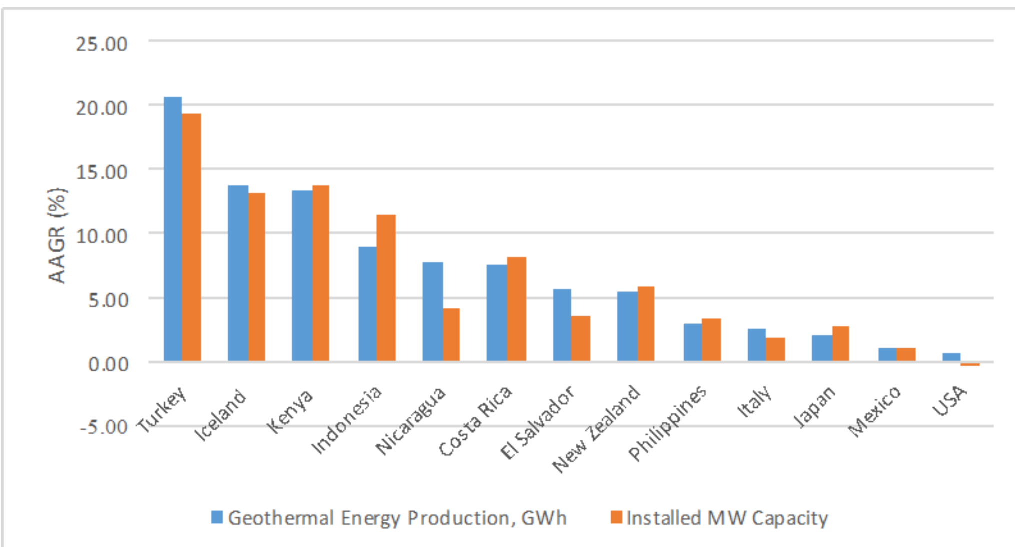


Figure II-3 Average Annual Growth of top producing countries, 1990 to 2015

Over the last 25 years, however, America and Asia have the smallest AAGR of less than 5%, both in terms of net MW installed capacity and GWh geothermal energy production. Africa, on the other hand, has the highest AAGR of about 14% both for the installed capacity and energy production.

It can also be observed that majority of the top geothermal energy producers have had no more than a 5% average annual growth rate, e.g., USA, Philippines, Mexico, Italy. On the other hand, some European countries, namely, Turkey and Iceland, have lead the rate of geothermal energy development, with at least a 13% average annual growth rate, followed by Kenya and Indonesia.

Figure II-4 and Figure II-5 presents the place of geothermal energy for electric power generation in the total energy mix for each continent and for top producing countries between 1990 to 2015 based on data from [31].

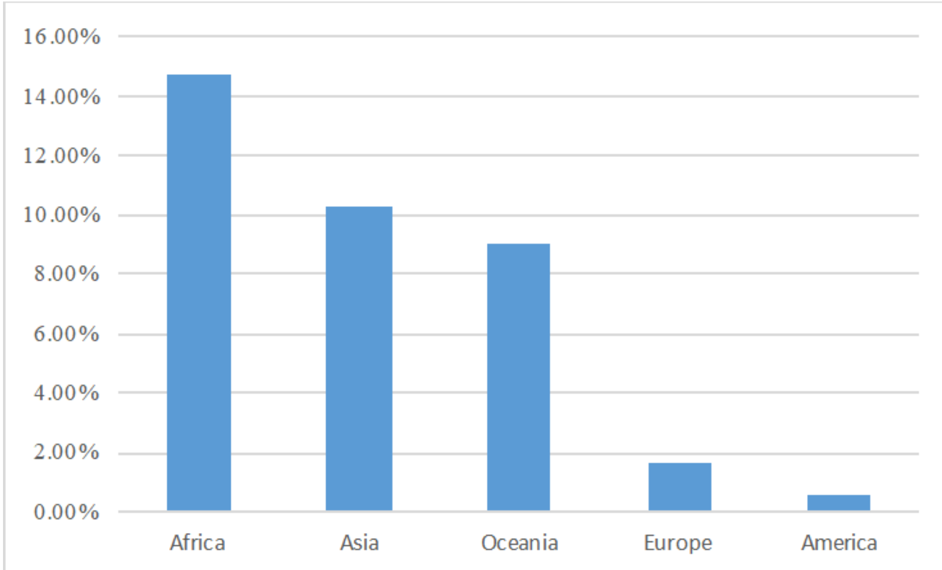


Figure II-4 Geothermal energy for electricity generation to total net energy production, per continent

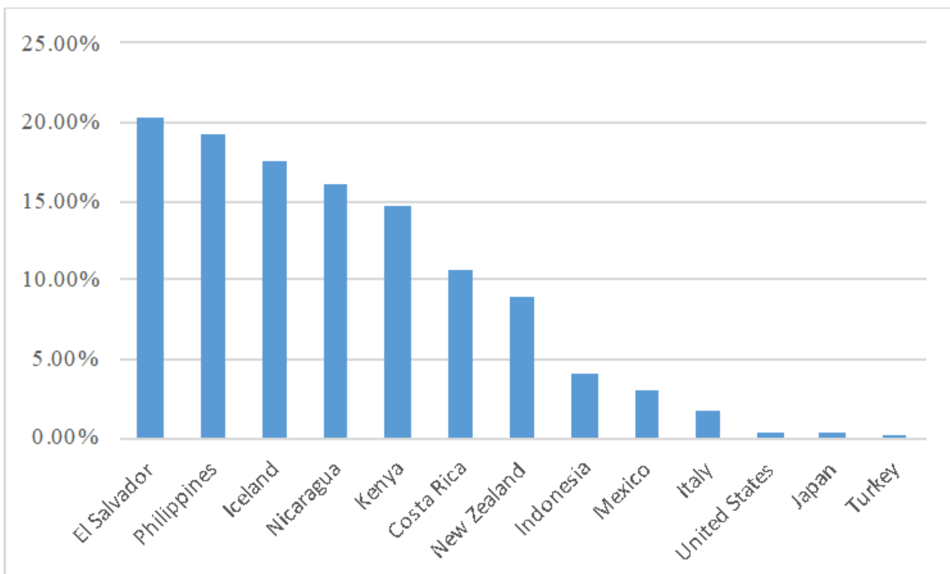


Figure II-5 Geothermal energy distribution to total energy production, per country

The high penetration since 1990 of geothermal energy for electricity generation into the mix of national electrical production is evident in Africa and Asia. America has the smallest contribution from geothermal energy to its total electricity production with less than 1%. In fact, most of the top producing countries have low geothermal energy contribution to total electricity production, i.e. less than 5%. USA, for example has less than a 0.5% geothermal energy contribution to its total electrical energy mix. On the other hand, Philippines has a 19% geothermal energy contribution to its total national electricity generation, similar to El Salvador with 20.33%.

III. CLASSIFICATION OF POWER DENSITY AMONG PRODUCING GEOTHERMAL FIELDS

There are 40 geothermal fields which were selected for assessment as part of this work. Information on average reservoir temperatures, average running operational electrical power capacity (MW), and production areas were all gathered from published sources. The producing area for each geothermal field is estimated from maps available in open-file references, i.e. with inferred resistivity boundary maps, resource maps with producing wells. On the other hand, information on the resource temperature for each geothermal field is based on temperature profiles or technical well data from available sources. The average long-term electrical power output is derived from historical annual energy production for each geothermal power plant from the time at which power plant started to generate steam for large-scale utilization to the most recent time at which data are available, except for The Geysers, for which the average operational capacity of the geothermal power plant is evaluated from 1990 to 2015. Also, the final year considered was not the same for all field, e.g., 2013 is used for the Philippines and Los Azufres, 2014 is used for New Zealand and Miravalles geothermal fields, and 2015 is used for Indonesia and The Geysers. This is due to the availability of most appropriate data. The plot of the power density against reservoir temperature for these fields is then compared with the other power density plots from [4], [5], [6]. The scatter plots of power density versus temperature form these different references were digitized to obtain the data for power density and reservoir temperature for some geothermal fields. Open-source, free software Webplotdigitizer Version 3.12 was used to obtain the data from the different plots. The results are analyzed according to the general characteristics of the system in terms of permeability and nature of the geothermal system from earlier studies ([32],[14]). Figure III-1 shows the comparison of power densities from the current and earlier works.

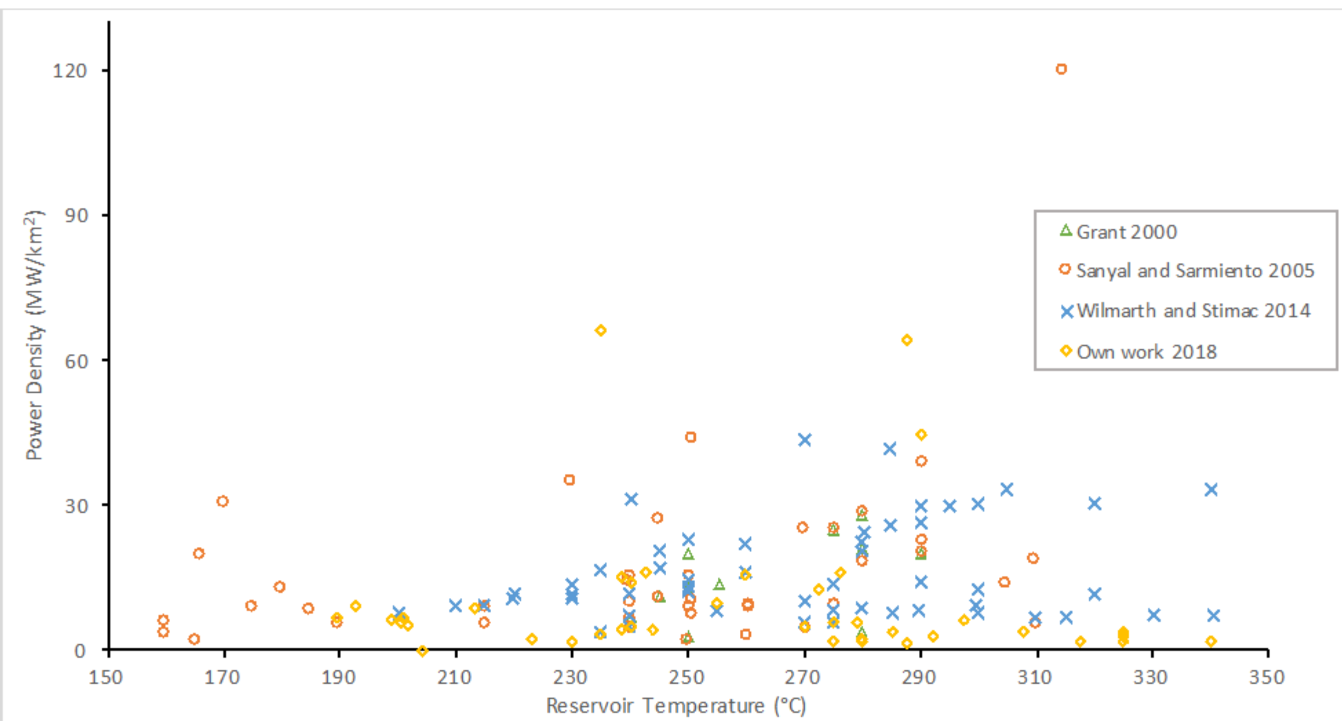


Figure III-1 Comparison of power densities from the present and previous studies ([4], [5], [6]) The power density plots from the different studies vary. While earlier studies ([4]–[6]) have used installed MW capacity in determining the power density of geothermal fields, this present study considered the historical annual energy generated to determine the average long-term MW capacity. This is to account the actual field performance of 40 geothermal fields worldwide from the time of its power plant operation for electricity production. It can be observed that power density values obtained from the present work are generally lower than those in the previous plots. This might be due to our use of the average running operational electrical power MW capacity from historical records which is usually less than the rated capacity of the geothermal power plant and designed MW capacity that is determined during earlier estimates. In addition, it may be observed that there is a weak correlation between the power density and the average reservoir temperature for all of the plots. Wilmarth and Stimac [6] had earlier made the same observation. Power density of more than 10 MW/km2 is observed at reservoir temperatures between 235 to 290°C. The power density of more than 75% of the selected geothermal fields worldwide is below 10 MW/km2.

The results of power density method to 40 geothermal fields are classified based on general permeability (Figure III-2) and the nature of geothermal systems (Figure III-3) from previous works ([32], [14]).

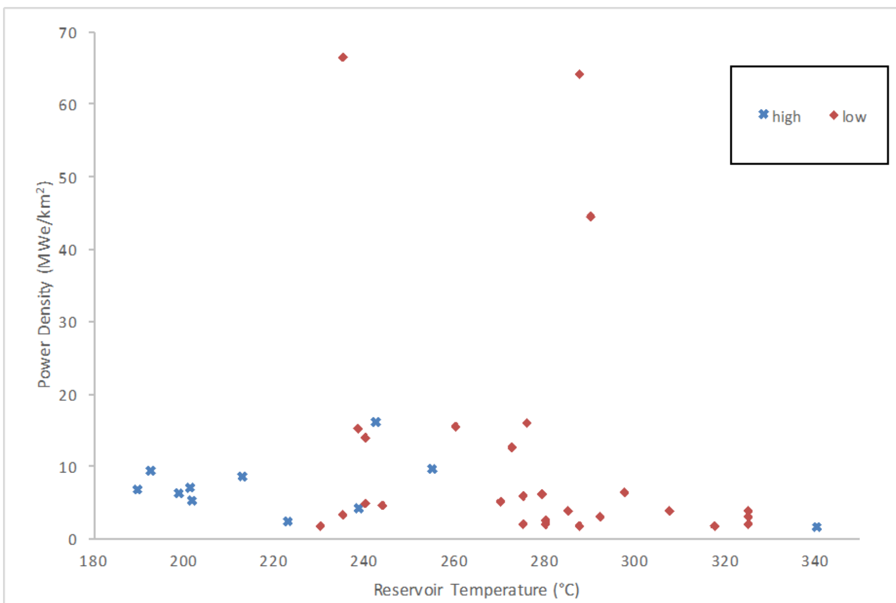


Figure III-2 Power density plot in terms of general permeability

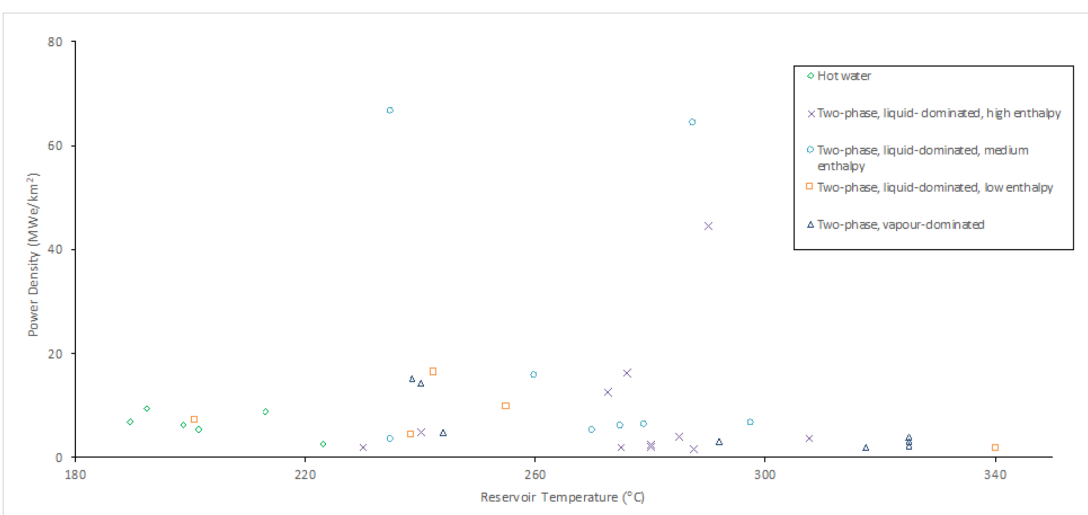


Figure III-3 Power density plot in terms of the nature of the geothermal system

It can be observed that about 70% of the geothermal fields have power densities greater than 10 MWe/km2 while 30% have less than 10 MWe/km2. Of this, about 68% of the selected geothermal fields have low permeability while 32% have high permeability, with an average reservoir temperature ranging from 230 to 325 °C. About 70% of the geothermal fields with low permeability have power density less than 10 MWe/km2 while 30% have power density more than 10 MWe/km2, e.g. Kamojang, Darajat, Gunung Salak, Reykjanes, Mahanagdong, Tiwi, Makban, Palinpinon. Moreover, Reykjanes and Mahanagdong geothermal fields, both identified to have low permeability, have the two highest power densities, both exceeding 60 MWe/km2. These geothermal fields have at least 85 MWe average running electrical power capacity for over a 20-year period, continuously operating for large-scale steam production from a production area of between 7 to 16 km2.

Moreover, there are more than 45% of the selected geothermal fields which fall in the two-phase, liquid-dominated, high- and medium enthalpy with generally low permeability while about 20% of low permeability are identified to be two-phase, vapor-dominated systems. The power densities for most fields for all of two-phase, liquid-dominated, high- and medium enthalpy and two-phase, vapor-dominated systems are less than 5 MW/km2, except for Makban, Reykjanes and Mahanagdong which have more than 40 MW/km2. These geothermal fields (Makban, Reykjanes and Mahanagdong) have been in operation for large-scale steam production of at least 20 years with an average running electrical power MW capacity of at least 85 MWe. Moreover, about 15% of the geothermal fields that have been identified as hot water systems are in USA, i.e., Beowawe Hot Spring, Brady Hot Spring, Steamboat Spring, Coso Hot Spring, Heber. These fields all have high permeability and power densities less than 10 MWe/km2. The average running electrical power MW capacity of 50% these fields is less than 60 MWe over a period of continuous steam production of 20 years.

Table III-1 presents the classification of geothermal fields in terms of the nature of the geothermal system and general permeability.

Table III-1 Classification of power density of 40 geothermal fields worldwide in terms of the nature of the geothermal system and general permeability

Nature of the Geothermal System		General Permeability	Power Density (MW/km^2)
Hot water		High	2 to 9.45
Two-phase, liquid-dominated	high- enthalpy	Low	1.71 to 16.15, except for Makban with 44.52
	medium- enthalpy	Low	3.38 to 15.57, except for Reykjanes and Mahanagdong with at least 60
	low-enthalpy	High	1.78 to 9.69, except for Miravalles with 16.28
Two-phase, vapor-dominated		Low	1.92 to 4.67, except for Kamojang and Darajat with at least 14

These results suggest that for hot water and two-phase, liquid-dominated, low-enthalpy geothermal systems, which are usually characterized as highly permeable, have power density in the range of 1.78 to 9.69 MW/km2, except for Miravalles with 16 MW/km2. Low permeable, two-phase, liquid-dominated, medium- and high-enthalpy have power densities in the range of 1.71 to 16.15 MW/km2, except for Makban, Reykjanes and Mahanagdong with more than 40 MW/km2. Two-phase, vapor-dominated geothermal fields have relatively low power densities, of no more than 5 MW/km2, with Kamojang and Darajat being exceptions with more than 14 MW/km2.

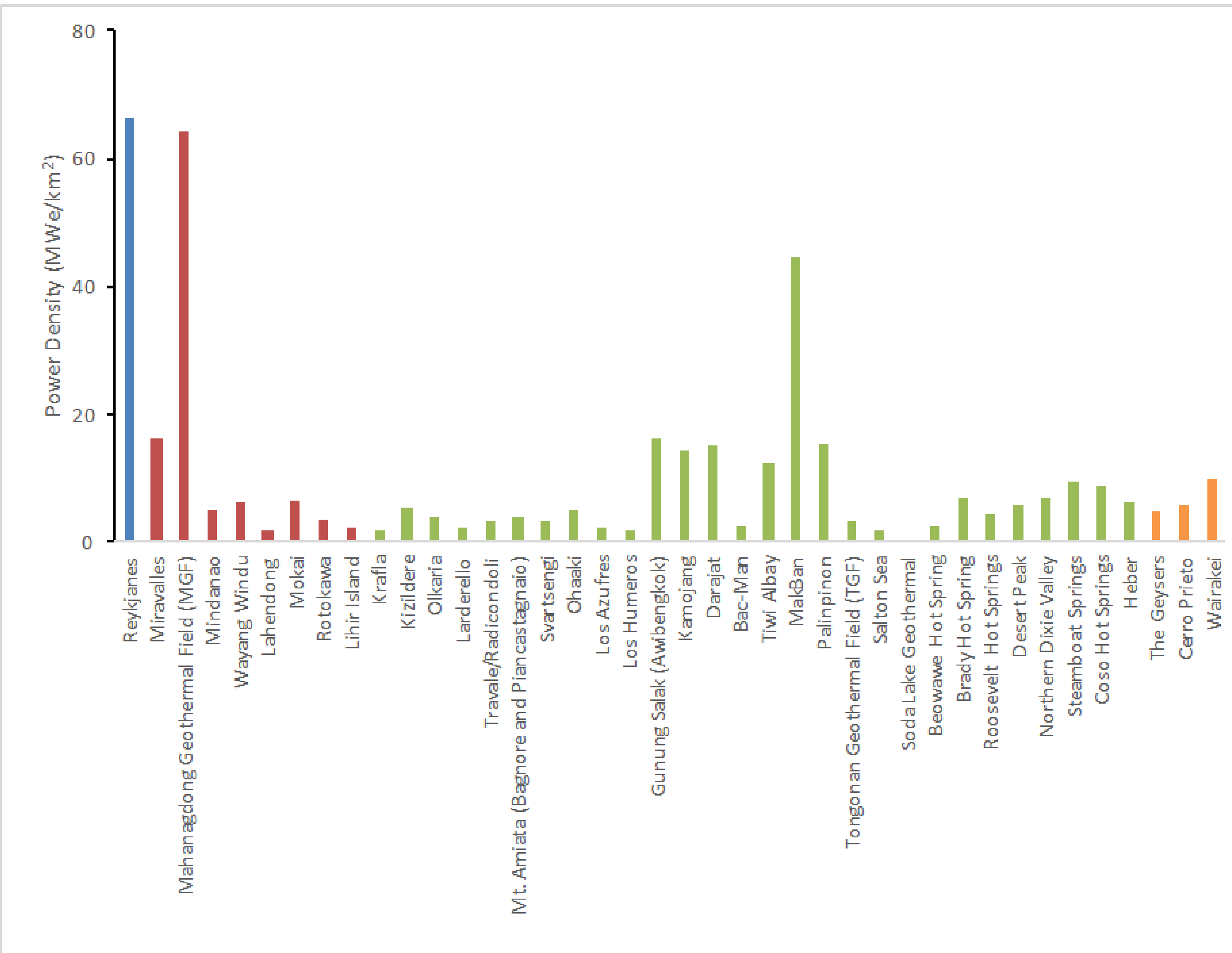
Table III-2 summarizes the power density based on the general permeability of 40 selected geothermal fields.

Table III-2 Power density classification in terms of general permeability of 40 selected geothermal fields

General Permeability	Power Density (MW/km^2)	Remarks
Low	1.71 to 16.15	Makban, Reykjanes, Mahanagdong, Kamojang, and Darajat have at least 14 MWe/km^2, operating for at least 20 years, with an average running electrical power MW capacity of at least 85 MWe.
High	1.78 to 9.69	Miravalles has a power density of at least 16 MWe, noting that the field has been operating for at least 20 years with an average running electrical power MW capacity of at least 100 MWe.

Figure III-4 shows the distribution of the selected geothermal fields based on the actual years of production.

Figure III-4 Power density in terms of actual years of energy production of the 40 selected geothermal fields



It can be observed that high power densities are evident in those fields that have been in large scale steam production for between 9 to 34 years, ie. Reykjanes, Mahanagdong and Makban, with at least 40 MWe/km2. In addition, about 70% of the selected geothermal fields which have been in operation for 20 to 40 years now have power densities of less than 10 MWe/km2, except for Makban, Gunung Salak and Palinpinon which have power densities greater than 15 MWe/km2. On the other hand, geothermal fields that have been in operation over 40 years such as Wairakei, The Geysers and Cerro Prieto, have actual average electrical power per area of less than 10 MWe/km2. This relationship was previously observed by Wilmarth and Stimac [6].

Values of power density vary significantly for each country. Power densities of all selected geothermal fields in the US are less than 10 MWe/km2. In the Philippines, about 60% of the selected geothermal fields have power densities greater than 12 MWe/km2 while the remaining fields have less than 5 MWe/km2. In Indonesia, majority of the geothermal fields have power densities from 14 to 16 MWe/km2. In Iceland, aside from Reykjanes that has the highest power density among the total selected fields (66.44 MWe/km2), the remaining fields (Krafla and Svartsengi) have power densities less than 5 MWe/km2. Lastly, the identified geothermal fields in Mexico, New Zealand and Italy have power densities less than 10 MWe/km2.

IV. VOLUMETRIC STORED HEAT CALCULATION

Only 14 selected geothermal fields worldwide are considered because these were the only fields for which all the data required were available. The total stored heat energy or total thermal energy in-place, Hth, for each field is computed using Equation IV-1 (after [33]):

$$\boldsymbol{H_{th}} = (1-\phi)c_r\rho_r V(T_i - T_f) + \phi\rho_{si}V(1-s_w)(h_{si}-h_{wi}) + \phi\rho_{wi}Vs_w(h_{wi}-h_{wf}) \qquad \text{Equation IV-1}$$

where:	ϕ	Rock porosity
	c_r	Specific heat of rock
	T_i Type equation here.	Initial average reservoir temperature
	T_f	Base temperature (180 ºC)
	S_w	Liquid saturation (1 for liquid-dominated reservoir)
	ρ_{si}, ρ_{wi}	Steam and water density at reservoir temperature
	h_{si} , h_{wi}	Steam and water enthalpy at reservoir temperature
	h_{wf}	Steam and water enthalpy at reservoir temperature
	V	Reservoir volume

Stored heat calculation involves parameters that generally exhibit uncertainty. Some parameters that are considered of high uncertainties are initial resource temperature and resource volume. The volume of the productive region is the product of reservoir thickness and reservoir area. The reservoir thickness is based on the drilled depths of the geothermal wells from temperature profiles and an additional 500 m below the production depth is included to represent the overall resource thickness. The reservoir area is estimated from the inferred resistivity boundary and maps of producing wells. The average reservoir temperatures are generally based on temperature profiles and well data.

The total annual energy production (GWh/year) of all geothermal power plant based on actual production is obtained from published references, except for The Geysers, in which the mean operational capacity of the geothermal power plant is used instead. With the computed total thermal energy in-place, total energy production from historical performance of the geothermal power plant, and power plant efficiency of 12%, the actual recovered heat stored energy from the geothermal reservoir is determined. All of the parameters used in the calculation are from available published references. The design MW capacity for each geothermal power plant is computed based on some standard recovery factor from various published references (See Appendix Table 1). The calculation is carried out using Microsoft Excel. To account for uncertainties in determining the total stored heat-in place, @Risk for risk analysis is used. @Risk is an add-in tool in Microsoft Excel that uses Monte Carlo simulation is used in the study. Characteristics of input parameters with high uncertainties in triangular distributions are determined with 1000 iterations in determining stored heat-in place. In this study, the design MW capacity pertains to the capacity of the power plant for large steam production for electricity generation based on geothermal reservoir parameters including recovery factor, conversion efficiency and economical plant life of 30 years. The design MW capacity is then compared to the average actual MW capacity based on historical performances of the power plant. Table IV-1 shows the result of the retrospective stored heat calculation of the 14 geothermal fields worldwide.

Table IV-1 Actual recovery factor from 14 producing regions

Geothermal Field	Years in operation	Standard Recovery Factor used (%)	Design MWe-yr			Actual MWe-yr	Actual Recovery Factor (%)		
			P90	P50	P10		P90	P50	P10
The Geysers	55	8 to 50	986.52	1667.43	2466.38	654.03	0.11	0.12	0.12
Makban	34	10 to 25	79.64	115.29	159.39	311.64	0.36	0.46	0.61
Tiwi	34	10 to 25	121.46	168.86	229.52	176.03	0.17	0.21	0.28
Palinpinon	30	10 to 25	52.73	73.30	97.05	124.54	0.25	0.30	0.36
Mahanagdong	17	10 to 25	162.55	206.25	263.55	513.93	0.20	0.23	0.27
Tongonan	30	18 to 25	46.18	62.82	82.22	92.90	0.17	0.21	0.27
Kamojang	32	8 to 20	68.83	90.64	118.69	211.50	0.17	0.19	0.21
Darajat	21	8 to 20	82.76	108.09	138.68	243.00	0.12	0.12	0.14
Los Azufres	31	10 to 17	421.69	602.08	818.44	97.76	0.02	0.03	0.04
Wairakei	56	20 to 50	107.13	153.09	200.49	193.83	0.56	0.68	0.86
Ohaaki	25	10 to 25	61.68	87.88	124.36	56.94	0.05	0.06	0.08
Mokai	15	10 to 30	115.69	160.76	209.30	79.09	0.07	0.08	0.09
Rotokawa	17	10 to 30	229.11	321.58	435.64	64.10	0.04	0.05	0.06
Miravalles	20	20 to 30	64.43	75.69	88.30	130.20	0.26	0.29	0.33

Some fields have exceeded the accepted maximum values for recovery factor, i.e. Makban, Palinpinon, Wairakei, while for some, the calculated recovery factor falls below the usual minimum recovery factor applied, i.e. Rotokawa, Mokai, Ohaaki, Los Azufres. More than 75% of the geothermal fields have actual recovery factor less than the most optimistic standard recovery factor used. This suggests that a high recovery factor was then used by many power plant investors in estimating the field capacity during the early exploration stage. In addition, over 60% of these geothermal fields have long-term average MW operational capacity exceeding its design MW capacity considering P50 or the "most likely" scenario, i.e. Miravalles, Darajat, Kamojang, Tongonan, Mahanagdong, Palinpinon, Makban. This suggests that the installed MW capacity of these fields should be re-evaluated for appropriate and updated power plant rating. The installed MW capacity of these fields might had been under-assessed or resource developments at later stage have been implemented after commissioning of the power plant [4].

It can also be observed that for most fields with an average operating capacity of at least 90 MWe, the actual recovered factor was at least 11%, for any length of period of geothermal operation. Some long-producing fields such as in the case of Wairakei, Makban, Palinpinon, and some fields with less than 30 years in large-scale steam production, i.e. Mahanagdong, Miravalles, have actual recovery factor of more than 20%. In addition, some fields of with small productive areas but has relatively long years in operation, i.e. Tongonan, Miravalles, have high recovery factors, typically greater than 15%. On the other hand, there are some fields with relatively large producing area but with relatively short periods of actual large-scale steam generation, i.e. Mahanagdong, which have relatively large actual recovery factors. Actual recovery factor between 3 to 8% are applicable for Los Azufres, Ohaaki, Mokai, and Rotokawa, all with less than 100 MWe average operating capacity. See Appendix Table 1 for reservoir characteristics considered for the selected geothermal fields.

It was also observed that there is less variation in the actual recovery factor for some low permeable, two-phase vapor dominated (Geyser, Darajat, Kamojang) and two-phase, liquid-dominated, medium- and high-enthalpy (Ohaaki, Mokai, Los Azufres, Rotokawa). The highest "most likely" recovery factors (P50) are applicable for a number of two-phase, liquid-dominated fields including Makban (0.46 > 0.25), Palinpinon (0.30 > 0.25), and Wairakei (0.68 > 0.50). Table IV-2 shows the classification of recovery factor in terms of the nature of geothermal field and general permeability.

Table IV-2 Actual recovery factor based on historical energy totals in terms of the nature of geothermal system, and general permeability.

Recovery Factor (%)	Nature of geothermal system and general permeability	Remarks
11 to 17	Two-phase, vapor-dominated with low permeability	Ex: Geyser, Tongonan, Kamojang, Darajat
17 to 36	Two-phase, liquid-dominated, high enthalpy of general low permeability	Ex: Makban, Tiwi
20 to 25	Two-phase, liquid-dominated, medium enthalpy of general low permeability	Ex: Palinpinon, Mahanagdong
26 to 56	Two-phase, liquid-dominated, low enthalpy of general high permeability	Ex: Miravalles, Wairakei
3 to 8	Some two-phase, liquid-dominated, high- and medium enthalpy of general low permeability	Ex: Los Azufres, Rotokawa

Results show that for most cases, at least 11% recovery factor is recommended for two-phase, vapor- and liquid-dominated with low permeability, except for Los Azufres and Rotokawa with less than 10% computed recovery factor.

The electrical capacity in MWe using power density and volumetric stored heat calculations are determined and presented in Figure IV-1. The actual MWe for each method is determined based on the historical records of each field, i.e., for volumetric stored heat calculation, the actual years in operation of the field is used instead of the standard plant life period of 30 years, and actual recovery factor was used instead of the standard recovery factors from published resources.

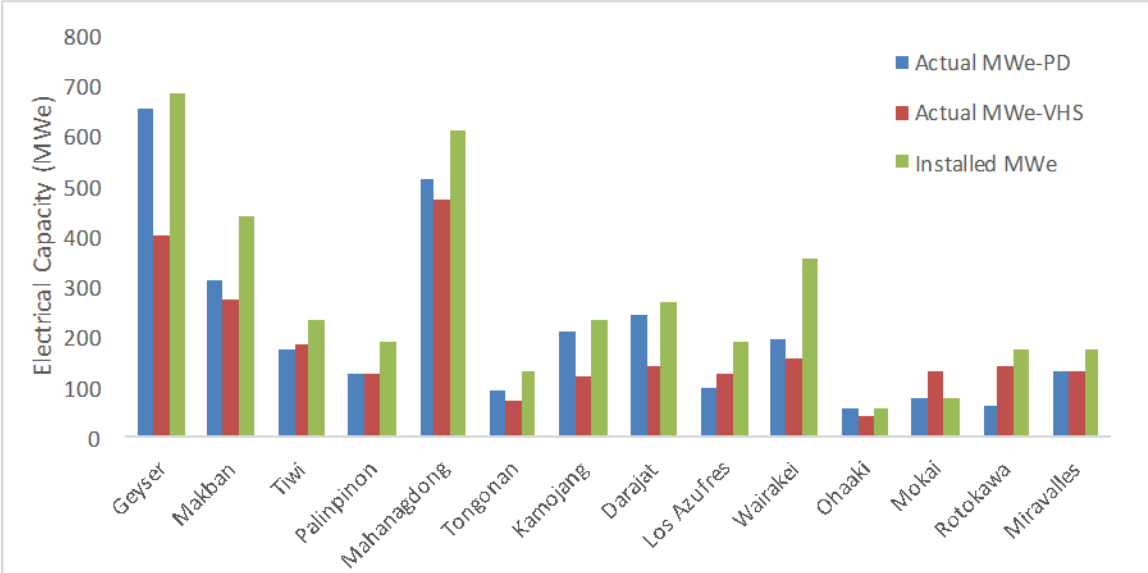


Figure IV-1 Calculated electrical capacity in MWe based on power density and volumetric stored heat calculations

It can be observed that installed electrical capacity (MWe) for each field is generally greater than the results of both methods. One reason for this is because during the early geothermal resource estimation, the values for most reservoir parameters are unknown and uncertain. In almost all cases, parameters are subject to uncertainties, including the initial reservoir temperature and reservoir volume. Thus, the electrical MW capacity that can be derived from the reservoir is subject to uncertainties as well. Another possible reason could be a subsequent change in the reservoir after few years of large steam generation. As a result, power plants capacity can be overestimated or underestimated based on the assumed values for each parameter and actual field performances. In terms of the average operating electrical MW capacity derived using the information on the actual total recovered heat-in place, this study presents that power density method and volumetric stored heat calculation can be used to re-evaluate the field performance of existing geothermal power plants. The result suggests that a re-evaluation of the existing power plant to maximize the geothermal resource potential in the field.

V. SUMMARY AND CONCLUSION

The net installed capacity and geothermal energy production of most countries varies with time. Countries such as Turkey and Iceland, and Kenya have greater average annual growth rate (at least 13%) than the top producing countries in terms of installed capacity, e.g., USA, Philippines, Mexico and Italy (less than 5%). In addition, the majority of the top producing countries have a low contribution of geothermal energy to the total electricity production, i.e. no more than 5%. On the other hand, Philippines and El Salvador have a ~20 % share of geothermal energy to the total electrical energy mix.

It was observed that over 75% of geothermal fields have power density below 10 MW/km2. Meanwhile, power density of more than 10 MW/km2 is applicable for fields with reservoir temperature between 235 to 290 °C. Most fields that are categorized as two-phase, liquid-dominated and two-phase, vapor-dominated with generally low permeability have power density below 5 MW/km2. For hot water system with high permeability, power density of less than 10 MW/km2 is observed. It was also observed that geothermal fields producing steam at large-scale for up to 34 years have power density at least 40 MW/km2 while for fields with over 40 years in geothermal steam production, e.g. Wairakei, The Geysers and Cerro Prieto, a low power density (below 10 MW/km2) is noted.

It was observed that at least 11% recovery factor is applicable for two-phase, vapor- and liquid-dominated with low permeability geothermal fields which has been in large steam production for at least 15 years and with at least 90 MW average running capacity. In general, the installed MW capacity for each power plant exceeded the results of the power density and volumetric stored heat methods which have considered historical records of the geothermal fields.

Appendix Table 1 Information on reservoir area, thickness, temperature, accumulative energy production, computed total thermal energy and standard recovery factor used of the 14 selected geothermal fields

Geothermal Field	Productive Area, km^2	Thickness, km	Average Reservoir Temperature	Years in operation	Accumulative energy production, GWh	Total Thermal Energy (H_{th}), J	Recovery Factor used (%)	Design MWe-year (P50)	Actual MWe-year	Actual Recovery Factor (%) (P50)
The Geysers	140 geothermal map of California [34]	2.00	244 temperature profiles [35]	55 (1960 to 2015)	384, 024.597 (1990 to 2015) [36]	4.37E+19	8 to 50 ([14], [37], [38])	1667.43	654.03	12
Makban	7 resisitvity boundary [39]	2.57	290 temperature profile [39]	34 (1979 to 2013)	72,860.98 (1979 to 2013) [26]	4.83E+18	10 to 25 ([2], [14], [40])	115.29	311.64	46
Tiwi	14 Location of production wells [41]	2.22	272.5 Technical well data [41]	34 (1979 to 2013)	50,285.87 (1979 to 2013) [26]	7.051E+18	10 to 25 ([2], [14], [40])	168.86	176.03	21
Palinpinon	8 resisitvity boundary [42]	2.60	240 temperature profile [43]	30 (1983 to 2013)	30,202.92 (1983 to 2013) [26]	3.054E+18	10 to 25 ([2], [14], [40])	73.30	124.54	30
Mahanagdong	16 Resistivity boundary [44]	2.00	287.5 temperature profiles [44]	17 (1996 to 2013)	62,791.15 (1996 to 2013) [26]	8.26E+18	10 to 25 ([14], [44])	206.25	513.93	23
Tongonan	4 [45]	2.25	292.0 [46]	30 (1983 to 2013)	17,591.28 (1977 to 2013) [26]	2.52E+18	18 to 25 ([2], [14], [15]))	62.82	92.90	21
Kamojang	15 Resistivity boundary [47]	2.03	240 Temperature profiles [47]	32 (1983 to 2015)	31,177.477 (1983 to 2015) [48]	4.92E+18	8 to 20 [2], [14]	90.64	211.50	19
Darajat	16 Gravity surveys [49]	2.45	238.5 Technical well data ([49], [50])	21 (1994 to 2015)	24,206.122 (1994 to 2015) [25]	5.82E+18	8 to 20 ([2], [14])	108.09	243.00	12
Los Azufres	48 Resistivity boundary [51]	2.65	280 Temperature profile [51]	31	28,509.41 (1982 to 2013) [24]	3.1E+19	10 to 17 [14]	602.08	97.76	3
Wairakei	25 resisitvity boundary ([52], [53])	1.55	255 temperature profiles [53]	56 (1958 to 2014)	70443.70 (1950 to 2014) [30]	3.12E+18	20 to 50 ([14], [38], [40])	153.09	193.83	68
Ohaaki	11 resisitvity boundary [54]	2.10	270 technical well data [55]	25 (1989 to 2014)	7,800 (1989 to 2014) [30]	3.87E+18	10 to 25 ([14], [40])	87.88	56.94	6
Mokai	12 resisitvity boundary [54]	1.68	297.5 temperature profiles [56]	15 (1999 to 2014)	14,880 (1999 to 2014)[30]	5.78E+18	10 to 30 ([14], [40])	160.76	79.09	8
Rotokawa	17 resisitvity boundary [57]	2.20	307.5 temperature profiles [58]	17 (1997 to 2014)	19,860 (1997 to 2014) [30]	1.16E+19	10 to 30 ([14], [40])	321.58	64.10	5
Miravalles	8 Resistivity boundary [59]	2.10	242.5 Temperature profiles [60]	20 (1994 to 2014)	20690.56 (1994 to 2014) [61]	2.157E+18	20 to 30 [14]	75.69	130.20	29

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