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An analysis of thermodynamic properties in both traditional and enhanced geothermal systems to compare thermal efficiencies

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Abstract: This meta-study draws upon previous research on both Enhanced Geothermal Systems (EGS) and traditional geothermal systems (GS), using these findings to compare and investigate the thermal efficiency of each system. Efficiency calculations include reservoir enthalpy, maximum drilling well temperature, power output (per unit mass of liquid) and mass flow rate of these systems to determine whether EGS's are viable as an alternative, more readily available renewable energy source. This meta-study suggests that EGS are more viable than naturally occurring GS in the context of future geothermal energy production as they perform with a similar average efficiency of 10-15% and, in addition, can be used in a wider range of geothermal environments.

Keywords: Geothermal Power, Enhanced Geothermal Systems, Geothermal Systems, Energy Analysis

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Nomenclature

GS	Traditional Geothermal Systems
EGS	Enhanced Geothermal Systems
Thermal Efficiency	The ratio between work done on the system (running capacity) and the heat & mass supplied to it (mass flow rate & reservoir enthalpy)
Reservoir Enthalpy	Total heat of a particular geothermal reservoir, equal to the internal energy of the system plus the product of pressure and volume
Geothermal Fluid	A gas or liquid used (usually water or CO_2) used in heat extraction for geothermal power plants
Permeability	A physical property of rock that indicates the ability for geothermal fluids to flow through it. A high permeability will allow fluids to pass through it more easily
Mass Fluid Rate	Represents the amount (mass) of a given substance that passes per unit of time, given in kilograms per second (Kg/s)
Installed Capacity	The intended (ideal) full-load sustained output capability of an energy facility, given in Kilo/Mega/Giga Watts of energy (KWe, MWe, GWe)
Electrical Output Capacity	The actual (real) electrical energy output of a system, given in Kilo/Mega/Giga Watt hours (KWh, MWh, GWh). This can also be KWe, MWe, GWe given a moment in time
Base Load	The minimum amount of electrical energy on demand over a period of time, given in Kilo/Mega/Giga Watt hours (KWh, MWh, GWh)

1. Introduction

Traditional geothermal energy originates from differential temperatures between the earths molten core and its crust. The heat exchange between these layers causes less dense material and water in the earth's mantle to significantly heat up, inducing an outwards convection of thermal energy [1]. Suitably, areas of existing thermal activity such as volcanic regions and tectonic plate boundaries have been the sites of traditional geothermal power generation, as geography provides the important elements for constant and effective energy extraction [1].

The most significant limitation with naturally occurring geothermal energy is in its lack of geographical versatility. Power plants such as the Wairakei Power Station in New Zealand, for example, relied upon its ideal location above the 'Taupo Volcanic Zone' where energy could be captured from steam arising from subsurface heated water channels [1]. In this region, shallow crust magma supplies heat to large deposits of clay and alkali-chloride rich hot springs to produce recorded temperatures greater than 230°C [1]. Similarly, in Japan, Russia, Mexico, Iceland, Indonesia, Philippines and the West coast of North America, geographical location has provided the heat, fluid and rock permeability resources for practical and economic geothermal energy development [2]. For much of the world, geothermal power has been an impossibility, due to lack of the major hot water reservoirs that could supply enough energy for a system to have efficient operational outputs.

In the mid-20th century, many influential governments around the world including China, India and the United States began to recognise the need for an increased renewable energy infrastructure to sustain the growing demand and increased consumption of electricity [3]. Technological mining developments in drilling, allowing for extended drill depth capacity in the 1970's and progressive research into geothermal engineering processes provided a solution to overcome the restrictions and limitations of traditional geothermal systems. This breakthrough was the introduction to enhanced geothermal systems, which in the U.S. alone was thought to possess just over 100GWe of economically attainable potential electrical capacity [4].

2. Enhanced Geothermal Systems

An enhanced geothermal system provides the possibility of resolving many of the limiting requirements of traditional geothermal power stations. The rationale for EGS is eliminating the need for pre-existing thermal activity. For a traditional GS, temperatures of 300°C or greater were essential for an effective geothermal operation. In EGS subsurface fractures are formed by drilling at significantly lower depths (3-10km in comparison to a few hundred meters). These are cracks within the earth that allow for a geothermal fluid (usually water) to be injected through a rock fracture system [4]. Because of this, it is theorised that EGS's could operate with similar efficiencies at as little as half the of the temperature at which GS systems operate [3].

Unlike a traditional system, alternative geothermal liquids can be chosen to maximize mass fluid rate and increase the systems internal enthalpy. Particular oils and gases such as supercritical CO_2 have been shown to further fracture the earth and artificially increase its permeability [5]. Upon contact with the earth, the geothermal fluid is naturally heated and brought back to the surface using a steam turbine or a binary power plant system to convert the heat energy into electricity [4]. Figure 1 below gives a visual operational representation of an enhanced geothermal system.

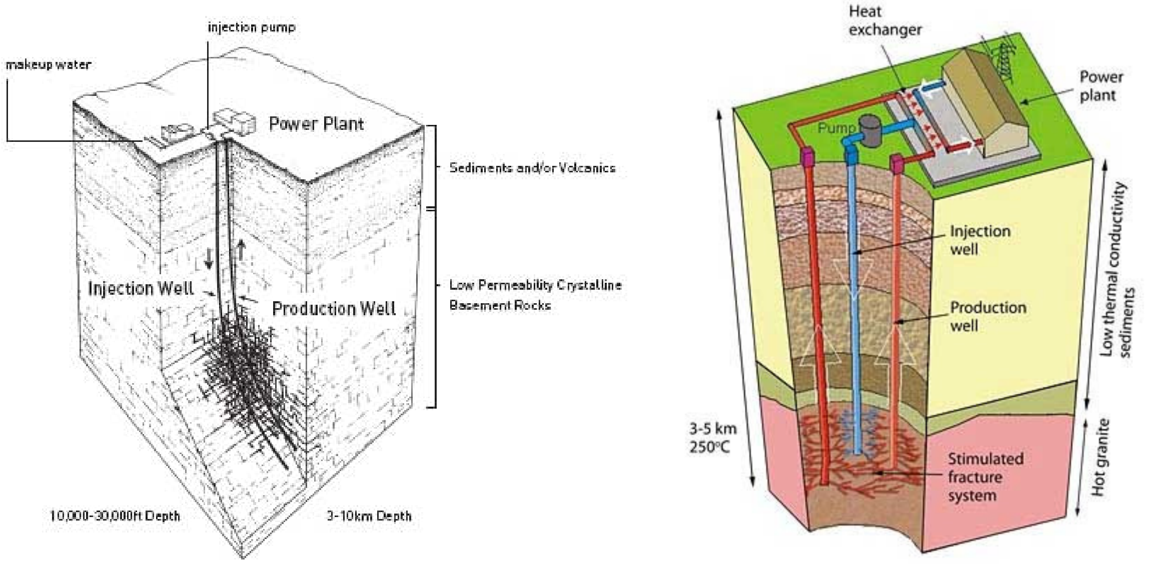

***Figure 1:** "A schematic of a conceptual two-well enhanced geothermal system in hot rock in a deep permeability crystalline basement formation" [4].*

Currently, geothermal power only accounts for 0.3% of the global electricity supply [7]. From 1950 to 2015 the total worldwide install capacity and power generation from geothermal power plants has steadily increased. It is predicted to almost double from a capacity of 12,635 MWe and an energy output of 73,549 GWh in 2015 to a capacity of 21,443 MWe with an uncalculated energy output production [8]. The figures below illustrate the relationship between installed capacities versus produced energy to gauge the growth of geothermal power production.

Year	Installed Capacity MWe	Produced Energy GWh
1950	200	
1955	270	
1960	386	
1965	520	
1970	720	
1975	1,180	
1980	2,110	
1985	4,764	
1990	5,834	
1995	6,832	38,035
2000	7,972	49,261
2005	8,933	55,709
2010	10,897	67,246
2015	12,635	73,549
2020	21,443	

***Table 1:** represents the "total worldwide installed capacity from 1950 up to the end of 2015 and short term forecasting" [8].*

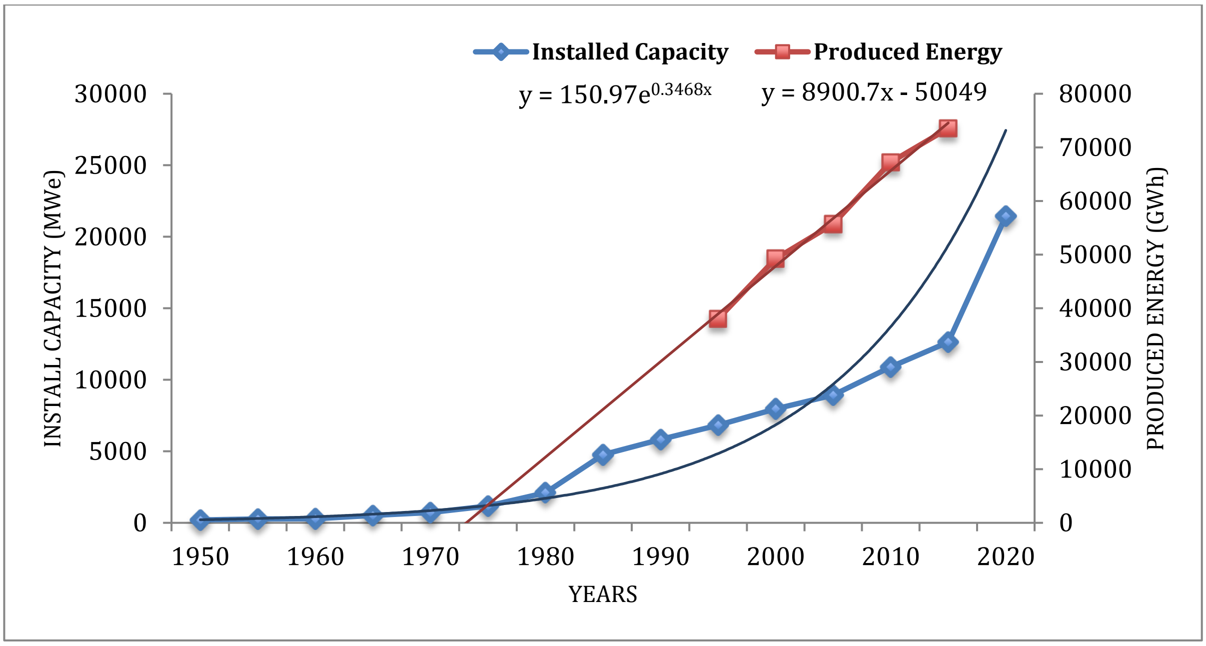

***Figure 2**: A line graph showing the worlds geothermal energy production from 1950 up to 2016. Installed capacity (Left, MWe) and produced electricity (right, GWh) [8]. Whilst installed capacity shows an exponential trend in growth from 1950 to 2020, produced energy shows a more linear progression.*

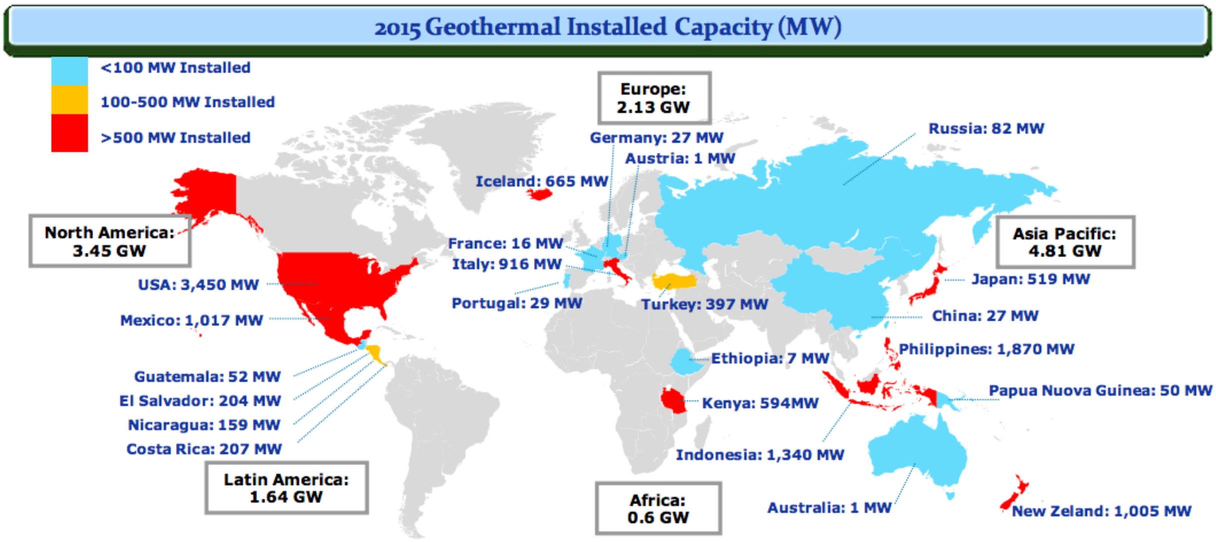

***Figure 3**: "Worldwide Install capacity of geothermal systems in 2015 [12.6 GWe] [8]" Showing that Asia Pacific is the biggest contributor to geothermal installed capacity, followed by North America, Europe, Latin America then Africa. Individually the United States supports all geothermal energy production in North America (3,450 MWe). Alternatively, the Asia Pacific region has been broken into 4 primary contributors notably, Japan (519 MWe), Philippines (1,870 MWe), Indonesia (1,340 MWe) and New Zealand (1,005 MWe). Australia contributes less than 0.03% to the Asia Pacific's geothermal energy production.*

These figures indicate that production of geothermal energy is predicted to increase exponentially in the next 5 to 10 years (shown in Table 1 and Figure 2). However, traditional geothermal systems remain dominant. EGS has so much potential that it is most likely it will surpass GS in the future. This is shown in Canada where the potential for EGS is significant. "There are an estimated 15,000 MWe or more available in untapped geothermal locations, 10,000 MWe of which are limited to an EGS set up" [8]. The results of this meta-study could inform future decision-making in regards to whether EGS represent a worthwhile investment for future energy Infrastructures.

3. Methods

The meta-study was conducted over three months by reviewing independent scientific reports and articles regarding power generation of both traditional and enhanced geothermal systems. Referenced sources were collected from ProQuest Science & Technology, Science Direct (Elsevier), Access Science and Web of Science Core Collection with a focus on reports less than 10 years old. Data was collected on six primary geothermal power attributes, including reservoir enthalpy, maximum primary well temperature, total system power output, mass flow rate of geothermal fluids, electrical output capacity and overall thermal efficiency. From this raw data, significant trends and figures were tabulated and graphed (represented in Figures 4-7).

Not all data variables for GS and EGS were attainable in our research. Some raw data tables were left incomplete for many of the calculations intended to be used in this report. Reports that did not supply sufficient data on well temperature, total system power output and types of geothermal fluids were excluded from averaging calculations, as they could not be derived any other way. Alternatively, unknown attributes such as thermal efficiency, net electrical output capacity, mass flow rates and thermal enthalpies, could be calculated by Equation 1 show below.

$$\boldsymbol{\eta_{act}}\ (\%) = \frac{\boldsymbol{W}}{\dot{\mathrm{m}} \times \mathbf{h}} \times \mathbf{100}$$

N_{act} (%)	Thermal (heat) efficiency of the entire system
W	Work done on a system, represented by the output capacity (kWe). Measurement of the electrical output capacity
ṁ	Mass of the system represented by the total mass flow rate (kg/s), mass of geothermal fluid passing through the system
h	Heat supplied to they system represented by the reservoir enthalpy (kJ/kg) – total internal radiant heat of the reservoir

Efficiencies of most GS were obtained from articles, by looking at raw data within the report. This ensured that all collected statistics were direct links to one specific power station and were not further elaborated on. This was to prevent any confusion between what was known to be fact and what was hypothetical analysis; however, many EGS attributes were not readily available. A multitude of reliable sources was carefully inspected before efficiency values were obtained. Finally, conclusions were drawn, using the evidence from the graphs and tables to establish which of the two geothermal system types was more efficient in terms of their general energy input vs power output and convenience of their geographical location.

4. Results and Discussion

An analysis found that within a search of 50 papers on the topic of geothermal energy production, 45 compared the output thresholds of only traditional geothermal systems, constructed before the introduction to EGS, while only five extensively mentioned EGS. As a relatively uncovered point of discussion, this report extrapolates data from papers and direct sites to draw a useful comparison between GS and EGS. Thermal efficiency analysis has focussed on four data variances; system electrical output capacity (Figure 4), well depth (Figure 5), enthalpy (Figure 6) and well temperatures (Figure 7). In doing so, the results cover comprehensive output figures that compare modern EGS with GS within their unique geographical parameters. This report illustrates the potential for regional scale implementation of geothermal power when traditionally geothermal systems are large-scale state wide operations.

All graphs below (Figures 4-7) compare the thermal efficiency of both GS and EGS systems against a relevant base parameter. Each parameter is a factor that can be controlled individually by the system operators to attain an optimal thermal efficiency. The comparison of these was made to understand if they could perform at the same efficiency as GS given that they operate at much lower temperature standards and can be developed in a much larger range of locations.

In comparing electrical output capacity versus thermal efficiency no obvious trends were found with GS or EGS. Out of 26 independent power stations, 21 GS had an average electrical output capacity of 97.8 MWe, while five EGS had an average electrical output capacity of 130 MWe. Two outlying data points significantly brought up these two averages, these being from the Cerro Prieto GS power plant in Mexico, and the Larderello EGS power plant in Italy, these plant were created to produce larger scale electrical energy when compared to the rest of the data points.

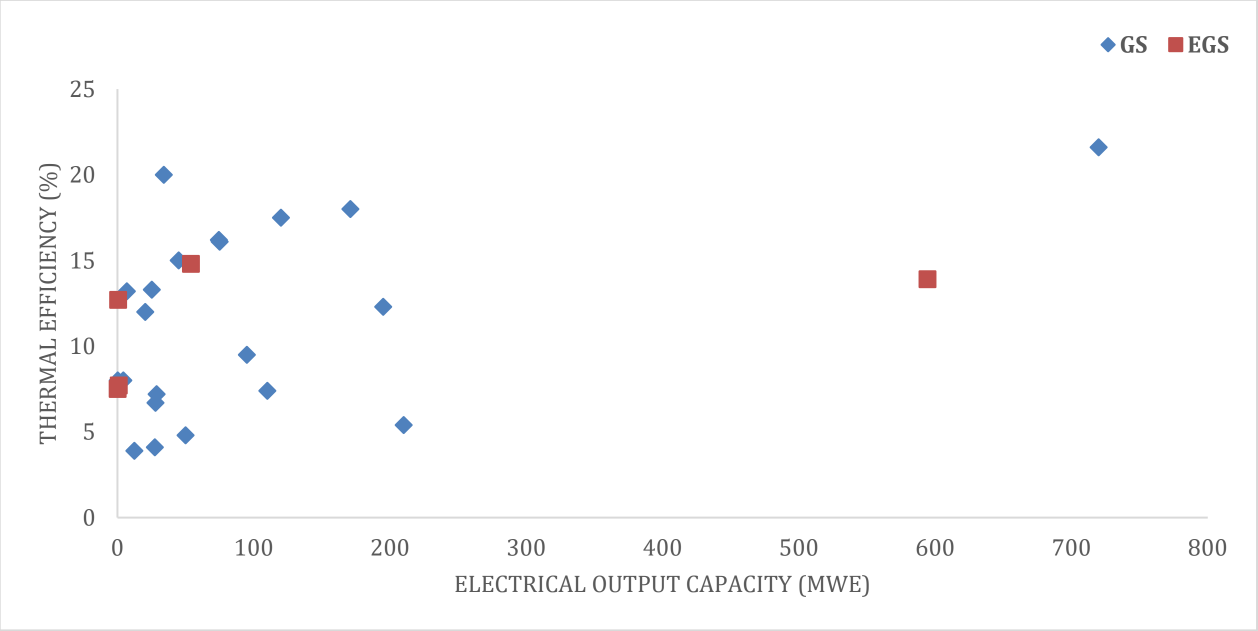

Figure 4. *A scatter plot comparing the thermal efficiencies of the geothermal systems varying against their electrical output capacity.*

Currently, geothermal power operates as a contributory source of energy supplied to cities and towns as part of a large-scale power grid, where different power generation methods (coal being the largest contributor in most countries) are used to reach the required base load. On average the amount of energy required for a developed city of 1 million people at any given time is roughly 1500 MWe for a standard base load [8]. Given values from Figure 4, both GS and EGS would currently hold placement within the small-medium scale bracket for current renewable energy systems. Despite this, comparing the two outlying electrical capacities shows that EGS has a much higher future growth potential than current traditional geothermal systems as a thermodynamically more viable case for increased investment in future sustainable energy.

Results gathered from well depth, and thermal efficiency comparisons were to a large extent inconclusive as it showed no clear trends connecting individual data points. Between both GS and EGS systems, independent system well depth averages were found to be 2.2 km, despite all papers expressing that EGS require significantly lower drilling capabilities.

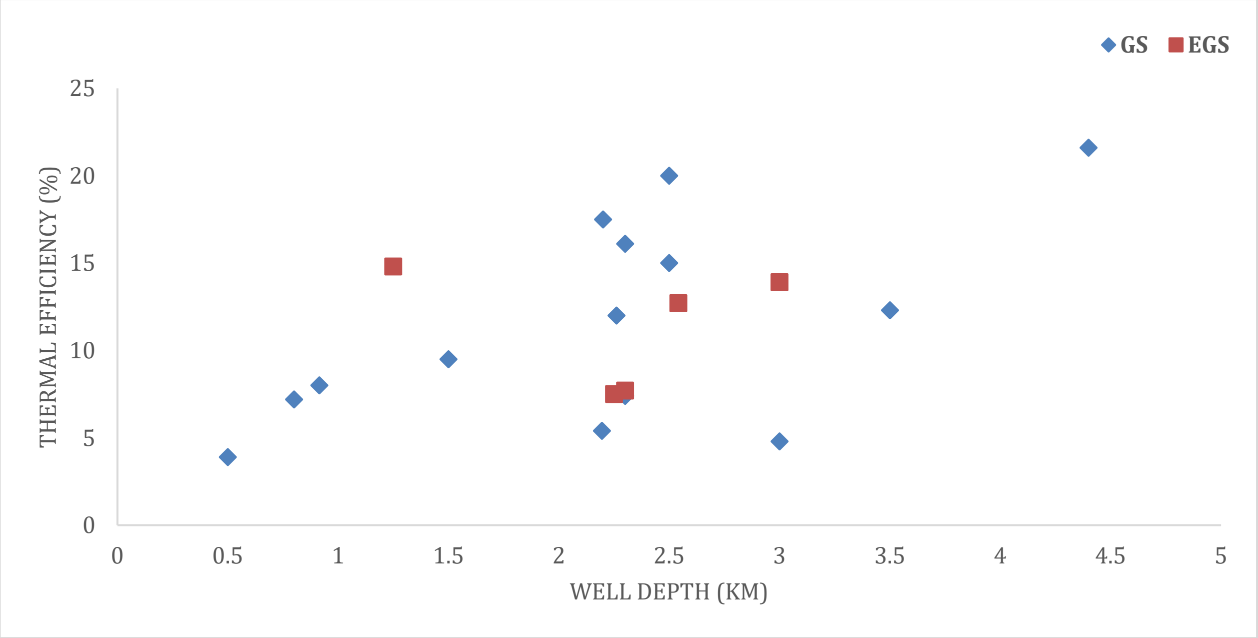

Figure 5. *A scatter plot comparing the thermal efficiencies of the geothermal systems varying against its primary well depth*

In the search for well depth data, three research papers concluded that particular depths had an influence on the efficiency of a geothermal system. It has been suggested that the reservoir enthalpy influences how much heat is extracted [32]. Theoretically, this does make sense as increasing depths would bring a system closer to the earth's molten core, but our results did not indicate this. External geographical factors including ground permeability and below surface temperature all influence the final well depth of a geothermal system. As a result, it could not be concluded that well depth had an impact on the amount of heat extracted or the thermal efficiency, rather it was the location that supplied the heat that influenced the well depth. From this, it suggests that due to enhanced geothermal systems geographical versatility, future renewable energy investments in geothermal power would lend itself to a system that utilised ground permeability rather than well depth to extract maximum energy supplies to reach higher thermal efficiencies.

For the reservoir enthalpy calculations, only three EGS values were usable, dissimilar to the other discussion figures (4, 5, 7) that contain all five EGS power plant values. This lack of data was due to difficulty in accessing all related data for EGS. Many privately owned power plants did not disclose their performance figures, meaning only three EGS reference points (Bruchsal, Germany; Berlín, El Salvadore and Larderello, Italy) could have a use for this analysis. The enthalpy of a system is an important measure as it shows the total heat and therefore energy of the reservoir. Figure 6 shows a well-distributed scatter plot of the systems thermal efficiency against reservoir enthalpy.

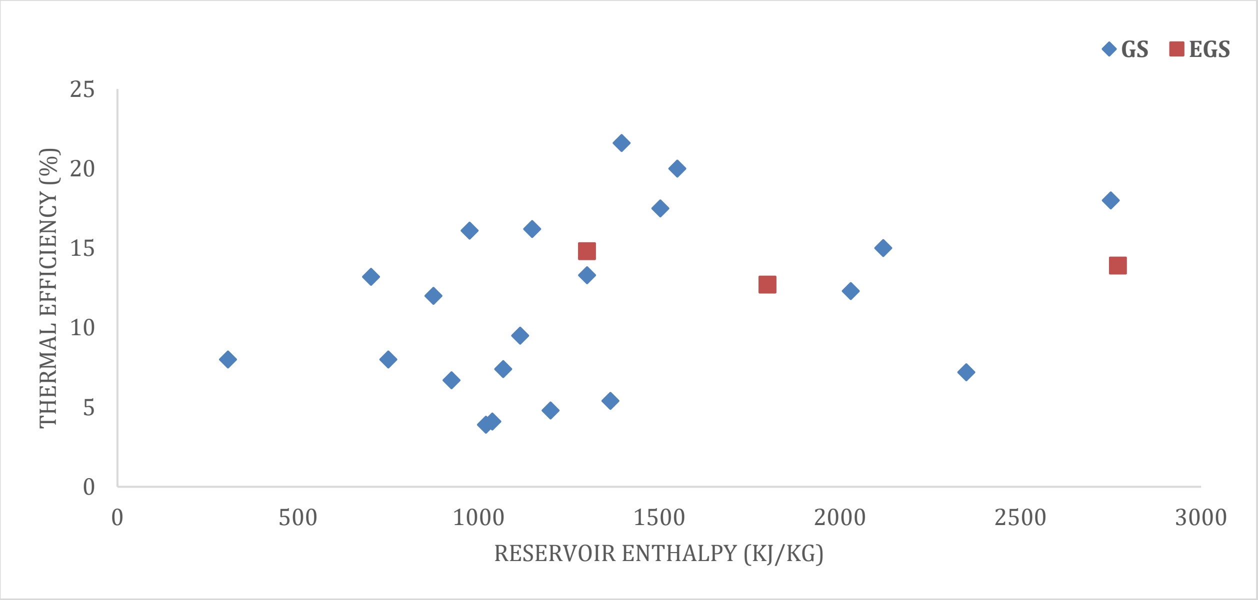

Figure 6. *A scatter plot comparing the thermal efficiencies of geothermal systems varying against their overall internal reservoir enthalpy*

If viewed from a thermodynamic standpoint it would be expected that as enthalpy increases, efficiency would also increase. The above data does not clearly discern this; instead, it shows no clear relation between energy efficiency and enthalpy. On the other hand, it does demonstrate that EGS perform within a consistent range of GS efficiency, in that they are found to occupy the middle (10-15% efficiency) of the GS data set. This again suggests that EGS have a versatility that GS can't provide, operating with the same efficient transfer of heat energy to electrical power despite significantly less influence from a thermally active area.

Once again, both GS and EGS are seen to produce a similar scatter of results. This time a trend appears from the collection of data points and is illustrated in Figure 7 as two separate positively increasing linear lines. Note that the gradient for EGS is slightly greater than the slope for GS, and a projection would show that the two lines would intercept each other at between 70 and 80ºC.

Well temperature is a fundamental element in a geothermal system, as many systems require a minimum amount of heat to convert a 'working' geothermal fluid to vapor. While both trend lines display increasing efficiencies as well a temperature increases, no accurate conclusion can be made about the GS as it does not have a linear relationship between efficiency and well temperature. This suggests that there are other factors such as plantation types that were not the focus on this report, that affect its efficiency. The linear relationship fits with EGS as its value range sit much closer to the averaging line. The EGS shows an ability to produce a linear trend increasing its output data reliability. A new plantation could use this data to gather a greater understanding of its potential final energy outputs and output efficiencies.

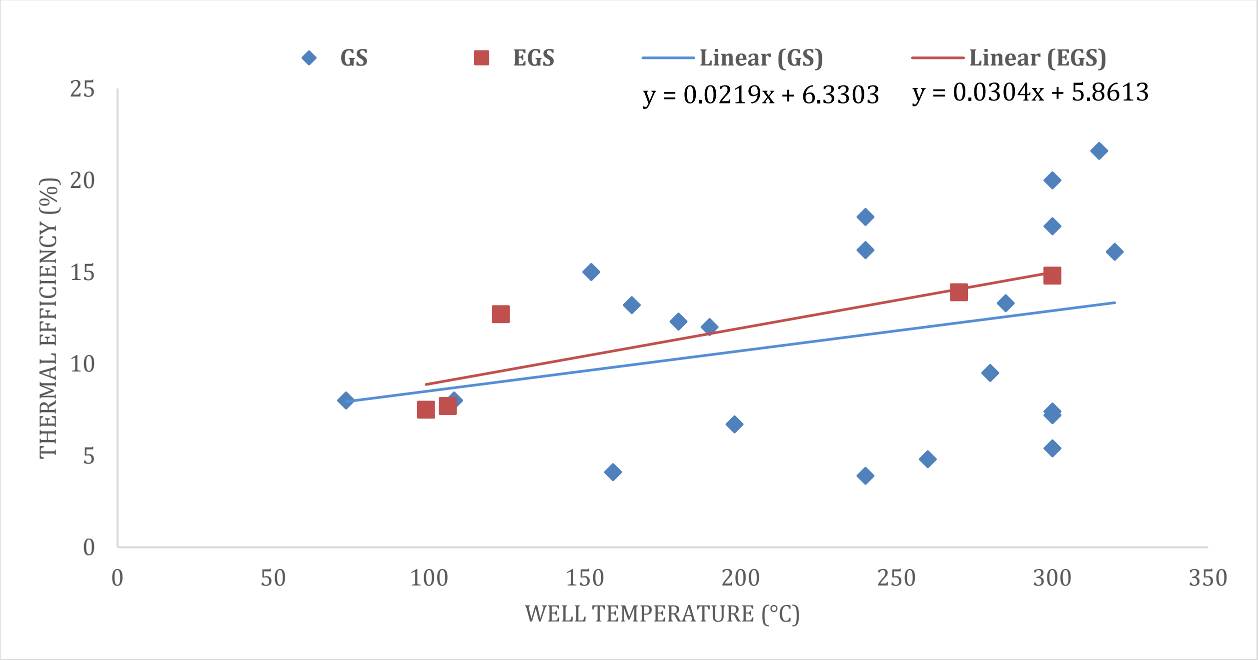

Figure 7. *A scatter plot with averaging trend line comparing the thermal efficiencies of the geothermal systems varying against its primary well temperature.*

It is important to note the limitations in accessibility and availability of data specific to enhanced geothermal systems. Results that were crucial for this discussion including reservoir enthalpy and maximum well depth were simply not provided by many of the independently run private geothermal power stations. Understandably for EGS, this is likely because it is still a relatively new form of geothermal energy extraction and is in its early stages of development. Fortunately, many governmental agencies, including the U.S. 'Department of Energy', the New Zealand 'Ministry of Business, Innovation, and Employment' and Australia's own 'Department of Environment and Energy' operate with a higher level of transparency and provide public access to outstanding amounts of energy data.

5. Conclusions

Out of the 14 EGS investigated, only five had enough open access information to be included in this meta-study. Comparatively, a traditional geothermal system is a technology that has been utilized for a far longer time, and thus, had larger amounts of available credible data. Because much of the data for an EGS is limited, future studies need to be conducted to make more informed and reliable comparisons. Additionally, further comparisons need to be made for EGS in different locations, to analyse optimal alternative geographical areas. Research in this area could enable scientists and engineers to adapt individual systems to their unique locations, thereby maximizing the efficiency on an ad-hoc basis.

This study analysed data from five enhanced geothermal systems, and 21 traditional geothermal systems to compare the efficiencies of both systems with regards to electrical capacity, reservoir temperature, well depth and working fluid/reservoir enthalpy. This comparison highlighted the ability of EGS to perform equally as well as GS in all researched aspects. Resultantly, it can be suggested that due to an EGS's ability to be used in a much wider variety of regions, it is overall the more attractive energy system for future investments in sustainable energy.

The results indicated that thermodynamically an EGS has the capability of producing thermal efficiencies equal to, if not greater than current full-scale operational GS while overall providing a significantly more controlled system. This control enables engineers' choice over size and scale of operations, tailoring conditions to match the demands of any given energy requirement (currently ranging from 100 kWe to 800 MWe) [37]. These findings suggest enhanced geothermal systems as a promising alternative to traditional geographically limited systems. Aided by a wider scope of available data in the future, research can be targeted towards determination of an optimal EGS set for specific locations as their use increases world-wide.

Acknowledgments

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Appendix 1 – Data used for analysis of GS and EGS

Geothermal Type	Plant name	Type	Capacity (MWe)	Max. Depth (m)	No. Production wells	Reservoir Enthalpy (kJ/kg)	Max. temp (Celsius)	Mass flow rate (kg/s)	Thermal Efficiency	References
GS	Amatitlan Guatemala	Binary Organic Rankine Cycle	25.2	-	4	1300	285	85.7	11.30%	[11], [12]
GS	Ngawha New Zealand	Binary Organic Rankine Cycle	75	2300	3	975	320	239.4	16.10%	[13], [12]
GS	Wairakei New Zealand	Binary Organic Rankine Cycle	171	-	53	2750	240	957.6	18.00%	[14]
GS	Rotokawa New Zealand	Binary Organic Rankine Cycle	34	2500	14	1550	300	76.4	20.00%	[11], [12]
GS	Chena Hot Springs USA	Binary Organic Rankine Cycle	0.21	915	2	306	73.3	33.4	8.00%	[15], [16], [17]
GS	Brady Hot Springs USA	Binary Organic Rankine Cycle	4.33	-	-	750	108	484.1	8.00%	[12]

GS	Heber USA	Binary Organic Rankine Cycle	6.87	-	-	702	165	126	13.20%	[18], [12]
GS	Ahuachapan El Salvador	Double-Flash	95	1500	16	1115	280	410	9.50%	[12], [19]
GS	Hellisheidi Iceland	Double-Flash	210	2195	30	1365	300	1431.1	5.40%	[20], [22]
GS	Hatchobaru Japan	Double-Flash	110	2300	20	1068	300	700	7.40%	[23]
GS	Cerro Prieto Mexico	Double-Flash	720	4400	164	1396	315	1195.2	21.60%	[24], [25]
GS	Mori Japan	Single-Flash	50	3000	10	1199	260	434.4	4.80%	[26]
GS	Miravalles III Costa Rica	Single-Flash	27.5	-	-	1038	159	320.6	4.10%	[27]
GS	Svartsengi Iceland	Single-Flash	74.4	-	13	1148	240	199.6	16.20%	[39]
GS	Nesjavellir Iceland	Single-Flash	120	2200	10	1503	300	228.6	17.50%	[30]
GS	Uenotai Japan	Single-Flash	28.8	800		2350	300	85.7	7.20%	[31]
GS	Onikobe Japan	Single-Flash	12.5	500	12	1020	240	157.5	3.90%	[11], [12]
GS	Takigami Japan	Single-Flash	28			925	198	68.5	6.70%	[28]
GS	Olkaria Kenya	Single-Flash	45	2500	31	2120	152	103.3	15.00%	[39]

GS	Los Azufres Mexico	Single-Flash	195	3500	39	2030	180	391.3	12.30%	[12], [33]
GS	Kizildere Turkey	Single-Flash	20.4	2261	9	875	190	320.8	12.00%	[34]
EGS	Bruchsal Germany	Binary Kalina	0.55	2542	1	1800	123	28.5-l/s	12.70%	[7]
EGS	Neustadt-Glewe Germany	Binary Organic Rankine Cycle	0.21	2250	2	-	99	35-l/s	7.50%	[7]
EGS	Altheim Austria	Binary Organic Rankine Cycle	1	2300	1	-	106	82-kg/s	7.70%	[7]
EGS	Berlín El Salvador	Binary Kalina	54	1250	14	1300	300	20kg/s	14.80%	[7]
EGS	Larderello Italy	Double-Flash	594.5	3000	200	2770	270	771.1	13.90%	[7], [10]