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Geothermal Power: Factors affecting the performance of Binary Plants.

Izabela Domanski [1,]*, Matthew Cappadona[2] , Oliver Fuller[3] and Zeb Krix[4]

University of Technology Sydney, Faculty of Science, P.O. Box 123, NSW 2007, Australia

[1] Email: Izabela.Domanski@student.uts.edu.au
[2] Email: Matthew.L.Cappadona@student.uts.edu.au
[3] Email: Oliver.K.Fuller@student.uts.edu.au
[4] Email: Zeb.E.Krix@student.uts.edu.au

* Author to whom correspondence should be addressed; Izabela.Domanski@student.uts.edu.au

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Abstract: A meta-study is conducted investigating the effect of plant parameters on the power output and efficiency of geothermal binary cycle power plants. Production well depth, geofluid temperature and mass flow rate are the parameters considered. An increase in mass flow rate is shown to increase both power output and efficiency. It is shown that a distinction can be made between two basic types of binary plants based off of mass flow and performance data. The well depth is shown to have no effect on plant performance. In addition, condenser parameters were investigated and the highest efficiency condenser system is determined.

Keywords: Geothermal energy; Power Plant; Binary cycle; Well depth; Temperature; Cooling methods; Mass flow rate; Power output; Efficiency; Meta Study.

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Nomenclature:

T	temperature	*Subscripts*	
$\dot{Q}$	heat flow		
h	specific enthalpy	out	preheater outlet
$\dot{m}$	mass flow	in	evaporator inlet
$\dot{W}$	work rate (power)	cout	cooling water outlet
c	specific heat capacity	cin	cooling water inlet
η	carnot efficiency		
performance	concerns efficiency and power output		
geofluid	heated brine sourced from subsurface reservoir		

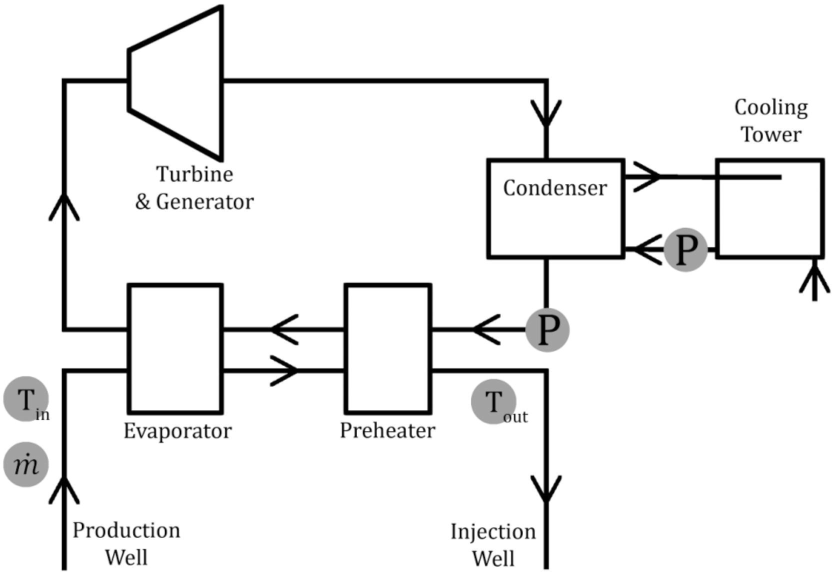
1. Introduction

Binary cycle power plants are the most in operation comprising ~ 47% of the total number (613) of geothermal plants worldwide [1]. A distinction between binary cycle and other geothermal systems is that binary plants are able to operate on low temperature geofluids. The Otake plant (no longer in operation) in Japan and Miravalles Unit 5 in Costa Rica both operate on the waste fluid from other geothermal plants that would otherwise be reinjected into a reservoir. Suitable temperatures for binary plants are typically < 150 ºC, in this temperature range other geothermal systems become inviable. Binary geothermal plants then have less heat available for conversion into work and produce a lower net power than other systems, as reflected in the fact that binary plants account for only 12% of the total power output from all geothermal systems [1]. Due to the low temperature, wells don’t necessarily produce water spontaneously and pumps are required, an effect of this is that water leaves the well as a compressed liquid. Compared with other renewable energy generators, geothermal power plants provide an advantage because of the consistent availability of their source of energy, as opposed to sunlight and wind which are only periodically available.

1.1 Working principles.

Binary cycle power plants use three separate cycles of fluid. Figure 1 shows a basic binary power plant. The first cycle is of heated geofluid produced from a reservoir and eventually reinjected down another well or used for other purposes. The second cycle is closed and runs the turbine, the fluid of this cycle is named the ‘working fluid’. It is heated by the geofluid at both the evaporator and pre-heater until it evaporates. This working fluid is directed to a turbine where it expands and produces work; it is then condensed and a pump returns it to the heat exchanger. This second cycle is similar to the working fluid cycles found in conventional types of power plants, such as coal fired or natural gas power plants. A cycle of cooling fluid condenses the working fluid after it has passed through the turbine. The working fluid is then transported back to the preheater to repeat the process.

Figure 1. The basic structure of a binary cycle geothermal power plant. Each 'P' stands for a pump. The point at which a parameter is measured is labelled with the symbol for that parameter.



2. Methods

2.1 *Methodology*

This meta study focused on binary cycle geothermal power plants and covered research published from 1995 to 2015, accessed via the databases Sciencedirect and Scopus. Material published by plant manufacturers and geothermal conferences was also used. 15 binary cycle power stations from around the world were chosen, offering a broad range of data to compare. Values for the parameters detailed below were taken from these sources for use in all work carried out. Appendix A. displays all data collected and calculated for this study. This data was used to produce Figures 2 – 5.

The parameters investigated are mass flow rate, geofluid temperature, cooling water temperature and production well depth. Mass flow rate is the mass of geothermal water flowing into the plant per unit time measured before the entrance to the evaporator. Geofluid temperature is measured both before entering the evaporator (T_{in}) and after leaving the pre-heater (T_{out}). Cooling water temperature is measured before entering condenser (T_{cin}) and after leaving the condenser (T_{cout}). It is important to note that these parameters vary with time and all measurements taken represent an average value. The raw plant data in [2] shows how the power output of the Wairakei plant varies over the year, with the maximum being around winter. Production well depth is the length measured from ground level to the end of the production well in the reservoir.

The performance parameters, power output and efficiency were also collected from the literature. When efficiency data was unavailable it was calculated using eqn. (1) below. The specific enthalpies of water in and out of the heat exchanger were calculated using pressure and temperature data and the CATT 3 software [3]. When pressure data was unavailable a further approximation was made and eqn. (2) was used. Both equations assume that all of the heat lost by the water is absorbed by the working fluid. Efficiency had to be calculated for 3 out of 15 plants, these are, Birdsville, Altheim and Wairakei. All of the data collected was produced by the source given (except in the cases mentioned).

$$\eta = \frac{\dot{W}}{\dot{Q}} = \frac{\dot{W}}{\dot{m}(h_{in} - h_{out})} \qquad (1)$$

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T \qquad (2)$$

3. Results and Discussion

3.1 Parameters Investigated

3.1.1 Mass Flow Rate

Mass flow was first related to power output, this relationship is shown in Figure 2. where each data point represents one power plant. The Te Huka plant is excluded from this plot as mass flow data was unavailable. The trend is for power output to increase with mass flow rate. More mass flowing into a plant results in a larger amount of heat that is available to be converted into work, hence we see that plants with higher mass flow rates produce more power. This leads to the question of whether not power output continues to increases beyond the range of this plot. If geothermal water is flowing through the plant too rapidly the amount of time available for heat to be exchanged to the working fluid decreases, the heat exchanging process tends toward an adiabatic one. This would result in an eventual decrease in the power output and suggests there is an optimum mass flow rate that will give the highest possible power output. If calculating an optimum value for mass flow for this data set were possible the result would not be applicable to any specific individual plant. In addition there is an upper limit placed on mass flow that is related to the well head pressure [4]. Below a certain pressure the well cannot increase its mass flow, this is referred to as a 'choked' well flow and is dependent on the individual plant's design. Although we hypothesise that power output will reach a maximum it is possible that the choked well flow isn't great enough for this to happen.

The hypothesised drop in power output is due to a decrease in the amount of heat flowing into the plant via the heat exchanger. As such we expect a reduction in the difference in temperature measured before and after the heat exchanger as mass flow increases. Figure 4. shows that the difference in temperature is lower for higher mass flow plants, which reflects the expectations. It is noted that 3 plants had to be left out of this figure for the sake of clarity, those plants are Dora II, Magmamax and Heber 2, reducing the total number of plants to 11. These plants had high temperature differences and high flow rates, which may be due to them having higher efficiency heat exchangers. Since their heat exchangers are of a different design they can't be expected to follow the same trend. The amount of heat that flows into the plant per unit time can be approximated using eqn. (2). From eqn. (2), it can be seen that an increase in both mass flow rate and the temperature difference results in more heat flowing into the plant and thus more power is able to be generated. This equation however is linear and will not show any drop off in heat flow with high mass flow.

From Figure 2. there appears to be two separate groups of plants. Those of a lower mass flow (below 300 kg/s, square symbol), which follow a clear trend and those of a higher mass flow (above 400 kg/s, triangle symbol), which are significantly more spread out. The existence of these two groups may be due to the design of each plant. It was found, by looking at the schematic for each plant, that plants from the first group were of a design similar to that in Figure 1. this is true for 7 out of these 9 plants. A trend line is given for this group only. 5 out of the 5 plants from the second group are systems with two turbines driving the same generator and sometimes with multiple generators. The exceptions are the Dora II and Magmamax plants from the low mass flow group who also have this design. Providing a reason as to why the specific differences in design affect each plot is beyond the scope of this study. Here we only show that the two types of plants behave differently. In Figure 3. the two groups are also visible. The first group again follows a more predictable trend than the second. In Figure 4. the three plants excluded are not from the same group.

Figure 3. shows the relationship between efficiency and mass flow. The efficiency used here is dependent on both the power output and the heat flow into the power plant (eqn. (1)). It was shown in the previous discussion that both of the parameters affecting efficiency ($\dot{Q}$, $\dot{W}$) increase with mass flow rate. In Figure 4. there is an increase in efficiency as mass flow increases. From the definition of efficiency this suggests that $\dot{W}$ increases with mass flow at a higher rate than $\dot{Q}$ so that the ratio between them increases. The relationship appears linear however an intersection with the origin is required since at zero mass flow the plant is no longer operating and cannot convert heat into work, giving a zero efficiency.

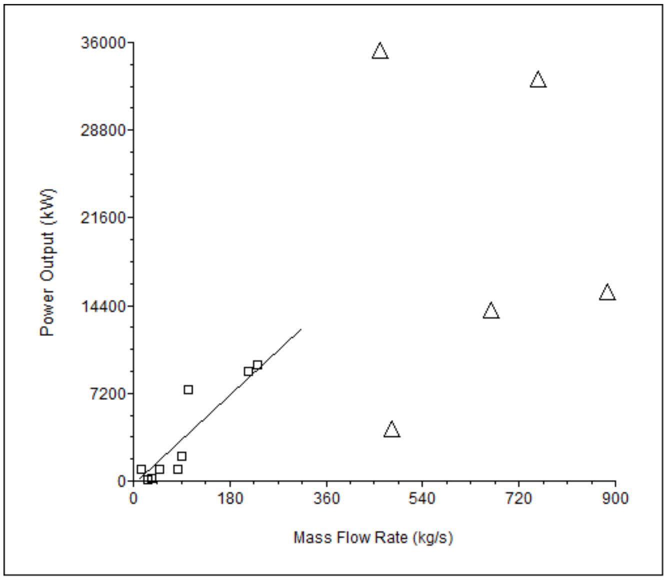


Figure 2. Net power output (kW) is plotted against mass flow rate (kg/s).

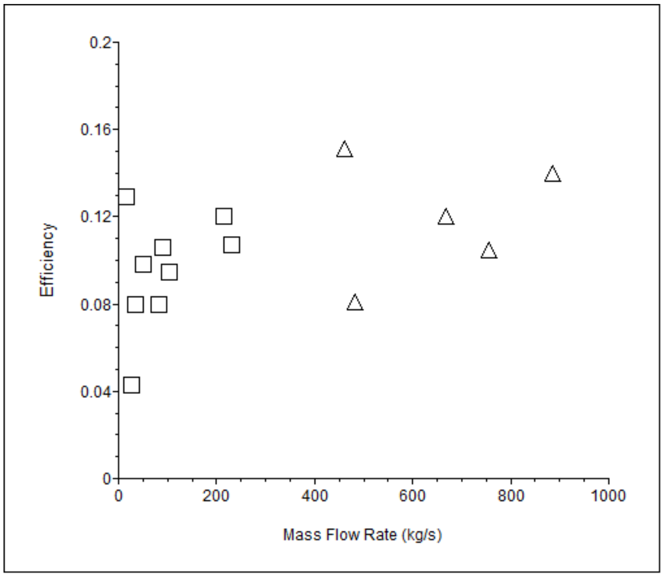


Figure 3. First Law efficiency is plotted against mass flow rate (kg/s).

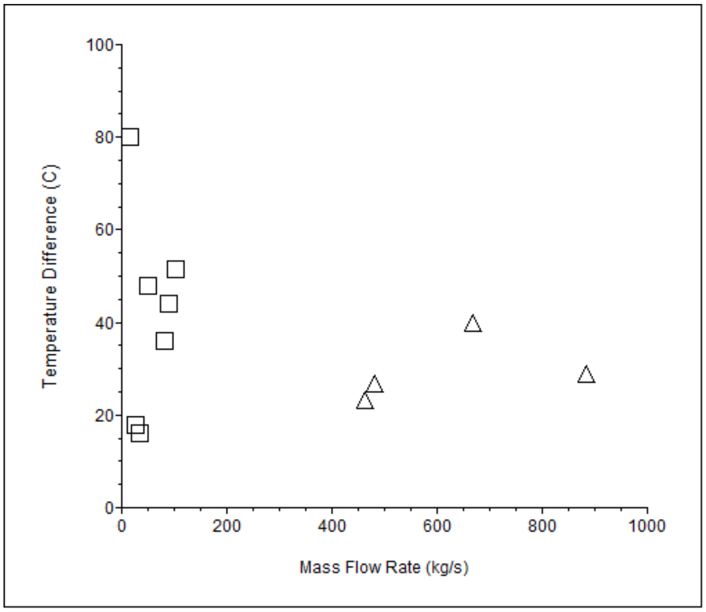


Figure 4. The temperature difference (Tin - Tout) is plotted against mass flow rate (kg/s).

3.1.2 Well depth

Well depth was investigated as a non thermodynamic parameter. Production wells carry the geofluid from the reservoir to the surface, while injection wells carry the fluid back into the reservoir. Only production wells were considered as any energy lost could directly affect the performance of the plant. The plants are usually situated in a thermally active field, where the production wells are located, and can utilise a number of wells. The number of production wells for the individual plants looked at ranged from 1 to 54. The average depths ranged from 213 to 3928 metres.

As the geofluid travels from the reservoir to the surface it loses energy. This is caused by wall friction, acceleration due to flashing, and gravity. Heat is lost through the casing if the well travels through cold formation rock [5]. Deeper wells lose more energy, which impacts on the efficiency of the plant [6]. Though well depth is an important factor in the design and financial outlay of constructing geothermal plants, the heat loss is a minor factor compared to the temperature of the reservoir in determining what type of geothermal system would be suited and the performance of the plant.

Drilling wells makes up a substantial fraction of the construction cost, between 30-40% [6], however this is determined by the depth of the reservoir which in turn is determined by the temperature of the geofluid and whether its suitable for power generation.

The relationship between well depth and other thermodynamic parameters was investigated however it became clear that well depth was only dependent on the depth of the reservoir, and had no relationship to any performance parameters. Plotting well depth against the performance parameters gives no discernable trend.

Table 1. Well Depth, No. of Production Wells.

Plant	Avg. Production Well Depth (metres)	No. of Production Wells
Chena Hot Springs (USA)	213	1
Las Pailas (Costa Rica)	1637	6
Wairakei (New Zealand)	600	54
Altheim (Austria)	2300	1
Dora II (Turkey)	1300	2
Heber 2 (USA)	3928	11
Birdsville (Australia)	1280	1
Husavik (Iceland)	710	3
Te Huka (New Zealand)	1100	3
Otake (Japan)	500	4
Brady (USA)	932	6
Tuzla-Canakkale (Turkey)	548	2

Magmamax (USA)	2450	-
Nigorikawa (Japan)	-	-
Miravalles Unit 5 (Costa Rica)	1750	-

3.1.3 Cooling Methods

There are three major cooling methods used in geothermal plants. Once-through, closed-loop and dry-cooling.

Once-through systems divert natural water sources and pass them through the condenser systems in the plant. These systems draw energy out of the refrigerant before expelling the water back into their original source. Sites that employ this method are built in locations where there is a flowing river that can be diverted through the plant and back into the source with minimal pumping. This is the most energy efficient way to cool the refrigerant as nature is supplying most of the energy required to move the water, however this deviates a large amount of water which disrupts habitats and can inject impurities into the water source [7].

Closed-loop systems initially draw water from a source but once it is in the system it is stored in a water tower. This tower exposes the water to air allowing it to cool before it cycles through the condenser. Some of the water is lost due to evaporation at the water tower which needs to be replaced; the only time additional water is drawn from the source. Using the closed loop system allows a plant to be totally self contained and doesn't require a moving water source. Closed-loop systems require more energy to move the water around the system as it has to be pumped from the tower to the condenser and back again. It has a higher water consumption and the water tower requires more land space than the once-through plant [7].

Rather than taking water and passing it through the condenser dry-cooling systems expose the refrigerant to ambient air in order to cool it. This can reduce power costs by a huge margin as water does not need to be pumped through the system. It does, however, decrease the overall efficiency of the plant meaning more fuel is needed to generate the same amount of energy as the above methods resulting in greater air pollution and environmental impacts. Dry-cooling is usually only used on smaller plants [7].

Table 2. Type of cooling system, temperature in and out of the condenser and condenser efficiency.

Plant	Cooling system	T_{cin} (C)	T_{cout} (C)	Condenser Efficiency (%)
Chena Hot Springs (USA)	Once-through	4.4	10	60

Las Pailas (Costa Rica)	Once-through	-	-	-
Wairakei (New Zealand)	Once-through	-	-	-
Altheim (Austria)	Once-through	10	18	40
Husavik (Iceland)	Once-through	5	25	80
Heber 2 (USA)	Closed-loop	20	28	30
Birdsville (Australia)	Closed-loop	25	30	2
Dora II (Turkey)	Closed-loop	17	29	40
Otake (Japan)	Closed-loop	-	-	-
Miravalles Unit 5 (Costa Rica)	Closed-loop	-	-	-
Magmamax (USA)	Closed-loop	-	-	-
Brady (USA)	Closed-loop	-	-	-
Nigorikawa (Japan)	Closed-loop	-	-	-
Tuzla-Canakkale (Turkey)	Dry-cooling	25.4	33	23
Te Huka (New Zealand)	Dry-cooling	-	-	-

The biggest factor when choosing a cooling method for a plant is the geothermal field's proximity to a water source, with once-through systems being the most efficient the closer to a running water source the better. However if there is a large distance from a water source to the plant or there is a natural or man-made obstruction that makes it impossible to divert the water source then closed-loop systems are the best alternative, requiring large amounts of water to be stored on site makes the overall area of the plant rather large, and allowing for the stored water to be sufficiently cooled between the condenser and the storage tank before it is recycled back through to the condenser requires a fairly complex pipe system as well as a pump to move the water round the circuit, reducing the net output of the plant.

The cooling water is the heat sink of a binary plant. The temperature of the cooling water needs to be reduced to increase the efficiency of the power plant. However, as the cooling water is often sourced from natural water supplies its temperature is uncontrollable. A warmer source of water requires a higher rate of flow to move the hotter water out of the condenser faster and allow for cooler water to draw more energy out of the system.

Condenser efficiency was calculated for 7 of the plants, 3 using the once-through method, 3 using the closed-loop method and 1 using dry cooling. This is the Carnot efficiency of a heat engine working between the temperatures T_{cin} and T_{cout}. No data could be found for the other plants. From this data we find that the average condenser efficiency of the one-through system is 60% while for the closed-loop system the efficiency is 24%.

3.1.4 Temperature In and Out

The binary cycle system is ideal for geographic locations where the geofluid is not exceptionally hot. By using three processes inside the cycle, hot water can be produced for the purpose of power production [8]. By researching in journals for the temperatures of the geofluid that goes from a heat source into the plant and out of the plant into a heat sink or reservoir, an efficiency of the heat exchanger may be calculated. Table 3. contains the data collected on geofluid temperature as well as calculated values for the carnot efficiency of each plant's heat exchanger.

The Carnot cycle is an ideal closed power cycle of thermal efficiency, η. This ideal process is a reversible heat transfer, therefore no temperature difference between the heat source and the working fluid occurs along this process [4]. The Carnot cycle sets a theoretical upper limit on the efficiency of these plants but they are considered accurate. It is important to note that this efficiency is the efficiency of the heat exchanger, not of the plant itself [9].

Basic binary plants have low thermal heat exchanger efficiencies mainly due to the small temperature difference between the heat source before and after the heat exchanger. As observed in Figure 5, it can be determined that the greater the difference in the temperature between T_{in} and T_{out}, the higher the heat exchanger efficiency. This is demonstrated in the linear relationship above. The reason that binary plants are so ideal is because they do not need high temperatures to produce geothermal power, however, it has been shown that the more heat that the plant can use from the incoming fluid, the higher the efficiency will be.

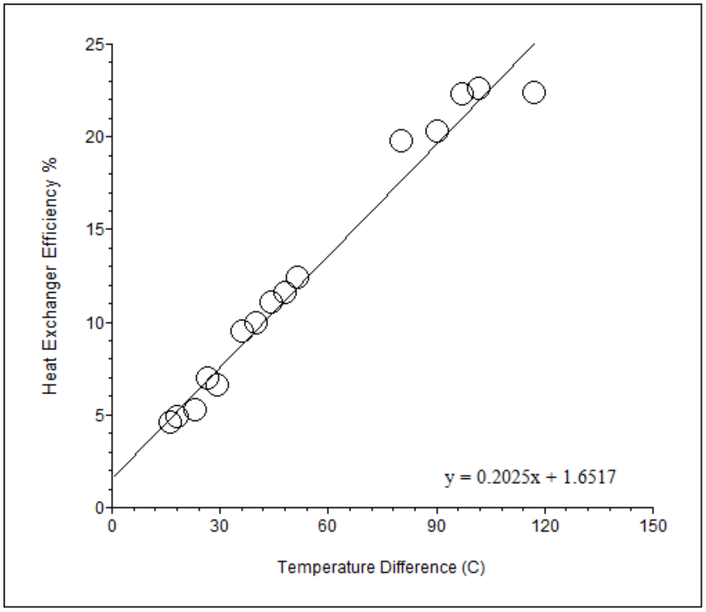
Table 3. Temperature in/out and calculated heat exchanger efficiency.

Plant	T_{in} (K)	T_{out} (K)	Efficiency η%
Chena Hot Springs (USA)	346.15	330.15	4.6
Las Pailas (Costa Rica)	438.4	415.26	5.3
Wairakei (New Zealand)	400.15	360.15	10.0
Altheim (Austria)	379.15	343.15	9.5
Dora II (Turkey)	443.15	353.15	20.3
Heber 2 (USA)	438.15	340.95	22.3

Birdsville (Australia)	371.15	353.15	4.9
Husavik (Iceland)	397.15	353.15	11.1
Te Huka (New Zealand)	523.15	406.15	22.4
Otake (Japan)	403.15	323.15	19.8
Nigorikawa (Japan)	413.15	365.15	11.6
Brady (USA)	380.95	354.36	7.0
Tuzla-Canakkale (Turkey)	415.15	363.75	12.4
Magmamax (USA)	449.82	348.15	22.6
Miravalles Unit 5 (Costa Rica)	438.15	409.15	6.6
		Average	12.7

The calculated values for heat exchanger efficiency show that the plants omitted from Figure 4. in section *3.1.1,* Dora II, Magmamax and Heber 2 have the three highest heat exchanger efficiencies of the plants considered in that section. This justifies their omission.

Figure 5. Heat exchanger efficiency dependence on the temperature difference.



3.1.5 Efficiency

This meta study investigated and analysed the degrees to which specific design factors affect binary power plant's efficiency. The mass flow rate at the evaporator, bore depth, cooling fluid efficiency and geofluid temperature are the major factors that were looked at. To summarise, the higher the difference in temperature between the fluid that comes into the plant and the fluid that leaves, the higher the efficiency of the overall plant. Also, the higher the mass flow rate, the higher the efficiency of the plant. The well depth does not affect the efficiency of the plant as concluded in this meta-study. The once-through system has been determined as the most efficient shown by the cooling fluid efficiency.

Thermal efficiency could not be calculated for Te Huka, as the mass flow rate could not be sourced or calculated. Should be noted however that its heat exchanger efficiency was the second highest out of the 15 plants investigated in this meta-study, which suggests its overall thermal efficiency would be at the higher end of the binary cycle plant efficiency range.

There are other factors that affect a binary power plants efficiency. These include, contaminants known as non compressible gases (NCGs), heat loss in pipes due to pipe material and pipe length and also turbine power. These are valid parameters but were not taken into consideration in the meta-study.

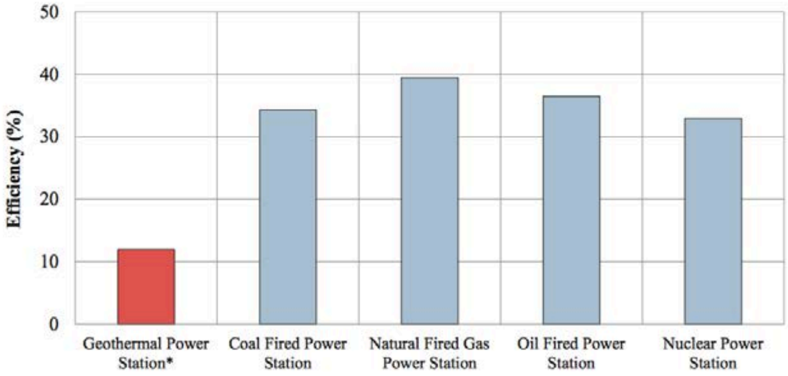
Table 4. Thermal Efficiency.

Plant	Thermal Efficiency %
Chena Hot Springs (USA)	8.0
Las Pailas (Costa Rica)	15.1
Wairakei (New Zealand)	18.0
Altheim (Austria)	7.7
Dora II (Turkey)	10.7
Heber 2 (USA)	10.5
Birdsville (Australia)	4.8
Husavik (Iceland)	10.6
Te Huka (New Zealand)	-
Otake (Japan)	12.9
Brady (USA)	8.1
Tuzla-Canakkale (Turkey)	9.5
Nigorikawa (Japan)	9.8
Miravalles Unit 5 (Costa Rica)	14.0
Magmamax (USA)	12.0

3.2 Comparison: Geothermal and other Power Plants

Binary power plants are similar to the more common types of power plants (e.g. Coal, Nuclear) when compared to other geothermal systems in that the cycle of the working fluid is closed. In single flash and dry steam geothermal plants turbines are driven by the geofluid itself. The following is a short summary of how binary plants compare to other methods for generating electricity.

Figure 6. Geothermal power station efficiency compared to other systems.[5]



A binary power plant emits 13-380 g/kWh of greenhouse (CO_2) gases annually [10].

3.2.1 Nuclear Power

Nuclear power emits from 0.1 to 134 g/kWh of greenhouse gases [11]. Comparing this value to a binary power plant puts the two on fairly equal footing,. Nuclear power plants are accountable for 10.9% of the world's energy production [12], whereas binary power plants produce 6%.

Global average efficiency for nuclear power generation is 33% [13]. Compared to binary cycle geothermal systems, where average efficiency can range from 7-12%, at low temperatures but can reach up to 20% at high temperatures [14].

3.2.2 Coal Fired Power

Coal fire and geothermal binary power differ greatly. One main difference is that of greenhouse (CO_2) emissions. Coal fired plants emit 1042 g/kWh of greenhouse gasses [10]. This is a very large difference, however when it is taken into consideration that binary power plants only produce 6% of the total power output in the world and coal fire produces at least 40%, it is understandable why coal fire produces more emissions worldwide.

Global average efficiency for coal fired power generation is 34% [13]. For binary cycle geothermal systems the average efficiency can range from 7-12%, at low temperatures but can reach up to 20% at high temperatures [14].

3.2.3 Oil Fired Power

The greenhouse gas emissions from oil-fired power stations is 758 g/kWh [10] which is large in comparison to a binary power plant system. Oil fired power pertains approximately 35% of the world's energy production output. This is an amount much greater than that of a binary plant.

Global average efficiency for oil fired power generation is 37% [13]. As mentioned above binary cycle average efficiency can range from 7-12%, at low temperatures but can reach up to 20% at high temperatures [14].

3.2.4 Natural Gas

A major difference between geothermal binary power plants and natural gas reserves is the greenhouse (CO_2) emissions. As mentioned previously, emissions from a binary power plants range from 13-380 g/kWh whereas emissions from natural gas constitute 453 g/kWh annually [10]. Natural gas is estimated to produce approximately 30% of the world's energy and this is compared to 6% for binary plants.

Global average efficiency for natural gas power generation is 40% [13]. Compared to binary cycle geothermal average efficiency which can range from 7-12%, at low temperatures but can reach up to 20% at high temperatures [14].

4. Conclusions

This paper has established some general statements about binary cycle geothermal power plants. Binary plants can differ drastically in design from one another. Since this is the case, the relationships discussed may be due to the individual design of each plant and not the parameter assumed to be the independent variable. This issue was overcome by the number of data points used. We conclude that power output and efficiency increase with mass flow rate and hypothesize that power output reaches a maximum at a given flow rate as the heat exchanging process between the geofluid and working fluid eventually becomes adiabatic at a high enough flow rate. This hypothesis is verified by data, which shows that the geothermal water in higher mass flow plants has a smaller difference in temperature before and after the heat exchange when compared to that of lower mass flow plants. It was also shown that two different basic plant designs respond differently to variations in mass flow. A distinction was made between these two types of binary plants however no explanation was given as to why each design alters the trend. The dependence of performance on mass flow for this collection of geothermal binary plants suggests that a similar relationship will be found when the parameters ($\dot{Q}$, $\dot{W}$, $\dot{m}$) are measured for a single plant.

The depth of the production well has no effect on plant performance. This is because the well depth is dictated entirely by the depth of the reservoir. If it were possible to vary the well depth of a single plant the amount of heat entering the plant would vary. However, from the data obtained there is no correlation.

The cooling system used by the plant depends less on efficiency and more on location and intended power output. With the once-through system being the most efficient it is ideal, however without a near by water source it is impractical. Closed-loop systems are the most common as the plants that use them can be built anywhere and the cooling water can be used for additional purposes, such as home heating, however this requires a large amount of space for the water to be stored and excessive pipes and pumps for transporting it. The dry-cooling system is the least efficient but also uses a minimal amount of water and takes up the least amount of space, it is ideal for small plants, arid regions, or locations where space is an issue.

As determined previously, the temperature into the evaporator inlet and the temperature out of the preheater outlet greatly dictate the efficiency of the binary power plant. The greater the difference in temperature between the two values, the greater the heat exchanger efficiency, which leads to an overall higher efficiency.

To improve the performance of a geothermal binary cycle power plant the following points need to be considered. Mass flow should be increased to the point of maximum efficiency and power output. Low temperature cooling water should be used in conjunction with a once-through cooling system to increase plant efficiency. High efficiency heat exchangers should be used as they increase the heat flow into the power plant. This meta-study has found these things to be beneficial to the performance of binary cycle geothermal power plants.

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5. Appendices

Collected data for all 15 plants.

Binary Geothermal Plants	Mass Flow rate (kg/s)	Source T_{in}(C)	Source T_{out}(C)	Heat Exchanger Efficiency*	T_{cin} (C)	T_{cout} (C)	Condenser Efficiency*	Avg. (m) Production Well Depth	No. of Production Wells	Thermal Efficiency	Net (kW) Power Output	References
Chena Hot Springs (USA	33.39	73	57	4.6	4.4	10	0.6	213	1	0.08	210	[15][16][17]
Las Pailas (Costa Rica)	461.94	165.2	142.1	5.3	-	-	-	1637	6	0.151	35360	[8]
Wairakei (New Zealand)	669.4	127	101	10.0	-	-	-	600	54	0.12*	14000	[2][18]
Husavik (Iceland)	90	124	80	11.1	5	25	0.8	710	3	0.106	2000	[9][19]
Altheim (Austria)	82	106	70	9.5	10	18	0.4	2300	1	0.08*	1000	[20]
Heber 2 (USA) <	756	165.6	67.8	22.3	20	28	0.3	3928	11	0.105	33000	[4][21]
Miravalles (Costa Rica)	885	165	136	6.6	-	-	-	1750	-	0.1397	15500	[4][8]
Otake (Japan)	14.7	130	50	19.8	-	-	-	500	4	0.129	1000	[9][22]
Nigorikawa (Japan)	50	140	92	11.6	-	-	-	-	-	0.0981	1000	[9][22]
Magmamax (USA)	214.2	176.7	75	22.6	-	-	-	2450	-	0.12	9000	[4]
Dora II (Turkey)	231.94	170	80	20.3	17.1	29.1	0.4	1300	2	0.107	9500	[23] [18]
Brady (USA)	482	107.8	81.11	7.0	-	-	-	932	6	0.081	4330	[9][24] [19]
Birdsville (Australia)	26	98	80	4.9	25	30	0.02	1280	1	0.043*	80	[25][24]
Te Huka (New Zealand)	-	250	133	22.4	-	-	-	1100	3	-	-	[18]
Tuzla-Canakkale (Turkey)	102.53	142	90.6	12.4	25.4	33	0.02	548	2	0.0947	7500	[5][26][27][22

> Indicates Once-through cooling system, applies to all plants below until the next symbol.
< Indicates Closed-loop cooling system.
^ Indicates Dry-cooling system.
* Value(s) were calculated by the authors of this study