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Review

Efficiency of geothermal power plants: A worldwide review

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ABSTRACT

The conversion efficiency of geothermal power developments is generally lower than that of all conventional thermal power plants. Confusion can be found in literature concerning the estimation of this conversion efficiency. Geothermal power plants conversion efficiency estimates that is based on the enthalpy of the produced geothermal fluid can be the most desirable for use during the first estimates of power potential of new wells and for resource estimation studies.

The overall conversion efficiency is affected by many parameters including the power plant design (single or double flash, triple flash, dry steam, binary, or hybrid system), size, gas content, dissolved minerals content, parasitic load, ambient conditions and other parameters.

This work is a worldwide review using published data from 94 geothermal plants (6 dry-steam, 34 single flash, 18 double flash, 31 binary, 2 hybrid steam-binary and 1 triple flash plant) to find conversion efficiencies based on the reservoir enthalpy.

The highest reported conversion efficiency is approximately 21% at the Darajat vapour-dominated system, with a worldwide efficiency average of around 12%. The use of binary plants in low-enthalpy resources has allowed the use of energy from fluid with enthalpy as low as 306 kJ/kg, resulting in a net conversion efficiency of about 1%.

A generic geothermal power conversion relation was developed based on the total produced enthalpy. Three more specific correlations are presented for single flash/dry steam plants, double flash plants and binary plants. The conversion efficiency of binary plants has the lowest confidence, mainly because of the common use of air cooling which is highly affected by local and seasonal changes in ambient temperatures.

Contents

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1. Introduction

Geothermal power development is witnessing a rapid growth worldwide. The short-term forecast indicates an installed capacity of 18,500 MWe by the year 2015. This represents an increase of approximately 73% from 2010 (Bertani, 2010).

Geothermal power generation is characterised by high fixed (initial) cost and a relatively low variable (running) cost (Dickson and Fanelli. 2003). Therefore, geothermal power stations are normally used for base load with reported high capacity and availability factors (AGEA, 2010).

The conversion efficiency is of significant importance for resource estimation studies during the early pre-feasibility and feasibility stages of the development and when calculating the power potential of newly drilled geothermal wells. The conversion efficiency is the ratio of net electric power generated (MW_e) to the geothermal heat produced/extracted from the reservoir (MW_{th}).

Geothermal power plants have lower efficiency relative to other thermal power plants, such as coal, natural gas, oil, and nuclear power stations (Fig. 1).

It is commonly assumed that only 10% of the energy from the produced geothermal fluid can be converted to electricity (IEA, 2007). Barbier (2002) suggests that the power conversion efficiency from geothermal steam ranges from 10 to 17%. While Dickson and Fanelli (2003) gave a 18% efficiency for a single flash system with inlet pressure of 6.5 bar. However, each geothermal power plant has its own conversion efficiency, which depends on many factors. For example, Chena Hot Springs (Aneke et al., 2011; Holdmann and List, 2007) binary plant has an efficiency of only 1% due to an average fluid enthalpy of 306 and a temperature of 73 °C, while Darajat (Ibrahim et al., 2005; Kaya et al., 2011) in Indonesia reaches an efficiency of 20.7%.

For resource estimation, the AGEA (2010) gave preference to using a specified process/technology rather than using an efficiency of conversion based on the energy removed.

This study reviews the efficiencies of geothermal power plants based on the type of plant and the features of the geothermal fluid. The efficiency of a power station is evaluated as follows: net electricity produced/thermal energy input (Ibrahim et al., 2005). In geothermal power plants, the energy input can be defined as total mass of fluid (kg/s) multiplied by the average production enthalpy (kJ/kg) as shown below:

$$\eta_{act}(\%) = \frac{W}{\dot{m} \times h} \times 100 \quad (1)$$

where W is the running capacity (kWe), $\dot{m}$ is the total mass flow rate (kg/s), and h is the reservoir enthalpy (kJ/kg).

Exergy analysis, which is the maximum power output that could theoretically be obtained from a geothermal system relative to the surrounding (ambient temperature) is not considered in this work. Exergy analysis is normally performed to optimise production from an "existing" energy conversion system once they reach their design operating conditions (DiPippo, 2012). Exergy analysis is used to identify those elements within a plant that are most in need of redesign to improve their efficiency (DiPippo, 2012).

This work provides a high-level assessment of the conversion efficiency of geothermal power plants based on available "published" data from the current worldwide experience.

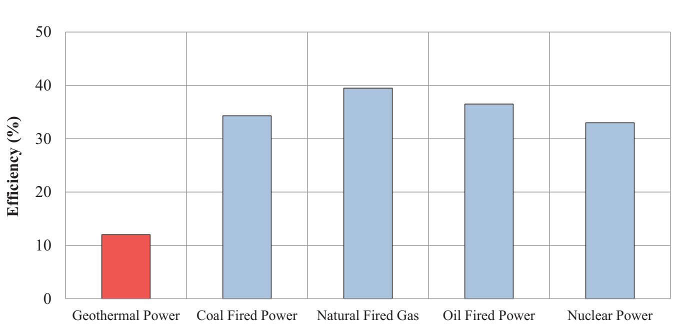


Fig. 1. Thermal power plant efficiency.
Source: Data from Roth (2004), Taylor et al. (2008) and this work*.

2. Factors affecting efficiency

Geothermal fluid is extracted from a production well, it passes through many processes and/or different pieces of equipment on its way to the power station. During this time the geothermal fluid loses energy that is not used to produce power.

As geothermal fluid enters the well from the reservoir it is considered as a constant enthalpy (throttling) process. However, as the fluid start to travel up the well, there will be a loss in energy (enthalpy). This is because as the fluid travels against gravity, friction with the casing, acceleration due to flashing and also as the there is some heat lost in the parts of the casing surrounded by cold formation/ground. On average the geothermal fluid loses about 50–100 kJ/kg of the enthalpy in most geothermal wells.

In liquid dominated systems, the produced two-phase geothermal fluid loses a significant amount of heat when separating steam from water. Only the separated steam is used for generation unless there is another separator or binary plant installed.

For example, the Kizildere (Simsek et al., 2005; Ar, 1985) single flash plant uses geothermal fluid with an enthalpy of 875 kJ/kg. Therefore, only 36% of the heat from the separator is sent to the turbine, while 64% of the energy is rejected. In high enthalpy, geothermal fluid will have more of the produced heat sent to the power station. An example of this is the Nesjavellir plant, which has an enthalpy of 1503 kJ/kg. 66% of the heat reaches the turbine. While the plants at Cerro Prieto and Svartsengi have respective enthalpies of 1396 and 1148 kJ/kg receives 68 and 70% respectively.

Double flash and/or bottoming binary plants can use heat more effectively than single flash. However, during the design of the separator, the main consideration is the silica (SiO_2) content of the geothermal fluid. During the flash process, a pressure drop is used to generate additional steam from the geothermal fluid. This results in an increase in the silica concentration of the remaining fluid (brine). This silica can build up a thick layer of solid deposit on the internal surfaces of pipelines, flash plants and on turbine blades impeding the flow of the fluid and leading to a drop in the conversion efficiency and an increase in maintenance costs.

Other factors affecting the conversion efficiency are: Non-condensable gas (NCG) content, heat loss from equipment, turbine and generator efficiency and power plant parasitic load (e.g. fans, pumps, and gas extraction system) (Barnett, 2007; Murakami, 2001a,b; Ballzus et al., 2000; Gunerhan and Coury, 2000; Kudo, 1996; DiPippo and Energy, 1978).

2.1. Non condensable gases (NCG) content

Unlike clean steam from a boiler/steam generator in a conventional thermal power plant, geothermal steam contains non-condensable gases (NCG) ranging from almost zero up to about 15% by weight in some geothermal fields. These gases not only degrade the quality of the steam and increase corrosion but also require the consumption of power to remove them from the power plant condenser. For this reason, a geothermal power plant requires a large capacity gas extraction system, which forms a significant portion of total capital cost and can consume a large amount of auxiliary power. The selection of an appropriate gas extraction system is therefore of particular important in geothermal power plants.

The NCG mainly consists of carbon dioxide (CO_2), hydrogen sulfide (H_2S) and some other gases in tracer quantities (e.g. CH_4, H_2, N_2, He, Ar, Ne). The effect of NCG's is not significant until the steam reaches the condenser (Millachine, 2011). Geothermal fluid containing NCG's lowers the power efficiency because it decreases the specific expansion work in the turbine and has adverse effect on the performance of a turbine (Vorum and Fitzler, 2000; Khalifa and Michaelides, 1978).

In the Kizildere geothermal field's average non-condensable gases percentage is 13% by weight (Gunerhan and Coury, 2000), meaning that the power consumption of the gas extraction system is comparatively high compared to all other power plants.

Steam containing NCG of 1% by weight reduces the power out by 0.59% in comparison with steam without NCG (Hudson, 1988).

$$\eta_{\text{NCG}} = 1 - 0.0059C \tag{2}$$

where C is the NCG content % by weight.

2.2. Parasitic load

Cooling the steam as it leaves the turbine is necessary in order to raise the power conversion efficiency with the drop in condenser pressure. Cooling the water for the condenser requires pumps and fans. A dry type cooling tower consumes twice as much electricity compared with a wet cooling tower (Mendrinos et al., 2006) it also ocupies twice the area. Some geothermal plants use production (down hole) pumps as well as reinjection pumps as an additional parasitic load.

Mutnovzky, Kamchatka (DiPippo, 2007) single flash plant turbine exhaust pressure is only 0.05 bar abs. The heat used in the turbine is notably higher than plants using similar enthalpy geothermal fluid in warmer environment.

Auxiliary power consumption, which includes all pumps, cooling equipment, and gas extractors in a power plant is subtracted from the gross power output.

$$\eta_{\text{apc}} = -1\frac{W_{\text{apc}}}{W_{\text{gross}}} \tag{3}$$

where W_{gross} is the gross electric power and W_{apc} is the total auxiliary power consumption.

W_{apc} is very dependent on the specifics design of the power conversion system. Generally it is significantly greater in binary and hybrid (steam and binary) systems compared with conventional condensing steam plants (Dickson and Fanelli, 2003).

The proportion of the W_{apc} to W_{gross} is also reduced with the increase in the size of the power plant and hence increasing the η_{apc}.

2.3. Heat loss

Geothermal fluid also loses heat as it flows in pipes, valves, separators and other steam gathering equipment with the size of the losses depending on the pipe size, insulator, the length of pipe, and the ambient temperature. The heat loss will result in some steam condensing at the bottom of the pipeline which is normally discharged in the drain pots. Therefore there will be a loss of steam mass flowing to the turbine. However, it is possible to consider the heat loss in the pipe as relatively negligible. For example, 80 t/h of steam at 180 °C is travelling in a 0.4 m diameter and 2.0 km long pipe. The pipe is insulated with 8 cm thick layer of fibreglass with an ambient temperature of 20 °C. In this case, the inlet steam enthalpy is 2777.1 kJ/kg while the outlet steam enthalpy is 2759.4 kJ/kg. Thus the energy loss is only 0.6% (Zarrouk, 2011).

For the above ambient temperature and pipe, the following equation can be derived.

$$\eta_{\text{pipe}} = 1 - 0.003L_p \tag{4}$$

where η_{pipe} is the pipe efficiency based on total geothermal energy and L_p is the pipe length in km.

Therefore keeping the pipelines short will not only reduce the capital cost, but also improves the plant efficiency.

2.4. Turbine efficiency

Once the steam reaches the power station it passes through the turbine that drives the generator. Wahl (1977) showed turbine efficiency vary between 60 and 80%. Dickson and Fanelli (2003) later demonstrated that the isentropic efficiency for a geothermal turbine would typically range between 81 and 85% (Dickson and Fanelli, 2003).

The turbine efficiency drops due to deviation from isentropic behaviour and the presence of moisture in the turbine during the steam expansion process. The Baumann rule shows that the presence of 1% average moisture causes a drop of about 1% turbine efficiency. The Baumann rule can be described in the following simple equations (Baumann, 1921; DiPippo, 2012; DiPippo and Energy, 1978; Leyzerovich, 2005; Nugroho, 2011):

$$\eta_t = \eta_{\text{td}} \times \left(a \times \frac{X_{\text{in}} + X_{\text{out}}}{2}\right) \tag{5}$$

where η_t is the turbine efficiency, η_{td} is the dry turbine efficiency which is about 0.85 (DiPippo and Energy, 1978), X_{in} is the turbine inlet dryness fraction (equal to 1), and X_{out} is the turbine outlet dryness fraction. The coefficient "a" is an empirical value known as the Baumann factor. Various experiments on different types of turbines reveal a range of values for "a" that vary from 0.4 to 2; however, a is usually assumed to be equal to 1.

2.5. Generators efficiency

The generators efficiency is relative to the power capacity (Storey, 2004). Table 1 gives a range of generators efficiency from different manufacturers. From Table 1 it is clear that the generator efficiency increase with the size of the generator and for the size of geothermal plants the generator efficiency range from 95.7 to 98.7% (Lund et al., 2010).

Using all the factors mentioned above, finding the power conversion efficiency can be achieved by using the following equation:

$$\eta = \dot{m}_s \times \Delta h \times \eta_t \times \eta_g \times \eta_{\text{ncg}} \times \eta_{\text{apc}} \times \eta_{\text{pipe}} \tag{6}$$

where η is the overall conversion efficiency, $\dot{m}_s$ is the steam flow rate in turbine, Δh is the enthalpy difference between turbine inlet an outlet.

3. Geothermal steam plant efficiency

The amount of energy that can be converted to electricity is limited by the second law of thermodynamics. It is also a function of and the optimum plant design and the efficiency of different components. Bodvarsson (1974), Nathenson (1975) and the AGEA (2010) gave a conversion efficiency based on geothermal fluid temperature only (Fig. 2).

However, Fig. 2 can only be used for liquid dominated reservoirs, which may not apply to systems with excess enthalpy and/or high enthalpy vapour dominated reservoirs. In this study, the conversion efficiency will be based on reservoir enthalpy.

There are three primary types of steam geothermal power plants, namely dry-steam (Fig. 3), single flash (Fig. 4), and double flash (Fig. 5) power plants. However, the dry-steam and single

Table 1
Typical generator efficiencies.

Manufacturer	Model	Power capacity (MVA)	Efficiency (%)	
Mitsubishi [33]	S16R-PTAA2	2.2	95.7	
Siemens [34]	SGen5-100A-4P		25–70	Up to 98.5
Siemens [34]	SGen5-100A-2p		25–300	Up to 98.7
GE [35]	W28		550	99

Numbers refer to numbered references in the list in the online supplement.

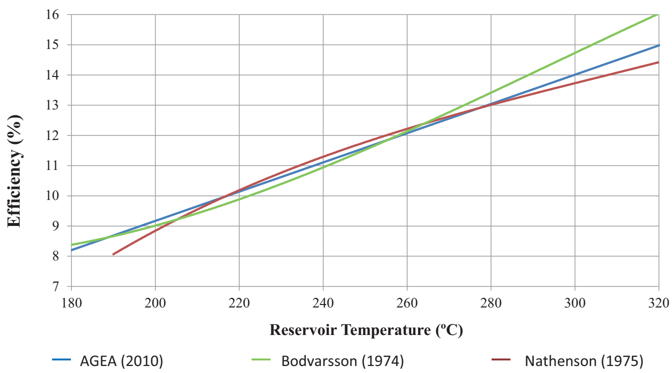
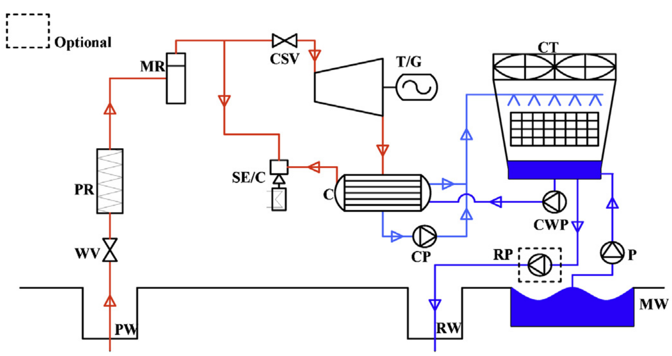
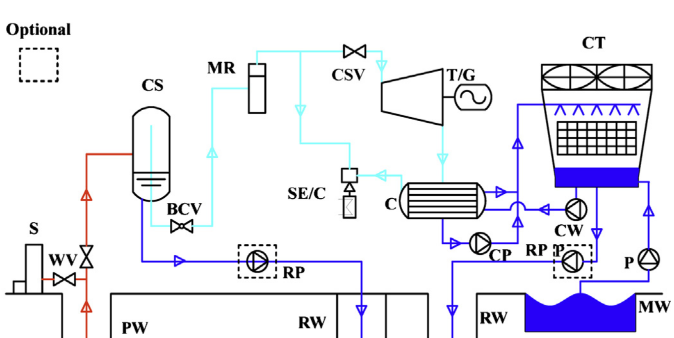


Fig. 2. Geothermal plant efficiency as a function of temperature.



PW	Production well	WV	Wellhead valve	PR	Particulate remover
MR	Moisture remover	C	condenser	CP	Condensate pump
CSV	Control and stop valve	SE/C	Steam ejector/condenser	T/G	Turbine and generator
CT	Cooling tower	CWP	Cooling water pump	RP	Reinjection pump
RW	Reinjection well	P	Pump	MW	Make-up water

Fig. 3. Simplified schematic of a dry steam plant.



PW	Production well	WV	Wellhead valve	S	Silencer
CS	Cyclone separator	BCV	Ball check valve	MR	Moisture remover
CSV	Control / stop valve	T/G	Turbine / generator	SE/C	Steam ejector/condenser
C	condenser	CT	Cooling tower	CWP	Cooling water pump
CP	Condensate pump	RP	Reinjection pump	RW	Reinjection well
P	Pump	MW	Make-up water		

Fig. 4. Simplified schematic for a single-flash plant.

Table 2
The single flash and dry steam power plant.

Field (plant name)	PS 1 (bar abs.)	P_{out} (bar abs.)
Pauzhetka [30]	2.5	0.08
Kizildere [10]	4.8	0.098
Akita (Onuma) [17]	2.45	0.108
Iwate (Kakkonda) [17]	4.5	0.135
Verkhne-Mutnovsky [23]	8	0.12
Mutnovsky [23]	6.2	0.05
Onikobe [17]	4.41	0.107
Ahuahapan [30]	5.58	0.083
Miravalles (Unit 1) [23]	6	0.125
Miravalles (Unit 2) [23]	6	0.1
Miravalles (Unit 3) [23]	5.6	0.09
Miravalles (Well head) [23]	5.9	0.99
Otake [17]	2.5	0.11
Cerro Prieto (CP-1) [23]	6.2	0.119
Svartsengi (Unit 5) [40]	6.5	0.1
Nesjavellir (Unit 1 and 2) [15]	12	0.28
Cerro Prieto (CP-4, Unit 1–4) [23]	10.5	0.115
Tokyo (Hachijyojima) [14]	10.7	1.43
Wayang Windu [41]	10.2	0.12
Suginoi [13]	3.9	0.29
Fukushima (Yanaizu-Nishiyama) [42]	3.9	–
Los Humeros [43]	8	–

Numbers refer to numbered references in the list in the online supplement.

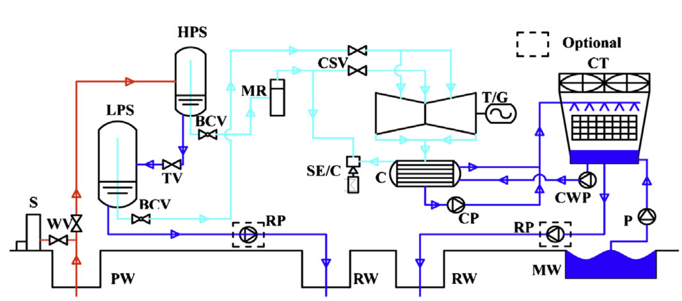
flash power plants are technically very similar (Figs. 3 and 4). It is possible that a single flash generation systems to be converted to dry steam when the field dries. For this reason dry steam data are presented together with single flash.

The power output for a steam turbine is calculated using the following equation (Çengel et al., 2008):

$$W_{st} = \eta_t \times \eta_g \times \dot{m}_s \times \Delta h \tag{7}$$

where W_{st} is the steam turbine power output (MWe), η_t is the isentropic turbine efficiency, η_g is the generator efficiency, $\dot{m}_s$ is the total mass of steam (kg/s), Δh is the enthalpy difference between the turbine inlets and outlets enthalpy (kJ/kg).

Available published data for dry-steam and single flash (Table 2) and double flash (Table 3).



PW	Production well	WV	Wellhead valve	S	Silencer
HPS	High pressure separator	LPS	Low pressure separator	BCV	Ball check valve
TV	Throttle valve	MR	Moisture remover	C	condenser
CSV	Control / stop valve	T/G	Turbine / generator	SE/C	Steam ejector/condenser
CT	Cooling tower	CWP	Cooling water pump	CP	Condensate pump
RP	Reinjection pump	RW	Reinjection well	P	Pump
MW	Make-up water				

Fig. 5. Simplified schematic for a double-flash plant.

Table 3
The double flash power plant data.

Field (Plant name)	PS 1 (bar abs.)	PS2 (bar abs.)	P_{out} (bar abs.)
Nevada (Brady Hot Springs) [44]	4.5	2.3	–
Nevada (Beowawe) [45]	4.21	0.93	0.044
Cerro Prieto (CP-1, Unit 5)[23]	4.15	2.05	0.111
Bouillante 1 [46]	6	1.4	0.096
Cerro prieto (CP-2, CP-3) [23]	10.75	3.16	0.114
Mori [47]	7.8	2.7	–
Kyushu [48]	6.3	1.4	–
Hachobaru 2 [48]	6.8	1.3	–
Banahaw 1,2,3,4 [48]	6.5	1.7	–
Tongonan 1,2,3 [48]	5.8	1.1	–
Ahuahapan [30]	5.48	1.5	0.083
Mindanao 2 [48]	6.8	3.5	–
Krafla 1,2 [48]	7.58	1.9	0.119
Heber [49]	3.8	1.1	0.12
Coso 1 [48]	5.6	1.2	–
Salton Sea 3 [48]	7.9	1.7	–
Geo East Mesa 1,2 [48]	3.0	1.1	–
Hellisheidi [50]	9	2	–
Kawerau [51]	13	2.9	–
Ohaaki [51]	10	4.5	–
Hachobaru 1 [17]	6.37	1.47	0.098

Numbers refer to numbered references in the list in the online supplement.

The average separator pressure is 6.2 bar abs. for single flash plants (Table 4). While the average separators pressures are 6.7 and 2 bar abs. respectively for double flash plants. Table 5 shows that: the average condenser pressure is 0.12 bar abs. This is excluding data from Miravalles and Hichijojima plants, which have back-pressure turbines.

3.1. Single flash and dry steam plants

The single flash power and dry steam data (Table 2) are applied to Eq. (1) to calculate the actual (η_{act} efficiency in comparison with the AGEA (2010) turbine efficiencies as shown in Fig. 6. The match with the conversion efficiency from the AGEA (2010) is very close from an enthalpy of about 1400 kJ/kg to 2800 kJ/kg (Fig. 6).

Note that Cerro Prieto (CP-1, Units 1–4) (DiPippo, 2012; Ocampo-Díaz et al., 2005) uses geothermal fluid with an enthalpy of 1396 kJ/kg and shows an abnormally high efficiency of 26%, which is much higher than that of a dry steam plants (15.1–17.5%). Conversely, Lihir (Holdmann and List, 2007), Los Humeros (Kruger et al., 1987; Quijano-León and Gutiérrez-Negrín, 2000), and Hachijojima (Murakami, 2001a,b) plants use fluid with enthalpies of over 2030 kJ/kg geothermal fluid, yet are shown to have oddly low efficiencies.

Hichijojima (Murakami, 2001a,b) geothermal fluid contains a high content of H_2S gas, which is non-condensable. The geothermal fluid is separated at 10.7 bar abs. The separated steam is sent to the steam scrubbing system in the plant at 10.7 bar abs. to trap the mist and improve steam quality. When the separated steam enters the turbine, its pressure is only 7.9 bar abs. and its outlet pressure is 1.43 bar abs. This outlet pressure is much higher than that of other geothermal power plants. It is probable that H_2S gas which accumulates in the condenser decreases heat transfer and raises the turbine outlet pressure. Thereby lowering turbine performance and power plant efficiency.

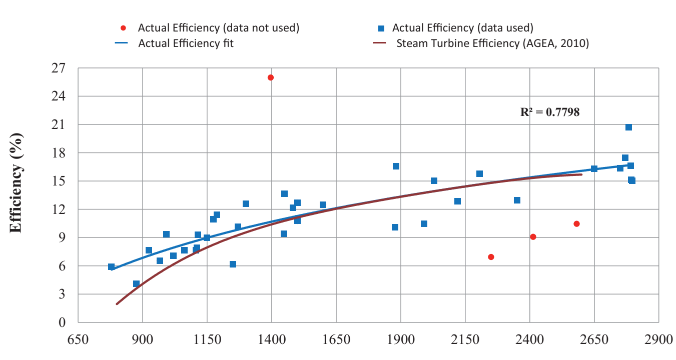


Fig. 6. The single flash and dry steam efficiency.

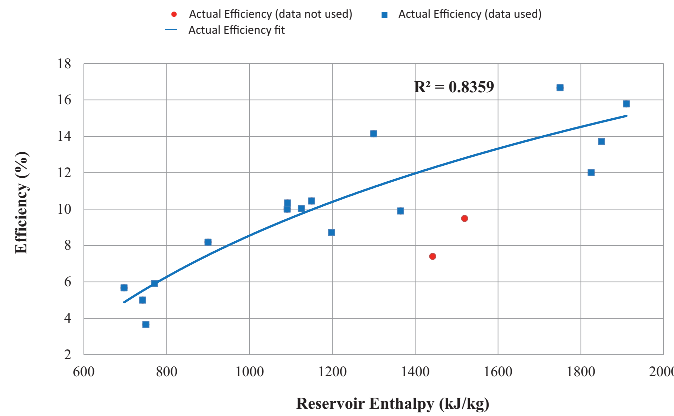


Fig. 7. The double flash actual efficiency.

Los Humeros (Kruger et al., 1987; Quijano-León and Gutiérrez-Negrín, 2000) has back-pressure units which operate with an exhaust equal to or in excess of atmospheric pressure. On the other hand, the condensing turbine exhaust pressure is lower than atmospheric pressure. The low efficiency at Lihir is due to a back-pressure turbine (Holdmann and List, 2007).

Similarly, Uenotai (Takayama et al., 2000) geothermal power plant, which uses geothermal fluid with a similar enthalpy to Lihir (Holdmann and List, 2007), is found to have an efficiency that is also slightly lower than the actual efficiency curve given in Fig. 6.

Soon after beginning operation at the Uenotai plant, the pressure at the main steam governing valve was found to increase rapidly when operating at the rated output, while the generator output decreased. It was found that evaporation and flashing had led to an increase in the silica content of the geothermal fluid. The Silica precipitated and resulted in a build-up of silica-rich scaling and a corresponding decrease in the plant efficiency.

Data from the following plants are excluded from the fitting: Lihir (Holdmann and List, 2007); Los Humeros (Kruger et al., 1987; Quijano-León and Gutiérrez-Negrín, 2000); Hachijojima (Murakami, 2001a,b); and Cerro Prieto (CP-1, Units 1–4) (DiPippo, 2012; Ocampo-Díaz et al., 2005), due to the discrepancies described in the previous above.

The single flash and dry steam efficiencies can be fitted with one simple model given below.

$$\eta_{act} = 8.7007 \ln(h) - 52.335 \quad (8)$$

3.2. Double flash power plants

Similarly, the double flash power plant data from Table 3 were also applied to Eq. (1) and shown in Fig. 7.

The double-flash steam plant shown in Fig. 7 is an improvement on the single-flash design. It produces about 15–20% more power output for the same geothermal fluid (DiPippo, 2012).

Cerro Prieto (CP-2) and (CP-3) (DiPippo, 2012; Ocampo-Díaz et al., 2005) using geothermal fluid of enthalpies 1442 and 1519 kJ/kg respectively have efficiencies of only 7.4% and 9.5% for actual efficiency. This is lower than the single flash actual efficiencies (10.9% and 11.4%). Therefore the results shown in Fig. 7,

Table 4
Single flash plant pressure showing separator and turbine exhaust pressure.

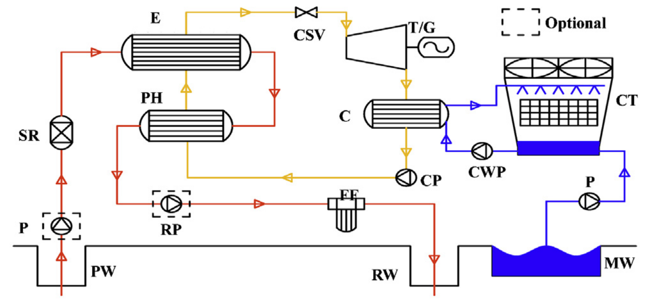
Country	Field (plant name)	No. unit	Type	Start date	Installed capacity (MWe)	Running capacity (MWe)	$\dot{m}$ (t/h)	$\dot{m}_s$ (t/h)	$\dot{m}_f$ (t/h)	h (kJ/kg)	Reference
Russia	Pauzhetka	3	1F	1967	11	11	864	–	–	780	[6,68]
Turkey	Kizildere	1	1F	1984	20.4	10	1000	114[a]	886[a]	875	[6,10,11]
Japan	Oita (Takigami)	1	1F	1996	25	25	1270	–	–	925	[6,69]
Japan	Akita (Onuma)	1	1F	1974	9.5	9.5	540	107	433	966	[6,17,69]
Japan	Iwate (Kakkonda)	2	1F	1978	80	75	2917	416	2501	992	[69–71]
Japan	Miyagi (Onikobe)	1	1F	1975	12.5	12.5	625	–	–	1020	[17,69,72,73]
USA	Utah-Roosevelt Hot Springs (Blundell1)	1	1F	1984	26	23	1020	180	840	1062	[32,63]
Costa Rica	Miravalles (1,2,3, Well heat unit)	4	1F	1993	144	132.5	5634	1188[a]	4446[a]	1107	[23,74,75]
France	Bouillante 2	1	1F	2004	11	11	450	90	360	1110	[46,76,77]
El Salvador	Ahuahapan (U1,2)	2	1F	1975	60	53.3	1848	373	1475	1115	[78,79]
Indonesia	Gunung Salak	6	1F	1994	330	330	11520	2520	9000	1149	[80–82]
Philippines	Mindanao (Mindanao1)	1	1F	1997	54.24	54.24	1515	–	–	1175	[83,84]
Mexico	Las Tres Virgenes	2	1F	2002	10	10	265	63	202	1188	[85,86]
Nicaragua	Momotombo (Unit 1–2)	2	1F	1983	70	29	1350	–	–	1250	[64,87]
El Salvador	Berlin (U1,2,3)	3	1F	1999	100	100	2790	774	2016	1270	[78,79]
Guatemala	Amatitlan-Geotermica Calderas	1	1F	2003	5	5	110	–	–	1300	[88,89]
Mexico	Cerro Prieto (CP-1, Units 1–4)	4	1F	1973	150	131	1300	450	850	1396	[23,52,85,90]
Iceland	Svartsengi (Unit 5)	1	1F	1999	30	30	792	288	504	1448	[40,91]
Philippines	Southern Negros (Palinpinon 1, 2)	7	1F	1983	192.5	192.5	3500	–	–	1450	[6,92]
Philippines	Leyte (Mahanagdong)	6	1F	1997	198	198	3958	–	–	1482	[93,94]
Japan	Akita (Sumikawa)	1	1F	1995	50	46.5	878	–	–	1500	[69,95,96]
Iceland	Nesjavellir (Unit 1,2)	2	1F	1998	60	60	1339	475	864	1500	[15,97]
Russia	Mutnovzky, Kamchatka	5	1F	1998	62	62	1118	496[a]	622[a]	1600	[6,23,68]
Mexico	Cerro Prieto (CP-4)	4	1F	2000	100	94	1785	1020	765	1877	[23,52,90,98]
Japan	Fukushima (Yanaizu-Nishiyama)	1	1F	1995	65	65	750	450	300	1882	[42,69]
Philippines	BacMan (Palayan, Cawayan, Botong)	4	1F	1993	150	150	2590	450	300	1990	[6,23,99,100]
Mexico	Los Azufres	12	1F	1982	185	185	2184	1668	516	2030	[85,101]
Kenya	Olkaria (Olkaria1)	3	1F	1981	45	31	410	285	125	2120	[102,103]
Indonesia	Sulawesi (Lahendong – U1)	1	1F	2002	20	20	206.7	144	62.7	2206	[80,104,105]
PNG	Lihir	4	1F	2003	36	36	830	–	–	2250	[6,106,107]
Japan	Akita (Uenotai)	1	1F	1994	28.8	28.8	340	–	–	2350	[54,69,108]
Mexico	Los Humeros	7	1F	1990	42	40	657	543	114	2413	[43,53,85]
Japan	Tokyo (Hachijyojima)	1	1F	1999	3.3	3.3	44	40[a]	4[a]	2582	[14,69]
USA	California – The Geyser	24	D	1971	1529	833	6950	6950	–	2650	[32,79,109–111]
New Zealand	Wairakei (Pohipi)	1	D	1996	25	25	200	200	–	2750	[6,112,113]
Italy	Larderello	21	D	1985	542.5	411.7	3060	3060	–	2770	[6,114]
Indonesia	Darajat	2	1F	1994	145	145	907	907	–	2783	[6,7,105]
Indonesia	Java (Kamojang)	3	D	1982	140	140	1086	1086	–	2792	[6,23,105]
Italy	Travale/Radicondoli	6	D	1986	160	126.6	1080	1080	–	2793	[114,115]
Japan	Iwate (Matsukawa)	1	D	1966	23.5	23.5	201	201	–	2797	[6,17,69]

Numbers refer to numbered references in the list in the online supplement.
[a] Mass of steam and brine are calculated based on separator pressures.

Table 5
Double flash plant pressure showing separators and turbine exhaust pressures.

Country	Field (plant name)	No. unit	Start date	Installed capacity (Mwe)	Running capacity (MWe)	$\dot{m}$ (t/h)	$\dot{m}_{s1}$ (t/h)	$\dot{m}_{s2}$ (t/h)	$\dot{m}_f$ (t/h)	h (kJ/kg)	Reference
USA	California-East Mesa (GEM2, 3)	2	1989	37	34.2	3116	196[a]	172[a]	2748[a]	697	[48,116,117]
Mexico	Cerro Prieto (CP-1, Unit 5)	1	1982	35	26.25	2550	143[a]	121[a]	2286	742	[23,85,90,118]
USA	Nevada (Brady Hot Springs)	3	1992	26	20	2630	188[a]	182[a]	2260[a]	750	[44,119]
USA	California-Heber (Heber)	1	1985	52	47	3720	302[a]	256[a]	3162[a]	771	[48,49,116]
USA	Nevada (Beowawe)	1	1985	16.7	16.7	817	109[a]	65[a]	643[a]	900	[45,120,121]
El Salvador	Ahuahapan (U3)	1	1981	35	28	924	–	–	737	1091	[78,79]
France	Bouillante 1	1	1984	4	4.7	150	30	12	108	1092	[46,76]
Japan	Oita (hatchobaru)	2	1977	110	80	2556	535[a]	220[a]	1801[a]	1125	[6,23,48,122]
New Zealand	Reporoa (Ohaaki)	2	1998	46.7	46.7	1400	269[a]	74[a]	1057[a]	1150	[6,51]
Japan	Mori	1	1982	50	50	1724	388	121	1215	1199	[47,69,123]
Iceland	Hellisheidi	5	2006	210	213	5679	1944	216	3519	1365	[50,124,125]
New Zealand	Kawerau	1	2008	100	95.7	1875	465	180	1230	1300	[51,126,127]
Mexico	Cerro Prieto (CP-2)	2	1984	220	172.5	5821	2021	281	3519	1442	[23,52,85,90]
Mexico	Cerro Prieto (CP-3)	2	1985	220	182	4550	1825	131	2594	1519	[23,52,85,90]
Philippines	Leyte (Tongonan 1)	3	1983	112.5	112.5	1389	721[a]	70[a]	598[a]	1750	[48,128,129]
Iceland	Krafla	2	1977	60	60	986	535[a]	43[a]	408[a]	1825	[6,48,130]
Philippines	Mindanao (Mindanao2)	1	1999	54.24	54.24	770	431[a]	17[a]	322[a]	1850	[48,83,131]
Philippines	Makiling-Banahaw (Plant A,B,C)	6	1979	330	330	3942	2207	–	1735	1910	[66,67]

Numbers refer to numbered references in the list in the online supplement.
[a] Mass of steam and brine are calculated based on separator pressures.



PW	Production well	P	Pump	SR	Sand remover
E	Evaporator	PH	Pre-heater	C	Condenser
CP	Condensate pump	RP	Reinjection pump	FF	Final filter
CSV	Control / stop valve	T/G	Turbine / generator	CWP	Cooling water pump
CT	Cooling tower	RW	Reinjection well	MW	Make-up water

Fig. 8. Simplified schematic of a basic binary geothermal power plant.

excludes the data from Cerro Prieto (CP-2) and (CP-3) (DiPippo, 2012; Ocampo-Díaz et al., 2005).

The efficiency of the double flash system is given in equation 9 using a simple best fit to the data in Fig. 7.

$$\eta_{act} = 10.166 \ \ln(h) - 61.68 \tag{9}$$

4. Efficiency of binary plants

Binary geothermal power plants are closed cycles that converts heat from the geothermal fluid into electricity by transferring the heat to another low boiling point working fluid to generate electricity (DiPippo, 2012; Saleh et al., 2007; Bliem and Mines, 1991). Fig. 8 shows a simple binary system commonly used.

Carnot and triangular are ideal closed power cycles of thermal efficiency. These ideal processes are reversible heat transfers. Therefore no temperature difference between the heat source and the working fluid occurs along this process (DiPippo, 2007).

It is easy to see that the efficiencies of the ideal Carnot cycle (Moran and Shapiro, 2006), η_c (Eq. (10)) and the ideal Triangular cycle (DiPippo, 1989), η_{tri} (Eq. (11)) are given in terms of the heat source and sink temperature T_{in} and T_{out}.

$$\eta_c = 1 - \frac{T_{out}}{T_{in}} = \frac{T_{in} - T_{out}}{T_{in}} \tag{10}$$

$$\eta_{tri} = \frac{T_{in} - T_{out}}{T_{in} + T_{out}} \tag{11}$$

A simple comparison between the two ideal efficiencies (Carnot and Triangular) for two different sink temperatures is given in Fig. 9. Dickson and Fanelli (2003) defined the net electric power generation based on operating temperature and the power produced. The thermal power from the geothermal fluid is conventionally

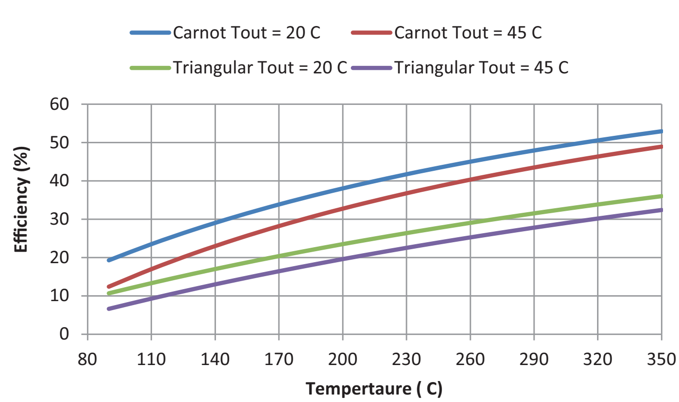


Fig. 9. Carnot and triangular ideal efficiency.

calculated relative to a temperature of 10 °C higher than the bottom-cycle temperature. The bottom-cycle temperature is normally assumed to be 40 °C (Dickson and Fanelli 2003; Hudson, 1988).

$$W = \frac{(0.18T_{in} - 10)\mathrm{ATP}}{278} \tag{12}$$

where W is the net electric power generated (kWe), T_{in} is the inlet temperature of the primary (geothermal) fluid (°C), and ATP is the available thermal power (kW).

The basis of the net electric power generated by DiPippo (2007) proposed a binary plant efficiency with reference to the Triangular cycle efficiency. DiPippo (2007) suggests that when applying Eq. (13) to a case where the inlet temperature is between 100 and 140 °C, the resulting relative efficiency will be roughly 58 ± 4% of the triangular efficiency given in Eq. (11) (DiPippo, 2007).

$$W = 2.47\,\dot{m}\left(\frac{T_{in} - T_0}{T_{in} + T_0}\right)(T_{in} - T_{out}) \tag{13}$$

when the average brine temperature is 120 °C, a specific heat of 4.25 kJ/kg/K has been assumed. W is the net electric power (kWe), $\dot{m}$ is the total mass (kg/s), T_{in} is the inlet temperature of the primary fluid (°C), T_0 is the dead-state temperature (20 °C) and T_{out} is the outlet temperature (°C).

However, the inlet temperature range in Table 6 is between 73 and 253 °C. The case of average brine is at 160 °C with a specific heat of 4.34 kJ/kg/K needs to be applied to Eq. (13).

$$W = 2.51\left(\frac{T_{in} - T_0}{T_{in} + T_0}\right)(T_{in} - T_{out}) \tag{14}$$

Only eight geothermal field outlet temperatures can be found in the published literature (Table 6). The estimate of the power that might be obtained is based on the assumption that the entire geothermal fluid mass is provided to binary plants. In order to find the net electric power (kWe) totals for the outlet temperature, the following equation by Tester et al. (2006) can be used:

$$T_{out} = T_{in} + \frac{W}{0.098701 - 0.0039645T_{in}} \tag{15}$$

where T_{out} is the outlet temperature (°C), W is the net electric power generated (kWe) for a total mass flow rate of one kg/s, and T_{in} is the inlet temperature of the primary fluid (°C).

Eq. (15) was used to calculate the outlet temperatures for 22 geothermal fields from Table 6.

The Berlin (U4) (Enex) plant uses brine from two separators. The maximum geothermal fluid flow rate is 1080 t/h at 185 °C. Los Azufres (U-11, 12) (Torres-Rodríguez et al., 2005) plant receives the first 280 t/h at 180 °C then gets injected, Blundell 2 (Larsen and Saunders, 2008) uses geothermal brine at 177 °C from the Blundell 1 separators and the Momotombo (Unit 3) (Enrique and Porras, 2006) uses the lower temperature brine at 155 °C before being injected.

Ngawha (Council, 2002a,b), Hatchobaru (DiPippo, 2012), Te Huka (NZGA) and Ribeira Grade (Holdmann and List, 2007) binary plants use two phase geothermal fluid. This means that the heat sources of these binary plants are much higher than those located between 228 °C and 253 °C shown in Fig. 10.

Hatchobaru binary plant is designed to use a sub-par well that cannot be connected to the main gathering system. Two phase geothermal fluid is separated at the wellhead. The separated steam and water are used for evaporating and pre-heating working fluid respectively (DiPippo, 2012).

Two net power conversion Eqs. (12) and (14), and the actual conversion efficiency (formulated based on data from Table 6) are shown in Figs. 10 and 11.

For an inlet temperature in °C of the geothermal (primary) fluid:

$$\eta_{act} = 6.9681\,\ln(T_{in}) - 29.713 \tag{16}$$

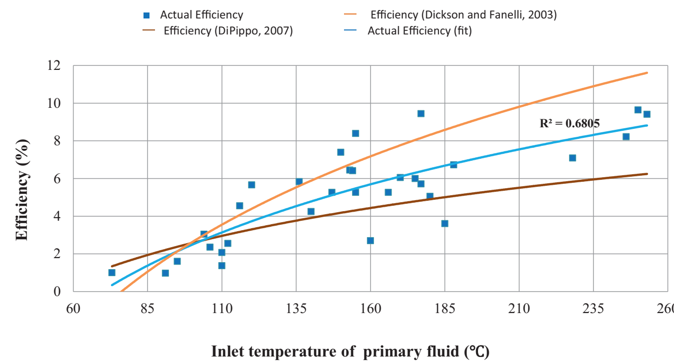


Fig. 10. The binary efficiency function of temperature.

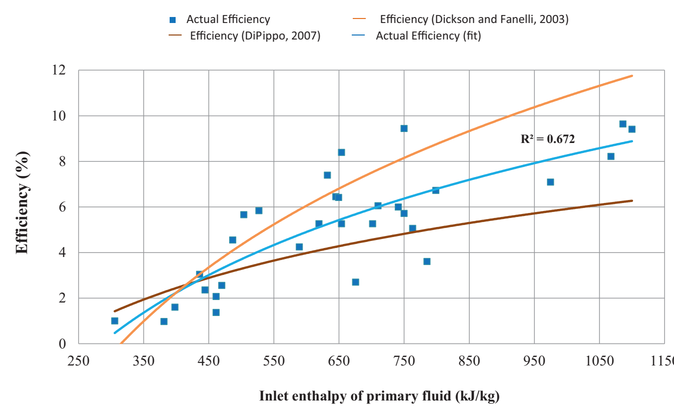


Fig. 11. The binary efficiency based on enthalpy.

For an inlet average enthalpy in kJ/kg of the primary fluid:

$$\eta_{act} = 6.6869\,\ln(h) - 37.929 \tag{17}$$

Figs. 10 and 11 shows that: fitting the reported field from Table 6 are more representative than the models given by Dickson and Fanelli (2003) and DiPippo (2007).

Binary plants utilising the exhaust steam from the back-pressure turbine and/or utilising separated brine are known as hybrid steam-binary systems (Fig. 12). These systems have a relatively high efficiency as the brine temperature can be dropped to low temperatures with minimum silica scaling at the same time no NCG extraction system is needed. However, these hybrid systems are less adaptable to changes in the geothermal reservoir, which is mainly the increase in the produced enthalpy with time as the reservoir dries. This will result in more steam for the backpressure

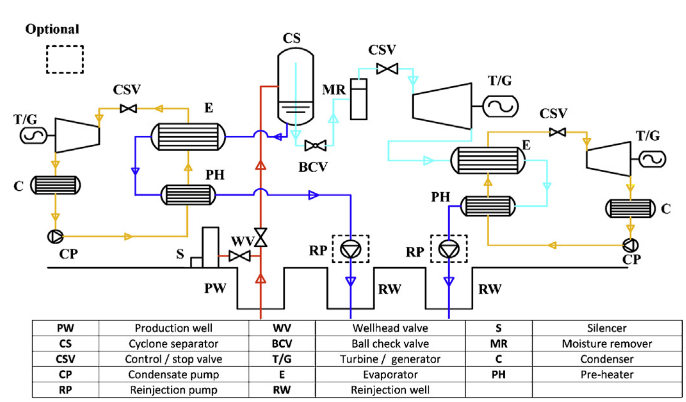


Fig. 12. Simplified schematic of a hybrid steam-binary geothermal power plant.

Table 6
The binary power plants data.

Country	Field (plant name)	No. unit	Start date	Installed capacity (MWe)	Running capacity (MWe)	$\dot{m}$ (t/h)	T_{in} (°C)	T_{out} (°C)	h (kJ/kg)	Reference
USA	Alaska (Chena Hot Springs)	2	2006	0.5	0.4	471	73	57	306	[4,5]
USA	Wyoming-Casper (Rmotc-Ghcg)	1	2008	0.25	0.171	166	91	52	381	[132,133]
Germany	Neustadt-Glew	1	2003	0.23	0.165	93	95	70	398	[134,135]
USA	Nevada (Wabuska)	3	1984	2.2	1.5	407	104	62[a]	436	[120,136]
Australa	Altheim	1	2002	1	0.5	172	106	70	444	[137,138]
Australa	Blumau	1	2001	0.2	0.18	103	110	85	461	[137,139,140]
USA	California-Honey Lake (Wineagle)	2	1985	0.7	0.6	226	110	82[a]	461	[120,141]
China	Nagqu	1	1993	1	1	300	112	77[a]	470	[6,142]
Thailand	Fang	1	1989	0.3	0.175	28	116	55[a]	487	[6,137,143]
Germany	Unter-Haching (Unter-Haching)	1	2009	3.36	3.36	424	120	44[a]	504	[134,144]
USA	California-East Mesa (Ormesa IE)	10	1989	10	9	1054	136	58[a]	527	[116,117,145]
USA	Idaho (Raft River)	1	2007	13	10	1440	140	85[a]	589	[32,146,147]
USA	California-East Mesa (Ormesa 1)	26	1987	24	24	2652	147	80[a]	619	[116,117,145]
Germany	Landau (landau)	1	2008	3	3	231	150	56[a]	632	[134,148]
USA	California-East Mesa (Ormesa IH)	12	1989	12	10.8	935	153	71[a]	645	[116,117,145]
USA	California-East Mesa (Ormesa 2)	20	1988	20	18	1555	154	73[a]	650	[116,117,145]
France	Soultz-Sous-Forets	1	2008	1.5	1.5	98	155	49[a]	654	[76,149,150]
Nicaragua	Momotombo (Unit 3)	1	2002	7.5	6	628	155	100	654	[64,87]
USA	Nevada-Washoe (Steamboat1,1A,2,3)	13	1986	35.1	31	6120	160	126[a]	676	[120,151,152]
USA	California-Heber (Heber2)	12	1993	33	33.5	3266	166	100	702	[116,153]
Turkey	Salavatli	1	2006	7.4	6.5	545	170	80	710	[6,154,155]
USA	California-Casa Diablo (MP-1,2/LES-1)	10	1984	40	40	3240	175	100[a]	741	[32,156,157]
Philippines	Makiling-Banahaw (Binary 1, 2, 3, 4)	6	1994	15.73	15.73	800	177	132	750	[158,159]
USA	Utah-Roosevelt Hot Springs (Blundell2)	1	2007	11	10	840	177	88	750	[32,63]
Mexico	Los Azufres (U-11,12)	2	1993	3	3	280	180	117[a]	763	[62,85]
El Salvador	Berlin (U4)	1	2008	9.4	8	1018	185	140[a]	785	[61,78]
USA	Nevada-Fallon (Soda Lake1)	3	1987	3.6	2.7	181	188	105[a]	799	[32,120]
New Zealand	Northland (Ngawha)	2	1997	10	8	417	228	142[a]	975	[65,160,161]
Japan	Oita (hatchobaru)	1	2006	2	2	82.1	246	146[a]	1068	[23,69]
New Zealand	Te Huka	1	2010	24	21.8	750	250	133[a]	1086	[51]
Portugal	Ribeira Grabde	4	1994	13	13	452	253	139[a]	1100	[6,162]

Numbers refer to numbered references in the list in the online supplement.
[a] Outlet temperature is calculated using Eq. (17).

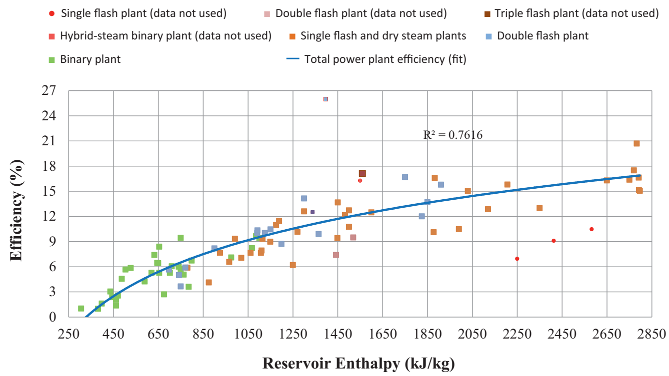


Fig. 13. Geothermal power plant generic efficiency.

steam turbine and the steam bottoming binary system at the same reduced brine flow for the brine side binary systems. Plant shutdown and system modification are likely to be needed with time (author's experience).

Data from only two such systems are publically available (Table 7).

5. Summary

Fitting all the available data (Tables 5–8) with one curve (Fig. 13) produces a generic model for the conversion efficiency as a function of enthalpy:

$$\eta_{act} = 7.8795\ \ln(h) - 45.651 \tag{18}$$

The data in Fig. 13 also gives a worldwide geothermal power plant average conversion efficiency of 12%.

Summary of the conversion efficiencies for binary, single flash–dry steam and double flash is given in Fig. 14. This clearly shows that double flash plants have higher conversion efficiency than single flash plants. However they have a lower efficiency than binary plants for the low enthalpy range (750–850 kJ/kg).

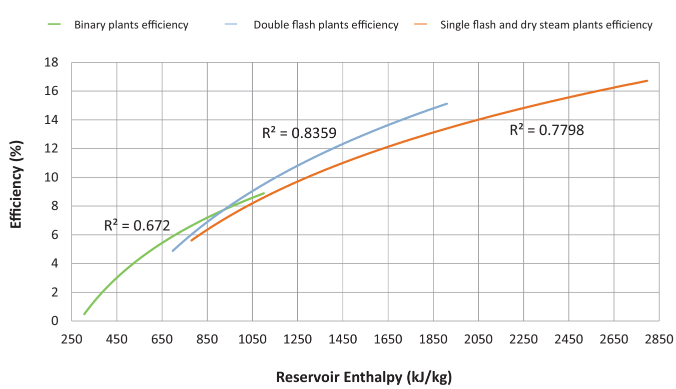


Fig. 14. Geothermal power plant efficiency summary.

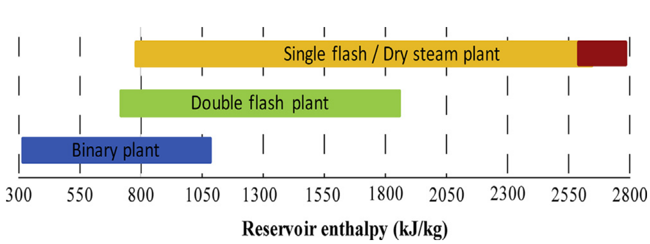


Fig. 15. Geothermal power plant operating enthalpy range based on current published data.

Table 7
The hybrid binary power plants data.

Country	Field (plant name)	No. unit	Type	Start date	Installed capacity (MWe)	Running capacity (MWe)	$\dot{m}$ (t/h)	h (kJ/kg)	Reference
New Zealand	Mokai (Mokai1)	6	Hybrid binary	2000	68	54.2	1168	1338	[6,112,163]
New Zealand	Rotokawa	5	Hybrid binary	1997	35	31	443	1550	[6,51,112]

Numbers refer to numbered references in the list in the online supplement.

Table 8
The triple flash power plant data.

Country	Field (plant name)	No. unit	Start date	Installed capacity (Mwe)	Running capacity (MWe)	$\dot{m}$ (t/h)	$\dot{m}_{s1}$ (t/h)	$\dot{m}_{s2}$ (t/h)	$\dot{m}_{s3}$ (t/h)	$\dot{m}_f$ (t/h)	h (kJ/kg)	Reference
New Zealand	Nga Awa Purua	1	2010	140	139	1875	617	111	105	1042	1560	[164]

Numbers refer to numbered references in the list in the online supplement.

Table 9
Summary geothermal power plant efficiency.

Type of power plant	Conversion efficiency	R^2
General geothermal plant	$7.8795\ln(h) - 45.651$	0.76
Single flash and dry steam plant	$8.7007\ln(h) - 52.335$	0.78
Double flash plant	$10.166\ln(h) - 61.680$	0.856
Binary plant	$6.6869\ln(h) - 37.930$	0.672

Fig. 15 shows the range of operating enthalpy for the different types of geothermal plants. Note that hybrid (steam-binary) and triple flash plants are not included as there are not many in use reported around the world. Fig. 15 shows that Single flash plants operate at a wider range of enthalpy (from ~800 to 2800 kJ/kg), while double flash operate at smaller range (from ~750 to 1900 kJ/kg). This is because as enthalpy increases the reservoir will dry up and there will be less produced water to justify a second flash. At the same time the wellhead pressure is (in dry steam wells) significantly reduce not permitting a second flash.

Binary plants can generate electricity from water as low as 73 °C (306 kJ/kg) to up to 1100 kJ/kg (Fig. 15). However, generation from higher enthalpy fluid is also possible, while for an enthalpy higher than ~1900 kJ/kg only single flash/dry steam plants is recommended.

Summary of the proposed models are given in Table 9.

It is clear that binary plants have a higher error margin than the other type of plants (Table 9). Most binary units use air cooling to reject heat which is strongly affected by the weather and ambient condition. These conditions vary from location to location and are seasonal depending on the time of the year.

6. Conclusions

Several factors affect the conversion efficiency of the geothermal power plants. This includes; system design, NCG content, heat loss from equipment, turbines and generators efficiencies, parasitic load, weather and other factors.

The following conclusions were based on total produced heat using published data from 94 geothermal power plants from around the world.

The average conversion efficiency of geothermal plants is 12%, which is lower that for all conventional thermal power plants.

Conversion efficiency ranges from 1% for some binary systems to as high as 21% for some dry steam plants (Darajat).

The average world-wide plant capacity factor: This is the ratio of the actual output of the power plant and its potential output if operated at full (design) capacity based on the data presented in Tables 5–7:

- 80.1% for single flash–dry steam plants.
- 91.5% for double flash plants.
- 92.7% for binary plants.

These results above are mainly because the total worldwide installed capacity in single flash–dry steam plants are much more than that of double flash and binary plants respectively.

Conversion efficiencies as a function of the reservoir enthalpy are given for single flash/dry steam, double flash, binary plants, and for a generic geothermal power plant.

The proposed correlations are relatively conservative, but give more realistic estimates compared with correlations that are a function of temperature. It should be of use for high level resource estimation studies, benchmarking purposes and for calculating the power potential of new production wells.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.geothermics.2013.11.001.

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