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# Reinjection in Geothermal Fields: A Worldwide Review Update

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**ABSTRACT**

Reinjection is a very important part of any geothermal development and it may become the key factor in the success or failure of the field. In 2010, we conducted a review of the worldwide experiences with injection in geothermal fields, based on information from 91 electric-power producing geothermal projects. In the present review, we have extended the database to include 126 field projects and added an additional five years of experience. In this updated review, various past and current reinjection strategies practised in the geothermal fields and the response of different types of geothermal reservoirs to these strategies were investigated. The location and amount of reinjection, as well as, problems and benefits associated with production were taken into consideration. This study shows that the design of reinjection is most often empirical and site-specific, because the effect of injection on production depends on the structure of the individual system. However, there are some generic similarities depending on whether the system is vapour-dominated, liquid-dominated or hot-water. Experience has shown that reinjection should be planned as early as possible in field development and it should be flexible, as it is likely to change with time. An optimum reinjection design should balance the requirements to sustain the reservoir pressure and to prevent early breakthrough of cold reinjected water. Also, the effects of reinjection on the natural hot recharge and, therefore, on energy recovery from the system may be important.

## 1. INTRODUCTION

A good understanding of past experience of reinjection practices is of high importance for the optimal development and management of a geothermal resource. In this work we have carried out an extensive literature survey of published data of electrical power development in the world to gather information on the worldwide experience of reinjection in geothermal fields. The work complements early results published by Kaya *et al.* (*2011*). In the present updated study we have extended the review to include most recent information about geothermal fields: such as their installed capacity, reservoir information, production and injection conditions, their reinjection strategies, and response of different types of geothermal reservoirs to these strategies. The reports and articles available in the open literature, mainly published after 2010, were the main sources of this review paper. Additional information is also reviewed to provide further details on these fields. This information includes data relevant to the steamfield (i.e. approximate distance between production and reinjection wells, type of the reservoir, reservoir temperature/enthalpy and reservoir depth), to the power plant (type of plants, installed capacity, annual electricity production, total and steam production rates) and to the type of reinjection (injection rate, strategy and response of the field to the reinjection strategy).

### 1.1 Categories of geothermal systems

The literature survey of worldwide reinjection presented in Kaya *et al.* (*2011*) indicates that the effect of injection on production depends on the structure of the individual system. To provide an optimum reinjection plan, geothermal systems should be evaluated according to their individual characteristics. However, there are generic similarities depending on the thermodynamic state, geological structure and hydrological setting.

To decide on the best reinjection strategy for each type of system it is important to recognize the dominant depletion mechanisms. For the three main types of systems these mechanisms can be summarized as follows:

a) Two-phase, vapour-dominated systems (VDS) run out of water while heat still remains in the rock matrix. Therefore it may be useful to reinject water infield, mainly above the depleted reservoir (e.g. The Geysers (Khan, 2010), Larderello (Arias *et al.*, 2010), Kamojang (Saptadji and Artika, 2012, Suryadarma *et al.*, 2010) and Darajat (Mahagyo *et al.*, 2010)).

b) In the two-phase, liquid-dominated systems (LDS) the pressure drop at the production wells is buffered by the boiling process. Therefore, in general these systems do not suffer from an excessive pressure decline. Also because these systems typically have good permeability they experience strong lateral recharge and do not run out of water. Rather they slowly cool down as boiling water and steam are extracted and are replaced by cooler recharge. However, reinjection in this type of system often results in adverse thermal breakthrough and a consequent move of reinjection away from the production zone (e.g. Bulalo (Capuno *et al.*, 2010), Tiwi (Menzies *et al.*, 2010), Ohaaki (Brockbank and Bixley, 2011) and Ahuachapan (Monterrosa and López, 2010)).

c) In hot-water systems (HWS) boiling does not take place before and/or after production; in this type of reservoir the pressure declines to the point where wells can no longer produce. Reinjection assists by providing an extra mass flow and boosting pressure. The ideal reinjection strategy requires the injection wells to be close enough to the production wells to provide pressure support but far enough to prevent premature flooding by cold water. In some fields, particularly those with a few large faults, thermal breakthrough has occurred rapidly, for example, Pauzhetsky (Kaya *et al.*, 2011, Kiryukhin *et al.*, 2010) and Brady Hot Springs (Faulds *et al.*, 2010).

Due to these dominant depletion mechanisms, an optimum reinjection plan should be tailored to the individual characteristics of each system. To assist with the evaluation of reinjection effects, the classification by Kaya *et al.* (*2011*), shown in Table 1, was used in the present study.

**Table 1: Categories of geothermal systems.**

| Category | | Temperature (T) | Production enthalpy (h) |
|---|---|---|---|
| Hot-water | | T < 220˚C | h < 943 kJ/kg |
| Two-phase, liquid-dominated | Low-enthalpy | 220˚C < T < 250˚C | 943 kJ/kg < h < 1100 kJ/kg |
| | Medium-enthalpy | 250˚C < T < 300˚C | 1100 kJ/kg < h < 1500 kJ/kg |
| | High-enthalpy | 250˚C < T < 330˚C | 1500 kJ/kg < h < 2600 kJ/kg |
| Two-phase, vapour-dominated | | 250˚C < T < 330˚C | 2600 kJ/kg < h < 2800 kJ/kg |

### 1.2 Location of reinjection wells

The location of reinjection wells relative to production wells is probably the most important issue in the design of a reinjection system. As it is described in Kaya *et al.* (*2011*), infield reinjection refers to injection wells located close to the production wells and within the hot part of system (i.e. within the resistivity boundary). Outfield reinjection refers to the injection wells further away from the production wells (~2 km or more) and outside the hot part of system; direct hydrological connection to production reservoir may not exist. Unfortunately, these definitions are not very precise and distances cannot be given definitively. Some authors (e.g. SKM (*2004*)) have attempted to define infield reinjection and outfield reinjection in terms of how well the injection wells and production wells are connected measured by pressure communication, and some others (Axelsson, 2012) have defined them based on how reinjection wells are located relative to main production zone (infield: in-between production wells, and outfield: outside of the main production field). However, this classification requires information that is not usually available, particularly before the injection wells are drilled, and therefore may not be practically useful (Kaya *et al.*, 2011).

In addition, reinjection wells are designed to intersect feed-zones at a certain interval. The following options are possible: at the same level to the main production reservoir, above the main reservoir (at shallower levels) or below the main reservoir (at deeper levels).

These locations are chosen depending on main objective of the reinjection (e.g. pressure support, water disposal).

## 2. INFORMATION AVAILABLE

The present study is based on publicly available information from 126 electric power generation geothermal fields around the world. The data gathered from the geothermal fields was focused on the following aspects: natural conditions of the reservoir (i.e. enthalpy/temperature); installed capacity/current generation; produced and injected mass flow rate; temperature of reinjection water; strategies and technology used during reinjection; impact of reinjection on power production and reservoir recharge; and main problems and obstacles associated with production and reinjection (e.g. cooling of production wells, silica or other types of scaling).

The effect of reinjection is also analysed according to the classification presented in Table 1. The initial temperatures/enthalpies used for each field were those prior to exploitation. In some instances, a geothermal field was evaluated based on the geothermal power plants, as they produce different sectors of the same field and their production enthalpy varies. For example the Wairakei-Tauhara field includes Poihipi, Te Mihi, Wairakei and Tauhara power plants (Newson, 2014). While the Poihipi plant mainly produces from a shallow vapour dominated zone, Tauhara produces mainly liquid from a low enthalpy zone. Therefore different reinjection strategies may be considered for the different sectors of the same field. At the same time, few fields from the previous analysis by Kaya *et al.* (*2011*) have been updated/changed as new information has become available, such as Lahendong, which was previously categorised as vapour-dominated but according to Brehme *et al.* (*2014*) it is a liquid-dominated reservoir. Figure 1 reflects the present field categorisation based on the reported enthalpies.

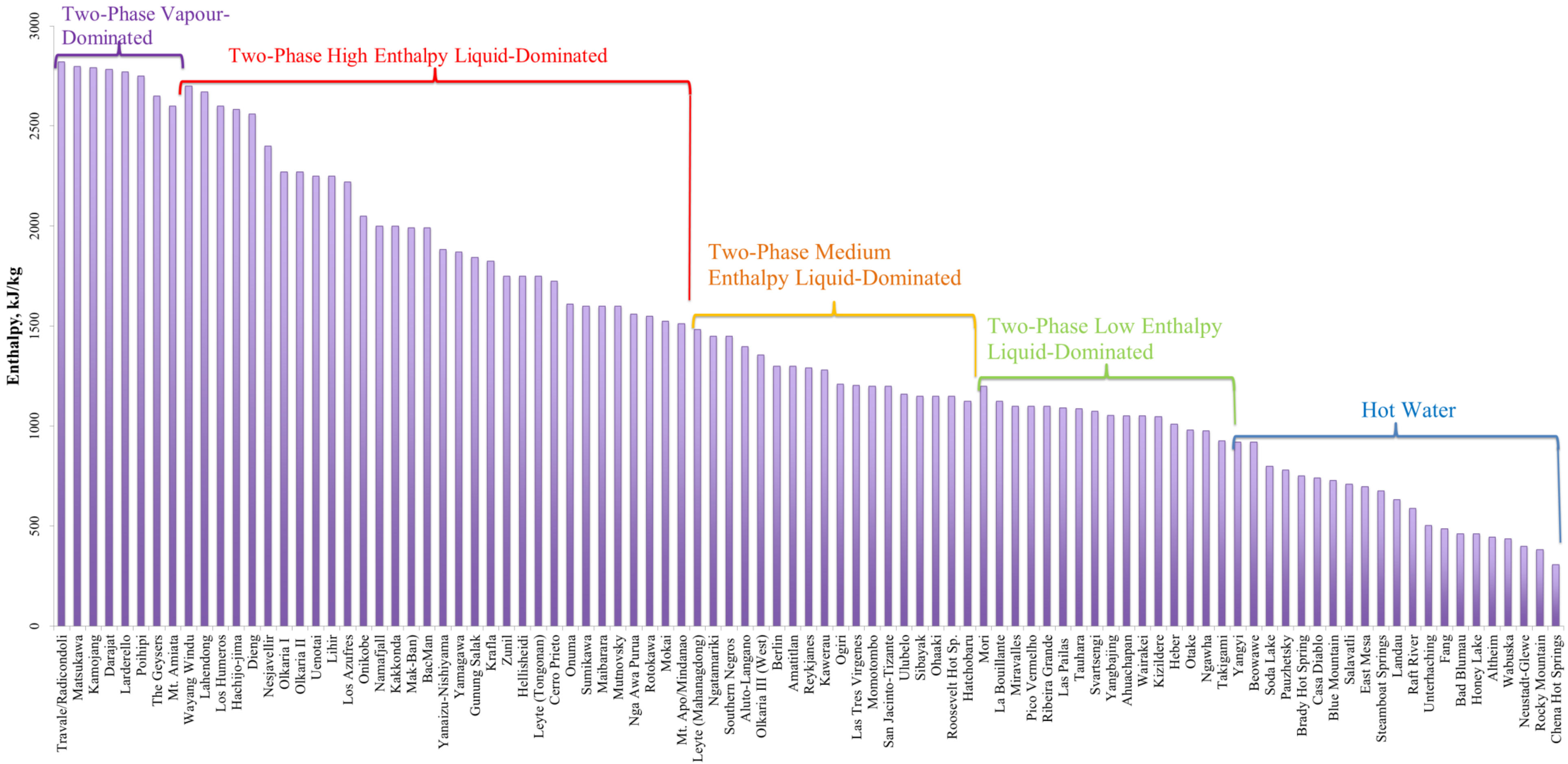



**Figure 1: Reservoir enthalpy for each field and type of system.**

Figure 2 gives the installed power capacity in megawatts (MWe) per type of system. According to our review, the world's total geothermal energy installed capacity up to date is approximately 12,280 MWe. Figure 2 shows that most of the geothermal power development comes from two-phase, liquid-dominated systems (67%), with 70 developed fields. However this data represents 99.93% of the total installed capacity, since five fields were not able to categorise, and other fields contained more than one type of system. Figure 2 also reveals that, the two-phase, vapour-dominated fields have a high installed capacity, representing one quarter of the world's installed capacity, even though the number of the geothermal fields is least for this type of systems (seven fields).

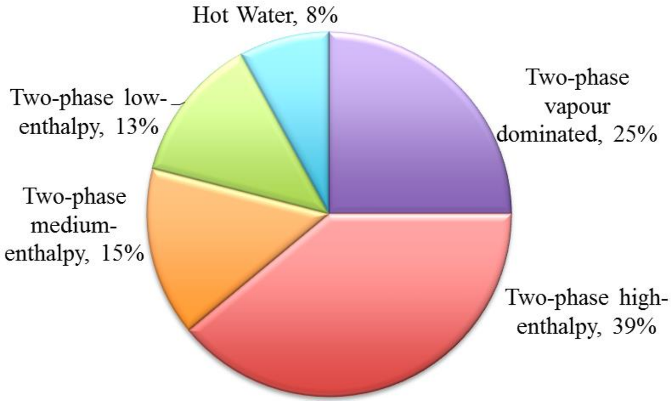



**Figure 2: Total installed capacity in MWe for the different types of geothermal systems.**

Figure 3 shows the capacity factors (percentage of generation from installed capacity) for each type of geothermal system. This analysis is based on publically available data from 89 active fields, representing 73.9% of the total installed capacity worldwide. In average, geothermal power plants operate within a range of 70% to 90% of their installed capacity, with higher capacity factors in two-phase, high- and low-enthalpy systems (90% and 88%, respectively). However, some fields run at lower ratings than the installed capacity of the plants, due to the availability of steam (Momotombo (Cuellar, 2013)) or variability of power demand in the energy market (Tongonan (Malibiran, 2014) and The Geysers (Sanyal and Enedy, 2011)), while others operate at full capacity (Tauhara (Newson, 2014) and Salavatli (Aksoy, 2014)).

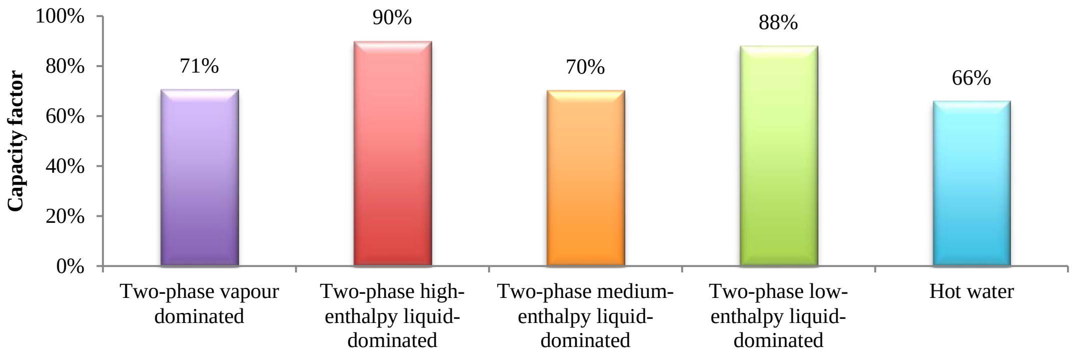
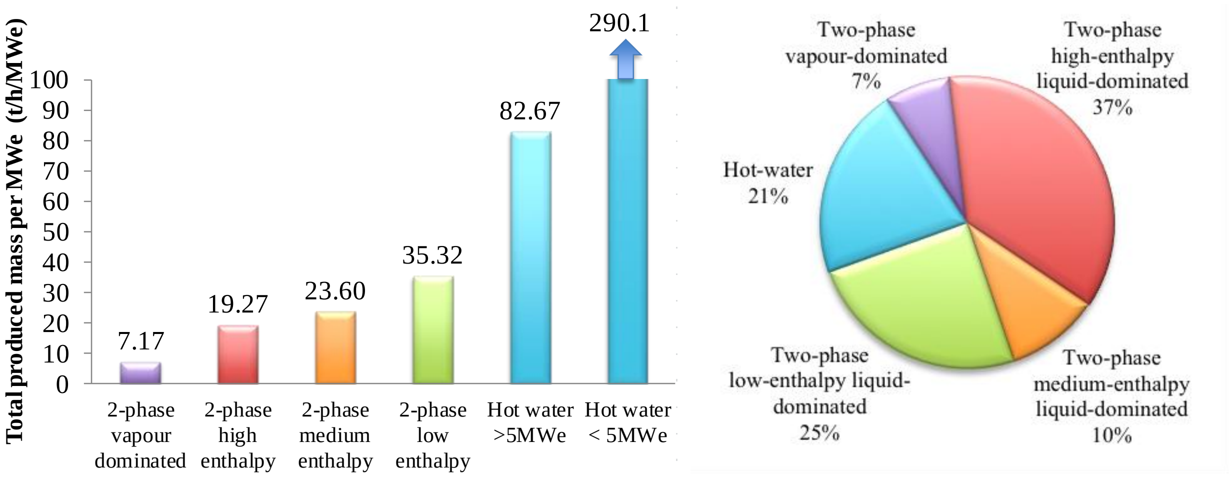



**Figure 3: Capacity factors for the different types of geothermal systems.**

The mass flow rate of fluid extracted from the reservoir to produce 1.0 MWe varies from one type of system to the other due to their energy density differences. Figure 4(a) presents the produced mass (t/h) per unit of power (MWe) for each type of system, with an additional subdivision for projects of hot-water system with less than 5 MWe of installed capacity, since more fluid is needed for electricity production due to higher parasitic load. Because of the limited published data, the information used in Figure 4(a) represents the data from 87 fields (accounting for 86 % of the total installed capacity), mostly using the corresponding actual power generation for given flow rates. Figure 4(a) show that the vapour-dominated systems require less fluid per MWe of power produced than any other system. In contrast, hot-water systems with 5 MWe or higher installed capacity need to have production rates that are approximately 11.5 times greater than a vapour-dominated system to generate 1.0 MWe of electricity, and about 40.5 times more fluid in hot-water systems with less than 5 MWe of installed capacity.

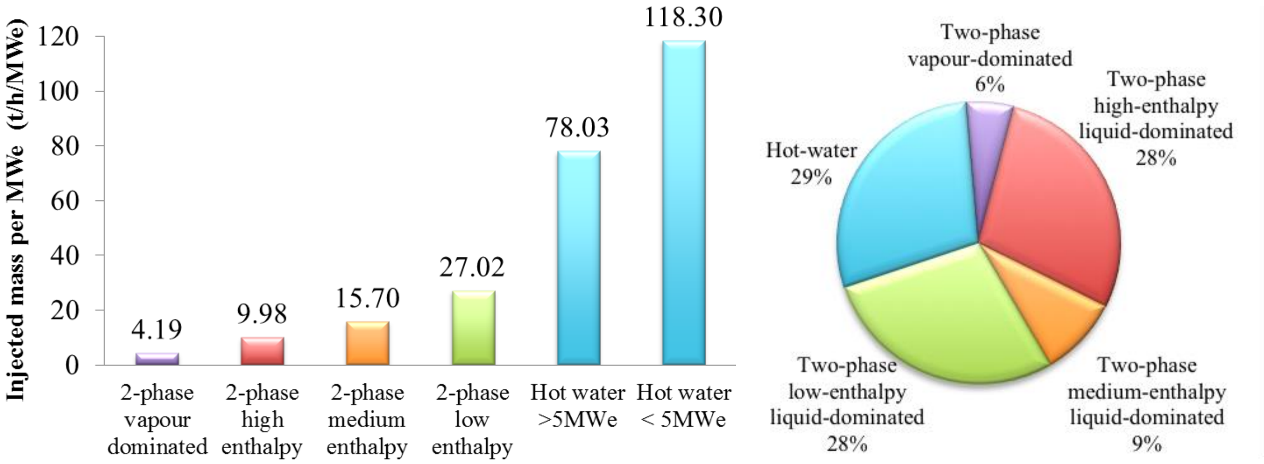
Figure 4(b) presents the contribution of each geothermal system to the total produced geothermal mass from the analysis of 87 fields (86% of the total installed capacity). The study showed that 72% of the total extracted geothermal fluid is from two-phase, liquid-dominated systems, which are also the majority within amount of currently active geothermal fields. High rates of fluid extraction in hot-water systems presented in Figure 4(a) are balanced with a low geothermal-based power generation from these type of systems compared to the rest of the systems, nevertheless, our review showed that these systems account for about 21% of the global mass production.




**(a)** **(b)**

**Figure 4: (a) Produced mass (t/h) per MWe for each type of geothermal system (b) total produced mass per type of system.**

Figure 5(a) presents the reinjection rate (t/h) per unit of power (MWe) for each type of geothermal system. The reinjected mass includes geothermal waste fluid (i.e. brine and condensates) and additional water, such as river water (Matsukawa (Hanano, 2003)), treated waste water (The Geysers (Sanyal and Enedy, 2011)) and supplementary water (Larderello (Cappetti *et al.*, 1995)) injected to artificially recharge the system. In this case, available information from 78 fields (representing 84.3% of the worldwide installed capacity) was used, mostly using the actual power generation for given injection rates. Figure 5(a) shows that injected flow rate per MWe and produced flow rate per MWe follow a similar trend (see Figure 4(a)).




**(a)** **(b)**

**Figure 5: (a) Injected mass (t/h) per MWe for each type of geothermal system (b) total injected mass per type of system.**

The total reinjected mass per system is presented in Figure 5(b). This figure shows that the predominant injection percentage is from liquid dominated systems (65%) whilst hot-water systems are the major single contributor of reinjected water with 29% of the total reinjected mass, As expected low-enthalpy systems (i.e. hot-water and low-enthalpy, liquid-dominated systems) have a higher contribution to the total injected mass, compared to the total produced mass, since they have more wastewater available to reinject.

Figure 6 presents the total produced mass flow rate compared to the total injected mass flow rate per type of system, using data from 69 fields (representing 78% of the total installed capacity). For this analysis, only geothermal projects with known production and injection rates, with their correspondent power generation, were used. The results in Figure 6 shows that vapour-dominated systems inject 58% of their mass withdrawal, which includes the external water added to cope with the relative low amount of residual fluid from production. For liquid-dominated, high-enthalpy systems, the percentage of produced mass reinjected back to the reservoir is around 53%, while medium- and low-enthalpy systems reinject 62% and 76% of their produced mass, respectively. Note that medium-enthalpy, liquid-dominated systems in Figure 6 have a low contribution of water production and reinjection because of the incompleteness of the information. Hot-water systems tend to reinject most of their production (92%) since many of them utilise closed loops binary systems. Within hot-water systems, those with installed capacity of ≥ 5 MWe reinject most of their production (94%) since many of them utilise closed loop binary systems. On the other hand, many hot-water systems of < 5 MWe of installed capacity utilise full surface discharge, decreasing the proportion (over all hot-water systems) of reinjection.

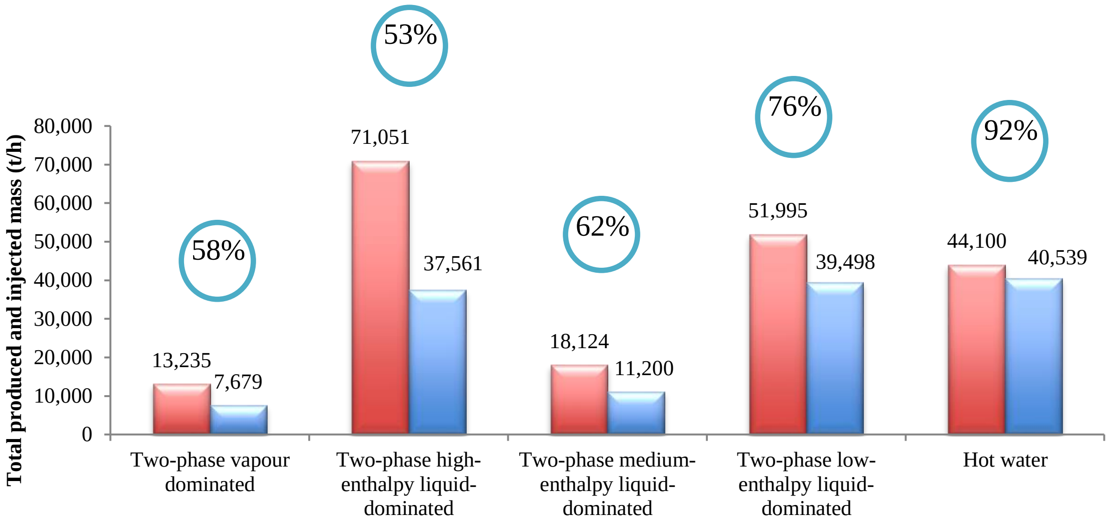



**Figure 6: Produced flow rate mass (red) and reinjected flow rate mass (blue) in t/h for each type of geothermal system, and the percentage of injected mass in terms of produced fluid. The values shown in blue circles represent the percentage of mass reinjection.**

The analysis of percentage of injected fluid presented in Figure 6 slightly varies from the data reported by Kaya *et al.* (*2011*). These changes correspond to increasing reinjection rates reported in fields, such as Ahuachapan (Mayorga, 2012), Hatchobaru (Franco and Vaccaro, 2014), Salavatli and Kizildere (Aksoy, 2014). Another variation found is that the amount of produced and injected fluid is higher than previously reported. This difference is due to increasing power production and new plants commissioned in the last 5 years, together with the additional available data used in the present study.

Figure 7 and Figure 8 present production and reinjection flow rate per unit of power generated by type of geothermal system on field-by-field basis. Data shows that there is a direct correlation between extracted and injected mass, together with the fact that fields producing from higher enthalpy systems require less fluid mass flow per MWe and inject less fluid per MWe than lower enthalpy systems.

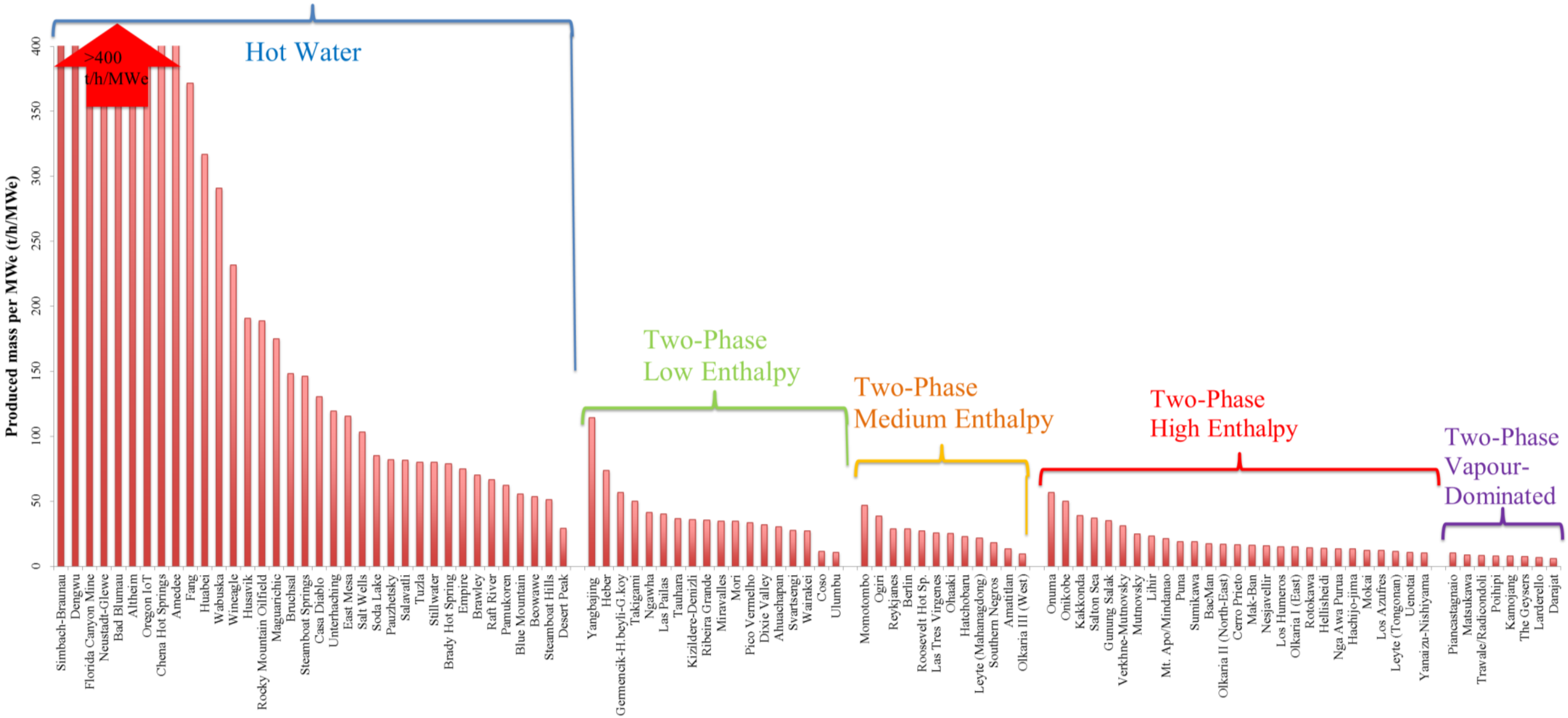



**Figure 7: Produced mass per MWe generated for each field.**

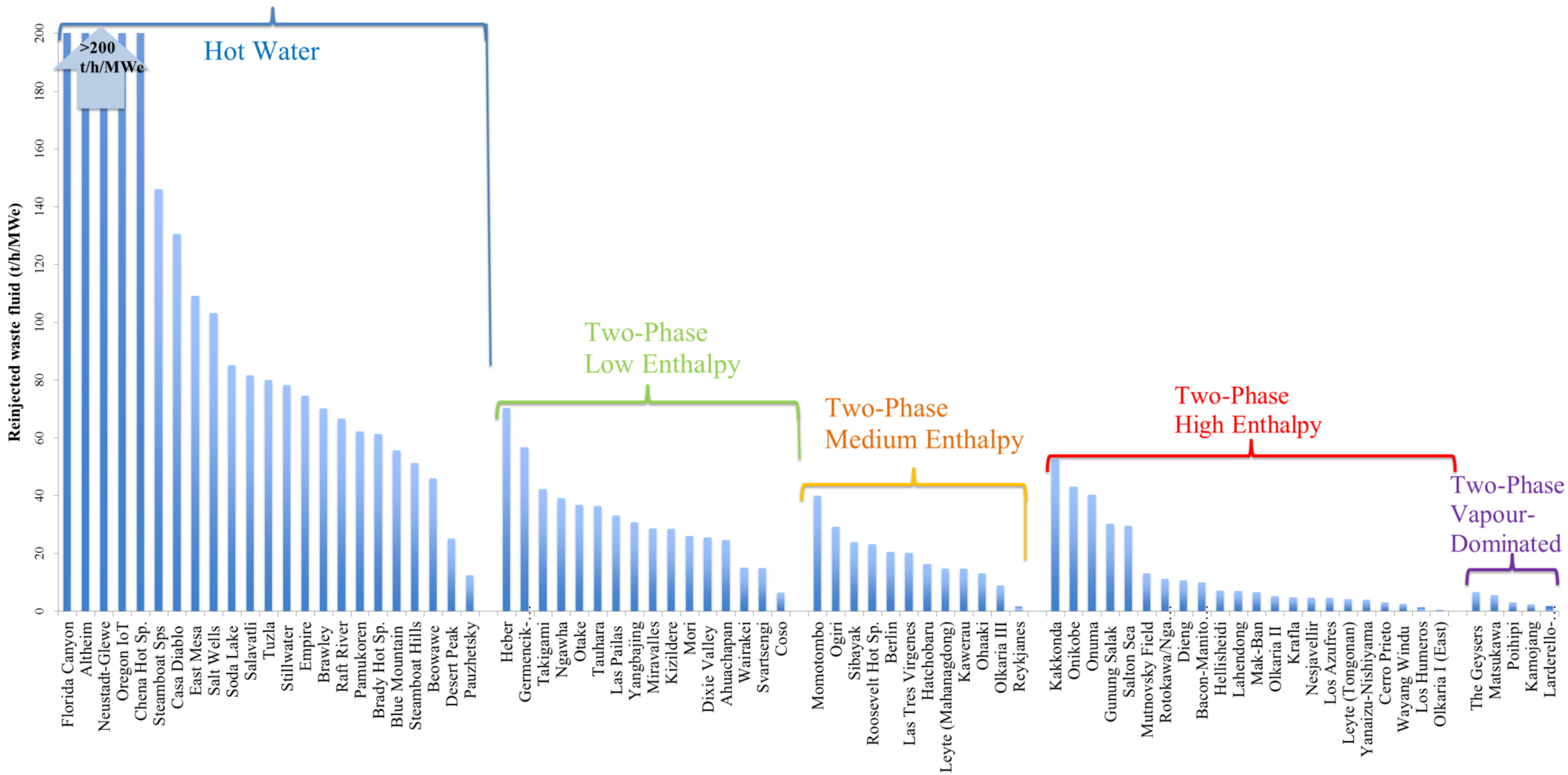



**Figure 8: Reinjected mass per MWe generated for fields with available data.**

Figure 9 shows the surface discharge rate of some fields. Part of the information presented represents actual data given in the literature and the rest was estimated when this information was not available. To estimate the surface discharge rate in hot-water systems, the value was taken as the total waste fluid from production; while in liquid-dominated systems the wastewater rate was calculated as the sum of the separated brine, plus 20% of the produced steam rate (assuming that steam losses vary between 75 and 90% (Kaya *et al.*, 2011)), minus the reinjected fluid (if applicable). Comparing the information presented by Kaya *et al.* (*2011*), some fields changed their surface brine disposal scheme to full reinjection (Los Azufres (Flores-Armenta and Gutiérrez-Negrín, 2011), Pico Vermelho (Carvalho *et al.*, 2013) and Momotombo (Cuellar, 2013)).

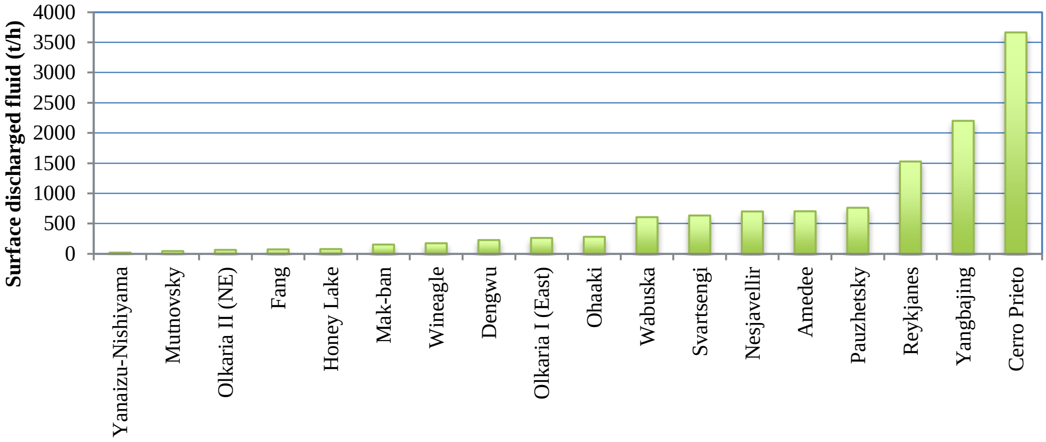



**Figure 9: Wastewater discharged to the surface.**

As mentioned in the previous section, the location of the reinjection zone is an important aspect during the design and the management of a reinjection strategy. Table 2 presents the distance ranges and average distances between production and reinjection zones for each type of system based on the most recent reported data and field maps available in open literature. The average distances correspond to the arithmetic average of 64 geothermal fields. The data in Table 2 shows that there is not a fixed distance for each type of system, but rather a wide distance range for injecting fluid back to the subsurface. Also, the gathered information indicates that the range of distance between production and injection zones decreases as the system increases in enthalpy, possibly due to the nature of each category in terms of the extension of their permeable zones around the hot production areas.

**Table 2: Distance ranges and average distance between production and injection zones per field category.**

| Category | | Distance range between production and reinjection zones (km) | Average distance between production and injection zones (km) |
|---|---|---|---|
| Hot-water | | 0.2 – 4.0 | 1.28 |
| Two-phase, liquid-dominated | Low-enthalpy | 0.2 – 5.0 | 1.45 |
| | Medium-enthalpy | 0.4 – 4.0 | 1.44 |
| | High-enthalpy | 0.2 – 2.0 | 1.13 |
| Two-phase, vapour-dominated | | Infield | |

The temperature of injected fluid is another important parameter to consider for an optimal reinjection strategy. This property depends to a great extent on the scaling potential faced when reinjecting geothermal wastewater. Also, a proper selection of the temperature of injected fluid is vital since the fluid temperature can alter the thermo-mechanical properties of natural fractures, thus varying the injectivity of the formation, as reported in Hellisheidi (Gunnarsson, 2011). Table 3 presents the temperature ranges of injected fluids, categorised by type of geothermal system, as well as the arithmetic averages of the injectates temperatures and temperature difference between the reservoir and injectates from 26 fields.

**Table 3: Reinjection fluid temperatures for the different types of systems.**

| Category | | Temperature ranges of injectates (˚C) | Average temperature of injectates (˚C) | Average temperature difference between reservoir and injectates (˚C) |
|---|---|---|---|---|
| Hot-water | | 50 - 100 | 76.5 | 54.94 |
| Two-phase, liquid-dominated | Low-enthalpy | 55 - 150 | 102.5 | 131.00 |
| | Medium-enthalpy | 30 - 175 | 109 | 185.61 |
| | High-enthalpy | 20 - 180 | 106 | 169.10 |
| Two-phase, vapour-dominated | | No data | | |

## 3. SUMMARY OF REINJECTION EXPERIENCE

Based on worldwide reinjection experience in different type of geothermal reservoirs, we have distilled the following summary. The results presented in this summary agree with Kaya *et al.* (*2011*) and provide additional examples and conclusions from new field data and reported experience.

1. Infield reinjection in two-phase, vapour-dominated systems (VDS) has an important role for maintaining steam productivity of the fields (e.g. Kamojang (Saptadji and Artika, 2012), Larderello (Arias *et al.*, 2010), Matsukawa (Hanano *et al.*, 1991) and The Geysers (Boyle and Majer, 2012)). However a few adverse effects have been reported when the production wells are too close to the injection wells (e.g. Darajat (Martiady *et al.*, 2011), Matsukawa (Hanano, 2003, Hanano *et al.*, 1991) and The Geysers (Boyle and Majer, 2012)).

2. The optimum depth for infield reinjection in VDSs varies depending on reservoir structure. For example the reinjection depth is preferred to be deep at Kamojang (Suryadarma *et al.*, 2010), on top of the reservoir at Larderello (Cappetti and Stefani, 1994) and at the same depth of the reservoir at The Geysers (Adams, 2011), in order to provide enough recharge and allow good residence time for injected fluid to heat up. This has been achieved by good naturally or induced fractured rocks (The Geysers (Dobson *et al.*, 2006)), vertical permeability and high superheating conditions (Larderello (Cappetti *et al.*, 1995, Cappetti and Stefani, 1994, Hanano *et al.*, 1991)). Furthermore, Larderello is an example where excellent producers have been sought as good reinjection wells (Cappetti and Stefani, 1994).

3. Most two-phase, high-enthalpy, liquid-dominated systems (HH-LDS) reinject infield at sites with lower temperatures than the production area (Uenotai (Butler *et al.*, 2005), Yamagawa (Okadaa *et al.*, 2000), Olkaria (Mariaria, 2012), Los Humeros (Urban and Lermo, 2013), and Mutnovsky (Kiryukhin *et al.*, 2010)). This reinjection strategy has resulted in good pressure support in Olkaria (Mariaria, 2012), Mokai (Kaya *et al.*, 2014) and Onuma (Horne, 1982), however an increase of water mass flow has been accompanied with this effect. Moreover, thermal and chemical breakthroughs have been experienced from infield reinjection in this type of systems (Krafla (Fridleifsson *et al.*, 2006), Gunung Salak (Julinawati and Molling, 2013), Los Azufres (Barragán *et al.*, 2011), Onikobe (Kaya *et al.*, 2011), Sumikawa (Kumagai and Kitao, 2000) and Rotokawa (Hunt and Bowyer, 2007). Therefore infield reinjection in HH-LDS is often complemented with edgefield or outfield reinjection targets to reduce the aforementioned negative reinjection effects, as seen in Uenotai (Butler *et al.*, 2005), Gunung Salak (Julinawati and Molling, 2013), Tongonan (Dacillo *et al.*, 2010), Bulalo (Capuno *et al.*, 2010, Vicedo *et al.*, 2008) and Mindanao (Emoricha *et al.*, 2010).

4. HH-LDS tend to reinject at the reservoir depth or deeper (Krafla (Einarsson *et al.*, 2010), Kakkonda (Arihara *et al.*, 1995), Los Azufres (Iglesias *et al.*, 2010), Rotokawa (Sherburn *et al.*, 2013), Lihir (O'Sullivan, 2014), Tongonan (Dacillo *et al.*, 2010), Salton Sea (Brodsky and Lajoie, 2013), and Puna (Kaya *et al.*, 2011)). The deep reinjection in Tongonan and Los Azufres has given good results as the deep reinjection allows better heat transfer. Reinjection at shallower depth than the production wells has been reported to complement the deep injection to dispose condensates (Hellisheidi (Hardarson *et al.*, 2010)), to minimize brine returns to reservoir (The Philippines (Sarmiento, 2008)) and when deep injection capacity is limited (Nesjavellir (Zarandi and Ivarsson, 2010) and Hellisheidi (Gunnarsson, 2011)).

5. Infield reinjection is common in many two-phase, medium enthalpy, liquid-dominated systems (MH-LDS), such as Amatitlan (Kaya *et al.*, 2011), Reykjanes (trials) (Sigurdsson, 2010), Sibayak (Kaya *et al.*, 2011) and Olkaria II (Axelsson *et al.*, 2013). Yet a thermal breakthrough is often observed with this strategy (Berlin (Monterrosa and Montalvo, 2006), Ogiri (Itoi *et al.*, 2010) and Momotombo (Porras and Bjornsson, 2010)). Some MH-LDS have opted to move further away the reinjection site (Hatchobaru (DiPippo, 2012, Kaya *et al.*, 2011), Ohaaki (Brockbank and Bixley, 2011), San Jacinto-Tizante (Randle and Ogryzlo, 2010), Tiwi (Menzies *et al.*, 2010) and Palinpinon (Malate and Aqui, 2010)) or have included edgefield or outfield reinjection wells (Blundell (Allis and Larsen, 2012)). Recovery of the field has been observed after moving the reinjection further away from the production wells (Kaya *et al.*, 2011).

6. For two-phase, low-enthalpy, liquid-dominated systems (LH-LDS), numerous cases of thermal breakthrough from infield reinjection have been reported (Miravalles (Ruiz, 2013), Las Pailas (Mora and Torres, 2013), Ahuachapan (Monterrosa and López, 2010), Svartsengi (Bjornsson and Steingrimsson, 1992), Otake (Horne, 1982), Mori (Hanano *et al.*, 2005), Wairakei (Hunt *et al.*, 1990) and Kizildere (Dünya and Dünya, 2010)). Moving reinjection wells further from production or diverting some of the reinjected flow to edgefield wells has successfully reversed the negative effects of infield

reinjection in LD-LHS (Miravalles (Ruiz, 2013), Wairakei (Bixley *et al.*, 2009) and Ahuachapan (Kaya *et al.*, 2011, Monterrosa and López, 2010)).

7. Different results are sought when varying the depth of reinjection in LH-LDS. Injection of fluid at reservoir depth has reported to give pressure support for the field (Dixie Valley (Kaya *et al.*, 2011, Rose and Clausen, 2014) and Tauhara (Contact Energy, 2010)), while a shallower reinjection has been considered to control subsidence (Tauhara (Contact Energy, 2010) and Takigami (Oka *et al.*, 2012)).

8. Positive gravity changes near reinjection sites have been recorded in Rotokawa (Hunt and Bowyer, 2007), Kamojang (Sofoyan *et al.*, 2010), Yanaizu-Nishiyama (Yamazawa *et al.*, 1999), Mutnovsky (Kiryukhin *et al.*, 2014), Takigami (Oka *et al.*, 2012) and Sumikawa (Tosha and Sugihara, 1997). This can be translated to mitigation of subsidence in the field. Also, reinjection rates can be determinant in ground deformation as such operations can lead to ground inflation (Mutnovsky (Kiryukhin *et al.*, 2014), Heber (Kaya *et al.*, 2011) and Empire (Eneva *et al.*, 2011)). However, reinjection might trigger a subsidence effect due to contraction of ground by cold reinjection, as experienced in Mokai (Hole *et al.*, 2007), where gravity gain happened afterwards as a two-phase zone was replaced by a cooler liquid zone (Kaya *et al.*, 2011).

9. The reinjection strategy for most hot-water systems (HWS) is to return the produced fluid near the production zone, i.e. infield (Landau (Evans *et al.*, 2012), Salavatli (Serpen and Aksoy, 2010), Desert Peak (Swyer and Davatzes, 2013), Steamboat Hills (Kaya *et al.*, 2011), Soda Lake (U.S. Department of the Interior Bureau of Land Management Carson City District, 2009), and Casa Diablo (Kaya *et al.*, 2011)) or edgefield (Empire (Kaya *et al.*, 2011), Beowawe (Garg *et al.*, 2007), Pauzhetsky (Kiryukhin *et al.*, 2010) and Neustadt-Glewe (Evans *et al.*, 2012)). There are records of HWS fields switching from an outfield reinjection to a closer site in order to reduce pressure drawdown. This can prevent cold groundwater infiltration into the reservoir (Beowawe (Dickey *et al.*, 2011, Garg *et al.*, 2007)) and/or decrease production losses (Brady Hot Springs (Krieger and Sponsler, 2002)). However, thermal effects in HWS are commonly experienced (Pauzhetsky (Kaya *et al.*, 2011), Casa Diablo (Kaya *et al.*, 2011), East Mesa (Kaya *et al.*, 2011), Steamboat Springs (Kaya *et al.*, 2011), Soda Lake (Echols *et al.*, 2011), Brady Hot Springs (Kaya *et al.*, 2011) and Chena Hot Springs (Holdmann, 2007)).

10. Shallow reinjection in HWS has shown a higher degree of thermal breakthrough than deeper injection (Casa Diablo (Kaya *et al.*, 2011) and Brady Hot Springs (Kaya *et al.*, 2011)). Shallow injection also can lead to ground inflation (Empire (Eneva *et al.*, 2011)). Injecting within the range of production depth has proved in Steamboat Springs to reduce the severity of thermal breakthrough (Kaya *et al.*, 2011). Furthermore, reinjection deeper than production depth has allowed the injected water to heat up before rising up to the pay zone in the Salavatli field (Gurbuz *et al.*, 2011, Serpen and Aksoy, 2010).

11. Partial reinjection is mainly implemented in two-phase, liquid dominated systems (LDS) such as Krafla (Ágústsson *et al.*, 2012), Nesjavellir (Zarandi and Ivarsson, 2010), Yanaizu-Nashiyama (Asanuma *et al.*, 2014), Olkaria (Mariaria, 2012), Cerro Prieto (Flores-Armenta and Gutiérrez-Negrín, 2011, García-Gutiérrez *et al.*, 2012, Kaya *et al.*, 2011), Bulalo (Kaya *et al.*, 2011), Tongonan (Dacillo *et al.*, 2010, Kaya *et al.*, 2011), Mutnovsky (Ilgen *et al.*, 2011), Reykjanes (Andresdottir, 2013, Hitaveita Sudurnesja HF, 2006), Kawerau (Teat, 2012), Ohaaki (New Zealand Geothermal Association, 2013), Yangbajing (Yi *et al.*, 2005), Svartsengi (Kaya *et al.*, 2011), Wairakei (Bixley *et al.*, 2009), Kizildere (Aksoy, 2014) and Pauzhetsky (Franco and Vaccaro, 2014, Kiryukhina, 2010). Although some of these fields used to implement total surface discharge, environmental constraints (chemical and heat pollution) on geothermal fluids (Yangbajing (Yi *et al.*, 2005) and Wairakei (Bixley *et al.*, 2009, Kaya *et al.*, 2011)), and benefits from mass recovery (Cerro Prieto (García-Gutiérrez *et al.*, 2012)) and pressure support for the reservoir (Wairakei (Bixley *et al.*, 2009)) have encouraged the gradual change of this water disposal scheme.

12. Complete surface discharge is still common in small scale power plants (< 5 MWe) based in HWS (Birdsville (Ergon Energy Corporation Limited, 2013), Dengwu (Luo *et al.*, 2012), Fang (Kaya *et al.*, 2011), Honey Lake (Sanyal *et al.*, 2006) and Wabuska (Sapp, 2007)).

13. The geothermal wastewater from power plants is often used for direct use applications (especially for residential heating and commercial bathing) before reinjection, (Suginoi (Taguchi *et al.*, 1996), Hachijo-Jima (Yamashita *et al.*, 2000), Hatchobaru (DiPippo, 2012), Kizildere (Aksoy, 2014) and Husavik (Verkis, 2013)).

14. Supplementary surface water addition into reinjection system is common in VDS to cope with the disproportion in recharge compared to the required production mass (Darajat (Kaya *et al.*, 2011, Mahagyo *et al.*, 2010), Matsukawa (Hanano, 2003), Kamojang (Sofoyan *et al.*, 2010) and The Geysers (Khan, 2010),). This strategy is also seen in LDS and HWS, where this practice is used to maintain reservoir pressure (Dixie Valley (Kaya *et al.*, 2014)), or to sustain surface features (Ngawha (Watson, 2013)). Furthermore, this operation can have a multiple benefits since the reinjection system can help with the disposal of municipal wastewater (e.g. The Geysers (Sanyal and Enedy, 2011) and Steamboat Hills (Kaya *et al.*, 2011)).

15. Unproductive or old production wells have been utilised for reinjection purposes with good results in VDS (The Geysers (Khan, 2010), Kamojang (Suryadarma *et al.*, 2010), and Larderello) and LDS (Olkaria (Mariaria, 2012), Las Tres Virgenes (Barragán *et al.*, 2010) and Ribeira Grande (Kaplan *et al.*, 2007)). This methodology brings savings in the cost and time associated with the drilling of new wells during early development. However, the negative effects of infield reinjection must be considered when the reinjection wells are located close to production wells (Ahuachapan (Kaya *et al.*,

2011), Tiwi (Menzies *et al.*, 2010) and The Geysers (Kaya *et al.*, 2011)). Monitoring and evaluation of the response of production to reinjection is highly recommended in this case (Kaya *et al.*, 2011, Suryadarma *et al.*, 2010).

16. Reinjection rate control is an effective tool for reservoir management used in many fields to mitigate thermal fronts (Bulalo (Capuno *et al.*, 2010) and Mahanagdong (Kaya *et al.*, 2014)), to reduce injection returns (Mindanao (Aragon and Sambrano, 2010) and Palinpinon (Malate and Aqui, 2010)), and to increase productivity (Gunung Salak (Acuña *et al.*, 2008) and Tiwi (Menzies *et al.*, 2010)). For example, in Tiwi and Gunung Salak, injection rates are decreased to lower the reservoir pressure, thus increasing the enthalpy of the system and the energy recovery (Acuña *et al.*, 2008, Menzies *et al.*, 2010). Moreover, in Tongonan (Dacillo *et al.*, 2010), a rate variation is critical for mitigating side effects in reinjection sites near production or with good connectivity to production wells . Establishing rate limits in certain wells (Tiwi (Menzies *et al.*, 2010)) and monitoring water chemistry (Mori (Hanano *et al.*, 2005)) can complement rate management.

17. Retention tanks or ponds are commonly used prior to reinjection in LDS as a way to mitigate the problem of scaling by polymerization of the silica before reinjection (Bacman (Panopio *et al.*, 2008), Nesjavellir (Zarandi and Ivarsson, 2010), Dieng (Pambudi *et al.*, 2014), Hatchobaru (DiPippo, 2012) and Cerro Prieto (Miranda-Herrera, 2012)). In Kawerau, the retention pond is used when the modified pH level of the separated water is not adequate for reinjection. This allows the silica to precipitate before reinjecting (McPherson and Koorey, 2013). Furthermore, the stored wastewater can also be used for other purposes, such as drilling operations (Olkaria (Mariaria, 2014)).

18. Cold reinjection has shown positive effects by increasing the injection capacity of the formation (Uenotai (Hisatani *et al.*, 2000), Ohaaki (Clotworthy, 2000), Palinpinon (Bermejo, 2013), Liubei (Xin *et al.*, 2012) and Hellisheidi (Gunnarsson, 2011)). Nevertheless, at the same time it can increase the risk of thermal breakthrough (Cerro Prieto (Cárdenas and Rodríguez, 2011) and Olkaria (Mariaria, 2011)). In such situation, prompt actions should be taken when cold reinjection returns are observed, such as moving cold reinjection further away from production wells (Uenotai (Hisatani *et al.*, 2000)), performing cold reinjection intermittently (Olkaria (Ofwona, 2011)), or using cold reinjection only for emergency cases (Tiwi (Villaseñor and Calibugan, 2011)).

19. Changes in the reinjection strategy have been extensively reported in all types of fields in response to production behaviour: from hot reinjection to cold reinjection for avoiding silica scaling (Hellisheidi (Gunnarsson, 2011) and Dieng (Pambudi *et al.*, 2014)); from infield to outfield reinjection to reduce thermal and chemical breakthrough (Brady Hot Springs (Krieger and Sponsler, 2002), Ohaaki (Brockbank and Bixley, 2011), Tiwi (Menzies *et al.*, 2010), Palinpinon (Malate and Aqui, 2010), Miravalles (Ruiz, 2013), Ahuachapan (Kaya *et al.*, 2011, Monterrosa and López, 2010) and Mori (Hanano *et al.*, 2005, Kaya *et al.*, 2011)); and from shallow to deeper reinjection depths for decreasing thermodynamic changes (Rotokawa (Hunt and Bowyer, 2007, Quinao *et al.*, 2013), Sumikawa (Kaya *et al.*, 2011, Kumagai and Kitao, 2000) and Casa Diablo (Kaya *et al.*, 2011)). On the other hand, relocating the production site away from the reinjection point has been reported in Otake (Taguchi *et al.*, 2006) and Pauzhetsky (Kiryukhin *et al.*, 2007).

20. The geological setting of the reinjection site play an important role in the effectiveness of reinjection as it can increase the negative thermal effects in the reservoir (The Geysers (Goyal, 1995, Khan, 2010), Hatchobaru (Yahara and Tokita, 2010), Momotombo (Porras and Bjornsson, 2010), Otake (Hayashi *et al.*, 1978) and Brady Hot Springs (Faulds *et al.*, 2010)). Faults can also act as barriers between reinjected fluids and hot reservoir (Hellisheidi (Gunnarsson, 2011), Gunung Salak (Acuña *et al.*, 2008), Takigami (Jalilinasrabady *et al.*, 2011) and Otake (Hayashi *et al.*, 1978)).

21. There is a direct correlation between reinjection and micro-earthquakes (MEQ) in some geothermal fields, especially in VDS and HH-LDS (Darajat (Pramono and Colombo, 2005), Larderello (Bolognesi, 2011), The Geysers (Altmann *et al.*, 2013), Krafla (Evans *et al.*, 2012), Hellisheidi (Gunnarsson, 2011), Yanaizu-Nishiyama (Asanuma *et al.*, 2014), Kakkonda (Tosha and Sugihara, 1997), Los Azufres (Noé *et al.*, 2013), Los Humeros (Urban and Lermo, 2013), Rotokawa (Sherburn *et al.*, 2013), Nga Awa Purua (Sherburn *et al.*, 2013), Salton Sea (Brodsky and Lajoie, 2013) and Puna (Kenedi *et al.*, 2010)). It has been reported that the seismic activity has possibly increased the porosity in the reservoir (Darajat (Pramono and Colombo, 2005)), enhanced the permeability (Larderello (Bolognesi, 2011)), and induced stress changes in rock (Los Azufres (Noé *et al.*, 2013)).

22. Enhanced Geothermal Systems (EGS) or hydraulic stimulations have been successfully utilised in a few conventional geothermal fields: The Geysers (Garcia *et al.*, 2012), Landau (Evans *et al.*, 2012), Desert Peak (Richter, 2013) and Raft River (Plummer *et al.*, 2014). At Desert Peak, the EGS program has successfully added 1.7 MWe of extra power production to the plant.

23. Chemical stimulation has been used to improve the injectivity of some reinjection wells (Mt. Amiata (Scali *et al.*, 2013), Los Azufres (Tello-López and Torres-Rodríguez, 2010) and Salavatli (Serpen and Aksoy, 2010)).

24. Pressure support from reinjection activities has been reported to aid in the contingency of cold-water inflow to the reservoir by creating or maintaining a pressure barrier between the cold inflow and the reservoir (Tongonan (Dacillo *et al.*, 2010), Beowawe (Dickey *et al.*, 2011) and Mori (Hanano *et al.*, 2005)). However, when the pressure support is not properly managed, a pressure differential between the production and the reinjection sites can induce cold injectates to flow into the reservoir (Hatchobaru (DiPippo, 2012)).

25. Reinjection provides low-gas working fluid to reservoir compared to the higher gas content from the natural deep fluid. This can result in improved plant efficiency with less gas in the geothermal steam going through the turbines. A lower steam/non-condensable gas (NCG) ratio has been reported when external fresh water has been added to the reinjection

system (Larderello (Arias *et al.*, 2010) and The Geysers (Sanyal and Enedy, 2011)), thus increasing the efficiency of the power plant. Additionally, a higher steam/NCG ratio has been experienced whilst only geothermal wastewater is reinjected (Wairakei (Contact Energy, 2010) and Coso (Kaya *et al.*, 2011)).

26. Reinjection wells have been successfully converted into production wells after a period of heat up in some fields, (Uenotai (Butler *et al.*, 2005, Nakao *et al.*, 2007), San Jacinto-Tizante (Randle and Ogryzlo, 2010), Palinpinon (Malate and Aqui, 2010) and Miravalles (Ruiz, 2013)).

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