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A Worldwide Review Update of Reinjection in Geothermal Fields

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ABSTRACT

Reinjection plays an essential role in maintaining sustainable development and management of geothermal resources. This paper presents an updated review of the worldwide experience of reinjection in electric-power producing geothermal fields. Data from 148 geothermal fields were used to investigate the impact of the main reinjection parameters, such as reinjection location (infield, outfield, edgefield), reinjection depth relative to production zone (deep, same level, shallow), distance from production wells, reinjected fluid temperature, and the amount of reinjection fluid, are taken into consideration. Positive and detrimental effects on the reservoir were assessed by considering the type of geothermal system. The change of reinjection strategy in response to production is also studied, while keeping in mind the historical information, to reveal the lessons learned from reinjection experiences of various fields. The survey demonstrates that: the dominant cause of the field production decline is related to whether the geothermal system is vapour-dominated, liquid-dominated, or hot water. However, the reinjection strategy should be site-specific and flexible, as it is likely to change with time due to thermal and chemical breakthrough into production wells, ground inflation, induced subsidence and seismic activities.

1. INTRODUCTION

Reinjection into geothermal fields plays an indispensable role not only as a method to dispose of wastewater that adversely affects the environment, but also to provide the necessary recharge for the geothermal system that eventually will sustain the geothermal exploitation. Thus, the implementation of reinjection part of geothermal field management has been increasing in the past decade. For the optimum development and effective management of the geothermal resource, it is crucial to have a good understanding of the current experience of industry practices. Nevertheless, finding the 'optimum' reinjection strategy is somewhat complicated because every geothermal field has its unique geological setting and reservoir characteristics.

Detrimental environmental problems in several geothermal systems were caused by a lack of knowledge and experience in the earlier phase of large-scale geothermal resource development. Poorly managed reinjection was often followed by negative consequences such as cooling of production wells and other obstacles associated with sustainable reservoir exploitation. However, the lessons learned from these early attempts of unsustainable geothermal development practices have brought about significant changes to the development practices worldwide.

In this work, we have conducted an extensive survey of open literature on power development around the world to capture global reinjection experiences. This research is an updated review which complements to earlier work by Diaz et al. (2016) and Kaya et al. (2011). We include the most recent information about power-producing geothermal fields in the world, e.g., power plants' installed capacity, production and injection conditions, current strategies in reinjection and the response of the reservoir to these strategies. Moreover, we also investigated additional parameters such as reservoir temperature, production enthalpy, the vertical and horizontal distance between reinjection and production zones to get the holistic understanding of reinjection strategies and their consequences. The objective of this study is to bring a qualitative review of reinjection strategies around the world. The results of this work provide generic guidelines for reinjection that can be useful for geothermal operators.

1.1 Categories of Geothermal Section

Previous literature survey presented in Diaz et al. (2016) and Kaya et al. (2011) states that the effect of reinjection is unique, depending on the type of the individual system, therefore, should be evaluated accordingly. Still, there are general characteristics or similarities of geothermal fields. This can be summarised as follows:

a. In Hot Water System (HWS), As the boiling does not occur before and after production in hot water systems, the risk of pressure drop is higher when the production is commenced without pressure maintenance by reinjection, which can lead to an output decline. Reinjection wells should provide pressure support to the system, but also needs to be placed with enough distance to avert thermal breakthrough.

b. In Liquid-Dominated System (LDS), boiling takes place. Pressure decline usually is fast before boiling occurs, then slows down. There are three sub-classifications: low enthalpy, medium enthalpy, and high enthalpy, by using the production enthalpy from the lowest to the highest.
   (i) Low enthalpy systems (LE-LDS). A low enthalpy system is characterised by considerably high fracture and permeability. This system often has strong recharge from the boundaries as pressure declines. Therefore, it is less likely to run out of water during production.
   (ii) Medium enthalpy systems (ME-LDS). A medium enthalpy system commonly has a lower permeability reservoir than low enthalpy systems. Only a few significant fractures exist in the field. The exploitation results in local boiling near production wells due to pressure drop, hence the fluid enthalpies are higher.

(iii) High enthalpy systems (HE-LDS). The similarity between high enthalpy and medium enthalpy lies in the small number of major fractures. High enthalpy system has tighter rock formations, hence lower permeability. This system also undergoes local boiling near production wells.

c. Vapour-dominated systems produce steam and contain voluminous immobile water. They have limited water recharge due to the low permeability nature of the reservoirs and the boundaries. As the production continues, the pressure drop will allow the immobile liquid to boil and become steam. However, eventually, the fluid inside the reservoir will runout while the heat remains in the rock matrix. Therefore, reinjection inside the system is often necessary to sustain production.

The geothermal system classification used for this study is based on the previous study by Kaya et al., (2011). Table 1 was used in the present study to assist with the evaluation of reinjection effects.

Table 1: Classification of geothermal systems.

Category		Temperature	Production Enthalpy
Warm water		T < 120˚C	h < 504 kJ/kg
Hot water		120 ˚C <T < 220˚C	h < 943 kJ/kg
Two-phase, liquid-dominated	Low enthalpy	220˚C < T < 250˚C	943 kJ/kg < h < 1,100 kJ/kg
	Medium enthalpy	250˚C < T < 300˚C	1,100 kJ/kg < h < 1,500 kJ/kg
	High enthalpy	250˚C < T < 330˚C	1,500 kJ/kg < h < 2,600 kJ/kg
Two-phase, vapour-dominated		220˚C < T < 300˚C	2,600 kJ/kg < h < 2,800 kJ/kg

1.2 Location

Spatial distance between reinjection wells and producing wells or hydraulic connection between them is a crucial parameter in the design of a reinjection system. Poor reinjection location selection often leads to detrimental effects on the reservoir and ultimately on geothermal exploitation. However, currently, there is no universally accepted rule for the definition of infield, outfield, and edgefield to describe the relative location of reinjection wells. Some authors (e.g., SKM, 2004) have defined infield reinjection and outfield reinjection in terms of how well the injection and production wells are connected, which is analyzed by pressure communication; others (e.g., Axelsson 2012) have classified them based on how reinjection wells are located relative to the main production zone (infield: in-between production wells, and outfield: outside of the main production field).

In this study, we have followed Diaz et al. (2016) and Axelsson et al. (2012) classification: Infield reinjection refers to injection wells locations that are close to the producing well and within the hot part of the system (resistivity boundary). Outfield reinjection is located outside the boundary of the system and might not directly connect hydrologically with the system. Edgefield or peripheral injection refers to the injection that is located at the edge of the boundary or in the outflow of the system but still hydrologically connected with the hot part of the system.

Unfortunately, this classification is not definite and precise. The distance parameter is not universal from one geothermal field to another since each system has distinct geological features. Moreover, these criteria are usually confirmed once the reinjection well has been drilled and more information about reservoir has been obtained.

2. INFORMATION AVAILABLE

The present study is based on the reports and publications available in the open literature from 148 electric power generation geothermal fields around the world. The gathered data will cover aspects such as the natural condition of the reservoirs (e.g. initial reservoir temperature and enthalpy); type of power plant design, its installed capacity/current generation; production and injection mass flow rate; reinjection temperature, summary of strategies and technology used in reinjection; the effect of reinjection on reservoir and production; and other issues or problem associated with reinjection, such as silica scaling, thermal and chemical front, microearthquakes, and ground deformation.

The strategy of reinjection and the following effects are analysed according to the classification of geothermal systems presented in Table 1. Most of the fields in this survey have utilised one reinjection strategy. However, in some cases, one field can have a unique production sector which has different reservoir conditions (temperature, enthalpy, or chemical composition). For example, the Wairakei-Tauhara field has Te Mihi, Wairakei, Poihipi, and Tauhara power plants. The Wairakei power plant produces from a low enthalpy system, while the Poihipi power plant generates from dry steam from the shallow vapour zone (Contact Energy Ltd., 2019). Therefore, in this study, different reinjection strategies are applied in different sectors. Previous analysis by Diaz et al. (2016) has been updated as new information has become available. For example, the classification of some fields in Japan (Yamagawa, Onuma) has changed from a high-enthalpy system to a medium or low enthalpy system based on the exergy assessment (Jalilinasrabady & Itoi, 2015). Figure 1 demonstrates the present field classification based on the updated reported enthalpies.

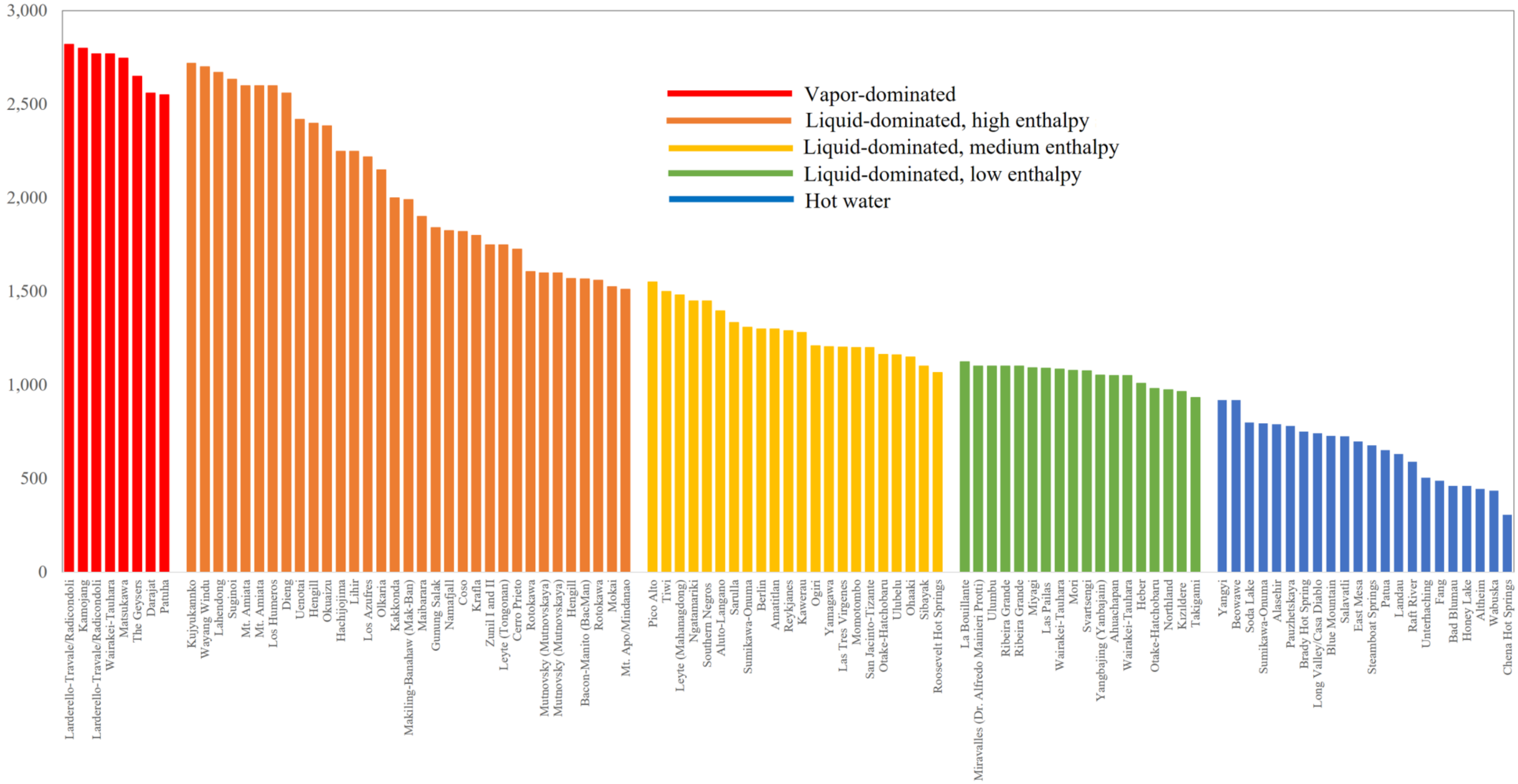

Figure 1: Reservoir enthalpy for each field and type of system

According to the present study, the world's total geothermal energy active installed capacity up to date is approximately 14,318 MWe. Figure 2 visualises the global map of geothermal power-producing countries as well as their installed capacities. USA, Indonesia, Philippines, Turkey, and New Zealand are the top five countries in installed geothermal capacity.

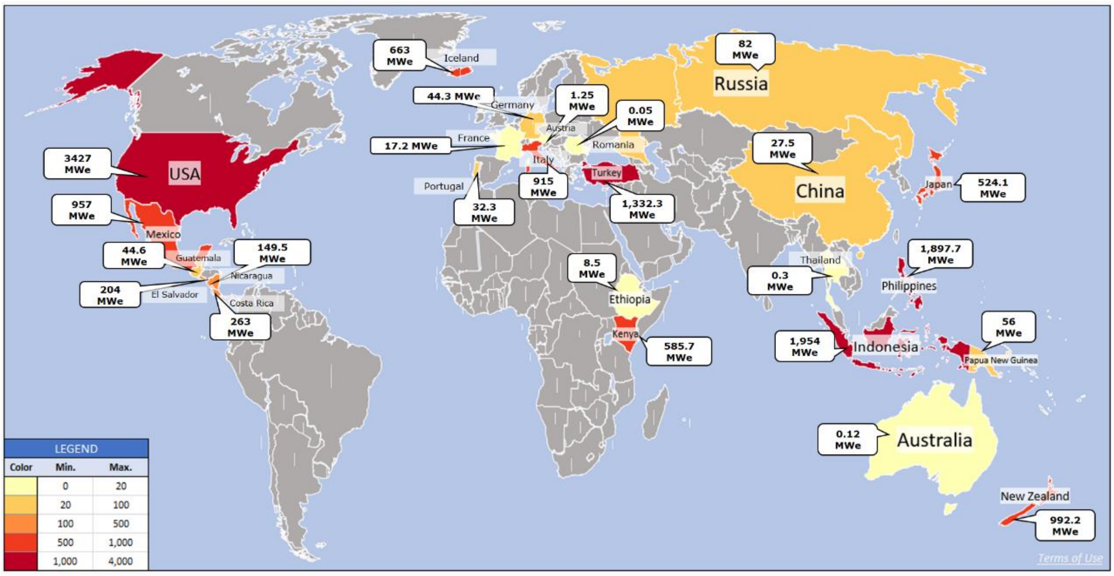

Figure 2: Global geothermal installed capacity map.

Figure 3 expresses the installed power capacity in megawatts (MWe) per type of system. Two fields (Mendeleevskaya-Goryachii Plyazh and Kagoshima geothermal field) are not included in the pie chart as they could not be classified due to the lack of information on their initial temperature and enthalpy values. Therefore, this figure represents 99.52% of the world's energy production from electric power-producing geothermal energy. Two-phase liquid-dominated systems (74 geothermal fields) provide most of the power generation, representing 68% of total installed capacity. This survey also shows that despite only eight vapour-dominated fields being developed, those fields have a high installed capacity (20% of the world's total capacity). On the contrary, hot water systems produce only 11% of the total installed capacity from 58 fields.

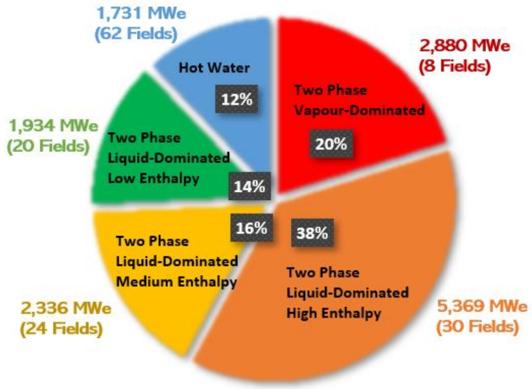

Figure 3: Total installed capacity in MWe and the number of fields for different types of geothermal systems.

The percentage of power generation from the installed capacity or the capacity factor of each type of geothermal system is presented in Figure 4. It should be noted that the availability of generation data is limited to 124 fields, representing 85% of the world's installed capacity. On average, geothermal power plants operate within a range of 70 – 85% capacity factor, with higher average capacity factors in the liquid-dominated systems (82%). Some fields have to expand the power plants installation, but the published data of generating capacity may not include the new plant in Las Pailas (Nietzen & Solis, 2019), thus contributing to a lower capacity factor. Some fields run at lower ratings than the installed capacity of the plants, due to a shortage in steam availability (Kamojang (Sofyan et al., 2019), and the power demand (market), e.g. The Geysers (Diaz et al., 2016)).

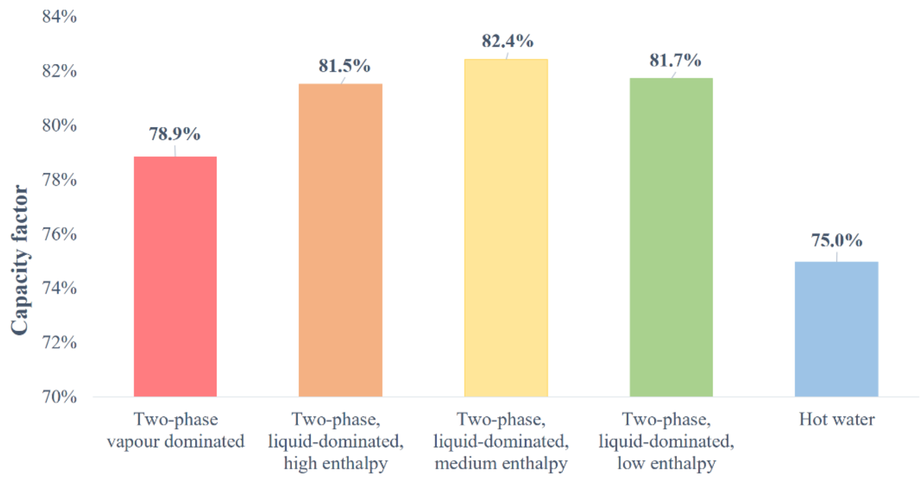

Figure 4: Capacity factors for different types of geothermal systems.

The capacity factors of hot water systems have risen from 66% to 75%, while for vapour-dominated systems they have risen from 71% to 78.9%, compared to 2015 data presented by Diaz et al., (2016). In some cases, changes in reservoir management, particularly reinjection strategies, have brought about a rise of power generation that results in higher capacity factor. On the other hand, both liquid-dominated high enthalpy systems and low enthalpy systems decrease from 90% and 88% to 81.5% and 82.4, respectively. The overall results agree with IRENA, (2017), stating that geothermal plants using direct steam deliver capacity factors higher than 80%, while projects utilising lower temperature resources (normally requiring downhole pumps) using binary plants deliver capacity factors of 60-80%.

The fluid extracted mass flow rate (t/h) from the reservoir to produce 1 MWe varies from one type of system to the other. Due to the limited published data, the information used in Figure 5a represents the data from 112 fields (accounting for 90% of the total installed capacity). Figure 5a also shows that for hot-water systems with less than 5 MWe of installed capacity, more mass is needed for every MWe produced, because of the high parasitic load. In contrast, vapour-dominated systems require much less fluid per MWe of power produced than any other system type. Hot-water systems with 5 MWe or higher installed capacity require 10 times more mass than vapour-dominated systems to generate 1 MWe and about 31 times more mass/MWe than hot-water systems with less than 5 MWe installed capacity.

Figure 5b shows the contribution of each type of geothermal system to the total geothermal fluid (259,206 t/h) produced worldwide based on data from 115 fields, which represent 93% of the total installed capacity. The study showed that 72% of the total extracted geothermal fluid is from two-phase systems. High rates of fluid extraction in hot water systems presented in Figure 5b are balanced with a low power generation from these types of systems compared to the rest of the systems. Nevertheless, this review shows that these systems account for about 21% of global mass production.

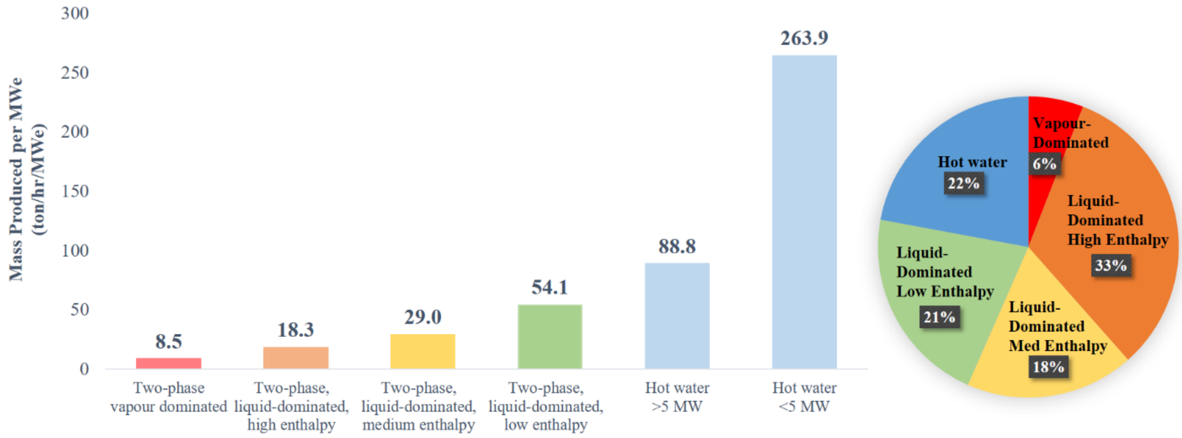

Figure 5: (a) Produced mass (t/h) per MWe for each type of geothermal system; (b) total produced mass per type of system.

Figure 6a shows the reinjection rate (t/h) per unit power (MWe) generated from each type of geothermal system. The reinjected mass also includes some of the additional water, not only brine and steam condensates. Available information from 91 fields (83% of the worldwide installed capacity) was used. This injected mass is also divided by the corresponding actual power generation. Figure 6a shows that the injected flow rate per MWe and the produced flow rate per MWe follow similar trends.

The contribution of each type of geothermal system to the total reinjected mass (162,651 t/h) using information from 90 fields is presented in Figure 6b. The predominant injection is from liquid-dominated systems (66%), while hot-water systems account for 29% of the total injected mass. Predictably, 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.

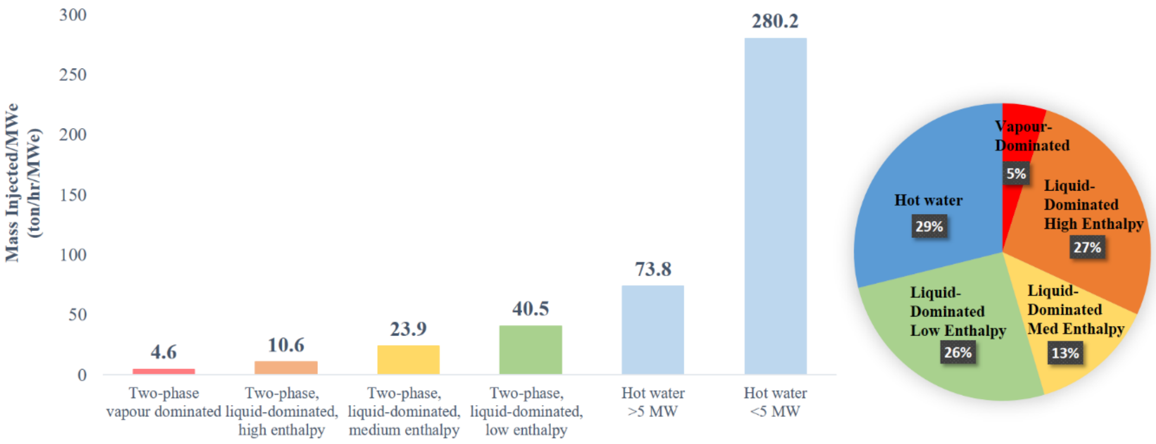

Figure 6: (a) Injected mass (t/h) per MWe for each type of geothermal system; (b) total injected mass per type of system.

Figure 7 presents the total produced mass flow rate compared to the total injected mass flow rate per type of system, using data from 78 fields (73% of the total worldwide installed capacity). For this analysis, only geothermal projects with known production and injection rates, and power generation were used. Figure 7 shows that vapour-dominated systems have 58% of their produced mass injected; this also includes the external water added to cover the low amount of residual liquid water after losing 70-90 % of the produced steam in the cooling towers. For liquid-dominated systems, high-enthalpy systems the percentage of produced mass reinjected back to the reservoir is around 57%, while medium- and low-enthalpy systems reinject 68% and 82% of their produced mass, respectively. Note that medium-enthalpy liquid-dominated systems have a low contribution of water production and reinjection because of the limited information on this type of system. Most of the production (98%) from hot-water systems tend to be reinjected since many of them utilise closed-loop binary systems. Nevertheless, many hot-water systems with less than 5 MWe installed capacity implement full surface discharge.

The percentage of injected fluid presented in Figure 7 varies slightly from previous data presented by Diaz et al., (2016). These changes correspond to increasing reinjection rates reported in fields; the amount of produced and injected fluid is higher than previously reported. This can be related to the increase in power production and new plants being commissioned in the past five years.

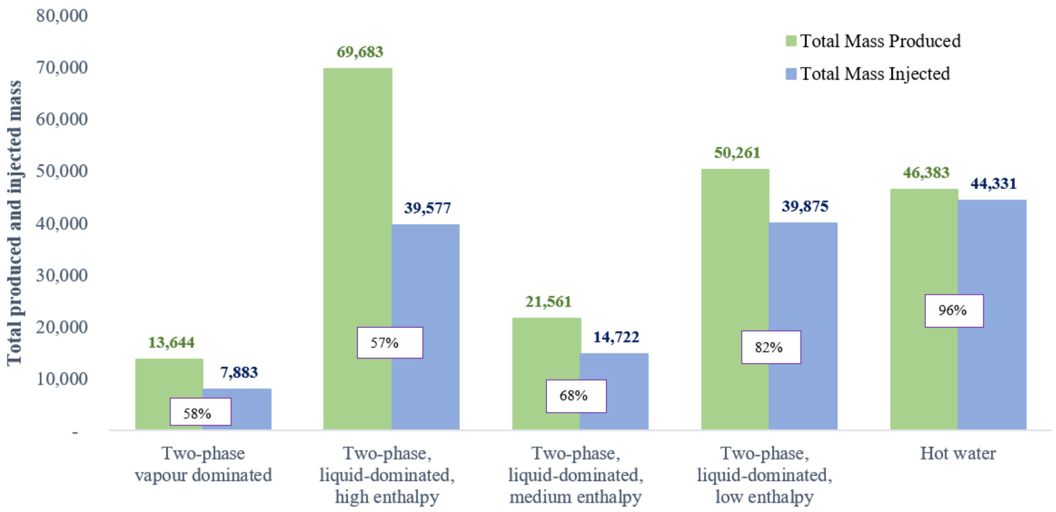

Figure 7: Produced flow rate mass (green) and reinjected flow rate mass (blue) in t/h for each type of geothermal system, and the percentage of injected mass (the values shown in purple squares).

Figure 8 and Figure 9 reveal the production and reinjection flow rates per unit of power generated by the different types of systems. The published 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. Additionally, individual characteristics of each geothermal field result in different values of extracted and injected mass per unit of power generation, among fields of the same category.

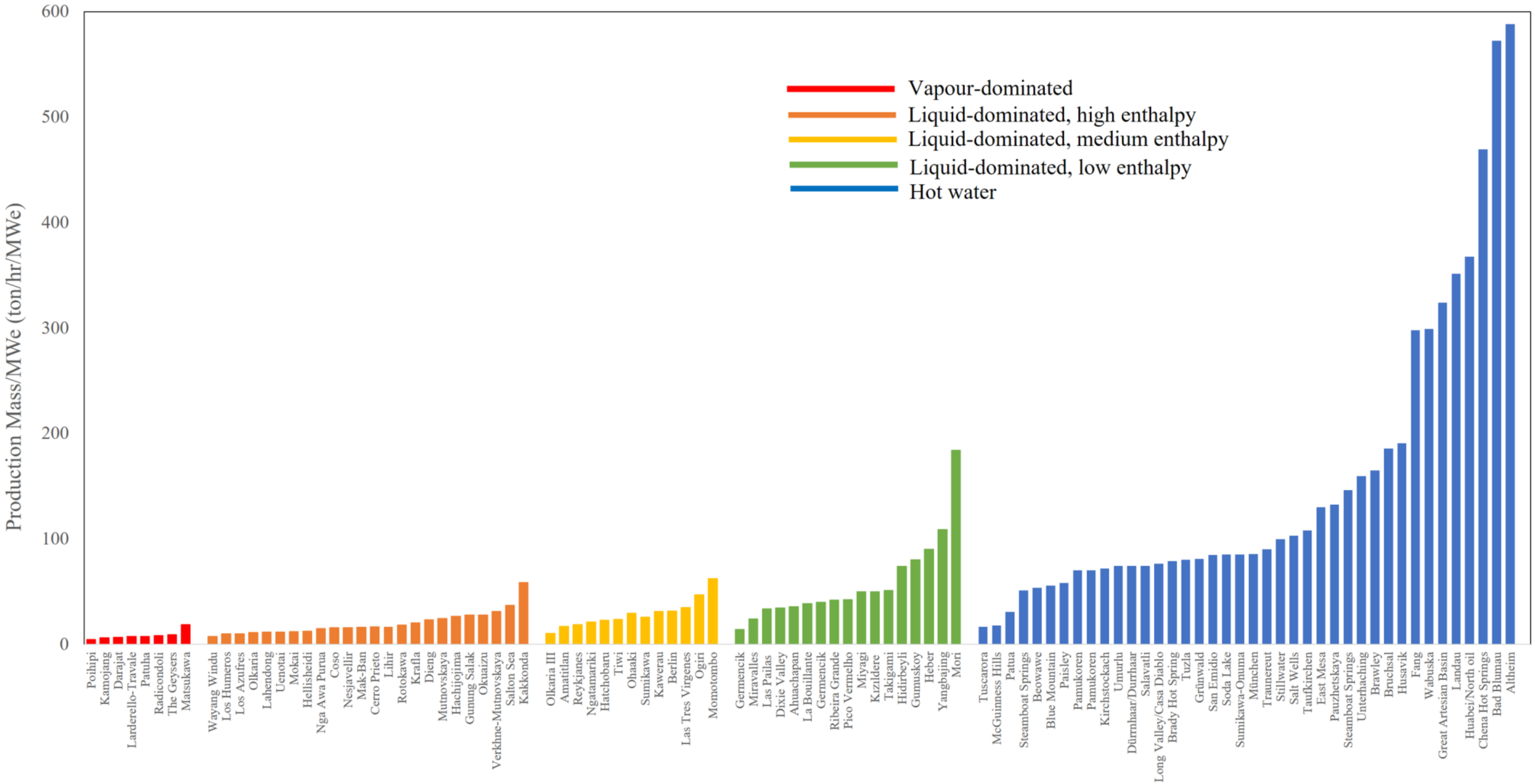

Figure 8: Produced mass in t/h per MWe generated for each geothermal field.

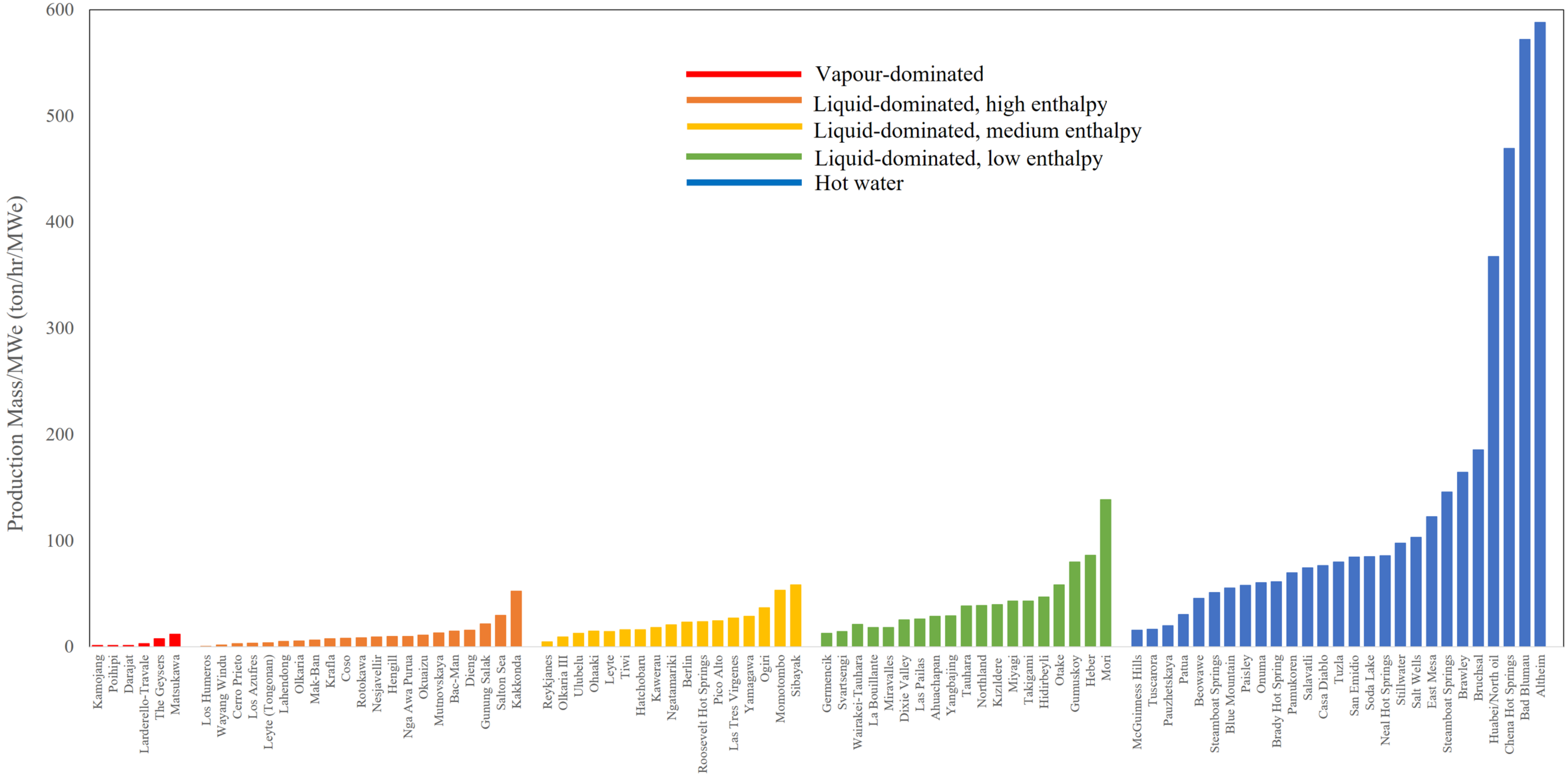

Figure 9: Injected mass in t/h per MWe generated for each geothermal field.

Figure 10 provides the surface discharge rate for some geothermal fields. Some of the information presented in this figure represents actual data given in the literature, and the remainder was estimated when this information was not available. To evaluate the surface discharge rate in hot-water systems, the value was taken as the total mass of waste fluid from production, while for liquid-dominated systems the wastewater rate was calculated as the sum of the separated brine and 20% of the produced steam rate (assuming that steam losses in cooling towers vary between 70% and 80% due to evaporation.

Comparing the results presented by Diaz et al. (Diaz et al., 2016) fields that previously applied surface disposal scheme, still disposes wastewater to the surface, especially in small, scale power plant of HWS fields (less than 5 MWe), such as Birdsville (ErgonEnergy, 2014), Fang (Wood, Kaewsomwang, & Singharajwarapan, 2016), Husavik (Diaz et al., 2016), Tsuchiyu (Renewable Energy World, 2015), Honey Lake (Diaz et al., 2016) and Wabuska (Diaz et al., 2016)). Other geothermal fields use wastewater for direct use applications without performing reinjection (Suginoi (Kudo, 1996), Namajfall (Diaz et al., 2016), Husavik (Diaz et al., 2016)). In many small geothermal fields, surface discharge is also practised at the very early period of field development (e.g. when there is only one well in the field) and during well tests (e.g. due to absence of adequate infrastructure in rural areas, such as lack of electrical transformers to operate injection pumps) (GT'2019, 2019)

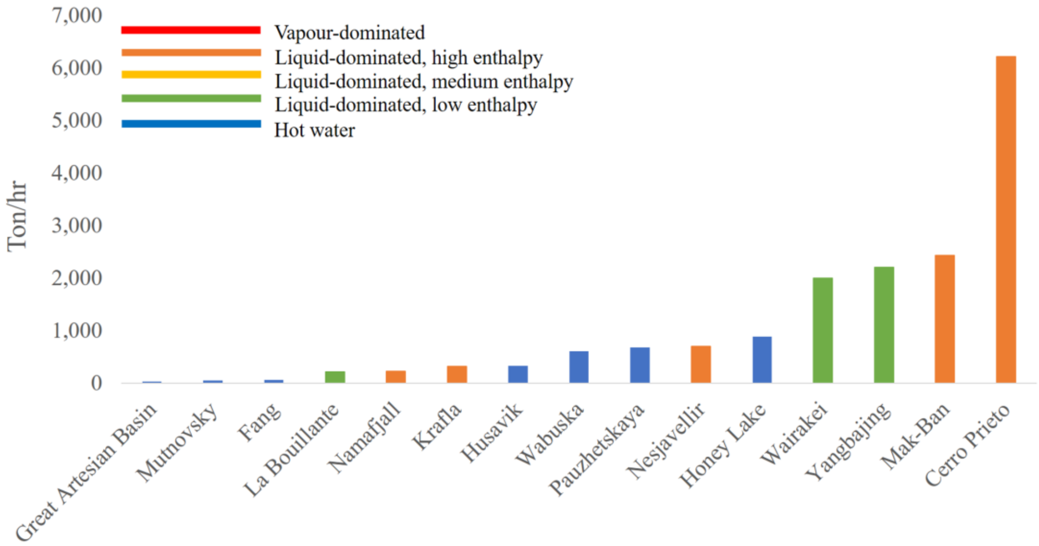

Figure 10. Wastewater surface discharge in t/hr for several geothermal fields

Many geothermal fields changed their reinjection strategies from partial reinjection at an earlier time to full reinjection (Momontobo (Diaz et al., 2016)) or at least reduced the amount of wastewater to the surface by increasing their mass injected). This is a strong indication that field operators understand the benefits of reinjection to the sustainability of their fields.

The location of the reinjection zone/target is an essential aspect during the design and the management of a reinjection strategy, as well as for the sustainability of geothermal fields. Table 2 illustrates the distance ranges and average distances between production and reinjection wells for each type of geothermal system based on the data and field maps (80 fields). The average distances tabulated are the arithmetic averages for each type of geothermal system.

The data in Table 2 demonstrate a wide range of distances between reinjection and production wells for each type of system. In VDS, wastewater is injected mostly infield, with only a few fields relocating their injection to the edgefield and outfields. In HWS, reinjection is practised both infield and outfield up to 6 km in the distance. The average distance between production and injection zones for the two-phase LDS indicates that the distance between production and injection zones decreases in the order of increasing production enthalpy. These practices are possibly due to the requirement of balancing the natural recharge, which depends on reservoir permeability, and the level of fracturing for each geothermal system (e.g., the high enthalpy version typically has a few major fractures which limit natural recharge, whereas the low enthalpy versions have more general fracturing and more widely spread permeability, which allow strong recharge).

Table 2: Distance ranges and the average distance between production and injection zones per geothermal system.

Category		Distance range between production and reinjection zones (km)	Average distance between production and injection zones (km)
Hot water		0.2 - 6	1.37
Two-phase, liquid-dominated	Low Enthalpy	0.2 - 4	1.37
	Medium Enthalpy	0.1 - 4	1.33
	High Enthalpy	0.5 - 3	1.26
Two-phase, vapour-dominated		Infield	

The temperature of injected fluid is another important parameter in an optimal reinjection strategy. The injected fluid temperature depends, to a great extent, on the scaling potential of reinjected geothermal wastewater. A proper selection of the temperature of injected fluid is also essential since the fluid temperature can alter the thermo-mechanical properties of natural fractures, thus varying the injectivity of the formation. Table 3 gives the temperature ranges of injected fluids for the different types of geothermal systems, as well as the arithmetic averages of the injectates' temperatures and the temperature differences between the reservoir and injectates (from 63 fields).

Table 3: Injectate temperature ranges and the average temperature difference between reservoir and injectates per geothermal system.

Category		Temperature ranges of injectates (˚C)	Average temperature of injectates (˚C)	Average temperature difference between reservoir and injectates (˚C)
Hot water		45 - 147.5	75	82.58
Two-phase, liquid-dominated	Low Enthalpy	30 - 163	100	128.28
	Medium Enthalpy	25 - 180	134	179.09
	High Enthalpy	30 - 226	110	186.59
Two-phase, vapour-dominated		condensate	30	210.00

3. REINJECTION EXPERIENCE SUMMARY

Based on worldwide reinjection experience in a different type of geothermal reservoirs, we have distilled the following summary. The results presented in this summary agree with Diaz et al. (2016) and Kaya et al. (2011) and provide additional examples and conclusions from new field data and reported experience.

1. In VDS, reinjection within the system boundary or infield location is mainly chosen for the reinjection wells to provide induced recharge and maintain steam productivity. However, some adverse effect has been observed in the production wells that are too close to injection wells. One of the reasons for cooling in VDS is the placement of reinjection wells at a low heat area (Matsukawa (Fukuda et al., 2018)). Temperature decrease also has been recorded when a high volume injection was performed in highly fractured rock (The Geysers (Diaz et al., 2016)). Therefore, changes in injection rate (The Geysers (Diaz et al., 2016), Kamojang (Diaz et al., 2016)) is often conducted to reduce the thermal front. Another cooling mechanism is the reinjection locations overlaps with the marginal natural recharge in some injection zones (Darajat (Simatupang et al., 2015)).

2. The optimum depth for infield reinjection in VDS varies and depends on their reservoir structure. Kamojang targets the deeper and lower permeability zone (Suryadarma et al., 2010). Darajat condensate also moves to a deeper zone based on meq (micro-earthquake) observation (Paramitasari et al., 2018). On the other hand, in Larderello wastewater is injected into the shallower level, taking advantage of the superheated condition and good vertical permeability in the systems (Diaz et al., 2016). Finally, The Geysers (Diaz et al., 2016) and Matsukawa (Fukuda et al., 2018) have almost the same injection level as producing depth, using natural and induced fractured rocks. These strategies, are selected to allow the condensate to reside and heat up before moving to production wells, which has been positively impacting steam production.

3. Infield location is marked as the dominant chosen location for reinjection in HE-LDS fields. This strategy has been beneficial to raise energy recovery by providing sufficient recharge (Gunung Salak (Libert, 2017), Los Humeros (Arellano, V.M., Barragán et al., 2015), Bacman (Espartinez & See, 2015), Los Humeros (Iglesias et al., 2015)), and minimise the rate of pressure decline (Olkaria (Ouma et al., 2016), Dieng (Sirait et al., 2015)). Nevertheless, many studies have reported chemical and thermal breakthrough issues due to the infield injection (Hellisheidi (Kristjansson et al., 2016), Gunung Salak (Libert, 2017), Uenotai (Diaz et al., 2016), Bacman (Espartinez & See, 2015), Tongonan (Uribe et al. , 2015), Los Azufres (Arellano et al., 2015)). For these circumstances, cooling mitigation is performed by transferring injection further or combining infield with the edge/outside boundary, as seen in Gunung Salak (Libert, 2017), Bac-Man (Espartinez & See, 2015), Tongonan (Uribe et al., 2015), Uenotai (Diaz et al., 2016), and Coso (Eneva et al., 2018)).

4. Injecting into the same or deeper levels than the production zone is common in HE-LDS (Gunung Salak (Diaz et al., 2016), Hellisheidi (Gunnarsson et al, 2016), Okuaizu (Okabe et al., 2016), Los Azufres (Diaz et al., 2016), Los Humeros (Iglesias et al., 2015), Mokai (Bromley et al., 2015), Rotokawa (Addison et al., 2017), Tongonan (Diaz et al., 2016), Kakkonda (Diaz et al., 2016), Lihir (Diaz et al., 2016), Maibarara (Maturgo et al., 2015), Mak-Ban (Diaz et al., 2016), Coso (Kaven et al. , 2014), Salton Sea (Diaz et al., 2016)). The deep reinjection in Tongonan and Los Azufres has given good results as the deep reinjection allows better heat transfer (Diaz et al., 2016). Shallow injection often complements deep reinjection, mostly for condensate injection (Rotokawa (Hernandez et al., 2015), and Hellisheidi (Gunnarsson et al., 2016)), or as mitigation for limited injection capacity in existing deep reinjection wells (Nesjavellir (Diaz et al., 2016)).

5. Infield reinjection is performed in many ME-LDS fields, such as Berlin (Diaz et al., 2016), Aluto Langano (Gherardi, Droghieri, & Magro, 2014), Reykjanes (Matthiasdottir et al., 2015), Ulubelu (Yuniar et al., 2015), and Roosevelt Hot Springs (Simmons et al., 2018). Yet, adverse effects such as chemical and thermal breakthrough has been reported when the distance of injection and production is too close (Berlin (Diaz et al., 2016), Sumikawa (Kaya et al., 2011), Reykjanes

(Guðni Axelsson et al., 2015), Ulubelu (Giriarso et al., 2015), Momontobo (Diaz et al., 2016), Roosevelt Hot Springs (Simmons et al., 2018), Tiwi (Sicad, 2015)). For that reason the operators opted to tackle this issue by moving the injection further away within the boundary (Hatchobaru (Diaz et al., 2016), Ulubelu (Siahaan et al., 2015)) or having included or ultimately moved the reinjection site to an edgefield/outfield location (Palinpinon (Solis & Taboco, 2015), Tiwi (Sicad, 2015), Sumikawa (Diaz et al., 2016)) to distribute the injection flow. Fortunately, recovery of the fields has been observed after moving the reinjection further away from the production wells.

6. As LE-LDS are often characterised by widespread fractures and strong lateral recharge nature, the large amount of injected water can jeopardise the interference with the hot reservoir. As a result, infield locations in LE-LDS should be overseen as they pose a higher risk of thermal decay, like what was reported in numerous cases, such as Las Pailas (Torres-Mora & Axelsson, 2015), Ahuachapan (Diaz et al., 2016), Mori (Diaz et al., 2016), Otake (Diaz et al., 2016), and Kizildere (Senturk, 2019). To combat this issue, a relocation injector to a further site is often chosen to reduce the cooling risk (Mori (Diaz et al., 2016), Otake (Diaz et al., 2016), Pico Vermelho (Rangel et al., 2017)). Moving further has helped production and enthalpy to recover (Ahuachapan (Diaz et al., 2016)).

7. In terms of reinjection depth selection in LE-LDS, usually the same or a deeper level are opted (Svartsengi (Sigrún Brá Sverrisdóttir, 2016), Yangbajain (Zhu et al., 2015)), resulting in pressure recovery, whereas shallower reinjection is also common to avoid subsidence (Wairakei (Diaz et al., 2016)) and sustain natural surface features (Tauhara (Diaz et al., 2016)). Often a combination of these two categories is applied to achieve both purposes (Wairakei (Dean et al., 2014), Kizildere (Senturk, 2019), Svartsengi (Diaz et al., 2016)).

8. The reinjection strategy for most HWS is to return the produced fluid adjacent to the production zone, i.e., infield (Bruchsal (Evans et al., 2012), Onuma (Diaz et al., 2016), Umurlu (Yucetas, Ergicay, & Akin, 2018), Brawley (Llenos & Michael, 2016), Steamboat Springs (Bjornsson et al., 2014)). This strategy positively keeps stabilising the reservoir pressure (Patua (Murphy et al., 2017), McGinness Hills (Lovekin et al., 2016), Bruchsal (Diaz et al., 2016)), maintain production (Landau (Evans et al., 2012)) and water level (Altheim (Diaz et al., 2016)). There are records of HWS fields switching from an outfield reinjection to a closer site to reduce pressure drawdown (Beowawe (Diaz et al., 2016)). The attempt of closer relocation can also prevent cold groundwater from infiltrating into the reservoir (Beowawe (Kirby et al., 2015)) or decrease production losses (Brady Hot Springs (Diaz et al., 2016)). Nonetheless, the chemical and thermal breakthrough is normally undergone in HWS, like reported in Onuma (Diaz et al., 2016), Pauzhetskaya (Diaz et al., 2016), Beowawe (Kirby et al., 2015), Blue Mountain (Swyer et al., 2016), Lightning Dock (Reimus et al., 2018), Casa Diablo (Diaz et al., 2016), Soda Lake (Diaz et al., 2016), and Tuscarora (Chabora et al, 2015). A further location for reinjection has been pursued to reduce these negative effects (Onuma (Diaz et al., 2016), Soda Lake (Benoit, 2016)).

9. In many cases peripheral location is chosen in liquid dominated system to to avoid the risk of cooling, especially during the earlier stage of development (Lahendong (Prabowo et al., 2015), Wayang Windu (Diaz et al., 2016), Mokai (Bromley et al., 2015), Rotokawa (Hernandez et al., 2015), Ngatamariki (Buscarlet et al., 2016)). Infield location usually accompanies edgefield to provide more recharge and support (Okuaizu (Okabe et al., 2016)), or due to reinjection capacity limitation (Hellisheidi (Gunnarsson et al., 2016)).

10. 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 (Diaz et al., 2016), Matsukawa (Diaz et al., 2016), Kamojang (Sofyan et al., 2019) and The Geysers (Enedy & Ca, 2016)). The source of surface water could be from municipal wastewater (The Geysers (Enedy & Ca, 2016)), rain and stream water (The Geysers (Enedy & Ca, 2016)), river (Matsukawa (Diaz et al., 2016)), lake (Kamojang (Diaz et al., 2016)), and groundwater (Kamojang (Sofyan et al., 2019)). This strategy is also observed in few LDS and HWS, where this practice is used to maintain reservoir pressure (Dixie Valley (W. R. Benoit, 2015)), impede steam decline (Coso (Eneva et al., 2018)), improve recharge (Okuaizu (Okabe et al., 2016)) or sustain the surface features (Ngawha (Sherburn et al., 2015)).

11. Partial injection is still performed in LDS (e.g., Nesjavellir (Diaz et al., 2016), Krafla (Mortensen & et.al, 2015), Olkaria East (Ouma et al., 2016), Cerro Prieto (Sarychikhina, Glowacka, & Mojarro, 2016), Los Humeros (Arellano et al., 2015), Leyte (Diaz et al., 2016), Mak-Ban (Diaz et al., 2016), and Motnovsky (Diaz et al., 2016), Reykjanes (Guðni Axelsson et al., 2015), Kawerau (Milicich et al. , 2016), Ohaaki (Sherburn et al., 2015), Yangbajing (Diaz et al., 2016), La Bouillante (Traineau et al., 2015), Svartsengi (Sigrún Brá Sverrisdóttir, 2016), Wairakei (Diaz et al., 2016)). Nevertheless, withdrawal of geothermal fluid without adequate additional fluid from reinjection would result in depressurisation, which eventually leads to steam decline, (Cerro Prieto (Miranda-Herrera, 2015)). In addition, the limited fluid renewal pressure drop can lead to subsidence (Yangbajing (Li et al., 2016), Wairakei (White et al., 2005)). Increasing injection rate has successfully reduced the subsidence rate (Svartsengi (De Freitas, 2018)).

12. The cooling effect can occur when shallow reinjection is carried out. In that case, the high shallow pressure will lead to gravity-driven coldwater inflow to the hot reservoir (Mokai (Bromley et al., 2015), Okuaizu (Okabe et al., 2016)). Several experiences reveal that deep injection is chosen as it provides better recharge and support than shallow injection and without much thermal decay, as this deep reinjection strategy allows the injectate to reside and heat up in reservoir (Kawerau (Milicich et al., 2016), Momontobo (Kaspereit et al., 2016)).

13. In other cases, pressure support from reinjection has been used to halt/mitigate natural recharge of cold water in some reservoirs by creating or upholding a pressure barrier between the cold inflow and the reservoir and eventually prevent crossflow (Tongonan (Uribe et al., 2015), Momontobo (Kaspereit et al., 2016), Mori (Diaz et al., 2016)). 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 (Beowawe (Kirby et al., 2015), Hatchobaru (Diaz et al., 2016)).

14. Some reports in a few fields noted that reinjection gives no or little pressure support even though the distance is close enough to the production zone (Zunil (Diaz et al., 2016), Takigami (Diaz et al., 2016), Casa Diablo (Report, 2017)). This happened as the injectates are diverted to the outflow zone instead of remaining in the hydrothermal system. Also, less pressure support occurred in several geothermal fields when the injection wells are concentrated in one region, resulting in the lack in another area (Lahendong (Prabowo et al., 2015)), or when reinjection is performed into or moved to the outfield (Beowawe (Kirby et al., 2015), Brady Hot Springs (Diaz et al., 2016)).

15. Controlling the reinjection rate is crucial for reservoir management in many geothermal fields. For example, in The Geysers (Diaz et al., 2016), and Gunung Salak (Diaz et al., 2016) injection rates are decreased to lower the reservoir pressure, thus increasing the enthalpy of the system and the energy recovery. Likewise, in Tongonan (Diaz et al., 2016), Olkaria (Ouma et al., 2016), Mak-Ban (Diaz et al., 2016), and Patua (Murphy et al., 2017), rate variation is critical for mitigating reservoir cooling when the reinjection sites are near production or have direct connectivity to production wells. Establishing rate limits in individual wells (Tiwi (Diaz et al., 2016)) and monitoring water chemistry (Mori (Diaz et al., 2016)) can also balance rate management. Reinjection rate control is also suggested for Lahendong field as a result of tracer testing (Prabowo et al., 2015).

16. Numerous reinjection practice shows that hot reinjection tends to be accompanied by injectivity drop, possibly due to mineral deposition in saturated conditions (Maibarara (Maturgo et al., 2015), Las Pailas (Nietzen et al., 2015)). Hence, cold injection is often temporarily used as a cheap and effective method to improve reinjection capacity or permeability or minimise scaling in some production/injection wells by attaining a hydraulic fracturing effect (Sumikawa (Diaz et al., 2016), Maibarara (Maturgo et al., 2015), Los Humeros (Luviano et al., 2015), Desert Peak (Dempsey et al., 2015), Raft River (Bradford et al., 2017), Wayang Windu (Diaz et al., 2016), Las Pailas (Zúñiga, 2012), La Bouillante (Diaz et al., 2016)). Nevertheless, this cold injection strategy should be observed as it can lead to the risk of a thermal breakthrough. In such circumstances, prompt actions should be taken when cold reinjection returns are found, such as moving cold reinjection further away from production wells after cold water stimulation (Uenotai (Diaz et al., 2016)), reinjecting intermittently or stopping cold reinjection once thermal breakthrough occurs (Olkaria (Ouma et al., 2016)), or using the wells for cold reinjection only in an emergency (Tiwi (Sicad, 2015)).

17. In some cases, silica scaling can be observed when hot reinjection is incorporated (Dieng (Diaz et al., 2016), Tiwi (Sicad, 2015), Dixie Valley (W. R. Benoit, 2015). Changing the strategy from hot to cooled injectate is often conducted by using retention tanks or storage ponds to polymerise silica prior to reinjection (e.g., Dieng (Pambudi et al., 2015), Cerro Prieto (Miranda-Herrera, 2015), Bacman (Diaz et al., 2016), Maibarara (Maturgo et al., 2015), Hatchobaru (Diaz et al., 2016)). The retention pond can only be used as scaling mitigation, but also when the modified pH level of the separated geothermal water is not adequate for reinjection, like in Kawerau (Diaz et al., 2016).

18. Calcite deposition related to reinjection can occur due to the mix of reinjected fluid with hot reservoir formation (Kizildere (Senturk, 2019), Bad Blumau (Diaz et al., 2016)).

19. There is strong link between meq activity and reinjection activity (Darajat (Paramitasari et al., 2018), The Geysers (Trugman et al., 2016) (Majer et al., 2017), Kamojang (Hendriansyah & Wicaksono, 2015), Larderello (Diaz et al., 2016)), Krafla (Flóvenz et al., 2015), Gunung Salak (Diaz et al., 2016), Mt Amiata-Piacastagnaio (Mazzoldi et al., 2015), Okuaizu (Okamoto et al., 2018), Kakkonda (Diaz et al., 2016), Cerro Prieto (Sarychikhina et al., 2016), Los Azufres (Diaz et al., 2016), Rotokawa-Nga Awa Purua (Sewell et al., 2015), Coso (Trugman et al., 2016), Salton sea (Crandall-Bear et al., 2018), Svartsengi (Flóvenz et al., 2015), Salavatli (Serpen et al., 2015), Unterhaching (Diaz et al., 2016), Brady hot springs (Cardiff et al., 2018)). MEQ occurs especially when deep injection has started (Mokai (Sherburn et al., 2015)), rapid change of injection rate (Hellisheidi (Kristjansdottir et al., 2016)), or injection rate is increased or becoming significant (Los Humeros (Urban & Lermo, 2017), Berlin (Kwiatek et al., 2014)). Change from deeper to shallower reinjection (Brady Hot Springs (Cardiff et al., 2018)), and maintaining a stable and constrained rate of reinjection (Salton sea (Crandall-Bear et al., 2018)) may limit seismicity.

20. The well interchangeable strategy is positively implemented in geothermal fields. Reinjection wells have been successfully converted into production wells after a period of heat up in some fields (Uenotai, San Jacinto, Palinpinon) (Diaz et al., 2016). In addition, old or poor production wells have been successfully utilised for reinjection in VDS (Kamojang 8 (Sujarmaitanto et al., 2015), Larderello (Diaz et al., 2016), The Geysers (Diaz et al., 2016)), HE-LDS (Hellisheidi (Kristjansson et al., 2016), Olkaria (Diaz et al., 2016), Krafla (Mortensen & et.al, 2015), Maibarara (Maturgo et al., 2015), Coso (Buck, 2016)), LE-LDS (Ribeira Grande (Diaz et al., 2016), Kizildere (Senturk, 2019)), Miravalles, 1 and HWS (Soda Lake (Lovekin et al., 2017)). This strategy can reduce the capital cost and risk for drilling additional wells. Nonetheless, the adverse effects of infield reinjection must be considered when the reinjection wells are located close to production wells. Monitoring and evaluation of the response of production to reinjection are highly advisable (Diaz et al., 2016).

21. In general, reinjection will avert subsidence that is caused by a pressure drop from geothermal exploitation (East Mesa, Wairakei-Tauhara, Takigami) (Diaz et al., 2016). However, injection-induced subsidence could happen due to contraction of the hot formations by cold reinjection, as experienced in Mokai (Bromley et al., 2015), and Casa Diablo (Report, 2017). Partial reinjection can also lead to subsidence as extracted mass is not adequately replaced, as occurred in Yangbajing (Li et al., 2016), and Cerro Prieto (Sarychikhina et al., 2016). Thus, increasing injection rates can be beneficial to reduce subsidence (Svartsengi (De Freitas, 2018)). Shallow reinjection can also preserve shallow pressure and lessen subsidence, as occurred in Wairakei (Diaz et al., 2016).

22. Increasing or high reinjection rates can be a factor contributing to the ground inflation/uplifting (Heber (Diaz et al., 2016), Raft River (Feigl et al., 2018), San Emidio (Diaz et al., 2016), Mutnovsky (Kiryukhin et al., 2015). The mechanism is that reinjection can cause an increase in pore pressure and fault slip that leads to surface deformation (Hellisheidi (Juncu et al., 2018)). The resolution to the problem can be redistributing the total amount of injection over a larger area (Imperial Valley (Sanyal et al., 1995)). This can be achieved by increasing the spacing of injection wells or reducing the injection rate.

23. In most cases, reinjection provides low gas working fluid compared to the higher gas content from the natural deep fluid. This can improve the plant efficiency with less gas in the geothermal steam going through the turbines. A lower non-condensable gas (NCG) content has been reported when makeup freshwater has been added to the reinjection system (Larderello (Diaz et al., 2016), The Geysers (Enedy & Ca, 2016), Coso (Buck, 2016)) thus increasing the efficiency of the power plant. Nonetheless, in certain fields, the loss of NCG can be denoted as a small net loss that leads to a slight pressure drop (Ngawha (Sherburn et al., 2015)). Similarly, CO_2 has a considerable role in reservoir performance and energy production, such as in Umurlu (Yucetas et al., 2018). All of these reasons encourage the attempt of NCG injection along with geothermal fluids in geothermal industries (Hellisheidi (Ingimundarson et al., 2015), Coso (Kolar et al. , 2015), Umurlu (Yucetas et al., 2018)).

24. The geological setting of reservoir reinjection targets plays an important role to raise the effectiveness of reinjection. For example, a few faults in the field could be used as a natural barrier to prevent cooling (Gunung Salak (Diaz et al., 2016), Rotokawa (Hernandez et al., 2015)). Besides, other unique geological features can also provide a setting that is highly advantageous for induced recharge from reinjection, such as 'U-tube path' faults (McGuinness Hills (Lovekin et al., 2016)) or high vertical permeability (Los Azufres (Diaz et al., 2016)). These particular settings allow deep injectate to flow in the longer path and heat up before returning to production wells. On the contrary, some structures can put the field management in jeopardy. When production and injection wells intersect with faults which are highly connected, then close monitoring of reinjection should be conducted regularly to prevent cooling (Alasehir (Aydin et al., 2018), Mak Ban (Diaz et al., 2016)). Faults can also contribute to a higher risk of cooling even though the distance of production and injection is far (Mt Apo (Diaz et al., 2016)). Other geological features can have localised permeability between a shallow or intermediate aquifer and deep reservoir, so injection should be managed in such manner that the pressure drawdown will not lead to downflow (Ngatamariki (Clearwater et al., 2015)).

25. In several geothermal fields, reinjection can be carried out by gravity flow (Wayang Windu (Diaz et al., 2016), Los Azufres (Gutiérrez Negrín & Lippmann, 2016), Ulubelu (Mubarok & Zarrouk, 2016), Tiwi (Sicad, 2015), Bruschal (Diaz et al., 2016)). Gravity flow is desirable as it does not need additional pumps and results in lower maintenance cost. This strategy is attainable when geothermal fields are located in highly fractured areas, so formation pressures encountered in those areas are usually abnormally low due to pressure gradients below hydrostatic, as it happened in The Geysers (Diaz et al., 2016). Besides, topography can also create a favourable position from the reinjection point of view since the water table remains below the wellhead (Serpen & Aksoy, 2014). In Aydin-Buharkent, the reinjection is going to be made without pumping due to the high-temperature difference, and the non-artesian and no pressure conditions (Mertoğlu et al., 2015).

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