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Geothermal Field Management: Various Cases from Top Geothermal Producer Countries

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ABSTRACT

Geothermal for power generation offers clean and reliable energy compared to other renewable energy such as solar and wind. However, its sustainability is depending on how the reservoir was managed during exploitation. Improper field management strategy may lead to rapidly declining reservoir pressure and production.

Devising a proper field and reservoir management requires a good understanding of the geothermal reservoir characteristics. One of the most important characteristics is the response of the reservoir to exploitation and reinjection. Obtaining those responses requires continuous monitoring of the reservoir performance for some periods of time. Therefore, typically as each phase of the development of the geothermal field progresses, one's knowledge and understanding of geothermal resources become clearer. A robust and precise field management strategy will impact in stabilize and increase the revenue of geothermal developers that secure payback period and maintain during the contract period until the next 30 years from the commercial operation date.

This paper aims to summarize geothermal field management strategies from various fields worldwide. The methodology used for this research is literature review and direct discussion with related experts on geothermal reservoir management. As the results of this research, lessons learned from various geothermal fields in worldwide can be extracted, it will consist of how to understand the uniqueness of each field and their approach and strategies to solve the problem with the objective to maintain and recover the production. The result of this study is expected can become a reliable reference for government and geothermal developers to develop robust geothermal field development strategies.

1. INTRODUCTION

1.1 Geothermal Typical Business Concept

Geothermal energy nowadays is becoming one of the reliable clean energy options for power generation since its capability to become baseload energy and its energy source does not depend on the world market condition since the resource is in underneath of respective area. The development project of geothermal energy exploitation itself has the characteristics of low-carbon, greener, high initial investments, and long payback period that make both investor and geothermal developer should manage their project efficiently.

The concept of geothermal energy business typically has stable revenue and will be increasing due to additional generation as the result of staging development as well as illustrated in Figure 1. Staging development is one of the wise options to mitigate resource risk for the geothermal project since the initial understanding of subsurface conditions is typically low and has high uncertainties. Proper monitoring and surveillance will become important to gain a robust understanding of subsurface conditions to ensure the sustainability of production since the typical geothermal contract with an electricity buyer in Indonesia is 30 years from the commercial operation date (Mulyadi, 2021).

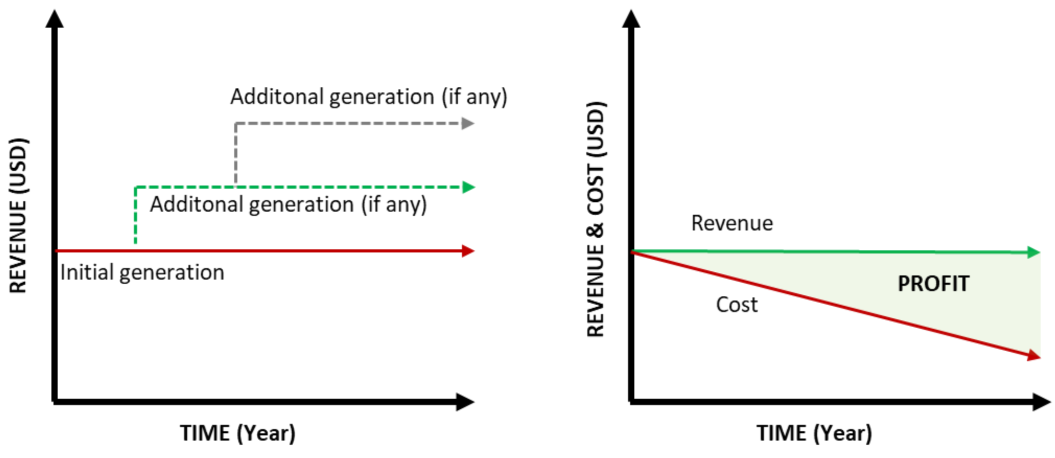

Figure 1: Typical geothermal energy business concept.

After the commercial operation date, a geothermal business will gain main revenue from electricity generated. But it should be noted that maintaining the steam production for electricity generation will require some cost as well for additional development drilling for spare/backup if there are any significant production declines, maintenance, repairing, and upgrading facilities, salary for worker, etc. As shown in Figure 2, the cost of drilling is one of the big portions to develop geothermal energy which implies the economics of geothermal development, which means if there is any additional drilling that has bad results will greatly impact the profit of the geothermal developer (Purwanto, 2021).

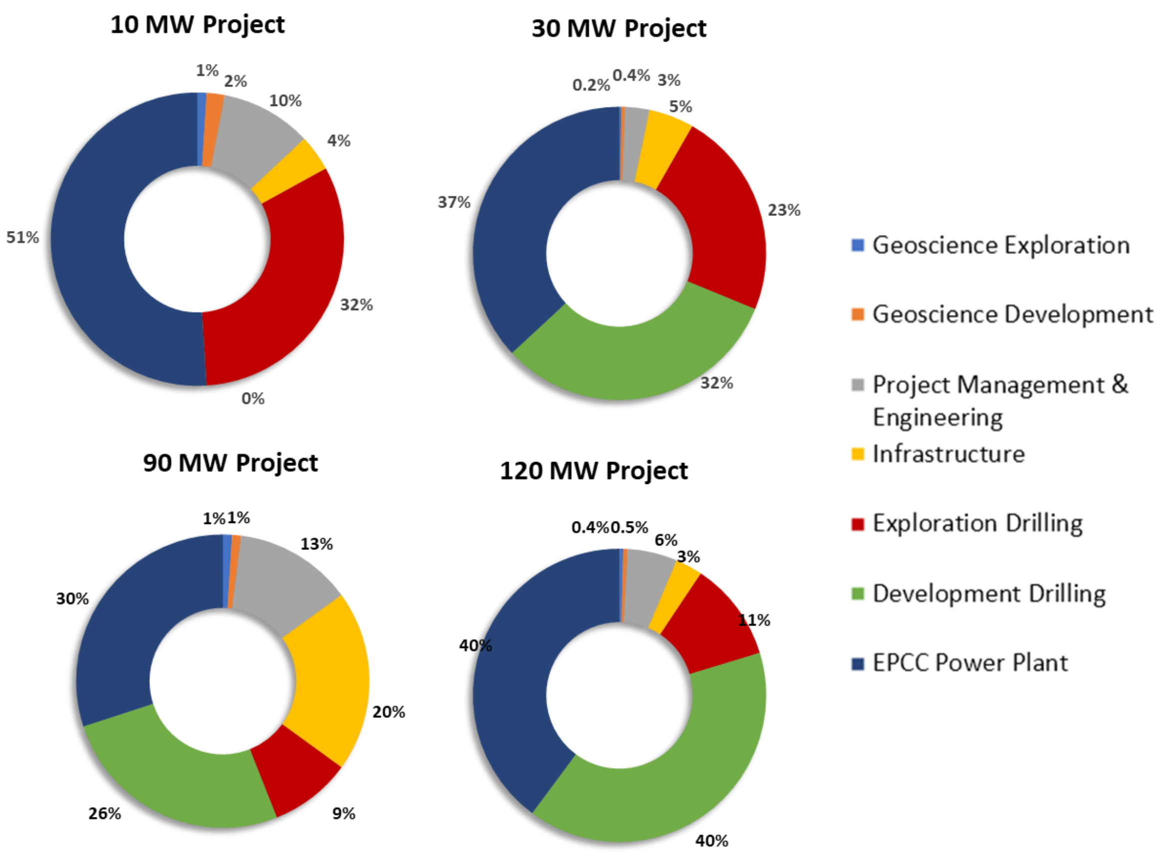

Figure 2: Cost distributions of four geothermal projects development in Indonesia (modified from Purwanto, 2021; Directorate General of Renewable Energy and Energy Conservation, 2020).

1.2 Research Objective and Method

This study aims to populate and summarize the geothermal field management strategy from past case histories in various fields in geothermal top producer countries. The methods used in this research are mainly from literature review to gather initial information, then supported with direct discussion with related experts on geothermal reservoir management. Figure 3 shows the thought process of workflow for this study.

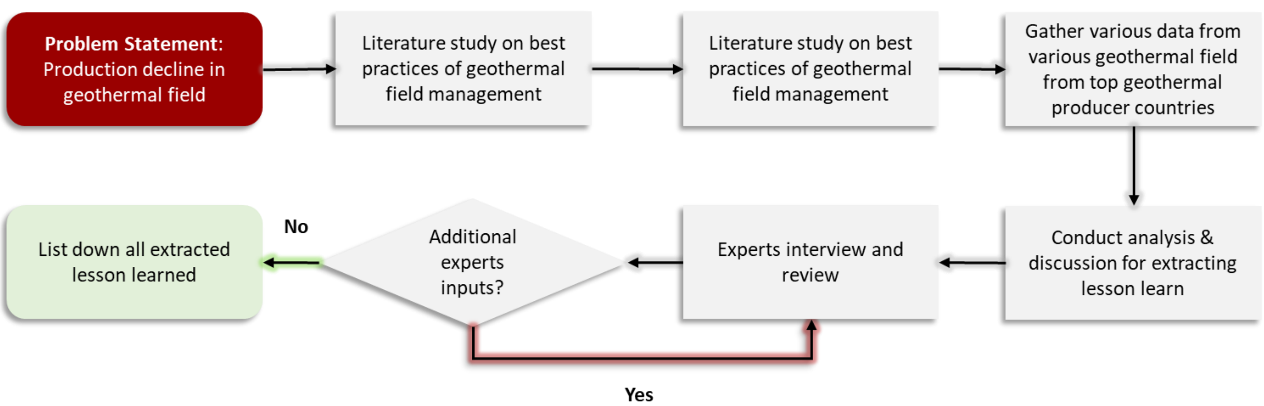

Figure 3: Thought process of the study

To achieve the key objectives of this research, the authors mapping and breakdown the key objective with offer several questions which the detail as follows:

1. Why field management strategy is important? Is the geothermal field need to be sustainable?
2. How about the field management strategy that has already been applied in various fields worldwide?
3. What is the lesson learned that can be taken from case histories to become the basis to develop proper reservoir field management?

The authors expect the result of this study can become a reliable reference for the government and geothermal developers to develop a robust geothermal field development strategy.

2. GEOTHERMAL FIELD MANAGEMENT

Field management is one of the vital key to maintain the sustainable production of geothermal energy that is mainly used for electricity generation and district heating. As each phase of the development of the geothermal field progresses, typically the knowledge understanding of geothermal resources in respective becomes more and more clear. A robust and precise field management strategy will impact in stabilize and increase the revenue of geothermal developers that secure a payback period and maintain at least until the end of the contract period.

Geothermal energy development should be renewable and sustainable. The concept of renewable and sustainable means that energy production is minimal and should last keep stable until an agreed-upon time, which is the ideal one that can be surpassed it even until hundreds of years like in the Larderello field that has been produced from 1904 until now that electrify around 26% energy demand in Italia. That's why a proper geothermal field management strategy is really important nowadays.

2.1 Start with Understanding the Conceptual Model

Conceptual models in the geothermal project is the illustration that describe essential features of geothermal systems that focused on data information regarding temperature, pressure, and fluid flow towards within and out of the system (Mortensen, A. K., & Axelsson, G., 2013). Generally geothermal conceptual model needs to cover several information, but not limited to:

- Heat source.
- Structure (faults).
- Hydrothermal alteration.
- Reservoir boundaries.
- Thermodynamic condition (steam, two-phase, temperature distribution, boiling, cooling, mixing, etc).
- Hydrology model (upflow and outflow zones).
- Well location.
- Production and Injection area.

In order to build a comprehensive conceptual model, requires an integrated approach from geological, geochemical, and geophysical interpretation along with information from well testing and production data that are unified to describe the physical features of the system. Conceptual models commonly used as the basis of exploration, development and utilization of geothermal systems which typically used as the basis of well targeting and setting depth as well as the basis for resource assessment and modeling, also driving production strategy and management plan of geothermal field (Mulyadi, 2021; Mortensen, A. K., & Axelsson, G., 2013).

2.2 Workflow in Developing Field Management Strategy

Several important elements of field management workflow need to be understood by all related parties in geothermal projects as presented in Figure 4. Starting from reservoir quality identification and characterization, a clear understanding of geothermal systems, reservoir characteristics, and dynamic behavior after several months/years from early production is very important. Geothermal developers should develop a proper and comprehensive data acquisition program as well as a surveillance plan to reduce the uncertainties of the reservoir behavior and list down any key issues that are faced during monitoring, especially in the golden time of production (1-2 years from COD).

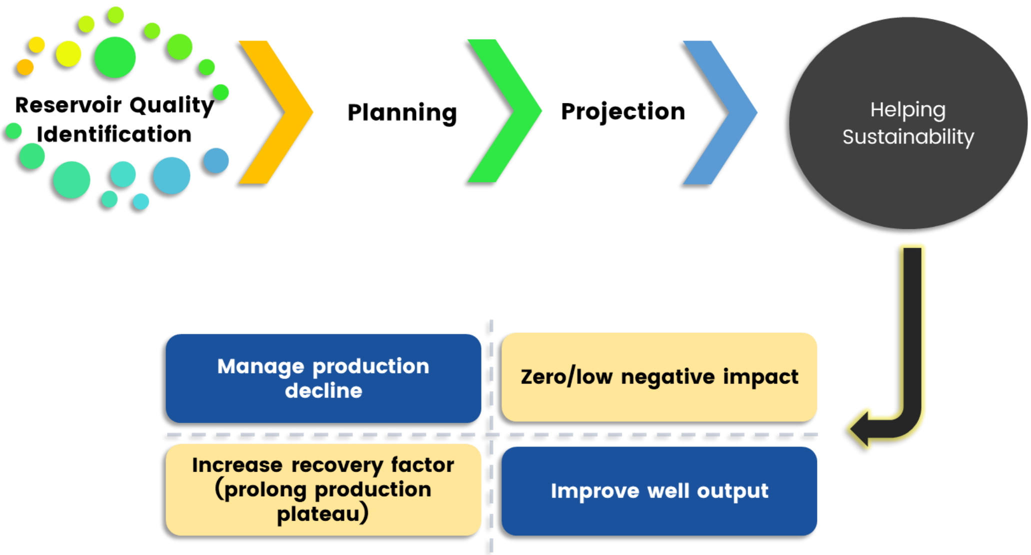

Figure 4: Simplified field management flow-thinking (modified from Mulyadi, 2021).

The result of the reservoir characterization is crucial since it will become the basis of planning and projection that can affect the planned strategy that will be applied to manage the sustainability of production for at least until the end of the contract. The impact of understanding of reservoir and subsurface characteristics will affect several management strategies, but not limited to:

- Well targeting for make-up well, as well as the project schedule for the upcoming drilling campaign.
- Optimization strategy from existing production well, as well as workover/well stimulation.
- Reinjection strategy with risk analysis that considers potential negative impact from planned reinjection strategy for reservoir condition and existing well.

2.3 Geothermal Field Management Strategy

Generally, the objective of a proper field management strategy is to maintain the electricity generation of the geothermal field. In order to manage production decline and improve electricity generated, as illustrated in Figure 5, there are several aspects that can be optimized to ensure the sustainability of production in the geothermal field i.e., reservoir management, injection wells, production optimization, surface facilities, and power plant.

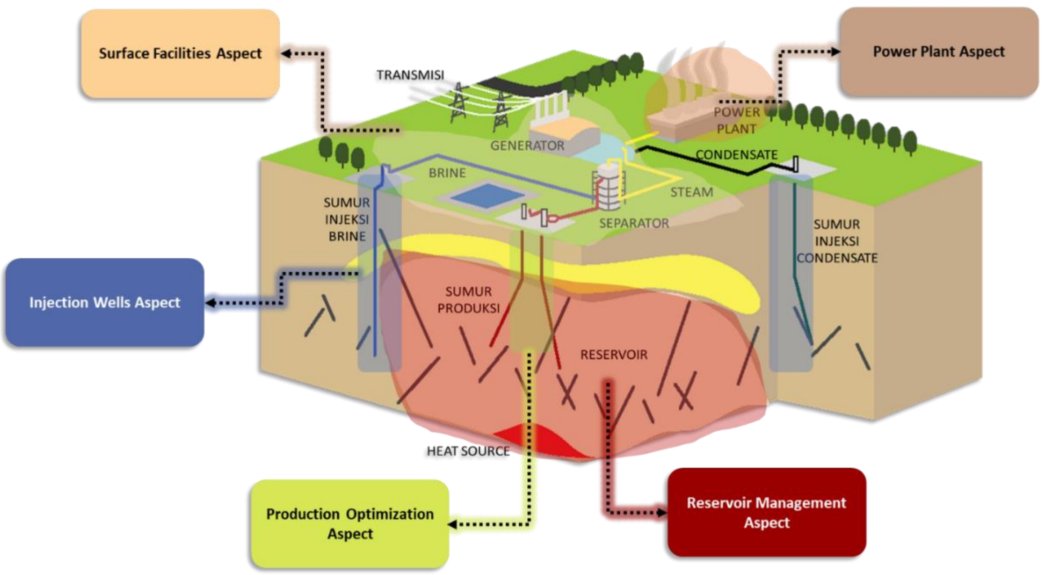

Figure 5: Key Aspects for Developing Proper Field Management Strategy (modified design from Saptadji, 2020).

Table 1 summarizes several strategies in various considered aspects to develop a robust field management strategy.

Table 1: Best Practices on Field Management Strategy (modified from Mulyadi, 2021)

Aspect	Strategies
Reservoir management	• Expand the steam cap. Obviously when the steam cap expanded, it can help to maintain the decline of steam production from existing well. Moreover, the effect of inducing the development of a steam cap will have potential on increasing production. • Manage reservoir liquid level and superheat. Maintaining liquid and certain level will help to reduce the decline of production, also maintenance the superheat as low as possible (<10 °C) until end of contract will prevent the effect of dry heat (condition where there is no more fluid left because there is heat with the implication can't extract the heat because there is no fluid flowing through it. • Active optimization of injection strategy as well as reducing the amount injection-related cooling for pressure support to reservoir. • Do comprehensive surveillance for better understanding of dynamic reservoir condition and reduce captured uncertainties that will be helping the projection and simulation close to the actual situation in subsurface. • Routine monitoring for production and injection (mass withdrawal), reservoir thermodynamic (pressure, temperature, saturation), as well as 2G monitoring (geochemistry – fluid, geophysics – micro gravity). • Balancing production, find the right balance between shallow and deep extraction. • Use probabilistic forecasts. Multiple realization forecast will help to reduce uncertainty and gain flexibility on decision-making in geothermal business by create room for errors for future adjustment. • Avoid flashing in the formation.
Injection wells	• Mitigate scale. Scale accumulation will decrease the injection capacity of the well. • Prevent corrosion and increasing reliability. Corrosion problem typically is close-related to the acidic reservoir fluid. To prevent corrosion, several efforts can be applied such as using corrosion-resistant material, cathodic protection, corrosion inhibitors, and corrosion-resistant cement. • Routine monitoring to ensure re-injection can improve heat recovery and pressure support.
Production optimization	• Stimulate and workover wells. Workover and well stimulation will help to increase production capacity from problematic well with goal to restore production to initial condition. • Drill multi-lateral wells. There is any potential for geothermal well to be drilled with multi-trajectory for increasing energy recovery. • Re-drill. This method can become one of option to non-commercial well that have low productivity. • Reactivation idle well. • Install downhole scale inhibitor. Scale inhibitor will be crucial in reducing the frequency of workover operation for reaming the scale since workover is expensive.
Surface facilities	• Remove bottlenecks to optimize the production. • Maximize capacity utilization. Proper monitoring and update of resource assessment will help to decide the feasibility of additional generation without overexploitation. • Ensure safety and reliability. • Remove scale in pipeline.
Power plant	• Power plant cost load optimization. • Optimize turbine inlet pressure. The higher turbine inlet pressure will affect on reducing required steam consumption to generate certain MW. If the steam consumption can be reduced from reservoir, it also can help the production decline. • Maintain and extend equipment life • Install additional capacity

As already presented in Table 1 above, various aspect needs to be considered for developing integrated field management strategy. In short, several ways can be optimized to create robust and integrated field management strategy to ensure the sustainability of geothermal energy production. Table 2 shows the example of approach for various objective of field management strategy that summarized from (Mulyadi, 2021).

Table 2: Example of Field Management Strategy Solutions for Various Key Challenges (modified from Mulyadi, 2021)

Field Management Objectives	Problem Statement (Key Challenge)	Alternative Solutions	Expected Results
Maintaining Production Decline at a Low level	• Repetitive and Frequent wellbore silica or calcite scaling deposition in the well results in high decline rates and threat to steam supply reliability. • Increase operation expenditure to mitigate scaling problems since workover operation requires an expensive cost.	• Reactive approach – requires frequent/regular well interventions (clean-out and acidizing) to recover the production. • Improved technology to optimize solutions.	• Reduce field decline rates. • Optimize well interventions method. • Reduce OPEX by applying LOW effort HIGH impact stimulation (well throttling, well washing, etc).
Reducing Production Decline Rates	• Wellbore scaling affects high decline rates. • Require frequent well interventions that can lead to high well intervention/stimulation costs.	• Proactive downhole scale mitigation in liquid wells using proven technology such as inserting scale inhibitors and any related approach that can decrease/inhibit scale deposition.	• Reduce field decline rates. • Reduce the frequency of well interventions/ stimulation. • Expand resource areas available for production to include sectors prone to wellbore scaling.
Improve Well Result and Forecast	• Challenge on obtaining good producer. • Challenge on improving the possibility success of make up well.	• Reduce uncertainty by updating the conceptual model and dynamic reservoir model with new acquired data. • Proper and comprehensive well targeting and well-ranking assessment for the increasing ratio of success well with high output.	• Additional electricity generations for new units or for spare up. • Cost efficiency.
Improving Well Output Capacity	• Challenging to find highly inter-connected features (sweep spot) that can improve well productivity. • Understanding high fracture distribution. • Improve the success ratio of make-up well beyond the proven area.	• Proactive conduct fracture characteristics identification by modelling fracture distribution as input for well targeting. • Comprehensive fracture characteristics will help in developing sweet spot distribution based on highly inter-connected fractures mapping which typically represents a high-permeability area.	• Increase the possibility of success of make-up well. • Reduce the number of make-up well by increasing the initial capacity of the make-up well. • Open organic growth opportunity to install additional unit.

3. FIELD MANAGEMENT EXPERIENCE WORLDWIDE AND LESSONS LEARNED

The utilization of geothermal energy for electricity generation started 120+ years ago when the Larderello field in Italia started commercially generating electricity. Then, nowadays geothermal energy for power generation is massively developed and is planned for clean energy solutions during fossil fuels phase out. But unfortunately based on case histories, several geothermal fields suffer a significant decline in electricity generation caused by various reasons which typically in some cases is because of improper field reinjection strategy. To keep this research concise, the authors start to do a breakdown of various reinjection strategies and its implication on related fields based on top geothermal producer countries which are presented in Figure 6.

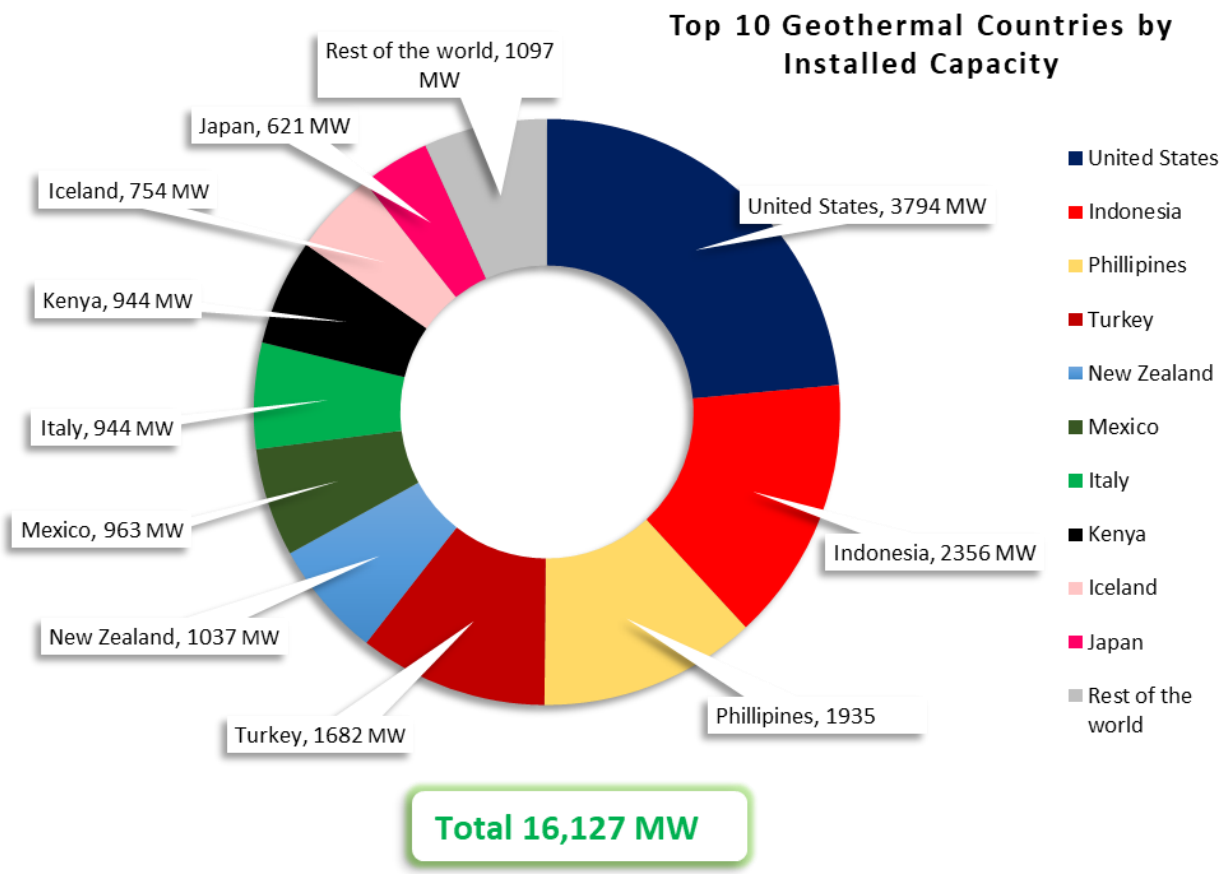

Figure 6: Top geothermal producer countries based on installed capacity in early 2022 (updated from EBTKE 2022; Thinkgeoenergy, 2023)

The general information, reinjection strategy, and the impact of reinjection of various fields in the world are summarized with the objective to extract the lesson learn from field management strategies that lead to making geothermal energy production more sustainable. The detailed summary is presented in Appendix 1.s

From various experiences worldwide, several summaries are presented in Table 3 that are separated by each of the categories of geothermal general characteristics which focused in vapour dominated and liquid-dominated systems since it related to most geothermal systems in Indonesia.

Table 3: Vapour and liquid-dominated fields experience summary of applied reinjection strategy

Category	General Information
Vapour Dominated System (VDS).	Steam is generated and there is a lot of immobile water in systems that are dominated by vapour. The low permeability of the reservoirs and the boundaries prevent them from receiving a lot of water recharge. Pressure will drop as production proceeds, allowing the immobile liquid to boil and transform into steam. While the heat is still present in the rock matrix, the fluid inside the reservoir will eventually run out. Therefore, to maintain production, reinjection within the system is frequently required (Kamila, Z. et al, 2020; Diaz et al., 2016; Kaya et al., 2011). This system typically has temperature ranging from 220 °C - 300 °C, with typical production enthalpy ranging from 2,600 - 2,800 kJ/kg (Kaya et al., 2011).
Reinjection strategy experience summary based on (Kamila, Z. et al, 2020; Diaz et al., 2016: Paramitasari et al., 2018; Simatupang et al., 2015; Suryadarma et al., 2010). • Reinjection within the system boundary or infield location is primarily selected for the reinjection wells in VDS to provide induced recharge and maintain steam productivity. • Some negative effects have been observed in production wells that are too close to injection wells. The placement of reinjection wells in a low-heat area is one of the reasons for cooling in VDS. • Temperature decreases have also been observed when a high-volume injection was performed in highly fractured rock. As a result, changes in injection rate are frequently used to reduce the thermal front like in The Geyser and Kamojang geothermal field.	

<table>
<tr><th>Category</th><th>General Information</th></tr>
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Another method of cooling is when the injection sites coincide with areas of marginal natural recharge in certain injection zones, such as in the Darajat geothermal field.
The optimal depth for infield reinjection in VDS varies and is ascertained by the reservoir structure. Like on Kamojang focuses on the deeper and lower permeability zone. Then, based on MEQ (micro-earthquake) observations, in Darajat condensate also moves to a deeper zone.
In Larderello, on the other hand, wastewater is injected into the shallower level, taking advantage of the superheated condition and good vertical permeability in the systems.
The Geysers have nearly the same injection level as producing depth, using natural and induced fractured rocks. These strategies are chosen to allow condensate to reside and heat up before moving to production wells, which has had a positive impact on steam production.
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<tr><td>High Enthalpy – Liquid Dominated System (HE-LDS).</td><td>Boiling occurs in a liquid-dominated system (LDS). Pressure drops rapidly before boiling occurs, then gradually slows. A high enthalpy system has tighter rock formations, resulting in lower permeability. This system also experiences local boiling near the production wells (Kamila, Z. et al, 2020; Diaz et al., 2016; Kaya et al., 2011)..

This system typically has temperature ranging from 220 °C - 300 °C, with typical production enthalpy ranging from 1,500 - 2,600 kJ/kg (Kaya et al., 2011).</td></tr>
<tr><td colspan="2">Reinjection strategy experience summary based on (Kamila, Z. et al, 2020; Eneva et al., 2018; Libert, 2017; Diaz et al., 2016; Ouma et al., 2016; Kristjansson et al., 2016; Ouma et al., 2016; Gunnarsson et al, 2016; Sarychikhina, Glowacka, & Mojarro, 2016; Prabowo et al., 2015; Barragán et al., 2015; Sirait et al., 2015; Uribe et al., 2015; Maturgo et al., 2015; Miranda-Herrera, 2015; Sherburn et al., 2015; Mortensen & et.al, 2015; Kaven et al., 2014; White et al., 2005).
In HE-LDS fields, the infield location is the most commonly chosen location for reinjection. This strategy has aided in increasing energy recovery by providing adequate recharge and helping to maintain production decline at a lower level like in Mount Salak, Bacman, Olkaria, and Dieng geothermal fields.
Despite this, numerous studies have reported chemical and thermal breakthrough issues as a result of infield injection as experienced in Hellsheidi and Mount Salak. In these cases, cooling mitigation is achieved by extending injection or combining the infield with the edge/outside boundary, as seen in Mount Salak.
In HE-LDS, injection into the same or deeper levels than the production zone is common as experienced in Mount Salak, Hellsheidi, Rotokawa, and Salton Sea.
Deep reinjection generally has produced positive results because it improves heat transfer. Then, shallow injection is frequently used in conjunction with deep reinjection, typically for condensate injection or as a means of compensating for limited injection capacity in existing deep reinjection wells like in the Hellisheidi and Nesjavellir geothermal fields.
In liquid-dominated systems, peripheral locations are frequently chosen to reduce the risk of cooling, particularly in the early stages of development like in Lahendong and Wayang Windu geothermal fields. Edgefield is typically accompanied by an infield location, either because reinjection capacity constrains require more support and recharge, or both like in Hellisheidi geothermal field.
In LDS, partial injection might be still used like in Nesjavellir, Olkaria East, Cerro Prieto, Mak-Ban, Ohaaki, and Wairakei geothermal fields. However, the removal of geothermal fluid without sufficient additional fluid from reinjection would cause depressurization, which ultimately results in the decline of steam like in the Cerro Prieto geothermal field. Additionally, subsidence may result from the limited fluid renewal pressure drop like in Wairakei geothermal field. The subsidence rate has been successfully decreased by increasing the injection rate.
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<tr><td>Low Enthalpy – Liquid Dominated System (LE-LDS).</td><td>A low enthalpy system is typically represented by extremely high fracture and permeability. As pressure drops, this system frequently experiences strong recharge from the boundaries. As a result, there is less chance of running out of water during production (Kamila, Z. et al, 2020; Diaz et al., 2016; Kaya et al., 2011).

This system typically has temperature ranging from 220 °C - 250 °C, with typical production enthalpy ranging from 943 – 1,100 kJ/kg (Kaya et al., 2011).</td></tr>
<tr><td colspan="2">Reinjection strategy experience summary based on (Kamila, Z. et al, 2020; Senturk, 2019; Diaz et al., 2016)
The large volume of injected water may jeopardize the interference with the hot reservoir as LE-LDS are frequently characterized by widespread fractures and strong lateral recharge nature. In order to prevent thermal decay, which has been reported in numerous cases like in Kizildere, infield locations in LE-LDS should be extra closely monitored. This problem is frequently addressed by moving the injector to a different location, which lowers the risk of cooling. Moving on has aided in the recovery of production and enthalpy.
In order to maintain natural surface features and prevent subsidence like in Wairakei, shallower reinjection is also typical in LE-LDS. However, choosing the same or a deeper level typically results in pressure recovery. To accomplish both goals, these two categories are frequently combined, as in the Wairakei and Kizildere geothermal fields.
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Based on various cases in the geothermal field worldwide and direct discussions with experts, there are several general lessons learned that can be extracted:

- Over exploitation in the geothermal field without having an understanding of subsurface conditions is not wise for the development of the geothermal project, ideally staging development was become a wise option to develop the geothermal project. There are three key sustainable indicators: environment, economic business, and social aspects. These indications must be considered in the management of the geothermal field and should be integrated. If the production rate is less than its production capacity rather than above it, sustainable management can be achieved (Mulyadi, 2021).

- Key parameters to optimize the economical aspect of the geothermal project also on a deep understanding of field characteristics for the development of dynamic reservoir modelling for running development scenarios. For example, if the developers already have information related to the typical thermodynamic distribution, then the boundary and whatever the shape of the reservoir itself or the volumetric itself, developers can continue to pour it in the form of a reservoir model. From the reservoir model, developers can make various development strategies, the number of wells required, then create projections from the reservoir simulation model that was previously developed. The projection will help to determine the economical aspect which is typically represented by the total cost required, net present value (NPV), and internal rate of return (IRR) (Dwikorianto, 2021; Mulyadi, 2021).

- Understanding subsurface conditions, and proper data acquisition is important from the early exploration phase. Knowledge of reservoir characteristics is important to develop and improve suitable exploitation strategies. There are four main conditions that can drive the field management strategy, those are pressure and temperature changes, production decline, formation physical changes, & fluid chemistry changes. This condition can be monitored by applying PTS measurement, production & reinjection monitoring, fluid lab analysis, microgravity & MEQ survey, and Inter-well tracer test. These kinds of data acquisition will give important data input for dynamic reservoir characterization and the results will be updated in the reservoir modeling. The optimal production and reinjection strategy will be developed using these data to maintain sustainability. Routine monitoring and surveillance become the most essential key to reducing subsurface uncertainties and gaining a deep understanding of dynamic reservoir conditions, especially in the crucial golden time of production (early production to 2nd year of production) (Dwikorianto, 2021; Mulyadi, 2021).

- Production decline is commonly caused by pressure decline and/or temperature depletion. The solution to these problems is reinjection into the reservoir to increase the reservoir fluid so that the pressure will be maintained. The reinjection strategy should be implemented carefully, to make sure the injected fluid is not caused a thermal breakthrough which decreases the reservoir temperature (Dwikorianto, 2021).

- In several cases, handling scaling becomes a problem that frequently might be faced. A scaling issue could be discovered in the production or reinjection pipelines. Several solutions are available, including mechanically adjusting the pH and temperature, high-pressure reinjection, using a cooling pond, and adding an inhibitor solution.

- Benchmarking studies with another geothermal field to gain similarity will be helpful as a part of developing good field management strategies (Mulyadi, 2021).

- Conduct join research or attracting available new technology providers to test the applicability in the respective field might be can help lower steam costs, eliminate excessive production decline of wells, and reduce operating costs (Dwikorianto, 2021; Mulyadi, 2021).

4. CONCLUSION

Several conclusions can be drawn from this study are:

- Field management is one of the vital keys to maintaining the sustainable production of geothermal energy, sustainable geothermal field needs robust and well-prepared field management by the close monitoring system to get update reservoir data for building the optimum production and reinjection strategies

- Each geothermal field has its unique key issues and approaches to solving the problems, deep understanding of the subsurface condition is required for reducing the uncertainties which will affect the strategy that might be applied by geothermal developers.

- Field management needs to be carried out from various sides, starting from reservoir management, production optimization, reinjection strategy, surface facilities reliability, also power plant efficiency.

- Benchmarking studies to other similar fields and exploring new technology might become alternatives to developing robust and comprehensive field management strategies.

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APPENDIX 1. Summary of Reinjection Strategy in Various Field Worldwide (modified from Kamila, Z. et al, 2020)

Country/ Field	General Information		Reinjection Strategy	Reinjection effect on the respective field	Additional Remarks
	Type of Information	Amount			
United States / The Geysers	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	VDS 1971 1,477 MWe 710 MWe 300 °C 2,650 kJ/kg 6,350 ton/hr 5,443 ton/hr	• From 1960 to 1969, there was a surface discharge. Condensates were injected from 1969 to 1982. (25 percent of mass-produced). • The injection rate was increased in 1982 with the addition of rainwater, and water from the northwest region had the highest rate of reinjection (Diaz et al., 2016). • As stated in (Enedy and Ca, 2016), the current strategy is performing infield injection, and the condensate injection is added with supplemented water. • The depths of reinjection are shallow and deep injection. The gravity-fed injection is achievable due to the high permeability of the fracture. The majority of injection wells were also production wells (Diaz et al., 2016).	• The productivity of wells has recovered over time. External city waste waters (artificial recharge) helped to stabilize reservoir pressure, halting the resource's ongoing decrease. The NCG in the produced steam has been diluted by reinjection in various portions of the system, optimizing generating efficiency and reducing greenhouse gas emissions (Enedy and Ca, 2016). • After massive external injection, the number of induced seismic events has increased, particularly for deep injection. There is a clear relationship between injection rates and seismic occurrences with M > 1.5 in the field's northwest, where most injections are performed and temperatures are greater (Majer et al., 2017; Diaz et al., 2016; Trugman and colleagues, 2016). • The temperature drop was caused by a high-volume injector located in the northwest corner of the field. Variations in pressure have also been observed (Diaz et al., 2016). • Radiogenic helium release from the reservoir rock matrix (magmatic source) is caused by injection-related fracturing (Diaz et al., 2016).	• Seismic events have been minimized, indicating that thermal stress is nearing equilibrium (Majer et al., 2017). • EGS tests were carried out in the field's northwest (Stimac et al., 2017). • Three substantial injection augmentation programs were implemented: excess rainwater in 1980, stream water into SE geysers beginning in 1997, and community wastewater (SRGRP) in 2002 (Enedy and Ca, 2016).
United States / Salton Sea	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	HE-LDS 1982 403.4 MWe 369 MWe 302-315°C Data N/A 12,945 ton/hr 10,353 ton/hr	• Since 1989, the injection has accounted for approximately 80 percent of total brine production (Barbour et al., 2016). • Some injection wells are in close proximity to producing wells. A large amount of solid deposition occurred, but it was reduced by altering the pH of the brine or removing the solids prior to injection (Diaz et al., 2016).	• Ground deformation was discovered around production and injection wells (Diaz et al., 2016). • Seismicity caused by injection has increased pore pressure (decrease effective stress). Seismicity rates are clearly sensitive to changes in injection and production rates (Crandall-Bear et al., 2018).	• The brine is hypersaline, containing almost any element in the periodic table (Diaz et al., 2016). • Injection and production are carried out at similar depths (Diaz et al., 2016).
Indonesia / Wayang Windu	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp	HE-LDS 1999 227 MWe 227 MWe 260 – 325°C	• Condensate and brine reinjected by gravity in the resource's southernmost region (within 2 km of the reservoir boundary) (Kamila, Z. et al., 2021).	• Hydraulic fracturing with cold water injection increased output (Diaz et al., 2016).	• Freshwater pumping and acidizing have aided in the recovery of well productivity (Diaz et al., 2016).

Country/ Field	General Information		Reinjection Strategy	Reinjection effect on the respective field	Additional Remarks
	Type of Information	Amount			
	Average Enthalpy Produced mass Injection mass	2,700 kJ/kg 1,544 ton/hr 576 ton/hr			
Indonesia / Mount Salak	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	HE-LDS 1994 377 MWe 377 MWe 240 – 316°C 1,842 kJ/kg 2,814 ton/hr 8,165 ton/hr	• This field performs a full reinjection strategy (Yoshioka et al., 201 5). • Injection wells are generally positioned infield for brine (1.5 km min distance) and outfield for condensate (two kilometers from production) (Libert, 2017). • Deep reinjection (Diaz et al., 2016). As flow barriers between production and injection wells, faults play an essential role. Adjustment of strategy in response to performance or chemical monitoring (Diaz et al., 2016).	• An adjustment in strategy has improved energy recovery. However, infield injection has caused a decline in temperature and enthalpy over time (Libert, 2017). • Production wells discharged injectates partially and varied in response to changes in injection rates and location. When the injection rate was lowered, the pressure dropped, causing the boiling process to occur. MEQ events are captured at the reinjection zone (Diaz et al., 2016).	• When it was first developed, the reservoir was completely liquid, but it subsequently formed a massive steam cap in the system's eastern half (Putri and Julinawati, 2018). • Greater injection distance is projected to improve reservoir performance as the recommendation results of the latest reservoir modeling (Diaz et al., 2016).
Indonesia / Lahendong	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	HE-LDS 1992 120 MWe 91 MWe 280 – 320°C 2,670 kJ/kg 692 ton/hr 500 ton/hr	• This field performs full reinjection strategy (Diaz et al., 2016). • In one peripheral NE area (1.5 kilometers from the nearest production cluster), Lahendong performs a cold reinjection system using brine and condensate (Prabowo et al., 2015). • Injection wells are located near a fault and have the lowest temperature in the fields (maximum of 110°C) (Diaz et al., 2016).	• Thermal breakout in the northern area projected by tracer test due to reinjection. • Based on tracer data, injection only to the north could affect the absence of recharge and pressure in the south (Prabowo et al., 2015).	• Considering the current tracer test, it is advised that the injection rate in the northern area be kept between 25 and 50 kg/s (Prabowo et al., 2015). • The fluids in the northern fields are acidic (Permana and Hartanto, 2015).
Indonesia / Kamojang	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	VDS 1978 235 MWe 235 MWe 235 – 245°C 2,800 kJ/kg 1,429 ton/hr 300 - 400 ton/hr for 200 MW	• Additional water and full condensates are used in the reinjection strategy (Sofyan et al., 2019). • Condensate is expected to move slowly and gradually heat and infiltrate the production zone because four out of the eight available infield unproductive wells have been used as injection wells and are situated in a deeper zone with low-medium permeability (Sujarmaitanto et al., 2015). (Suryadarma and Dwikorianto, 2010). • The injection strategy is adjusted frequently by implementing injection	• Current injections reported that help in reducing to Kamojang field's steam decline (Diaz et al., 2016). However, the amount of reinjection condensate is insufficient to maintain stable production (Sofyan et al., 2019). • Depending on the location of the injection wells, injection had a variable effect on productivity (no impact, loss, or minimizing decline), impacting several wells positively as well as others negatively (Febriani et al., 2015). • Thermal contraction cracking causes MEQ events near injection wells. In production, a minor injection breakthrough has occurred (Kamila Z. et al., 2020).	• Kamojang is confronted with a significant lack of water injection mass (naturally from the reservoir and artificially from other sources) in comparison to produced mass, resulting in a decline in field mass production and insustainable production (Sofyan et al., 2019).

Country/ Field	General Information		Reinjection Strategy	Reinjection effect on the respective field	Additional Remarks
	Type of Information	Amount			
			wells repositioning and injection (Kamila Z. et al., 2020).		
Indonesia / Darajat	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	VDS 1994 270 MWe 270 MWe 240 °C 2,569 kJ/kg 1,764 ton/hr 448 ton/hr	• Reinjection strategy consists of comprises additional water and full condensates (Diaz et al., 2016). • Beginning in late 2011, an infield reinjection well was decommissioned and relocated to the edgefield in the northeast corner of the boundary (Diaz et al., 2016). • Prior to 2011, injection in the central portion (infield), as well as deep and shallow depth, was performed for nearly 20 years (Paramitasari et al., 2018)	• The new edgefield strategy prevents further cooling caused by rapidly boiling in the reservoir's central and southern sections, which led in a higher contribution of boiled condensate to the steam produced. However, the chemical breakthrough is now being reported in the northern portion of the field (Kamila Z. et al., 2020). • The MEQ cluster shows that the injectate condensate at the system's periphery appears to move deeper into the reservoir. Overall improvement in field-wide production performance as the rate of decline decreases (Paramitasari et al., 2018). • MEQ caused by injection occurs deep beneath the injector (Paramitasari et al., 2018).	• Condensate reinjection has improved productivity and cleaned the scale (Suryanta et al., 2015). • Condensate reinjection has enhanced productivity while also cleaning the scale (Suryanta et al., 2015). • It has been confirmed that the liquid is supplied by the marginal recharge in the central part of the producing area, where the old infield area is located (Simatupang et al., 2015).
Philippines / Tiwi	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	HE-LDS 1979 234 MWe 140 MWe 310-350 °C 1,050-2,800 kJ/kg 3,297 ton/hr 2,289.6 ton/hr	• In 1993 and 2000, 100 percent brine injection and condensate injection were accomplished (Diaz et al., 2016). • Currently, the Southeast Hot Brine Injection System (SEHBIS) is the main disposal system for brine produced in the Nag and Kap areas (including both edgefield and outfield) (Sicad, 2015). • The separate brine disposal system in west Tiwi is known as MatRidge Brine Disposal System (MRBDS) in the northwest part/outfield from Mat Bar brine (Calibugan et al., 2015) • Previously, MRBDS brine flowed into ponds before gravity-flowing to injection wells (referred to as "cold brine"). However, some wells in the west have been converted from cold to hot reinjection, and injection rates are limited in certain wells until one injection well is re-drilled to increase the injection rate.	• Initially, there was a rapid cooling observed, and one producer even stopped steam flow due to a 22 C temperature decrease (Diaz et al., 2016). • Temperature and flow of steam Even though they have little communication recovered reinjection has increased mass flow and constant enthalpy south of the field (Calibugan et al., 2015). • Since 2003, some dry and superheated steam wells in the field's northwest have become two-phase, which is associated with the infield and outfield reinjection in the Mat area. No significant thermal breakthrough has been reported after switching reinjection to the outfield (Sicad, 2015). • Reinjection rate limitations have contributed to the low negative reinjection impact (Diaz et al., 2016). • Southeast reinjection has increased mass flow and constant enthalpy south of the field, despite the fact that they have little communication (Calibugan and colleagues, 2015) • Since 2003, some dry and superheated steam wells in the field's northwest have become two-phase,	• Aside from hooking up idle wells, another round of injection well workover is currently being proposed in the SEHBIS area to provide additional capacity in outfield wells and reduce the utilization of edgefield wells. (Sicad, 2015).

Country/ Field	General Information		Reinjection Strategy	Reinjection effect on the respective field	Additional Remarks
	Type of Information	Amount			
			Currently, the ponds are not completely abandoned but are occasionally used for well start-ups or high-level separator upsets (Sicad, 2015). • Some of the brine is mixed with dry superheated well to be de-superheated (Sicad, 2015). • Deep reinjection is one of the strategies performed in Tiwi (Diaz et al., 2016). • Condensate reinjection is only used in emergency situations (now only used in brine disposal). Silica saturation is always monitored (Sicad, 2015). • Surface discharge from 1979 to 1983, followed by partial infield reinjection from 1983 to 1993 to recover from pressure drawdown in Nag. The first brine injectors in the Nag area were idle, corrosive well production wells (Diaz et al., 2016). • In 1984, injection was relocated to the SE edgefield first, and then to the outfield (4 km) because the capacity of the edgefield was insufficient (Sicad, 2015). • Infield reinjection (400 m from production) tests were conducted from 2003 to 2013 to mitigate dry-out in some wells (Diaz et al., 2016).	which is associated with the infield and outfield reinjection in the Mat area.	
Philippines / Makiling-Banahaw (Mak-Ban)	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	HE-LDS 1979 458.53 MWe 240 MWe 337 °C 1,990 kJ/kg 6,901 ton/hr for 425.73 MWe	• Injection of brine was concentrated on edgefield areas in the east and west between 1979 and 1987. Due to a thermal front experience in 1987, the injection was moved 2–3 km west of the producing area (Kamila, Z. et al, 2020).	• Outfield injection was added subsequently as a result of the heat breakthrough that edgefield injection wells experienced in 1987. The thermal front problem has been resolved and temperature recovery has been made possible by injection rate control and outfield injection. • A breakthrough in injection has occurred with Edgefield hot reinjection. In order to generate fluids, brine has contributed. Additionally, injectate has had an impact on the reservoir, resulting in a reduction in average steam flashes.	• The central up-flow coincides with the intersection of multiple faults in the middle of the geothermal system (Kamila, Z. et al, 2020).

Country/ Field	General Information		Reinjection Strategy	Reinjection effect on the respective field	Additional Remarks
	Type of Information	Amount			
		2,812 ton/hr for 425.73 MWe		• Tracer tests have indicated that the injected fluids could be sufficiently heated (Diaz et al., 2016).	
Turkey / Kizildere	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	LE-LDS 2007 266.85 MWe 227.29 MWe 245 °C 1,047 kJ/kg 6,600 ton/hr 5,000 ton/hr	• This field performs full reinjection. Currently, nearly 80 % of the fluid is being reinjected (Satman et al., 2017). • The wells are mostly concentrated on the west side cluster, with a few in the east side cluster surrounding the production cluster (Garg et al., 2015a). • The temperature of reinjection is 110 °C. (Kamila, Z, et al., 2021). • To prevent scaling, an inhibitor is used. Previously, surface discharge was measured from 1984 to 2002 (Kamila, Z, et al., 2021). • Experiments with intermittent infield reinjection were carried out around 1999. The formal reinjection scheme began in 2002 with an infield well located further away from the production zone than the previous experiment (Kamila, Z, et al., 2021). • In 2010, 20% of the total produced fluid was injected into four wells. Deep and shallow reinjection are used in tandem (Kamila, Z, et al., 2021).	• Some return was observed in production wells near injection (via CO2 content decline) (Kamila, Z, et al., 2021). • In 1984, a lack of reinjection combined with scaling causes a decrease in production (calcite precipitation concerns in the reinjection rock formation) (Lewis et al., 2015). • In 1999, infield reinjection experiments reduced fluid production in the well closest to the injection (200 m). The current infield injection scheme has provided pressure support since 2002. Cooling was observed in the nearby area around 2004. Some return was observed in production wells near injection (via CO2 content decline) (Kamila, Z, et al., 2021). • In 1984, lack of reinjection along with scaling leads production decline, (Calcite precipitation concerns in the reinjection rock formation) reinjection well, and eventually, it was shut-in. By 2009, infield reinjection had reduced the reservoir temperature by 4 °C (Kamila, Z, et al., 2021).	• The first injection strategy was performed in shallow zones on the system's eastern side. • The results of interference and tracer tests show that pressure support from these injection wells was limited. • When the KZD-III production wells began to produce, total net production increased significantly (Kamila, Z, et al., 2021). • Furthermore, KZD-III production wells produce from deeper zones than KZD-I and KZD-II wells. With this type of shift in production strategy, there is an urgent need to revise the injection strategy as well. As a result, as the first step in a new injection strategy, two former production wells in the production region were diverted to injection at the end of 2018 (Kamila, Z, et al., 2021). • The second step in the plan was deeper injection from three wells on the field's western side. These wells will soon be subjected to tracer and interference tests (Kamila, Z, et al., 2021. • The final step is to designate another injection region near the production wells in the southeast. Greater pressure support on production wells is hoped for as a result of these changes (Kamila, Z, et al., 2021). • Wastewater is being used for space heating and greenhouse production (Halaço glu et al., 2018).

Country/ Field	General Information		Reinjection Strategy	Reinjection effect on the respective field	Additional Remarks
	Type of Information	Amount			
Turkey / Alasehir	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	LE-LDS 2014 214.02 MWe 189.42 MWe 190 °C Data N/A 2,350 ton/hr 2,000 ton/hr	• This field was performing a full reinjection strategy (Akin, 2019). • The reinjection temperature was 95.5 °C (Kamila, Z, et al., 2021).	• Pressure support in production wells (Aydin et al., 2018). • The chemical breakthrough was observed and some wells have shown signs of slight cooling (enthalpy has been decreasing to 35 kJ/Kk), and NCG drop is also unavoidable (Aydin et al., 2018).	• The fluid flow direction is controlled by E-W trending normal faults in the Alasehir reservoir. The intersection of S-N direction normal faults with E-W trending faults results in a highly intersected and robust fractured network. The production and injection wells are therefore aligned on the same flow patterns (Kamila, Z, et al., 2021). • Due to the fact that the majority of wells are connected by intersected faults, the production and injection strategies used by the majority of field operators have a significant impact on each other (Aydin et al., 2018).
New Zealand / Ohaaki	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	ME-LDS 1988 46 MWe 40 MWe >300 °C 1,150 kJ/kg 1,004 ton/hr 525 n/hr	• Shallow infield technique was applied for early production and reinjection (500 m away from production), followed by a deeper edge of resistivity boundary (Diaz et al., 2016). • Injector relocation to the resistivity boundary's outer field in 1993 (Sherburn et al., 2015).	• Reinjection was relocated to the edge of the resistivity boundary by 1993 because of shallow reservoirs' negative effects on reinjection returns to production (enthalpy drop) (Diaz et al., 2016). • Rapidly returning fluids to production wells after being extensively reinjected. Enthalpy loss was one of the negative impacts of this. In light of this, reinjection moved back into the shallower area outside the barrier (Sherburn et al., 2015).	• Currently, 60–70% of the air is reinjected; the remaining air is vented through cooling towers (Sherburn et al., 2015).
New Zealand / Wairakei	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	VDS 1996 55 MWe 45 MWe 180 °C 2,770 kJ/kg 200 ton/hr for 25 MWe 75 ton/hr for 25 MWe	• This field was performing full condensate reinjection (Kamila, Z, et al., 2021). • The outfield location on the field's western side is used to inject power plant condensates into a 1 injection well (Diaz et al., 2016).	• In two wells, injection raises the shallow groundwater level (Diaz et al., 2016).	• Wairakei does not have a vapour-dominated reservoir (Kamila, Z, et al., 2021). • However, a shallow steam zone formed in the Te Mihi area as a result of the pressure decline (Kamila, Z, et al., 2021). • This zone is then used to generate steam for the Poihipi plant from two shallow production wells (Diaz et al., 2016).
Mexico / Cerro Prieto	Geothermal System Start Date	HE-LDS 1973 570 MWe	• This field is performed partial reinjection. • The majority of the brine is hot-injected, with the remainder being sent to	• Despite a chemical breakthrough, reinjection has slowed the decline rate of steam production in some wells (Diaz et al., 2016).	• Reinjected water in the northwest moves faster horizontally than vertically, whereas injection fluid in

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	Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	570 MWe 280-350°C 1,725 kJ/kg 11,934 ton/hr 2,237 ton/hr	evaporation ponds via open channels, where it cools and allows the silica to precipitate before being pumped and reinjected (Kamila, Z, et al., 2020). • However, some of the separated water is reinjected again, either hot or cold (Miranda-Herrera, 2015). • Initially, this field discharged surface water into evaporation ponds. In 1989, partial infield reinjection began in sector CP I using former production wells. The reinjection was then relocated to 500-2600 m depth west of CP I (Kamila, Z, et al., 2020). • Hot reinjection (150 C) began in 2005. The best injection zone was discovered to be NW of the CP I sector. The acid injection was carried out in order to restore injection capacity in some wells (Kamila, Z, et al., 2020).	• Nonetheless, CP I has gradually experienced a decrease in enthalpy production as a result of cold reinjection and natural recharge (Diaz et al., 2016). • By 2012, there was a shortage of approximately 4000 T/year steam to maintain 570 MW of electrical production (Miranda-Herrera, 2015). • Some wells' injection capacity has decreased due to the high concentration of solids in the injected water, whereas other wells have maintained constant injection capacity for years. The permeability of the rock formation in each well influences these various behaviors (Diaz et al., 2016). • Subsidence and triggered seismicity have occurred (as a result of injection/production in conjunction with a complex tectonic environment) (Sarychikhina et al., 2016)	the southwest performs the opposite (Diaz et al., 2016). • The field is divided into four sectors: CP I (west), CPII (southeast), CP III (north), and CP IV (east of CP III) (Diaz et al., 2016).
Mexico / Los Azufres	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	HE-LDS 1982 252 MWe 224.8 MWe 240-280 °C 2,220 kJ/kg 2,209 ton/hr in 2014 763.5 ton/hr in 2014	• Full reinjection (Hernandez et al., 2015). Brine & condensate injection started in 1983 (Diaz et al., 2016). • The injection returns as liquid or steam in the southern zone. Some wells might be constant while others might be intermittent. • In contrast, wells in the north zone started intermittently producing steam or condensed steam after 2005 as a result of the boiling of reinjection fluids (Arellano et al., 2015). • A reinjection well in the southern field between 2000 and 2005 caused the reservoir's temperature and enthalpy to decline, which changed the production fluid's phase from vapour to 2-phase. The separated water is cooled in ponds prior to being reinjected by gravity and at	• A chemical and thermal breakthrough, particularly in the southern area, which was linked to the distance between production and injection. • In the south zone, the injection return as a liquid or steam. Some wells might be constant and intermittent in other wells. • In contrast, wells in the north zone produce steam or condensed steam from the boiling of reinjection fluids began to produce intermittently after 2005 (Arellano et al., 2015b). • Between 2000-2005 one reinjection well in the southern field triggered a drop in the temperature and enthalpy of the reservoir, thus changing in production fluid phase from vapour to 2-phase. • Thus, few actions were taken. In 2004, the injection rate in the south was lowered, and enthalpy inclined. And in 2005, reinjection operation in the south was relocated further, which turned the production fluid	• Another study in a deeper well found that strong vertical permeability may have prevented thermal interference since injectates boiled sufficiently at depth to produce steam upflow (Diaz et al., 2016). • Results from in-field reinjection tests performed in the northeast of the field showed good hydraulic connectivity with neighboring producers, probably due to geological faults (Diaz et al., 2016). • Seismic events recorded nearby reinjection (Diaz et al., 2016).

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			atmospheric conditions of 40 ◦C (Guti´errez Negrín and Lippmann, 2016; Diaz et al., 2016). • To stop pressure decline, it was suggested that an old producing well should be installed in the NE field's field. Acid treatment in injectors increases injectivity rates (Diaz et al., 2016).	into a vapour-dominated fluid again (Diaz et al., 2016).	
Italy / Larderello	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	VDS 1913 594.5 MWe 487.1 MWe 220 – 350°C 2,770 kJ/kg 3,700 ton/hr 1,437 ton/hr	• The reinjection strategy of this field consists of additional water and full condensates. • Since 1979, the injection has been primarily performed in the central part of the field at Valle Secolo due to its high permeability and Superheating conditions. Excellent vertical permeability allows for effective shallow reinjection (Diaz et al., 2016). • Deep peripheral injection, on the other hand, produces a slower response to liquid accumulation and steam recovery (Diaz et al., 2016). • After 1994, reinjection was carried out in zones where the wells produced significant amounts of fluid during the initial phase and where the well spacing was closest; reinjection was also carried out at the reservoir's top, using wells that were good producers (Diaz et al., 2016).	• Since 1970, the current shallow reinjection strategy has been beneficial, particularly in depleted areas, allowing reservoir pressure and steam production to increase while the steam/gas ratio decreases (Diaz et al., 2016). • There was no liquid water breakthrough in general; however, it is assumed that pressure in the upper reservoir was recovered by the formation of liquid plumes, which slightly reduced the temperature (Diaz et al., 2016). • There was some chemical breakthrough. MEQ events of low magnitude were recorded after reinjection began (Diaz et al., 2016). • Water does not penetrate to depth, forming liquid plumes, so reinjection in non-fracture formation is ineffective. After lowering the injection rate, such liquid plumes evaporated (Diaz et al., 2016).	• The system's subsidence rate is 25 cm/year. Boron is an important component of the steam that is present as boric acid. • The reservoir is likely to be critically stressed because the system is linked to natural seismicity (Diaz et al., 2016). • Experiments in 1994 that alternated the use of single wells as injection and production wells yielded positive results (Diaz et al., 2016).
Italy / Travale/ Radicondoli	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	VDS 1973 200 MWe 153.4 MWe 190 – 250°C 2,820 kJ/kg 2,820 ton/hr 1,296 ton/hr	• Due to its high-pressure nature, reinjection had not been used in the Travale/Radicondoli geothermal area prior to 2009. Condensates are reinjected into the outfield using a 20 km long pipe. 2016 (Diaz et al.).	• No records were found.	• The content of NCG is 4-8%/wt (Diaz et al., 2016)

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Kenya / Olkaria I (East)	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	HE-LDS 1981 185 MWe 185 MWe 250 -290°C 2,270 kJ/kg 1,970 ton/hr 785 n/hr	• Since 1993, Unit 1-3 has been obligated to apply partial infield reinjection; the remaining brine is transferred to an open disposable lagoon, where it is pumped and used for drilling (Gitobu, 2017). • Repurposed production wells, or reinjection wells, are situated 600 m or less south of the high-temperature zone. Both hot (158 °C) and cool injections are used for reinjection. • Using water from Lake Michigan, cold infield reinjection (20°C and 100 T/h) was done near the center of the fields in 1996 and 1997. (Diaz et al., 2016). • For units 4-5 (IAU), Reinjection has 7 hot reinjections ranging from 900 to 1700 m and 3 shallow wells (600 m) for cool reinjection (approximately full). • Condensate is between 20 and 23 C, while the brine is 188 C. (Gitobu, 2017).	• The rate of pressure decline has been decreased with the support of reinjection. Olkaria East has seen a moderate pressure drop of 12 bars. In conclusion, reinjection in the Olkaria East field enhanced well output but caused a loss in enthalpy, which recovered when the intermittent cold injection was stopped (Ouma et al., 2016). • In certain circumstances, hot reinjection has enhanced steam and brine rates while preventing a steam decline in surrounding wells. Meanwhile, cold reinjection affects some wells in both positive and negative effects (Diaz et al., 2016).	• In 2011, Olkaria I production wells supplied some of the steam for Olkaria II's power plant because of an excess of production enthalpy (Diaz et al., 2016) • The East field's wellhead units provide 38.3 MW (Ouma et al., 2016)
Kenya / Olkaria II (North-East)	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	HE-LDS 2003 105 MWe 105 MWe 250-290 °C 2100 kJ/kg 1280 ton/hr 641 ton/hr	• Since 2009, the furthest reinjection wells have received twice the rate of injection than the closer ones. • Full hot infield reinjection is positioned 600–1000 m south and north of production. • To maintain the reservoir pressure in Olkaria I, cold condensates are injected 500–1,000 meters west of the producing field through an injection well in the area between Olkaria II and I. (Diaz et al., 2016; Ouma et al., 2016).	• The rate of pressure decline has been reduced with the support of reinjection. The moderate pressure decline in Olkaria North East, which was 13 bars, has kept some production wells operating at steadily increasing steam and water flow while maintaining enthalpy and minimizing the need for makeup wells (Ouma et al., 2016). • Compared to the rest of the system, the north reinjection zone has lower enthalpies (because of the deeper target which produces more liquid than shallow steam zones). The cold reinjection reported no negative effects (Diaz et al., 2016).	• Production drilling is continuing to increase the field's capacity to 140 MW (Omenda and Mangi, 2016).
Iceland / Krafla	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass	HE-LDS 1978 60 MWe 60 MWe 320 °C 1,800 kJ/kg 1,221 ton/hr	• Partial reinjection is performed on three wells (Mortensen et al., 2015). • One underperforming deep production well was successfully upgraded to an improved injector that can hold 18% of total mass extraction (Mortensen et al., 2015).	• The overall field performance indicates negligible enthalpy change (no significant cooling) (Juliusson et al., 2015). According to Fl'ovenz et al. (2015), MEQ occurrences around injection are significant, especially at lower depths, that are linked to fracturing closes and openings.	• Because the fluid cannot be produced because the casing was broken by the fluid's extremely high temperature and high acidity, reinjection is done through an IDDP well (Juliusson et al., 2015).

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	Injection mass	479 ton/hr	• The other injection well is located SE to supply pressure support and an IDDP well to inject water into the deeper superheated zone in order to cause the steam to condense and neutralize the acid in the steam (Markusson and Hauksson, 2015). • Water from the power plant was disposed of as surface runoff, where it was mixed with groundwater (Olafsson et al., 2015).		
Iceland / Hengil-Hellisheidi	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	HE-LDS 2006 303 MWe 303 MWe 303 °C 1,570 kJ/kg 3,780 ton/hr 2,948 ton/hr	• This field performs a full reinjection strategy (Gunnarsson et al., 2016). • The faulted periphery of the volcanic area contains two deep reinjection zones (Edgefield). The condensed steam flows to shallow wells (Gunnarsson et al., 2016). • Additional infield reinjection is implemented to address the temporary capacity limit in the reinjection zone by converting unproductive producers into injector wells. The injectate temperature is normally 60-80 degrees Celsius, but it can reach 120-174 degrees Celsius during thermal plant maintenance (Kristjansson et al., 2016).	• Reinjection capacity decreases over time, probably due to scaling (Kristjansson et al., 2016; (Van den Heuvel and Benning, 2016). • Since the injection is governed by fractures (Diaz et al., 2016), the overall capacity varies depending on the injectate temperature (the lower T, the higher permeability and down-hole water flow) (Gunnarsson, 2013). • Reinjection in two Edgefield zones appears to benefit nearby well performance without cooling. However, infield zones show a rapid change in enthalpy near reinjection wells, indicating a thermal breakthrough (Gunnarsson et al., 2016). • Rising pressure has the potential to suppress boiling and prevent higher enthalpy (Gunnarsson et al., 2016). • The rapid change in injection rate would amplify seismicity (Kristjansdottir et al., 2016). • Reinjection increases pore pressure and fault slip, resulting in surface deformation (Juncu et al., 2018).	• This field has a high production density of 40 MW/km2 in the most productive areas (Gunnarsson et al., 2016). • Hellisheidi's output has been continuously decreasing. As a result, the operation will be linked to new resources in the Hverahlid field in order to reach near-full capacity generation (Kristjansson et al., 2016). • As part of geothermal gas (NCG) re-injection projects, a pilot-scale gas separation station was built (Gunnarsson et al., 2015).
Iceland / Hengil-Nesjavellir	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	HE-LDS 1998 120 MWe 120 MWe 300 °C 2,100 – 2,700 kJ/kg 1,872 ton/hr 1,152 ton/hr	• With a distance from the producing zone of 0.6-3 km, partial reinjection is carried out (infield and outfield). Before brine and condensate are pumped by a pump at 55 °C into a deep and heated aquifer, silica is polymerized using a retention tank. The excess is pumped to a shallow well that is interconnected with groundwater (Diaz et al., 2016).	• The chemical composition and rise in temperature of the water in the shallow aquifer, which is used for cooling, were both impacted by the disposal of wastewater into shallow wells. This might result in lowering productivity. These impacts would stop if the reinjection wells were deeper (Diaz et al., 2016).	• In warm aquifer reinjection investigations, a tracer test conducted in 2004 demonstrated that the injected water did not reach the geothermal reservoir (Diaz et al., 2016).

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Japan / Hatchobaru	Geothermal System Start Date Installed Capacity Current Generation Reservoir Temp Average Enthalpy Produced mass Injection mass	HE-LDS 1977 112 MWe 77.12 MWe 250 – 290°C 1,164 kJ/kg 2,520 ton/hr 1,800 ton/hr	• Reinjection and production wells have been positioned "side by side" since 1982. (reinjection in the northwest and production in the southeast). • Since it was difficult to locate another permeable level for the injection, reinjection and production are both at the same depth. The minimum underground distance between reinjection and producing wells was 140 m. • Reinjection wells were moved 500 meters away from the closest producing well in 1992. • In recent years, reinjection has moved as far north as it can go without interfering with producing wells. In the reservoir's outflow zone, there are reinjection wells. Separated water and excess condensate are pumped into the reservoir at a temperature and pressure of around 90 °C. Since many years ago, around a third of the field's waste brine has been pipelined to the Otake field to be reinjected there. • At the reinjection line, there is a settling pond to minimize the issue of silica scaling brought on by supersaturated brine with amorphous silica (Diaz et al., 2016).	• When production lowers the pressure in the NW and injection raises the pressure in the SE, the pressure differential that drives fluid flow in the reservoir from SE to NW is disturbed, allowing cold injectate to return to the production zone and ruining some formerly excellent production wells. • The problem system was where the cool water returned so rapidly. There were also chemical fronts. Relocating the wells farther away allowed the production to be recovered. • From 1992 to 2002, the water level rose in the injection site, reducing injectivity; as a result, side-tracked wells targeted deeper zones along a fault, causing a decline in the water level. • Loss of injectivity issues caused by silica deposition was successfully reduced by pH modification of brine. (Kamila, Z. et al, 2020).	