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Integrated Reservoir Management Strategies for Sustained Production at Krafla Geothermal Field, NE-Iceland

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ABSTRACT

The Krafla high-temperature geothermal field in northeast Iceland has been in operation since 1978, currently with 60 MW of installed capacity. Declining output over time has resulted from reservoir pressure drawdown due to mass extraction and scaling-induced clogging in high-enthalpy production wells. To enhance sustainable utilization and mitigate production decline, a combination of five strategies has been implemented, but these combined efforts have helped maintain full production capacity offsetting an estimated decline rate of 3% per year. Infield reinjection has emerged as the most impactful measure, but stimulation efforts have increased steam supply by up to 16%, delaying the need for drilling new makeup wells, while also lowering the environmental impact through further reduction in CO_2 concentration in produced steam due to reinjection of degassed brine. These results underscore the potential of integrated production and reinjection strategies to enhance both sustainability and environmental stewardship in high-temperature geothermal fields.

1 INTRODUCTION

Reinjection of degassed brine is a key strategy for enhancing the long-term sustainability of high-temperature geothermal operations (Kamila et al, 2021; Kaya et al, 2011). By returning treated fluids to the subsurface, operators aim to increase operational efficiency, boost well output, and reduce the frequency of drilling new make-up wells, an approach that supports both economic and environmental goals. Similar strategies have been successfully implemented at major geothermal fields such as The Geysers in the United States (Barker et al, 1995; Goyal, 1999) and Larderello in Italy (Cei et al, 2020+1), where reinjection management has played a central role in stabilising reservoir pressure and sustaining production over decades.

Beyond improving well output and restoring reservoir pressure, reinjection also contributes to lower climate and environmental impact by reducing CO_2 concentrations in produced steam and limiting surface disposal of geothermal fluids. However, reinjection also introduces operational risks. Injecting cooler fluids too close to production zones can lead to localised cooling, sudden pressure drops, or unintended flow paths within the geothermal reservoir. Effective management therefore requires careful control of reinjection distance, injected volume, and fluid temperature to ensure that the benefits in the form of enhanced efficiency, sustained output, and reduced environmental footprint are realised without compromising reservoir stability.

The incorporation of reinjection into routine operations at Krafla is informed by experiences from the above-mentioned mature geothermal fields but adapted to the reservoir conditions at Krafla geothermal field. In parallel with the expansion of reinjection, Landsvirkjun has implemented a range of complementary reservoir management measures, including strategic resting of high-enthalpy wells to promote pressure recovery and targeted optimisation of reinjection across the field, and continuous refinement of reservoir management based on updated flow data and geochemical data. Together, these approaches form an integrated management framework aimed at maximising sustainable output while maintaining reservoir health, reducing environmental impacts, and extending the long-term viability of geothermal power production at Krafla.

2 PRODUCTION HISTORY OF KRAFLA GEOTHERMAL FIELD

The Krafla geothermal field has a production history closely tied to the dynamic volcanic environment of the Krafla central volcano. Geothermal development began in the 1970s, but progress was affected by the Krafla Fires rifting episode (1975–1984), during which repeated magma intrusions and surface eruptions affected drilling operations and infrastructure. Despite these challenges, power production commenced in 1978, supported by a high-temperature reservoir with magma known to reside only 2–3 km below the surface (Ármannsson et al, 1987). Over the following decades, production expanded incrementally and by 1999 the

power plant reached a capacity of 60 MW_e (Nielsen et al., 2000), which has been maintained until this day. Since 2000 production at Krafla geothermal field has been stable with an average mass production of 8000-10000 ktonnes pr. year (fig. 1).

The reinjection strategy at the Krafla geothermal field has been developed progressively as part of long-term reservoir management aimed at maintaining sustainable production from the high temperature geothermal reservoir. Sustained reinjection commenced in 2002, but early operations relied primarily on deep peripheral reinjection, but since 2014 the reservoir management and reinjection strategies have progressively diversified, and currently five different methods are employed depending on observed well recovery and power demand.

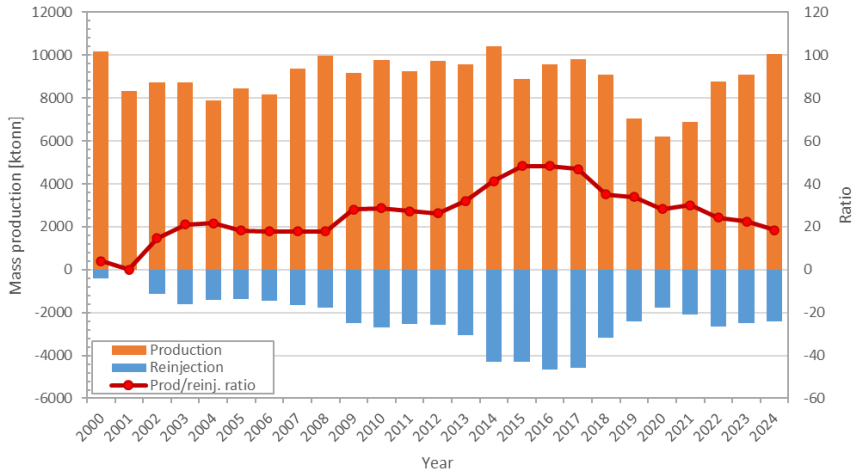


Figure 1. Mass production at Krafla geothermal field 2000-2024. Since 2014 reinjection temporarily increased 2014-2019.

2.1 Seasonal Well Resting

Landsvirkjun operates both hydropower and geothermal power plants, and power generation is strategically balanced between these resources to optimise overall production and ensure long-term sustainability. During years with high precipitation, water levels in hydropower reservoirs reach maximum levels, allowing greater flexibility in hydropower output. When hydropower availability is strong, geothermal production can be temporarily reduced by shutting in selected wells (fig. 2), giving the geothermal reservoir an opportunity to recover pressure.

Between 2019 and 2021, a sequence of years with favourable precipitation resulted in lower demand for geothermal power generation. During this period, summer production at Krafla was reduced to approximately 50 MWe, enabling targeted pressure recovery in parts of the reservoir. The extent of recovery depends on several factors, including the duration of well shut-in, thermal conditions in the reservoir, and the magnitude of prior pressure drawdown within the reservoir.

In earlier operational phases, resting strategies focused primarily on medium- and low-enthalpy wells, partly to reduce surface discharge of brine. As understanding of reservoir dynamics improved, operational practice shifted toward strategically resting high-enthalpy wells. These wells have experienced the greatest pressure draw down and therefore show the most significant productivity recovery, when temporarily shut in. However, selecting which wells to rest requires careful evaluation. Repeated shut-in of high-temperature, high-enthalpy wells can increase thermal and mechanical stress on the casing, elevating the risk of casing deformation or failure. Consequently, well-resting strategies must balance reservoir recovery benefits against long-term well integrity considerations.

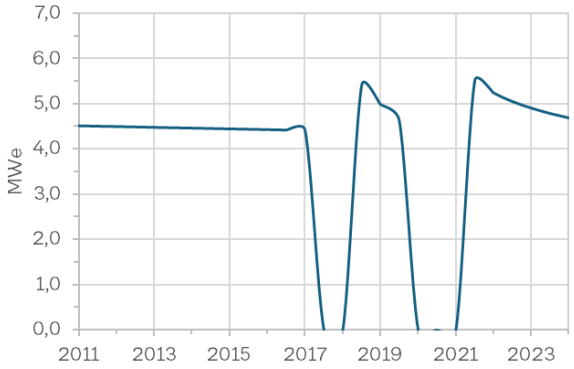


Figure 2. Example of recovery of output of well KJ-21 at Krafla following temporary shut-in.

2.2 Mechanical and Chemical Well Cleaning

The Krafla geothermal field has a long production history, characterized by both high- and low-enthalpy wells that reflect the heterogeneous temperature conditions of the reservoir (Mortensen et al., 2009). Continued production under declining reservoir pressure has contributed to significant scaling within wellbores. Silica scaling is the predominant issue across the field, whereas calcite deposition is mainly associated with lower-enthalpy wells. Scale removal has primarily relied on mechanical cleaning, in which drill rigs are used to mill out silica deposits. This process is technically challenging because silica scale progressively recrystallizes into harder phases such as chalcedony and quartz, limiting the achievable degree of cleaning. Consequently, wells have often been only partially cleaned for scale during maintenance operations. Despite these constraints, mechanical cleaning has led to measurable improvements in power output. Although the magnitude of the gains was lower than initially expected, the performance enhancement has proven to be sustained over extended periods. Moreover, when reservoir pressure subsequently increased in the zones feeding these wells, their output rose further, demonstrating the added benefit of reducing wellbore constrictions as part of an integrated reservoir-management strategy.

Chemical removal of wellbore and near-wellbore formation scale has also been explored at Krafla as a complementary remediation strategy. Calcite dissolution treatments using acid-based treatments have been applied on several occasions in low-enthalpy wells in the past, where calcite scaling is prevalent. In recent years, efforts have shifted toward developing chemical methods for dissolving silica scale in high-enthalpy wells—a considerably more challenging task due to the low solubility and progressive recrystallisation of silica into chalcedony and quartz. Such treatments typically employ highly reactive alkaline solutions or chelating agents to enhance silica solubility, but they carry an elevated risk of damaging well casings, thus candidate wells must be selected with great care. Early field trials have demonstrated measurable and sustained improvements in well output following treatment, however continued optimization is required to improve outcomes and reduce operational risk in future applications

2.3 Push-Pull Reinjection

Acid wells are a recurring issue in the deeper parts of the Krafla geothermal field, where superheated conditions are found (Einarsson et al., 2010). To improve the fluid quality around affected wellbores, temporary reinjection has been applied followed by a shut-in period to allow the wells to recover and reheat, an approach analogous to the push–pull method described by Cea et al. (2021). This treatment appears to sustain improved fluid quality in the longer term, while a gradual but sustained improvement in well output is observed.

2.4 Infield reinjection management

Reinjection has become an increasingly central component of reservoir management strategy at Krafla, aimed at maintaining pressure support, mitigating thermal decline, and sustaining long-term production. Over the past decade, two complementary approaches have been implemented in the field: (1) large-volume infield reinjection designed to restore pressure conditions at subfield scale, and (2) targeted micro-reinjection within the production area to restore output from declining wells. The following sections outline the application of these two reinjection strategies and evaluate their contrasting reservoir responses.

2.4.1 Large-volume infield reinjection

Between 2014 and 2018, reinjection at the Krafla geothermal field increased substantially, primarily through reinjection into well KJ-39, which effectively doubled the field's reinjection capacity (Fig. 1) (Mortensen et al.,

2020+1). KJ-39 is located closer to, and is more hydraulically connected with, the production wells in Suðurhlíðar and Leirbotnar subfields (fig. 3).

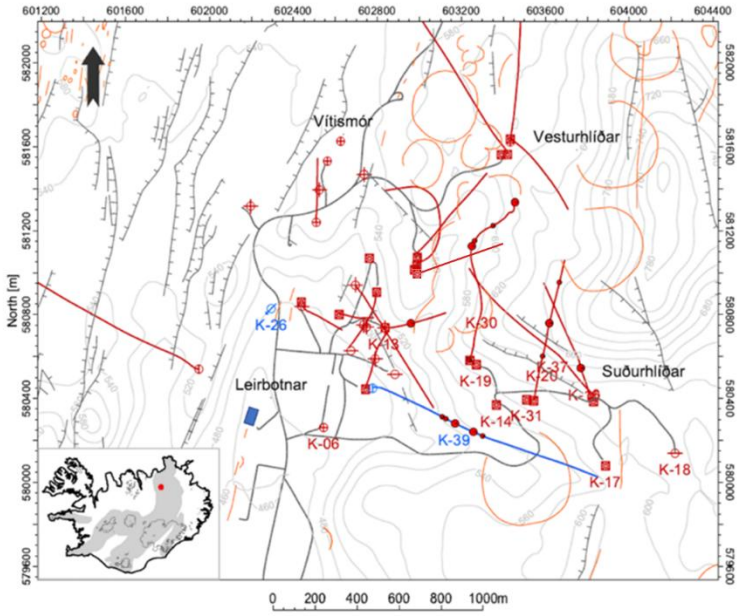


Figure 3. Krafla Well field. Production wells are red while reinjection wells K-26 and K-39 are blue. Red dots on well trajectories indicate location of significant aquifer zones in some of the wells.

This change produced contrasting responses across the two subfields. In Leirbotnar, where production is dominated by low-enthalpy wells, increased reinjection into KJ-39 enhanced pressure support and led to a marked increase in output. In contrast, Suðurhlíðar is characterized by high-enthalpy wells, and reinjection into KJ-39 resulted in thermal breakthrough and a rapid decline in produced enthalpy. After approximately four years, reinjection into KJ-39 was first reduced and later stopped entirely as several wells in Suðurhlíðar could not maintain production pressure.

After reinjection into KJ-39 was halted, the Suðurhlíðar wells recovered rapidly and production increased by a further 150-200%, an improvement that has been sustained for the past six years. In contrast, pressure support in the Leirbotnar subfield decreased after reinjection ceased, and output from the low-enthalpy wells has returned to pre–KJ-39 reinjection levels.

2.4.2 Infield micro-reinjection

In 2023, Krafla entered a new operational phase with the initiation of in-field micro-reinjection. Two previously unproductive wells located on a central platform were selected as injection targets, enabling the use of brine produced from a nearby productive well on the same platform. To facilitate this approach, a horizontal separator, implemented as a pipe enlargement, was installed at the production well, with dedicated connections from the base of the separator to each of the two injection wells (fig. 4). Small-scale reinjection of hot brine began in summer 2023. The injection wells are situated near production wells that historically delivered high output but had experienced marked decline in recent years. Shortly after micro-reinjection commenced, both output and pressure in these production wells increased significantly, indicating a positive reservoir response to the new operational strategy.



Figure 4. Horizontal separator in the form of pipe enlargement from production well for extraction of brine for reinjection into wells at the same platform.

3 MAINTAINING SUSTAINBLE PRODUCTION

Through these combined reservoir-management measures, steam supply has been maintained at levels sufficient to ensure full capacity at power plant when required. Resting wells can provide short-term recovery in productivity, although this option is only feasible during periods of reduced power demand or when hydropower capacity is sufficient to offset temporary reductions in geothermal output. Push–pull stimulation can also yield temporary gains, but because the associated pressure cycling may increase the risk of casing damage, it is mainly applied in cases where improved steam quality is needed, particularly in wells producing corrosive fluids. Although wells remain offline during reinjection, the short-term productivity loss is generally outweighed by sustained improvements in fluid chemistry and output observed after the treatment.

Mechanical and chemical cleaning have been applied on a limited scale and have produced measurable and sustained increases in well output. Nevertheless, the overall success rate and operational reliability of these methods require further optimization before they can be deployed more broadly.

In-field micro-reinjection has delivered the most substantial and sustained productivity improvements (fig. 4). In the Suðurhlíðar and Vesturhlíðar subfields, where the reservoir is characterised by high-enthalpy, two-phase conditions, several wells have experienced marked decline due to localised pressure drawdown. Targeted infield reinjection has helped stabilise reservoir conditions and restore well output. Because infield reinjection is close to production wells, infield reinjection must be carefully controlled to avoid thermal breakthrough. Large-volume injection, such as in KJ-39, demonstrated the risk of temporary productivity loss. Nevertheless, due to Krafla's shallow heat source and high permeability, rapid recovery occurred, and affected wells now show improved performance, underscoring the long-term value of controlled reinjection of degassed brine.

When applied under favourable conditions, infield micro-reinjection has provided substantial gains and is considered a highly valuable reservoir management intervention. Overall, approximately 70% of the observed productivity gains across the field can be attributed to in-field reinjection strategies (fig. 5, 6).

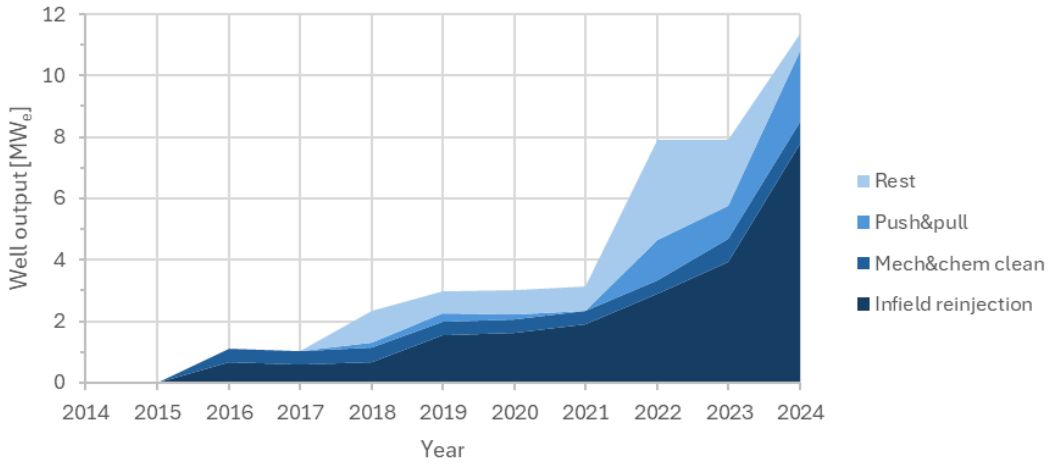


Figure 5. Recovered well output with respect to optimization method from 2014-2024.

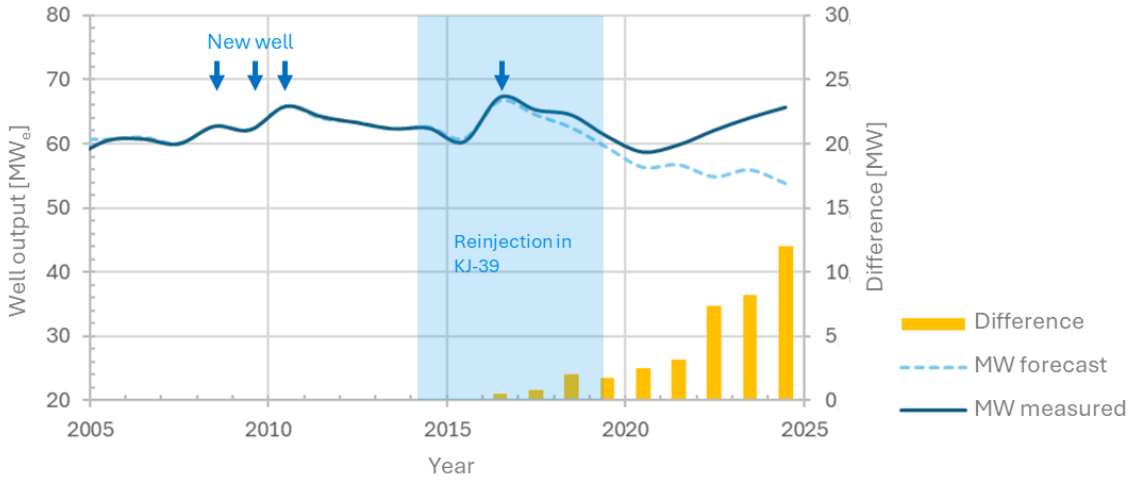


Figure 6. Measured well output vs. forecast well output following optimization of production and reinjection.

4 ENVIRONMENTAL IMPROVEMENTS

Reinjection of degassed brine provides an additional reservoir management benefit by introducing a low-gas fluid that can heat, boil, and be re-produced by nearby wells. Steam derived from the boiling of degassed brine contain significantly lower non-condensable gas (NCG) concentrations, which reduces the overall gas content of wells hydraulically connected to the reinjection zone. In several production wells that showed marked output increases following infield reinjection, the rise in steam flow was not accompanied by a proportional increase in NCG concentration. This behaviour indicates that a portion of the incremental steam originates from the in situ boiling of reinjected, degassed brine rather than from enhanced mobilisation of native reservoir fluids.

A comparison of predicted CO_2 decline with measured concentrations in these wells estimates that infield reinjection has reduced CO_2 emissions from the Krafla Power Plant by approximately 3,000 tonnes per year over the last six years or equivalent to an ~8% decrease in CO_2 emissions (fig. 7). Because some infield reinjection campaigns are temporary, these reductions in emissions are expected to vary over time and scale in proportion to the volume of degassed brine reinjected into the reservoir.

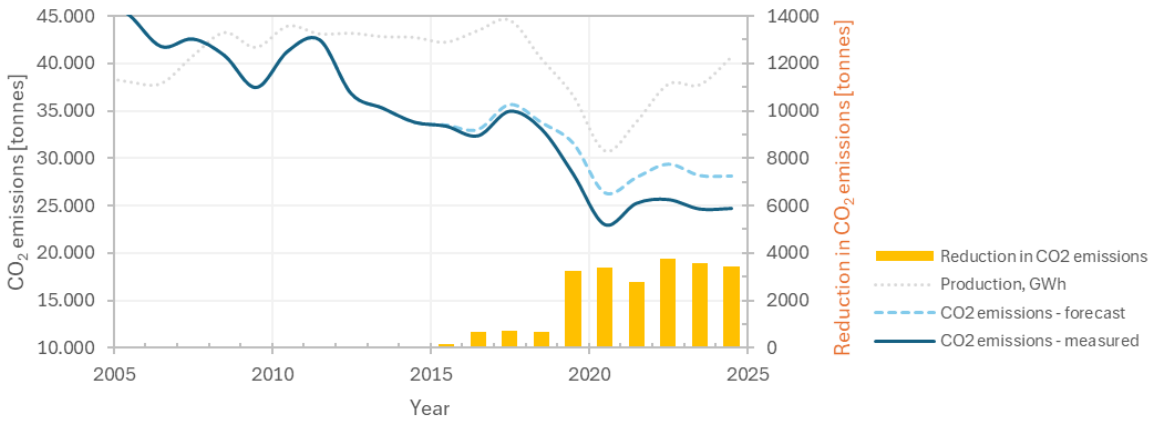


Figure 7. Change in measured CO_2 emissions compared to emission forecast.

5 CONCLUSIONS

The results from two decades of reservoir-management development at the Krafla geothermal field demonstrate that sustained, adaptive reinjection, combined with complementary operational measures, can significantly enhance both reservoir performance and environmental outcomes in a high-temperature volcanic setting.

Large volume infield reinjection provided essential pressure support but also highlighted the sensitivity of high-enthalpy zones to thermal breakthrough, informing the transition toward more targeted micro-reinjection strategies. Micro-reinjection has since delivered the most substantial benefits, restoring output in wells affected by localized drawdown and accounting for the majority of productivity gains observed in recent years. Seasonal resting of high-enthalpy wells, selective push–pull treatments, and mechanical or chemical cleaning have further contributed to maintaining reliable steam supply, though their effectiveness varies with reservoir conditions and operational constraints.

Reinjection of degassed brine has additionally produced measurable reductions in CO_2 emissions, demonstrating that reservoir-management decisions can directly support climate and environmental objectives. Collectively, these findings show that reinjection at Krafla is most successful when integrated into a dynamic, data-driven management framework that accounts for spatial variability in reservoir response. This approach has enabled Krafla Geothermal Power Plant to maintain long-term sustainable production while reducing its environmental footprint and provides insight for other high-temperature fields operating under similar geological and operational conditions.

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