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Cost-Effective Silica Elimination in Geothermal Operations: The CaSil Advantage

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ABSTRACT

Silica scaling poses a significant challenge to geothermal energy production worldwide, blocking valves, heat exchangers, and reinjection wells, and effectively limiting energy output. Existing mitigation strategies are only partially effective, requiring costly and time-consuming maintenance.

CaSil Technologies Ltd has developed a proprietary transformative solution that tackles silica scaling at its source. Instead of delaying silica precipitation, the CaSil process chemically captures dissolved silica and converts it into a nanostructured calcium silicate hydrate (CaSil) material. With fast reaction kinetics, it reduces the Silica Saturation Index (SSI) to well below 1, effectively eliminating silica scaling. The resulting CaSil particles are small, stable, and non-adherent, allowing them to flow freely through equipment without sticking to metal surfaces or forming a scale.

The CaSil technology has been successfully demonstrated on automated pilot scale across four geothermal fields in New Zealand, each with distinct brine chemistries. In all cases, the SSI was consistently reduced to well below 1, confirming the technology's broad applicability. Initial laboratory work for brine from Dieng, Indonesia further validated its effectiveness under challenging conditions with a highly silica supersaturated and hyper-saline brine. In addition to its technical performance, CaSil offers a cost-competitive solution with multiple co-benefits. This paper presents a cost–benefit analysis comparing CaSil to conventional silica mitigation methods, highlighting its economic and operational advantages.

1 INTRODUCTION

1.1 Silica Scaling

Silica scaling is the largest unsolved bottleneck for geothermal resource utilisation. Intractable scale forms due to supersaturation of dissolved silica species caused by the concentration of dissolved mineral constituents during the flashing process as well as cooling of the brine in binary cycle heat exchangers which lowers silica solubility. The polymerisation process of silica starts after an induction period which length is dependent on the degree of supersaturation and pH of the fluid (García et al. 2005; Iler 1979; Makrides et al. 1980).

All surface and subsurface infrastructure can be affected by silica scale from the point of supersaturation. This means pipework, heat exchangers, reinjection well liners, and even the geological formation around the reinjection well itself get blocked gradually by scale deposits. Costly workovers are required with aggressive chemicals to dissolve the scale or to mechanically remove it. These cleaning procedures may also require a full or partial shut of the power station to gain access to an asset for cleaning, increasing opportunity cost in which no electricity can be generated (Richardson et al. 2014, Zarrouk et al. 2014, Candido and Zarrouk 2017).

1.2 Current Mitigation Technologies

To proactively manage silica scale and slow down or prevent the precipitation of silica scale different mitigation techniques and technologies have been developed. The most effective approach is to minimise heat extraction from the fluid so that the Silica Saturation Index (SSI), the fraction of dissolved silica over the solubility of silica at the current process conditions, always remains below or close to 1. The fluid is then reinjected, and a silica scale free operation is possible. This is called hot reinjection; however, this technique comes with the significant drawback of poor resource utilisation which results in a high levelised cost of electricity (Brown 2011).

Alternatively, inhibitor products can be injected into the brine stream which aim to keep the polymerised silica particles in suspension and separated from each other so that they cannot agglomerate and form a scale. These may work better on brines with small degrees of supersaturation but have largely been found not effective. Silica

still scales with these products present, so only a minor improvement for the operation of a power station may be found for a more compatible brine composition (Gill and Jacobs 2011, Longval et al. 2024).

Another mitigation approach is the dosing of acid. As mentioned above, the induction period after which silica polymerisation starts is dependent on the pH of the fluid. With this method, the aim is to delay the onset of scaling sufficiently to reinject the fluid before polymerisation occurs. However, this is also not always wholly successful, and scaling can only be reduced rather than eliminated. Additionally, Health & Safety concerns around transport, storage, and use of highly concentrated acid exist with this method as well as the introduction of corrosion for all wetted materials at the lowered pH (Gunnarsson and Arnórsson 2005).

1.3 The CaSil Technology

As an alternative to the currently used mitigation methods above, we have developed a novel technology which addresses the root cause of silica scale, which is the presence of dissolved silica supersaturated in geothermal brine. When silica becomes supersaturated a treatment agent is injected into the brine which rapidly transforms silica into a discrete nanostructured calcium silicate (CaSil) product. The reaction is completed within seconds and lowers the SSI to << 1. This is achieved by removing dissolved silica entities from solution as well as simultaneously raising the pH of the brine to increase the solubility of silica, tackling the problem from two sides. This approach stands in stark contrast to both inhibitor products and acid dosing which leave silica in solution, aim to delay the scaling, and cannot change the SSI of the brine. The CaSil material forms a finely dispersed suspension which does not stick to surfaces and stays in suspension by the natural turbulence of the flowing brine. Prior to reinjection, the CaSil material is continuously separated from the brine stream. It forms the basis of several environmentally beneficial product applications, so the CaSil material itself has commercial value.

The significant reduction in SSI by the CaSil technology allows for scale free operation of surface and subsurface equipment, obviating cleaning cost and required shutdowns. This leads to more power production over time due to the elimination of saw-tooth production profiles of binary plants caused by scaling and increased plant availability. The favourable fluid chemistry also allows the brine to be cooled much further than currently possible, which unlocks the possibility of installing an additional downstream binary plant for further energy production in applicable geothermal plants (Schweig et al. 2024).

1.4 CaSil Technology Effectiveness

The CaSil technology has been demonstrated in four different geothermal resources in New Zealand on continuous and automated pilot scale. Furthermore, a laboratory assessment of modelled and real geothermal brine from Dieng in Indonesia has been carried out. Results for the effectiveness of treatment are shown in Figure 1.

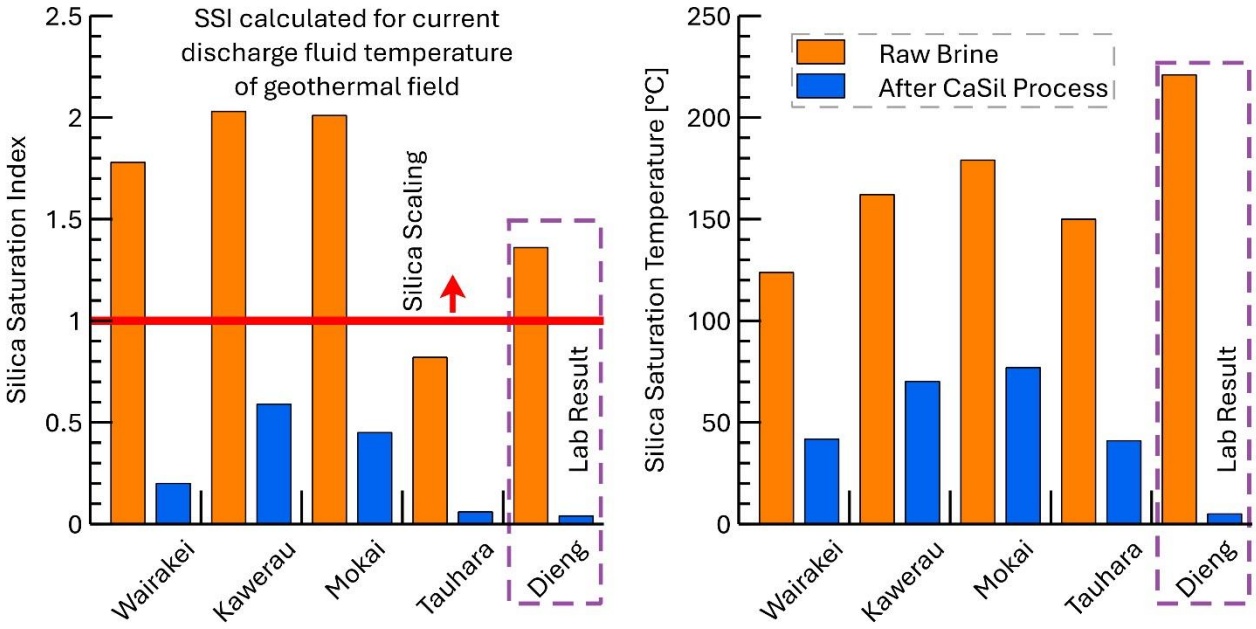


Figure 1. Calculated Silica Saturation Index and Temperature for the tested geothermal resources before and after CaSil treatment. SSI values are calculated for the respective fluid temperature of each field.

For all processed fluids a significant reduction in SSI could be achieved with the CaSil technology. Sourced fluids at Wairakei, Kawerau, and Mokai had an SSI of 1.8-2, being well supersaturated in silica where polymerisation and scaling start to occur. After treatment, the SSI was lowered to 0.2 in Wairakei, whereas Mokai and Kawerau showed a reduction to approximately 0.5. The reason for the higher SSI after treatment for the latter two fields is the more acidic nature of the sourced brine which can influence the CaSil process chemistry. At the Tauhara geothermal field, the fluid of a direct-heat park at the He Ahi Eco Business Park was tested. Currently, the fluid is reinjected at >150 °C, where silica is still undersaturated. However, the CaSil technology chemically removes silica from the brine and managed to reliably reduce the SSI in this field as well.

When considering the Silica Saturation Temperature, the fluid temperature at which an SSI = 1 is achieved, the resulting brine chemistry allows the brine to be cooled down to 40-75 °C before silica can start to polymerise again. This is a result unrivalled by any other scale mitigation technology which clearly sets the CaSil technology apart, demonstrating its superior attributes.

We have also conducted a laboratory trial with brine from Dieng, Indonesia. First, the appropriate process chemistry was determined utilising synthetically made brine modelled after the brine composition of the field. Afterwards, the results were validated with a sample of actual brine which was acidified for transport to prevent silica from polymerising. The results of this validation with actual brine are depicted in Figure 1. At process conditions of 180 °C, the hypersaline brine already has an SSI = 1.36, containing 1137 ppm of SiO_2. However, this calculation does not consider the significant total dissolved solids content of the brine, which additionally affects the solubility of silica, so the real SSI value will be even higher. Currently, the fluid cannot be utilised for any further power production due to the severe scaling rate. Instead, it is ponded for silica to polymerise and deposit before reinjected into the reservoir. After CaSil treatment, the SiO_2 concentration was reduced to 77 ppm, resulting in an SSI = 0.04 at process temperature (Borrmann et al. 2024, Schweig et al. 2024).

The significant reduction in both SSI and SST demonstrate the ability of the CaSil technology to unlock new generation capacity which cannot be achieved by any other means. Especially for high silica and high salinity brines where inhibitor products and acid dosing cannot work effectively anymore due to the high SiO_2 concentrations and high degree of silica supersaturation, CaSil can play a crucial role in enabling scale free operations of binary plants, generating more electricity over time by eliminating the reduction in power output due to scaling. It also eliminates the need for well workovers or drilling of make-up reinjection wells, and even unlocking more generation capacity from already sourced fluid. The technology is applicable to a wide range of brine compositions and can be easily retrofitted to existing plants or included in greenfield power stations.

2 QUANTITATIVE TECHNOLOGY COMPARISON

2.1 Basis of Calculation

To quantitatively compare an unmitigated base scenario (no scale mitigation), inhibitor products, acid dosing, and the CaSil technology and their effects on cost and generated revenue of a binary cycle plant a suitable calculation model was developed. It uses a variety of inputs and assumptions which will be detailed here.

The most important input into the calculation is the silica scaling rate. For the presented example below a scaling rate of 20 mm/year was used, which represents the observed field scaling rate at Dieng at process conditions (Wahyudityo et al. 2013). The example assumes a binary plant to be installed downstream of the current operation, so the outlet temperature would be lower respectively, increasing the scaling rate even more. The fluid contains 1173 ppm of SiO_2 as mentioned above.

Silica scale inside the binary plant heat exchanger is assumed to build up linearly and will trigger a plant shutdown when 2 mm of deposits have formed. This assumption allows for the time the unit is operating between cleans, which last for 3 days in which no electricity can be generated. The length of time required for cleaning is dependent on the morphology of the scale, utilised de-scaling method (mechanical vs. chemical), and degree of scaling and may vary significantly from plant to plant. Due to scaling, the heat transfer also reduces over time due to a reduced heat transfer coefficient and an increased pressure drop. Therefore, the power output of the binary plant drops over time until the scale is removed. The assumption for the model is a linear reduction to 80 % of its nominal power output over the operating time between cleans as reported of the binary plant in Wairakei, New Zealand (Zarrouk et al. 2014). After the heat exchanger has been cleaned, the power output returns to 100 %. The cost for each cleaning cycle is assumed to be US$116k (Candido and Zarrouk 2017). For ease of calculation no plant shutdowns were included outside of the required cleaning cycles.

The modelled binary plant was assumed to take 1600 t/h of brine and reduce the brine temperature by 50 °C, at a net efficiency of η_{net} = 13 %, therefore having a power output of 12.1 MW_{net}. By using the net power output excludes parasitic loads from the calculation and only considers salable electricity at US$75/MWh.

The reduction in scaling rates for both inhibition agents and acid dosing is assumed to be 25 % and 65 % respectively and based off literature values (Gallup and Barcelon 2005). Due to the undersaturated brine chemistry of the CaSil technology, a scaling reduction of 100 % is assumed. Capex cost for an acid dosing plant of that size is assumed to be US$1.73M. Due to the similar setup but lower safety requirements, the capital cost for sequestering agents is assumed to be half of that. A CaSil technology plant of this size is estimated to be approximately US$10.38M due to the higher complexity in treatment agent preparation and separation of CaSil material. For operating expenses an average of published cost for previously tested inhibitor products was taken from Gallup and Barcelon and adjusted for inflation (5 ppm dosing rate, US$4.5/kg). A required acid dosing quantity of 7400 kg/day of 98 % sulfuric acid was assumed based on the Kawerau geothermal plant in New Zealand (Addison et al. 2015), at an acid cost of US$280/t. Both inhibitor and acid dosing rates are based on the brine flow rate and the annual operating cost can therefore be calculated to be US$315k and US$807k respectively with a 5-10 % allowance for electricity and labour. However, the dosing quantity of acid is dependent on brine chemistry and changes from site to site due to chemical species which may provide a pH buffer. Operational cost for the CaSil technology is dependent on the flow rate as well as the SiO_2 concentration. For this case, Opex in the order of US$1.44M are estimated. Naturally, Capex and Opex of each technology may vary depending on the flow rate, brine composition, power plant geographic location, ease of sourcing the required chemicals and transport to site, and current exchange rates (1 USD = 1.73 NZD at the time of writing this paper).

Due to progressive scaling, reinjection wells and associated pipework must be cleaned regularly in well interventions. The cost for a well intervention is assumed to be US$1.7M/well. Once a reinjection well or the reservoir around it has been blocked too much and cannot be recovered a make-up well must be drilled, which is assumed to cost US$4M/well (Akindipe and Witter 2025). The assumptions of the quantity of which a well intervention must be performed or new reinjection well drilled for each technology scenario is given in Table 1 along with the Capex and Opex.

The commercial value of the CaSil material is not considered in this model, only the geothermal side of the CaSil Technology. However, the material would add to the generated revenue stream, enhancing the overall business opportunities and economic value of the CaSil technology.

Table 1. Summary of assumptions for Capex, Opex, required quantity of well interventions, and new reinjection wells drilled for each assessed technology scenario in USD.

	Unmitigated	Inhibition Agents	Acid Dosing	CaSil Technology
Capex	$0	$865k	$1.73M	$10.38M
Opex	$0 per year	$315k per year	$807k per year	$1.44M per year
Well Interventions	3 wells per year	2 wells per year	2 wells per year	None
Make-up wells drilled in 20 year lifecycle	10x	6x	3x	0x

2.2 Lifetime Cost and Revenue

When comparing the Capex and Opex of the three technologies, inhibitor products and acid dosing appear relatively inexpensive and straightforward solutions for mitigating silica scale. In contrast, the CaSil technology requires a higher upfront investment and greater operational expenditure, almost 80 % more than acid dosing. While this may suggest a higher cost on a short-term basis, such a view overlooks the long-term technical and economic performance of each approach. As discussed, inhibitors and acid dosing are only partially effective and unsuitable for high-silica, high-salinity brines, where scaling remains a persistent limitation. When evaluated over the full project lifecycle, the overall picture changes significantly, and the advantages of the CaSil technology become apparent.

A fair comparison must therefore consider the total cost and revenue over the plant's lifetime. Figure 2 illustrates the 20-year cost breakdown, including Capex, Opex, binary plant cleaning, well interventions, and make-up well drilling, as well as the corresponding lifetime revenue from electricity sales. The monetary loss from reduced

power output due to progressive scaling and downtime for cleaning is shown as a hatched area, highlighting the cumulative financial impact of less effective mitigation methods.

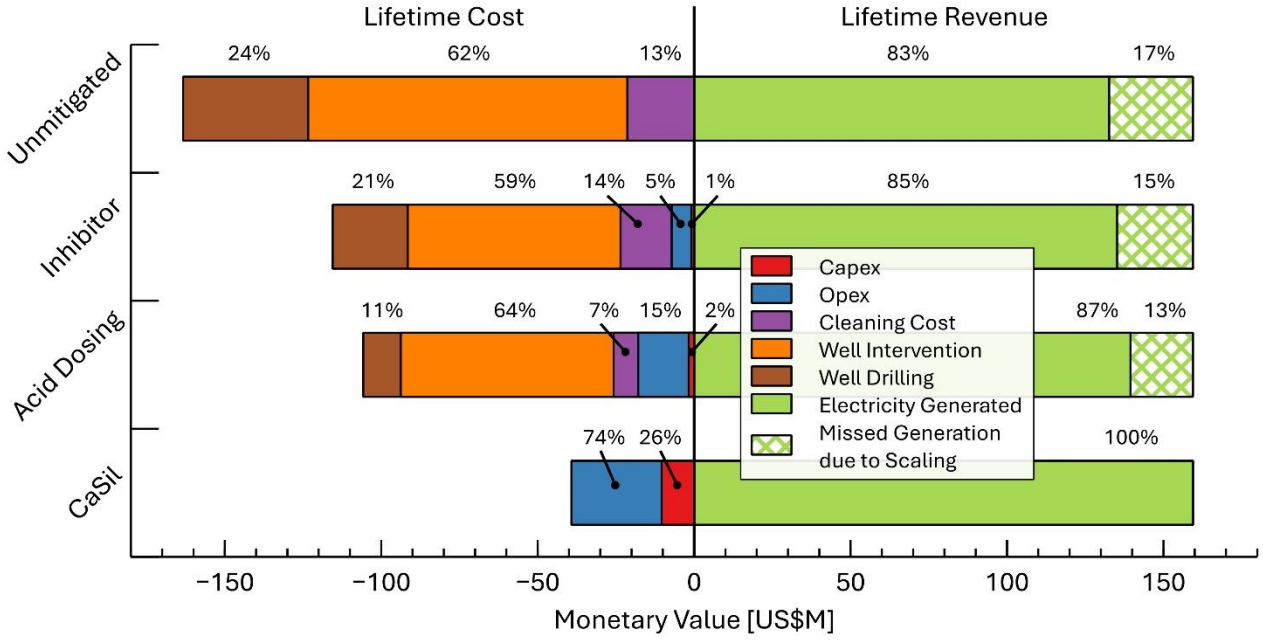


Figure 2. Lifetime cost and generated revenue for 20-year lifecycle for unmitigated base case, use of inhibitor agents, acid dosing, and the CaSil technology. Percentage values for each category are percentages of the total cost or revenue for each technology.

The unmitigated base case, in which no technology to manage silica scaling is utilised, shows the largest lifetime costs through heavy silica scaling, which is to be expected. A significant reduction in total cost can be achieved once a silica management technology is included in the plant design. The use of inhibitors and acid dosing show similar lifetime costs. However, these far outweigh the total cost of the CaSil technology.

The largest contributor to the total cost is well interventions (orange, 59-64 %). While bull heading chemicals for reservoir stimulation is significantly cheaper, it is not as effective as a precise application with a coiled tubing unit. Whichever technology is used, has a significant impact on the cleaning cost per well. The total cost is also dependent on the required frequency and complexity of the job. Very porous reservoirs will show more leniency towards scaling before injectivity drops to unacceptable levels, whereas tight formations require more immediate and frequent attention. The model assumed a cleaning cost of $1.7M per well with the prescribed frequency detailed in Table 1. These assumptions were made with an unmitigated scaling rate of 20 mm/year in mind and will significantly change for scenarios with much lower scaling rates. However, even if the well intervention frequency drops by a factor of two, the lifetime cost of both conventional scale mitigation technologies would still be higher than the CaSil cost.

Drilling cost for make-up wells contribute moderately to the total cost (brown, 11-25 %) and again, are very dependent on the individual formation, porosity, and required drill depth. Formations requiring deeper wells would show additional cost added to this category respectively. In contrast, the CaSil technology can preserve and even rejuvenate scaled wells and formations, which will be discussed in more detail in section 3.

The cost for cleaning the binary plant heat exchanger unit (purple, 7-14%) makes up a smaller part of the total lifetime cost for each scenario. This is despite the unmitigated scenario needing up to 10 annual shuts for cleaning, while inhibitors require 7 and acid dosing 3-4 shuts per year.

As described earlier, the process chemistry of the CaSil technology completely eliminates silica scaling by lowering the SSI << 1. This means, no silica scale forms in the heat exchanger and more electricity can be generated over time compared to the unmitigated, inhibitor, and acid dosing scenario where gradual fouling occurs. Based on the assumption that the binary plant is cleaned when the performance output drops to 80 % and at least one cleaning event occurs per calendar year, mathematically, the generation capacity that is lost to scaling is 10 % in all cases. Additionally, opportunity costs arise from the unit being out of service for three days during cleaning in which no revenue can be generated. This raises the total missed revenue due to scaling to 13 % for acid dosing, 15 % for inhibitors, and 17 % for the unmitigated base case. It is noteworthy that there no

significant change between the three scenarios despite significantly different cleaning frequencies. However, if the average cleaning outage requires more time than the assumed three days, the difference will be more pronounced. Under this assumption the lost revenue due to scaling over time has a much bigger impact on the total lost revenue compared to the relatively short timeframe for cleaning during which the unit is shut down. It is worth noting that the percentual decrease in revenue remains the same for differently sized plants. This means that the absolute monetary value lost to scaling becomes even larger for bigger sized plants.

The total cost advantage of the CaSil technology comes from the avoidance of maintenance cost like cleaning, well interventions, and make-up well drilling. However, these are dependent on local scaling rates, the reservoir formation, and permeability. By eliminating silica scaling more revenue is generated which increases the lifetime profitability of the CaSil technology (see section 2.3 for gross profit comparison).

While the detailed profitability must be considered on a case-by-case basis, some general deductions can be drawn from the above results. When silica scaling rates are very high or significant maintenance efforts for reinjection wells are required, the CaSil technology can play an important role in increasing the lifetime profitability of a geothermal resource compared to conventional mitigation methods. For medium scaling rates where the acid dosing effectiveness is higher and less residual deposition occurs, the CaSil technology has a reduced competitive advantage because less maintenance costs are incurred. For low scaling rates, sequestering agents and acid dosing will be a more competitive solution to scale mitigation due to the lower capital and operational cost. Therefore, each technology has a space in the geothermal industry where its competitive advantage can be applied, depending on the individual scaling rates and plant configuration.

2.3 Technology Profitability

To determine the profitability of each technology the total gross profit generated by the modelled binary plant must be considered. For this purpose, an 8 % allowance for parasitic load was made, which raises the power output from 12.1 MW_{net} to 13.2 MW_{gross}. The purchase price for this binary plant would be US$30.3M, assuming building cost of US$2.3M/MW. Figure 3 shows the cost of each technology scenario including the Capex for the binary power station over time as well as the achieved gross profit over the plant lifetime. For a more accurate model regular preventative maintenance costs for the binary plant should be included as well. However, this was omitted in this calculation due to a lack of data.

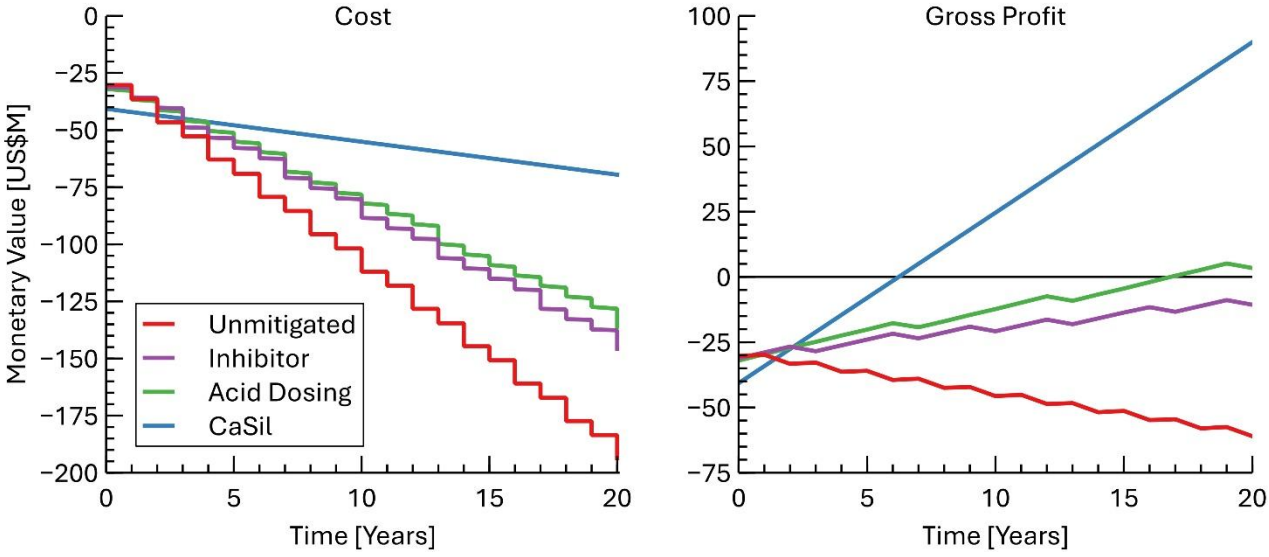


Figure 3. Cost over time including Capex for power station for each technology scenario (left) and gross profit over time (right).

In the graph above illustrating cost over time (left), the costs for binary plant cleaning, well interventions, and drilling of make-up wells were added at the end of each year which creates the steps in each line. The height difference between each step represents the amount of effort required to clean silica scale and maintain the geothermal field. The Opex were added gradually over the year to differentiate them more clearly. In the unmitigated scenario no Opex are required, so the line between each year remains horizontal. Due to the relatively small Opex for inhibitors, the line appears horizontal. In contrast, for the acid dosing and CaSil scenarios a clear downward trend can be seen. For the more costly operating expenditure of the CaSil technology, the contribution is larger.

The gross profit (right) is determined by subtracting the cost incurred from the realised revenue from electricity sales. In all scenarios the Capex for the power station ($30.3M) plus the individual technology Capex as detailed in Table 1 are incurred in the beginning. Sharp changes in the trajectory of a line during the lifecycle indicate a significant expenditure from well drilling which under these assumptions cause an annual loss (i.e. a drop in gross profit).

The graphs illustrate that a binary plant power station without silica scaling mitigation technology under these operating conditions would never be profitable and only incur costs. Instead, with the CaSil technology the binary plant and required CaSil equipment amortises just after 6 years of operation. An acid dosing solution would require approximately 17 years to pay off, whereas the use of inhibitors offers a positive cash flow but fails to break even during the 20-year lifespan of the plant. Despite the larger capital and operational expenditures of the CaSil technology, the crossover point between CaSil, sequestering products, and acid dosing is achieved after approximately 2 years of operations. After that, the CaSil technology clearly outperforms its competitors.

Depending on the local requirements and pre-existing assets, the installation cost for a binary plant may differ significantly. For a geothermal plant that is currently not using binary technology due to silica scaling, the installation cost could be significantly cheaper due to pre-existing wells, flash plants, and electrical switchyard. In other instances, all of these assets may be new builds, so higher costs are incurred. Table 2 shows the amortisation period for plant and equipment for different installation costs.

Table 2. Amortisation period for geothermal power plant and silica scale mitigation technology for different installation cost, using the same inputs and assumptions as before.

Installation Cost	Unmitigated	Inhibition Agents	Acid Dosing	CaSil Technology
$1.7M/MW	Losses incurred	After 20 years	13.5 years	5.1 years
$2.3M/MW	Losses incurred	After 20 years	16.9 years	6.2 years
$2.9M/MW	Losses incurred	After 20 years	After 20 years	7.4 years

When considering the levelised cost of electricity (LCOE, see Table 3), which is the cost to produce a MWh of electricity, a significant 30-40 % reduction in cost can be seen by utilising a silica scaling mitigation technology. When applying the CaSil technology to the modelled scenario, a cost reduction of 85 % is possible compared to the unmitigated base case. When compared to acid dosing, the LCOE with CaSil is 75 % lower. However, this does not include any other required costs for operating the power station.

Table 3. Levelised cost of electricity for all modelled cases, considering the modelled cost and revenue of heat exchanger cleaning, reinjection well interventions, make-up well drilling, and produced electricity.

Unmitigated	Inhibition Agents	Acid Dosing	CaSil Technology
$92	$64	$56	$14
100 %	69 %	61 %	15 %

The above modelling shows a clear case for the CaSil technology when considering the amortisation period of a binary plant under these operating conditions and levelised cost of electricity. For the unmitigated base case and inhibition product scenario, no economical operation of the binary plant would be possible. Installing a binary plant would be a net loss over its lifetime. While the acid dosing scenario achieved its break-even point, it took a significant amount of time, approximately 17 years. In contrast, the CaSil technology could reach profitability in approximately 36 % of that time with significantly lower cost of electricity generation.

It should also be repeated that the commercial value of the CaSil material itself is not considered in this modelling approach which will have a significant positive impact on the overall process economics and gross profit achieved as another revenue stream is added. However, the commercial value of the material is dependent on the country of production, location, and presence of national industries which can use the product generated. This modelling is outside the scope of this paper though and will be discussed in the future.

2.4 Sensitivity of Inputs

To evaluate the sensitivity of the assumptions regarding well intervention and drilling costs on the profitability of each modelled technology, two additional cases were developed. The assumptions listed in Table 1 are considered the base case for analysis. In the second scenario, it is assumed that only half of the well interventions and make-up wells are required. For instance, when inhibitor agents or acid dosing are used, only one well requires an intervention each year instead of two. The third scenario considers the extreme case where no cleaning is required at all. Of course, this is completely unrealistic with an unmitigated scaling rate of 20 mm/year but illustrates the maximum possible performance of each technology compared to the CaSil technology. As discussed in section 2.2, an important financial advantage of the CaSil technology is the obviation of well cleaning and redrilling costs. All scenarios are considering the cleaning cost when a plant shutdown is required ($116k per cleaning cycle). The gross profit over time for each modelled scenario is depicted in Figure 4, new amortisation periods and LCOE in Table 4, using $2.3M/MW for the power plant cost.

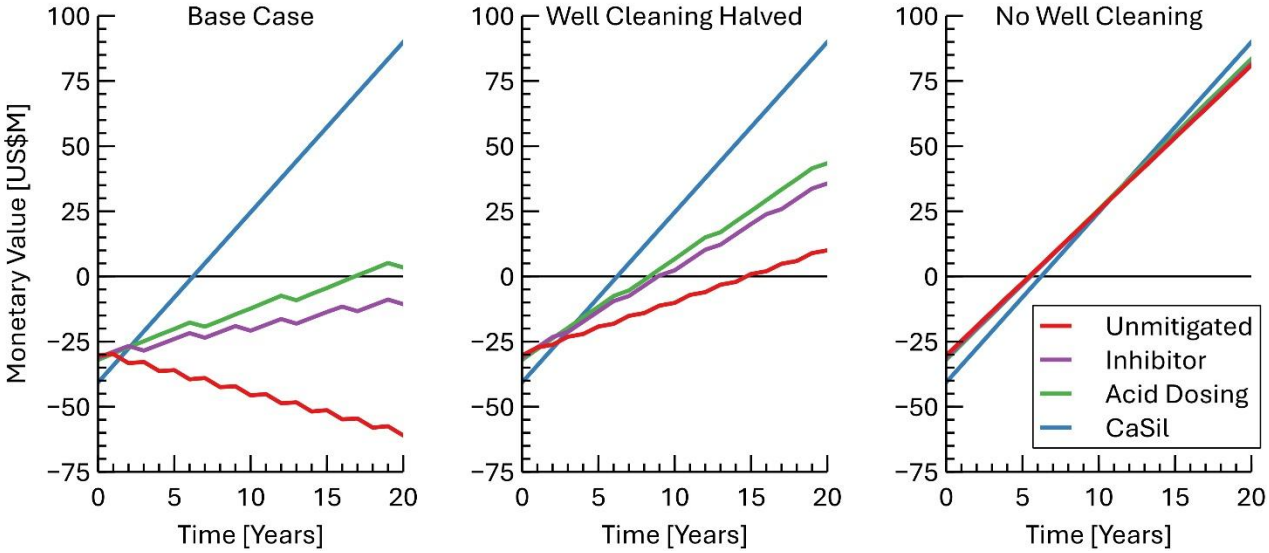


Figure 4. Sensitivity analysis of well cleaning costs as major contributor to total costs for conventional silica scale mitigation techniques. Gross profit of base case (left), number of well cleaning cases halved (middle) where only half the well interventions are performed and reinjection wells drilled, and no well cleaning case (right) where no well interventions or additional drilling is required.

Table 4. Amortisation period and LCOE for modelled base case, half well cleaning, and no well cleaning scenario, using $2.3M/MW for installation cost of binary plant.

		Base Case		Half Well Cleaning		No Well Cleaning	
Amortisation Period	Unmitigated	Losses incurred		14.7 years		5.5 years	
	Inhibitor	After 20 years		8.9 years		5.5 years	
	Acid Dosing	16.9 years		8.3 years		5.5 years	
	CaSil	6.2 years		6.2 years		6.2 years	
LCOE	Unmitigated	$92	100 %	$52	100 %	$12	100 %
	Inhibitor	$64	69 %	$38	73 %	$12	103 %
	Acid Dosing	$56	61 %	$34	66 %	$13	107 %
	CaSil	$14	15 %	$14	26 %	$14	112 %

As Figure 4 and Table 4 show, amortisation for the unmitigated, inhibitor, and acid dosing scenario occurs significantly faster and all technologies are cash positive after a 20-year lifecycle. However, the CaSil technology is still able to outperform all other cases in total produced gross profit after 20 years of operation. In the second scenario, CaSil achieves just over 2x the total gross profit compared to acid dosing. In the case where no well interventions or drilling are performed, which is unrealistic, CaSil can still achieve an 8 % larger gross profit after 20 years compared to acid dosing due to the increased amount of electricity generated and lower downtime.

3 QUALITATIVE TECHNOLOGY COMPARISON

Table 5. Qualitative technology comparison for selected aspects.

	Inhibition Agents	Acid Dosing	CaSil Technology
Working principle	Preventing silica agglomeration but keeping SiO_2 in solution	Slowing down silica polymerization but keeping SiO_2 in solution	Taking SiO_2 out of solution and raising solubility
Expected Silica Scaling Reduction	Works better for low SiO_2 concentrations		
Antimony + Sulfide Scaling	Acidic inhibitors promote	Promotes, due to lower pH, especially at low temperatures	Prevents, due to higher pH, even at low temperatures
Increase in power generation compared to unmitigated operation	↑	↑↑	↑↑↑↑
Additional revenue of product	N/A	N/A	Yes
Corrosion	Possible	Increased	Reduced
Dissolution of silica scale over time	No	No	Yes
HSE Risks	Aggressive chemicals needed	Aggressive chemicals needed	Minimal

Table 5 presents a qualitative comparison of the technologies addressed, highlighting key differences. Inhibitor products and acid dosing keep SiO_2 in suspension by preventing silica particle agglomeration and delaying polymerisation respectively. However, scale can still form, and only a partial reduction in scaling rate is achieved. The CaSil technology instead addresses the root cause by transforming dissolved silica into a different, stable material, reducing the SSI << 1 and thereby eliminating silica scaling.

The higher pH of CaSil treated brine eliminates antimony and other sulfide scales, which are significantly more soluble at alkaline pH levels. This keeps binary plant heat exchangers free of these deposits even at low fluid temperatures. In contrast, acidic inhibitors and acid dosing promote the formation of such scales.

Quantitative analysis shows that CaSil reduces cleaning frequency and maximises the power output of binary plants, yielding over 10 % additional revenue from electricity sales in existing assets. Furthermore, the CaSil material itself has commercial value, converting silica from a cost centre into a revenue-generating product.

Corrosion presents a challenge for some inhibitor products and is a major concern for acid dosing, where effectiveness depends directly on brine acidity. A compromise is often required between silica inhibition and acceptable corrosion rates without significantly increasing maintenance needs. The higher fluid pH of the CaSil process shifts the chemistry toward the passivation zone of steel, thereby reducing corrosion rates.

The undersaturated nature of CaSil-treated brine also allows for the gradual dissolution of existing silica scale within pipework and geological formations, progressively cleaning and rejuvenating the assets. This in-situ cleaning capability is unique to the CaSil technology and not available with any other method.

Aggressive chemicals are currently used for heat exchanger cleans, well workovers, and drilling operations, posing considerable health, safety, and environmental risks. These risks can be significantly reduced with CaSil, as the technology eliminates the need for such chemical cleaning procedures.

4 CONCLUSION

Silica scale mitigation is an important aspect of operating a geothermal power plant. At present, inhibitor products and acid dosing are the predominant methods used to slow down silica precipitation. These technologies keep SiO_2 in suspension by delaying polymerisation or preventing particle agglomeration; however, scale still forms in pipework and reinjection wells, and only partial mitigation is achieved. To maintain operability, costly heat exchanger cleans, well interventions, or the drilling of make-up wells are often required.

The CaSil technology addresses the root cause of the problem by transforming dissolved silica into a nanostructured calcium silicate product before precipitation can occur. The finely dispersed CaSil particles do

not adhere to metal surfaces and can pass freely through binary plant heat exchangers. This transformation lowers the SSI << 1, completely eliminates silica scaling and allows the plant to sustain higher electricity generation over time.

Quantitative analysis indicates that CaSil offers a significant financial advantage over inhibitor products or acid dosing by reducing cleaning intervals and maintenance costs while increasing power output. The technology provides particular benefit in high-silica, high-salinity, or antimony-rich brines and in formations with tight reinjection permeability, where scaling typically limits performance. However, for low-scaling geothermal fields, the lower Capex and Opex of inhibitor products and acid dosing can make them the more economical option.

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