Update on the CaSil technology: economically solving global silica scaling, enabling low temperature direct heat extraction and electricity generation

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ABSTRACT

Silica scaling remains the world-wide largest unsolved problem in the full utilisation of geothermal resources. Dissolved silica becomes supersaturated during cooling and steam production leading to intractable scale that blocks pipework, heat exchangers and reinjection wells. This blockage can significantly lower the efficiency of heat exchangers which causes a direct decline in electricity production and sales over time. Regular and costly maintenance is required which necessitates plant downtime. Conventional silica scale mitigation methods are not wholly successful and come with drawbacks such as high cost or corrosion concerns.

The proprietary CaSil Technology utilises a disruptive approach of transforming dissolved silica entities into a novel calcium silicate (CaSil) product, forming discrete particles that remain suspended and do not adhere to metal surfaces. Within seconds, the technology achieves a significant reduction in the silica saturation index to well below 1. The robust process is compatible with a wide range of brine compositions, irrespective of the initial silica concentration, ensuring reliable prevention of silica scaling. Furthermore, the CaSil Technology enables safe lowering of brine temperatures beyond current limits without inducing any silica scaling. This opens new business opportunities for additional process heat utilisation in for example greenhouses, aquaculture or milk powder production, thus supporting the decarbonisation of industry.

Successful trials on development plant scale across three different geothermal resources in New Zealand have been undertaken. The technology seamlessly integrates into existing geothermal operations or greenfield plants, offering a versatile solution.

This paper presents data from the trials and highlights the effectiveness of the technology to prevent silica scaling while unlocking the full potential of geothermal resources for enhanced heat extraction. By addressing the silica scaling challenge in a novel and disruptive way, CaSil Technologies paves the way for the sustainable and efficient utilisation of geothermal energy resources on a global scale.

1. INTRODUCTION

1.1 Silica Scaling

The earth's core holds practically inexhaustible amounts of thermal energy. This energy can be extracted to produce electricity particularly in tectonic plate boundary areas with volcanic activity. Figure 1 shows a schematic diagram of an exemplary geothermal power station. Hot water, steam, or a mixture of both is extracted from a natural or artificially created geothermal reservoir. The sourced fluid typically contains a mixture of different minerals in solution, such as chloride-based salts, precious metals and silica. The specific composition is dependent on the pressure, temperature and rock structure of the resource and varies from location to location. However, steam is required for the technical utilisation, which is produced by reducing the pressure of sourced water in a flash vessel. This causes a portion of the liquid to boil off as steam that can then be used to drive a turbine and produce electricity.

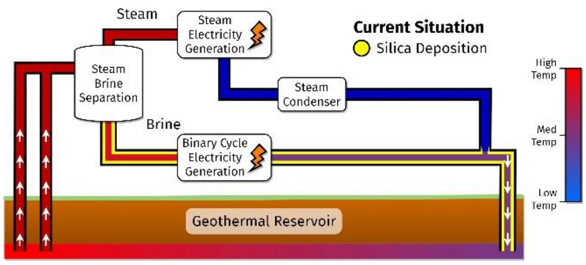

Figure 1: Schematic diagram of a geothermal power plant.

The mass reduction of the liquid phase causes the dissolved chemical species to concentrate in the brine. Additionally, the water temperature decreases to the respective pressure-dependent boiling point. This causes the silica solubility to decrease which is dependent on the fluid temperature. Typically, silica becomes supersaturated after the flashing stage due to the two simultaneously occurring effects and leads to unwanted scaling. This is a well-documented problem in geothermal resource utilisation and a world-wide challenge (Iler 1979; García et al. 2005).

Silica starts to polymerise after a short induction period. The length of this period and the rate at which the polymerisation takes place depend on the pH value of the brine, salt content and degree of supersaturation (Makrides et al. 1980). A hard and intractable scale forms which blocks pipes, valves, heat exchangers and even reinjection wells (marked yellow in Figure 1). Some of the remaining heat energy in the brine after steam production can be utilised to generate additional electricity by a downstream binary cycle plant. However, this promotes additional scaling as the fluid temperature is lowered and the silica solubility decreases further. Finally, the spent fluid is reinjected underground at medium temperatures.

The formation of silica scale in all process equipment significantly lowers the efficiency of the power plant. Scaled heat exchangers have a significantly lower heat transfer rate and increased pressure loss which leads to a loss in electricity production and sales over time. Blocked pipework must be exchanged and affected reinjection wells worked over to reinstate the required flow capacity. New wells may need to be drilled. Costly cleaning and maintenance efforts are required which necessitate plant shutdowns and adding further losses of revenue. A balance between heat exploitation for power generation and required maintenance efforts is necessary to ensure an economical operation.

Several strategies and methods have been developed and adopted by industry in an attempt to manage or mitigate silica scaling. For example, the temperature of the fluid can be kept deliberately high after the flashing process to provide a higher silica solubility and limit the mineral concentration after steam production. The hot fluid is reinjected or discarded quickly before silica starts to polymerise after its induction period. However, significant amounts of thermal energy of the brine are left unused. Other methods work by delaying the polymerisation process. This can be done with sequestering agents which disperse silicate ions or by addition of acid which prolongs the induction period. However, existing silica scale mitigation technologies fall short of providing a comprehensive solution. All of these methods are costly and cannot fully prevent silica scaling, making cleaning efforts still necessary. They can also introduce significant corrosion issues which need to be managed as well (Gunnarsson and Arnórsson 2005; Thorhallsson 2011; Richardson et al. 2014).

1.2 CaSil Technology

The Calcium Silicate (CaSil) technology has been developed to address the shortcomings of currently utilised silica scaling mitigation efforts. The technology offers a novel and disruptive solution which can wholly eliminate silica scaling in geothermal resource utilisation. Additionally, significantly lower brine temperatures are possible after the CaSil technology treatment without inducing silica scaling than with any other commercially available and economical technology. This unlocks the full potential of geothermal resource utilisation for power generation and direct-heat applications. Figure 2 shows a schematic diagram of the CaSil technology interfacing with a typical geothermal power station.

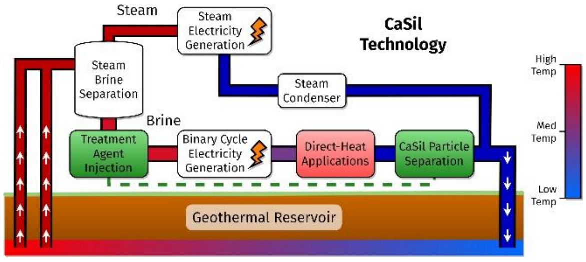

Figure 2: Schematic diagram of the CaSil technology interfacing with a geothermal power plant.

A treatment agent is injected into the geothermal brine as soon as silica reaches a supersaturated state, which typically occurs after the flashing process. The dissolved silica is rapidly transformed into a novel nanostructured calcium silicate (CaSil) material which does not stick to metal surfaces and has unique chemical and structural properties. The chemical reaction is completed within seconds and forms a colloidal suspension with discrete particles. The suspension can easily flow through pipework and heat exchangers used in a binary cycle plant or for direct-heat applications. Little turbulence is needed to keep all CaSil particles in suspension. Finally, the CaSil is separated as a useful material before brine reinjection.

By transforming the silica, the residual silica concentration is actively lowered which leads to a reduction of the silica saturation index (SSI) significantly below 1. Silica scaling is effectively prevented at currently common discharge temperatures of geothermal power stations (medium temperatures, see Figure 1). Currently, the electricity output of binary cycle units experiences a saw-tooth production profile which is caused by gradual silica scaling. Valuable production capacity is lost until costly cleaning efforts are undertaken. However, scaling starts again immediately after cleaning. With the CaSil technology no silica scaling can occur which means a stable production curve at full output can be realised. This can equal an estimated increase in generated electricity of up to 25 % over time with the same existing asset.

Additionally, to the increase in sales revenue from binary cycle power production, more heat energy can be extracted safely from the medium temperature brine before an SSI of 1 is re-established. This can be done in additional downstream binary cycle plants or through heat supply to direct-heat applications like greenhouses, aquaculture or milk powder preparation. Thereby, the CaSil technology aids in the decarbonisation of industry and adds additional revenue streams to the plant owner (see also section 4). The lower brine temperature at reinjection aids with the injectivity of reinjection wells through the slight cooling and contraction of the immediate rock strata below and increased density of the water.

The CaSil technology can be readily installed into existing geothermal power stations or greenfield projects to offer a comprehensive silica scaling prevention technology as well as enable the full utilisation of a geothermal resource.

2. CASIL DEVELOPMENT PLANT

The CaSil Technology has been successfully demonstrated at different geothermal fields in New Zealand. Development of the process on a continuous scale started 2017 at Wairakei where significant research was undertaken to characterise and understand the CaSil process and product properties under field conditions using real geothermal brine with all its impurities and possible side reactions. Upon completion of the work, the CaSil plant was relocated to Kawerau in 2021. The robust process worked without complications with the significantly different brine chemistry. In 2023 the development plant was installed at the Mokai geothermal field (see Figure 3) and delivered equally satisfying results (see Figure 5 for all three sites).

The CaSil development plant is fully automated and capable of processing up to 3 t/h of geothermal brine. Different plant configurations can be tested as well as tie-in scenarios into a geothermal power station. All unit operations of a large-scale process are represented in this plant. The individual process chemistry required for an optimal CaSil process can differ slightly between geothermal fields and depends on the unique chemical composition of the brine. Additionally, complementing batch experiments can be conducted in our mobile laboratory that has a large capability of on-site experiments and sample analysis.

The continuous process on development plant scale allows the testing of various dosing regimens and evaluation of its effectiveness well before significant financial commitments need to be made. Batch experiments can be used to expand the process knowledge for edge cases or special scenarios.

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The collected data can be used to inform a large-scale process design.

Figure 3: CaSil Development Plant installed at Mokai, New Zealand.

3. FIELD RESULTS

3.1 Silica Saturation Index over Time at Wairakei

While the CaSil development plant was deployed in Wairakei, we took regular samples of the incoming brine as well as the fluid after treatment. Figure 4 presents the silica saturation index over the course of one workday, which varies considerably. The SSI has been calculated for an incoming fluid temperature of 95 °C.

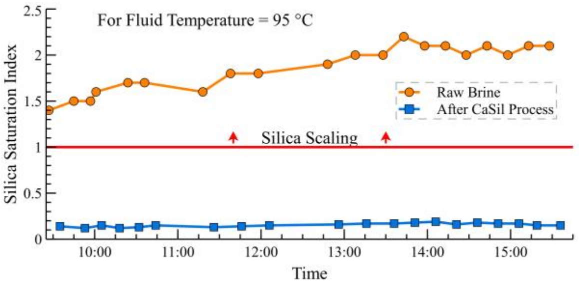

Figure 4: Silica saturation index calculated for 95 °C over time for sampled raw brine and CaSil treated brine utilizing fluid from Wairakei, New Zealand.

The raw brine (orange line) was already supersaturated in silica once we sourced it. In the morning an SSI of approximately 1.4 was recorded. Over the course of the day the silica concentration rose, which meant the SSI increased accordingly. A maximum SSI value of 2.2 was observed. Since silica starts to polymerise at an SSI > 1, the brine was already polymerising and scaling in the morning and got progressively worse as the day continued. This change in chemical composition is natural and expected from geothermal wells and shows that the scaling rate can go through cycles.

After treating the sourced brine with the CaSil technology (blue line) the SSI was reduced significantly, to below 0.19, within seconds of dosing. Silica scaling was effectively prevented. Additionally, the SSI of the treated brine remained relatively constant over the day, despite the increase in silica observed. This means that the treatment success is independent on the incoming silica concentration and a consistent silica scale prevention plan can be guaranteed. The CaSil chemistry and process technology are very robust.

3.2 Silica Saturation Index and Temperature for different geothermal fields

The treatment success for all three different fields (Wairakei, Kawerau, Mokai) is depicted in Figure 5. Both the SSI and silica saturation temperature (SST), the temperature at which the SSI = 1, have been calculated. The average initial SSI and SST are depicted.

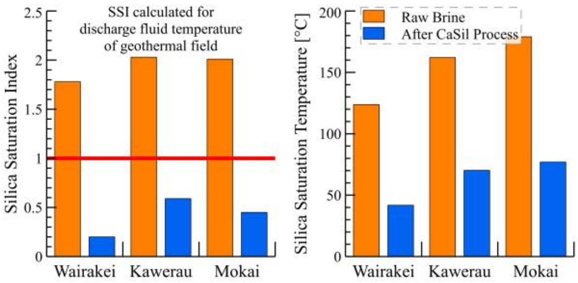

Figure 5: Silica saturation index for Wairakei, Kawerau and Mokai geothermal fields in New Zealand for sampled raw brine and CaSil treated brine at field discharge temperature.

As previously shown, the SSI was reduced to below 0.19 after the CaSil treatment in Wairakei. This means that the temperature of the brine could be safely reduced to about 42 °C, without inducing any more silica scaling. Significant amounts of thermal energy have been made available for economic extraction without silica scaling through the CaSil treatment (see also Figure 7). The discharge temperature at Wairakei after the existing binary cycle is about 87 °C (Zarrouk et al. 2014) which is too cold for additional electricity generation. However, the additional heat recovery made available by the CaSil technology could be used for direct-heat applications.

In Kawerau an initial SSI of approximately 2 was recorded in the sourced brine. This equals an SST of 162 °C which means silica scaling occurs under current operating conditions as observed by Addison et al. (2015). After treatment, the SSI dropped to 0.6 with an SST of approximately 70 °C. Similarly, an initial SSI of 2 was recorded in Mokai which was reduced to 0.45 after treatment. The SST was 77 °C. For a conventional power generation plant these SST values are more than sufficient to stop all silica scaling in process equipment, ensure clean heat exchangers for binary cycles and a stable power production profile at maximum rating.

The increase in SST of Kawerau and Mokai brines compared to Wairakei can be explained by the fluid chemistry. Wairakei is an alkaline resource with a pH = 8.5, whereas Kawerau and Mokai brines are more acidic. This slightly affects the CaSil process chemistry. However, the robust process chemistry can be readily adjusted so that lower SST values are realised and further heat extraction down to low temperatures for direct-heat applications remain possible without silica scaling.

4. UNLOCKING GEOTHERMAL RESOURCES

4.1 Enhanced Energy Generation

As previously mentioned, hot brine injection as a silica scaling mitigation method is a technique used by industry. This is typically used by geothermal plants with significant scaling problems and very high silica concentrations. By applying the CaSil technology to these fields, the SSI can be

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sufficiently lowered to allow a downstream binary cycle to operate without silica scaling.

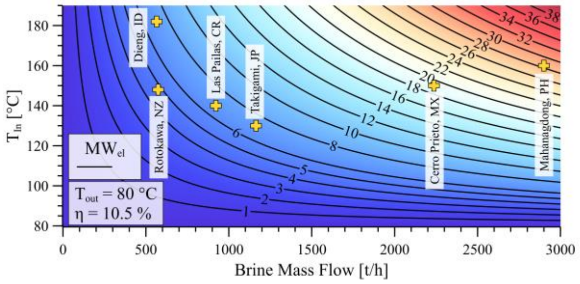

Figure 6: Additional electricity that can be generated in MW_{el}.

The amount of electricity (in MW_{el}) that can be additionally generated from geothermal resources is plotted in Figure 6. The incoming brine temperature (current discharge temperature) and total brine flow rate are used to identify the total potential installed capacity of a downstream binary plant in MW_{el}. An outlet temperature of 80 °C is assumed, which is a safe discharge temperature after CaSil treatment (see Figure 5). A conservative efficiency factor for the binary of 10.5 % is assumed.

In the Dieng geothermal plant in Indonesia, brine is discharged into an open channel at 182 °C, with an SiO_2 concentration of 1093 ppm and a flow rate of 565 t/h (Rudiyanto et al. 2021, Juhri et al. 2023). Silica can precipitate in the channel before the water is reinjected in order to protect the reinjection wells from severe silica scaling. For a very conservative estimate, a bottoming binary cycle could produce at least 7 MW_{el} more from this resource than currently possible, an 11.6 % uplift to the currently existing 60 MW_{el} production. However, accounting for the very high incoming brine temperature, the plant efficiency factor would be significantly higher than the assumed 10.5 %, boosting the energy output even further. Instead of a binary cycle plant an additional flash cycle could also be installed which typically has a higher efficiency.

Similarly, at the Rotokawa power station in New Zealand 574 t/h of 148 °C hot brine is discharged at SSI = 1. The high load of silica prevents any further heat extraction (Wilson et al. 2007, Addison et al. 2015). As depicted in Figure 6, about 4.8 MW_{el} could be produced additionally with the CaSil Technology. Again, a significantly higher efficiency factor can be expected for a real production plant.

Temperature and brine flow rate values for Las Pailas (Costa Rica), Takigami (Japan), Cerro Prieto (Mexico) and Mahanagdong (Indonesia) power plants were taken from Kamila et al. (2021). Similar significant improvements regarding electricity production could be made in these plants with high silica loads and scaling rates by implementing the CaSil technology.

4.2 Direct-Heat Applications

Geothermal plants which can already economically lower the brine temperature through electricity generation to the 100 °C region are not going to experience the same generation uplift as seen in Figure 6. However, they will still profit significantly from the elimination of the typical saw-tooth production profile, generating up to 25 % more electricity over time by including the CaSil technology in their operation as a silica scale elimination scheme. While small downstream binary plants are possible to install, the big opportunities are in the sale of heat energy. This is also a possibility for plants with currently high scaling rates as valuable heat energy will be left in the brine after any binary cycle plant (80 °C discharge temperature assumed for Figure 6).

Figure 7 shows the amount of heat energy in MW_{th} that can be extracted from a geothermal brine by using the difference in temperature ($\Delta T = T_{in} - T_{out}$, y-axis) and available brine mass flow. Multiple exemplary power stations are marked in the diagram.

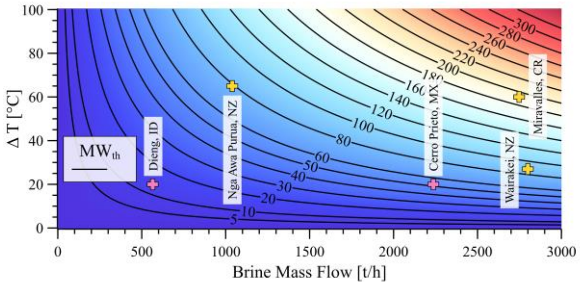

Figure 7: Heat energy that can safely be extracted in MW_{th}.

As seen in Figure 5, the SST of the treated brine from Wairakei was reduced to 42 °C in the CaSil development plant. Currently, Wairakei discharges 2800 t/h of brine at 87 °C (Zarrouk et al. 2014). A total ΔT of 45 °C would be available before silica can polymerise again (87 °C - 42 °C = ΔT 45 °C). However, for these ultra-low temperatures very large heat exchangers are required which is not economical. Therefore, an outlet temperature of 60 °C is more realistically assumed, giving a ΔT = 27 °C. A total of 88 MW_{th} can be extracted from the brine to be used in direct-heat applications. This is a significant new revenue stream for plant operators that is currently not available.

Similarly, the Nga Awa Purua power station in New Zealand discharges 1039 t/h of brine at 125 °C (Gray 2010). If a new discharge temperature of 60 °C is assumed again, 78 MW_{th} are available to be sold to heat consumers. Assuming this process heat is replacing existing gas fired boilers, up to 132.829 t_{CO_2e} could be offset for the Nga Awa Purua example alone (54 g_{CO_2e}/GJ, MFE 2022). In the Miravalles power plant in Costa Rica 2748 t/h of fluid is discharged at approximately 120 °C (Moya and DiPippo 2007). For this plant, 192 MW_{th} would be available for direct-heat customers. This illustrates the significant new business opportunities for direct-heat usage and how much geothermal energy can contribute to the decarbonisation of industries requiring such process heat, which is uniquely enabled by the CaSil technology.

Additionally, the prior examples of the Dieng and Cerro Prieto power stations are depicted. Figure 6 highlighted the additional electricity that can be generated from these resources. However, there is still surplus thermal energy in the brine which can also be used for direct-heat applications. The plotted data points assume a ΔT of 20 °C (T_{in} = 80 °C – T_{out} = 60 °C). For Dieng approximately 13 MW_{th} are available while Cerro Prieto could sustain 52 MW_{th} of heat take-off.

Heat intensive processes like the operation of greenhouses, aquaculture or milk drying are but a few examples of direct-heat applications that can benefit from low-grade heat that geothermal power stations are currently forced to discard (Hall and Climo 2015). Typically, greenhouses require approximately 1-2 MW_{th}/ha, with a 60 % load factor, depending on their location (Mertoglu et al. 2003). Using the Nga Awa Purua station as example, 39-78 hectare of greenhouses could be sustained at their peak heat demand (coldest night in the year) from the heat energy of that station. During daylight hours, when greenhouses don't require much heat energy input, additional heat customers can be supplied, maximising the heat supply.

4.3 Wider Implications of the CaSil Technology

As shown in Figure 5, the silica saturation temperature of the geothermal brine after the CaSil treatment is significantly reduced compared to the initial value. This means that no silica scaling is possible until the brine temperature is reduced below the new SST. As mentioned before, this means no silica scaling occurs during normal power plant operations which saves on maintenance cost and plant downtime. Additionally, constant power production for binary plants is ensured compared to the current saw-tooth production profile, generating up to 25 % more electricity over time with a given asset.

Some binary plants not only suffer from silica scaling but also antimony and arsenic precipitation. Lower brine temperatures exacerbate this problem as these species are less soluble at these temperatures. They form a hard deposit which precipitates in the porous structure of silica scale, acting as a reinforcement (Wilson et al. 2007). During the CaSil process the pH of the brine is raised. This leads to an increase in solubility of antimony and arsenic which means lower brine temperatures are possible for energy generation without risking scale formation.

Due to the higher brine pH after CaSil treatment, the chemistry can fall into the passivating area of steel. This can be engineered by the process chemistry of the technology and is dependent on the individual brine chemistry of the geothermal field. This means, general corrosion of pipework and process equipment is reduced or prevented, enabling more cost savings.

Co-precipitation of additional species in the CaSil material can occur. Notably, the formation and entrapment of calcium carbonate species has been observed for geothermal fluids with elevated HCO_3^- concentrations such as Kawerau. These do not affect the process negatively. Additionally, low concentrations of arsenic can be trapped in the pore water of the CaSil particles. However, these can be significantly reduced in a washing process. Antimony has not been found in any CaSil material precipitated from geothermal resources or in laboratory experiments.

Lowering the brine temperature further than currently possible brings two additional advantages for reinjection. Firstly, the cooler water is slightly denser which leads to an increased down-hole pressure in the reinjection wells. This raises the injectivity, allowing for more fluid to be reinjected in a given well. Secondly, the colder water cools the immediate rock strata around the reinjection well. This causes the rock to contract and open up rock fissures which further increases injectivity. Naturally, the reinjection of cooler fluid requires careful field management so no cold spots can develop in the reservoir or breakthroughs occur.

5. CONCLUSION

Silica scaling is the single largest hinderance worldwide in the full utilisation of geothermal resources. The intractable scale blocks pipework, heat exchangers and reinjection wells, lowering the efficiency of the plant, reducing the electricity output and necessitating costly maintenance. Current mitigation efforts fall significantly short of providing a definitive long-term solution to silica scaling. All of them require a trade-off between energy production and required maintenance. Additionally, significant amounts of heat energy are left in the brine and must be discarded due to severe scaling rates at low temperatures.

The CaSil technology is a novel and disruptive technique that uniquely provides a comprehensive silica scale elimination plan for a wide range of geothermal resources. Additionally, the full potential of geothermal energy is unlocked by significantly lowering the silica saturation temperature to unprecedented levels in an economical way. The technology can be readily interfaced with existing geothermal plants or greenfield developments.

A CaSil development plant proved the viability and effectiveness of the technology at the Wairakei, Kawerau and Mokai geothermal resource in New Zealand. Silica saturation temperatures as low as 42 °C were achieved in the field. Further, the CaSil process chemistry can be adjusted so that even lower temperatures without silica scaling are possible.

Geothermal power plants with severe scaling rates which are forced to discharge brine at very high temperatures can benefit significantly from the CaSil technology as downstream binary plants are unlocked that can boost the overall electricity generation significantly from the same amount of sourced brine, which is hitherto unobtainable. Generation plants with less severe scaling problems achieve an uplift in performance by eliminating the typical saw-tooth production profile from binary plants due to progressive silica scaling.

Also, significant new business opportunities are unlocked with the sales of heat energy for direct-heat applications such as greenhouses, aquaculture or food product drying. This contributes to the decarbonisation of industry, where geothermal energy can have a significant impact as well.

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