# Improving Geothermal System Performance through Collective Knowledge Building and Technology Development

# (PERFORM)

# End report

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PERFORM is one of nine projects under the GEOTHERMICA – ERA NET The overarching target of PERFORM is to improve geothermal system performance, lower operational expenses and extend the life-time of infrastructure by the concept of combining data collection, predictive modelling, innovative technology development and in-situ validation. The improvement of geothermal plant performance from the proposed work is expected to result in an increase of the energy output by 10 to 50%. In order to reach this goal PERFORM will establish a single and shared knowledge database, build predictive models and demonstrate new and improved, cost-effective technologies which will reduce or even eliminate flow-obstructive scaling, clogging, and resistance to fluid (re-)injection at eight geothermal plants across Europe.

This project has been subsidized through the ERANET Cofund GEOTHERMICA (Project no. 731117), from the European Commission, Topsector Energy subsidy from the Ministry of Economic Affairs of the Netherlands, Federal Ministry for Economic Affairs and Energy of Germany and EUDP.

# Management summary

Despite years of experience with geothermal systems, the geothermal sector still faces a significant number of underperforming doublets, posing a strong limitation on a region's growth of geothermal energy utilization. A key operational challenge in geothermal energy production is restricted flow. Major obstacles for geothermal flow are scaling (mineral deposition), clogging (solid micro-particle deposition), corrosion and inefficient injection strategies. These issues result in high and mostly unforeseen costs for workovers (Higher OPEX), and additionally reduce production (Less Revenue). In order to overcome these challenges, the consolidation and sharing of knowledge, including validated strategies for prevention and mitigation needs to be in place.

Therefore, a consortium[1] of companies and research organizations across Europe proposed a GEOTHERMICA project, PERFORM, which has been granted at 2018. The overarching target of PERFORM is

- to improve geothermal system performance
- lower operational expenses (OPEX)
- and extend the life-time of infrastructure

by the concept of combining data collection, predictive modelling, innovative technology development and in-situ validation.

To reach the goals of PERFORM a single and shared knowledge database has been established which is accessible via: www.geothermperform.eu. In this project, number of predictive models have been built and improved, and cost-effective technologies have been demonstrated to reduce or even eliminate flow-obstructive scaling, clogging, and resistance to fluid (re-)injection. The new developed technologies comprise the use of specific adsorption materials (cation filters e.g. zeolite, chitosan) to remove $Pb^{2+}$ and $Cu^{2+}$ from solution and the $H_2S$ removal by flocculation. On top of that the PERFORM consortium developed a best practice guide and an interactive web-based tool. With this tool, the geothermal operators can plan future operations, see which mitigation measures can reduce their challenges and optimize production/injection. The web tool is designed in such a way to guarantee a maximum and an economical energy production and can be found on the website www.geothermperform.eu as well.

Graphical summary in the next pages presents the main aspects, important challenges, and suggested solutions that have been considered or realized in PERFORM project.

[1] consisting of the *Geological Survey of Denmark and Greenland* (GEUS) and *FORCE Technology* from Denmark, *Helmholtz Centre Potsdam German Research Centre for Geosciences* (GFZ) and *Hydroisotop GmbH* from Germany and *Ammerlaan Geothermie B.V.*, *Greenwell Westland B.V.*, *Wageningen Food & Biobased Research* and *TNO* from the Netherlands

# Graphical summary

**www.GeothermPerform.EU**

**PERFORM**

**Taking on challenges of GEOTHERMAL plants**

## CHALLENGES

Geothermal plants often face challenges that reduce the plant performance. The **PERFORM** platform provides recommendations to help operators to avoid or mitigate the following issues:

- Corrosion (Uniform, Pitting and Crevice, Galvanic, $CO_2$, Microbial induced and $H_2S$ induced)
- Scaling (Carbonate and Heavy metal scales)
- Fines migration and filtering
- Reservoir injectivity

PERFORM especially focuses low enthalpy geothermal systems targeting 1-4 km deep sedimentary reservoirs.

## TOOLS and SOLUTIONS

- **Coupled flow-chemistry models**: evaluate scaling and reservoir injectivity.
- **Web-based toolbox**: An interactive web tool developed for operational advice. With this web tool, geothermal operator can plan future operations, see which mitigation measures can reduce their challenges and optimize production/injection. The web tool is designed in such a way to <u>guarantee maximum and economical energy production</u>.
- **Best Practice Guide**: It is an easy-to-use document showing best practices to minimize scaling and corrosion.

The identified challenges linked to geothermal operations that are investigated:

Developed/practiced methods to face these challenges:

| Challenges | Suggested Solutions |
|---|---|
| Calcite scaling | Limit $CO_2$ outgassing by maintaining a high enough top side pressure with sufficient $CO_2$ remaining in solution |
| Heavy metal scaling | Use element specific adsorption materials (cation filters e.g. zeolite, chitosan) to remove heavy metals from solution |
| $H_2S$-induced corrosion | Remove $H_2S$ by reaction with added iron-based substances and removal of the particles by filtering |
| Galvanic corrosion | ▪ Use high-alloyed materials for devices in contact with the geothermal fluid<br>▪ Use element specific adsorption materials (cation filters e.g. zeolite, chitosan) to remove $Pb^{2+}$ and $Cu^{2+}$ from solution |

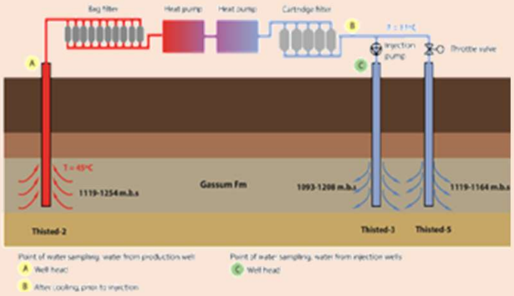
**Examples of CHALLENGES and SOLUTIONS investigated in PERFORM**

PERFORM established a single and shared knowledge database, build predictive models and demonstrated new and improved, cost-effective technologies which will reduce or even eliminate flow-obstructive scaling, corrosion and resistance to fluid (re)-injection at geothermal plants.

**TO IMPROVE THE PERFORMANCE OF GEOTHERMAL SYSTEMS** | **EXTEND INFRASTRUCTURE LIFECYCLE** | **REDUCE OPERATIONAL COSTS (OPEX)**

## A comprehensive KNOWLEDGE Database and WEB Application

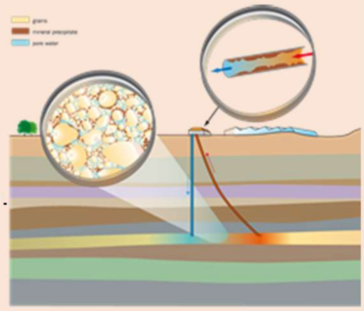
- Data from several sites (6 key sites)
- State-of-the-art data mining and machine learning techniques
- Lessons learned from operations
- Open access database



www.GeothermPerform.eu

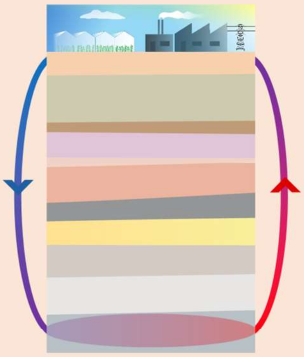
## Integrated Predictive Models

To make PREDICTIONS for PRODUCTIVITY and INJECTIVITY based on the CURRENT and MODIFIED operation.



- Enhance reservoir performance
- Optimize geothermal operations for scaling prevention
- Improve modelling tools and the selection of thermodynamic databases
- Assess risks of seismicity

## Performing Experiments and Field Tests



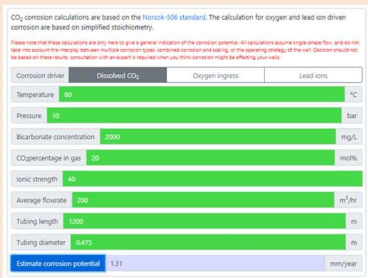
- Control of the pressure, $CO_2$ content and/or pH
- Injection temperature optimization
- $H_2S$ removal by flocculation
- Cation filter
- Particle filters

## Designing an Operational Advice TOOLBOX

- Best practice for scaling and corrosion minimization

Mechanisms and types | Monitoring methods
Sampling procedures | Mitigation measures

- Interactive well check for scaling and corrosion
- Economic assessment tool for the scaling and corrosion mitigation measures



# Table of Content

# 1 Introduction

This report is the public end report of the GEOTHERMICA project PERFORM. This report is Deliverable 5.8_Public. In Table 1 the project details are listed.

**Table 1 Project details**

| | |
|---|---|
| Project title | Improving Geothermal System Performance through Collective Knowledge Building and Technology Development (PERFORM) |
| Project ID | 170155-44011 |
| Coordinator | TNO, Viola van Pul |
| Project website | www.geothermperform.eu |
| Reporting period | May 2018- Oct 2021 |

In Table 2 the participants of the project are listed.

**Table 2 Participants**

| Organisation | Main contact(s) | E-mail(s) | Phone |
|---|---|---|---|
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# 2 Short description of activities and final results

In this chapter a short description of the activities other than mentioned in the proposal and obtained results per work package is given.

## Work package 1: Learn and understand

In this work package, a database and a public website have been established. The address of the website is www.geothermperform.eu. The result of this work package, including data collection, availability, and data evaluation, are described in Kristensen et al. 2020. Below, a summary from Kristensen et al. 2020 has been given.

To understand and predict possible productivity and injectivity problems at the geothermal sites, better knowledge of the mineralogical assemblage of the reservoir rocks and the composition of the formation water is essential. On that background, a comprehensive PERFORM database has been established, which includes geological, geochemical, and geo-mechanical information as well as operational data from sensors at the plants, and the data have been analysed using a range of methods and tools.

Seven key geothermal sites named in the project proposal have shared relevant parts of their data (Thisted, Margretheholm and Sønderborg in Denmark; Groß Schönebeck in Germany; Honselersdijk and Pijnacker Nootdorp in Netherlands; and Schlattingen in Switzerland), and data from additional sites have been obtained from a Dutch database, from the Danish research project GEOTHERM, and from the published literature. Thus, the information represents a variety of geothermal reservoir types and geological settings. To share, present and disseminate data, a PERFORM website has been constructed, managed and maintained by GEUS; https://www.geothermperform.eu. The data on the website are public, but some proprietary data provided by private companies are kept confidential in a separate folder with restricted access.

The PERFORM website includes 4 major sections with common knowledge, assessments and data, focussing on how to avoid or mitigate problems of geothermal plants:

1. **Operational challenges**; corrosion, scaling, fines migration, mineral dissolution etc.
2. **Solution and tools**; Saturation Index, potential solutions to operational problems, best practice guide, link to WP4 toolbox/app.
3. **Data;** geochemical and geothermal data, data availability, maps, list of plants etc.
4. **Publications and general project information**; published study results, project reports etc.

The collected data have been analysed to check its quality, test analytical tools and elaborate on potential causes for observed productivity and injectivity problems. Application of machine learning techniques to the production data from sensors at the Sønderborg site shows that anomalies in sensor output can be detected automatically. Such variations in the data can reflect many aspects of the operation, but it could be caused by the onset of scaling or corrosion. For time series of data, where gaps exist, machine learning allows estimation of the values for missing datapoints. Such analysis of production data can be used to support the operation of a geothermal well.

Correlation analysis and principal component analysis were applied to identify systematic variations and correlations within the datasets and the tendency for mineral precipitation was determined with thermodynamic calculations. Our interpretations of the results indicate that:

- Calcium carbonate scaling can be largely avoided by maintaining an operational pressure exceeding the bubbling point. The operators of the plants are for most part able to do so.
- The concentrations of Ba and $SO_4^{2-}$ in the vast majority of formation waters are at, or close to, equilibrium with barite ($BaSO_4$) at reservoir conditions but supersaturated at the surface after cooling. Despite this, significant precipitation of barite is only reported at few sites. We interpret that the barite scaling forming here reflect that the produced water is hot and Ca-rich – and that such formation water characteristics are likely to induce barite precipitation. If calculations of saturation states were accurate for a broader range of solution compositions (i.e., in Ca-rich brines), we foresee that the extent of barite formation could be predicted. If

formation water composition and temperature can be estimated prior to drilling, risks might even be assessable beforehand.

- For the sites in the database, substantial galvanic corrosion by dissolved Pb or Cu occurs only where these elements coexist with elevated concentrations of chloride in the formation water. Tentatively, the threshold chloride concentration for such corrosion is ~100,000 mg/L. However, the correlation between galvanic corrosion and chloride concentration is only empirically based i.e. it has not been possible to establish theoretical evidence for this apparent correlation.
- Corrosion by oxygen ingress occurs at high rates and may cause the formation of substantial amounts of iron-oxides that can potentially cause clogging of sand screens in injection wells. Therefore, introduction of oxygen into the geothermal water stream should be avoided. Most operators of the plants are for most part able to do so by maintaining an increased operation pressure.
- Data on the corrosion rate from the Sønderborg site, however, indicates that oxygen may well ingress here. In addition, bottom-hole samples at the site contain poorly soluble iron oxides, similar to in nature to the mill scale observed on left over tubing at the surface. This suggests that the injection problems at the Sønderborg site could stem from inadequately prepared infrastructure, with corrosion possibly promoting the migration of the mill scales.
- Corrosion related to sulphide formation in plants with high $SO_4^{2-}$ concentrations in the formation water may be a process causing decreased injectivity due to clogging of sand screens with corrosion products. However, the importance of this process is not fully understood and should be subject to future studies.

The results show that operations based on hot, $Cl^-$ rich formation waters are particularly challenging because of an increased potential for galvanic corrosion. If such waters also contain large concentrations of Ca, the risk of barite scale formation is also increased if $SO_4^{2-}$ is present in the geothermal brine. Such knowledge could be included during the selection of materials for the infrastructure to minimise corrosion and during the design of the plant to ensure that mitigating measures, such as inhibitors or filters for cation removal, can be timely applied.

## 2.2 Work package 2: Predict and validate

This work package is designed to apply cutting edge numerical modelling approaches to support strategy development for improving geothermal performance. The modelling work aims to:

1. **Provide a knowledge base on the processes involved in scaling and injectivity**. We aim to make the best use of the data collected in WP1 as input in the models, as well as provide input for WP1 on the processes of scaling.
2. **Reduce and constrain uncertainty in geochemical modelling** by benchmarking thermodynamic databases available for PHREEQC, to enable selection of the most suitable database for modelling of geothermal systems.
3. **Improve numerical modelling tools** by the development of novel flow-chemistry coupled models to be used for site assessments. Models are designed to predict and improve reservoir and topside geothermal performance by limiting scaling and enhancing injectivity.
4. **Improve numerical modelling tools** by the development of novel coupled thermo-hydraulic-mechanic-chemical models with the aim of (i) modelling the change in injectivity due to temperature changes and related chemical reactions, (ii) modelling the potential for induced seismicity in the context of cold-water injection.
5. **Facilitate WP3** in the setup and interpretation of the experiments and field tests.
6. **Facilitate WP4** in the development of the operational advice toolbox by providing model tools and simulation results on scaling management.

The model developments and model results summary explained in this section.

**Task 2.1 Develop modelling tools to enhance production performance by predicting and guiding the prevention of scaling/clogging** (objective number 2)

The work was aimed at reducing and constraining uncertainty in geochemical modelling by a benchmark of available thermodynamic databases for the widely used software PHRREQC. This will enable the selection of the most suitable database for modelling geothermal systems.

Modelling of geochemical reactions allows the prediction of the outcome of interventions such as geothermal exploitation. The degree to which the modelling portrays reality depends in part on the ability of the thermodynamic data to describe solubility of gasses and solids accurately. For most modelling software, the thermodynamic data is typically compiled in databases, which have been tested to some extent. However, the true capabilities of the databases are most often not well defined. This study tests the performance if 13 PHREEQC databases, benchmarking them against an empirical dataset with 3147 measurements of the solubility of $CO_2$(g), $N_2$(g), $CO_2$(g) - $N_2$(g) mixtures, calcite, and barite at variable temperature, pressure and electrolyte concentration.

Compared to earlier benchmarking of PHREEQC databases, our approach allows selection of databases based on the objective criterium that calculations should match empirical data at or near the modelled conditions as closely as possible. We exemplify how this approach can be implemented during database selection and modification for the simulation of calcite scaling in a model geothermal well. Comparing eight databases, we conclude that the databases with higher discrepancy from measured values at the modelled conditions can produce results that deviate by more than 50% from those of the best performing databases.

The results summarized above can be found in more detail in deliverable 2.1 and will become available in a scientific publication.

**Task 2.2 Application of the numerical tools on the technologies of $CO_2$-(re)injection and pH control** (objective number 3)
The work was focused on optimizing geothermal operations for scaling prevention. To achieve this, an automated coupled modelling workflow was developed for combined flow-geochemistry simulation of scaling in geothermal doublets. The workflow contained a Matlab coupling script, a LedaFlow model for flow dynamics and a PHREEQC model for geochemical calculations of scaling. The model developments included the creation of the Matlab script as well as improvements of the geochemical model, such as an improved way to implement gasses and a more appropriate thermodynamic database (according to work in task 2.1).

The coupled model was tested and adapted to conform with observations of calcite scaling at the Ammerlaan geothermal plant in the Netherlands. The model results were successful in capturing the scaling behaviour, with calcite scaling occurring with a separator tank pressure of 2 bar and the prevention of scaling with a tank pressure of 4 bar. The model was used to evaluate the effects of different topside operating conditions (pressure control) and the presence of heat pumps and/or booster pumps on scaling potentials. Furthermore, the possibility of pH control by acid dosing was explored. Acid dosing could be an alternative to the currently used strategy of keeping the topside under sufficient pressure to keep enough $CO_2$ in solution for a low pH that prevents carbonate scaling. Lowering the pH with acid dosing will allow for a lower pressure and more outgassing and use of $CH_4$.

From the modelling results, it can be concluded that scaling is minimized when:

- The topside pressure is kept elevated. Calcite scaling can be prevented if $CO_2$ outgassing is kept low by keeping the separator tank pressure high enough.
- Heat pump are not used. Heat pumps extract additional heat from the brine at the heat exchanger, leading to (additional) barite scaling.

- Flowrates are kept low. An increased flowrate leads to lower pressures in the producer well. As a result, more $CO_2$ exsolves at the topside, leading to an increase in calcite formation. Results show that calcite scaling is very sensitive to $CO_2$ exsolution, underlining the importance of keeping the $CO_2$ in solution.
- Acid dosing is applied. With acid dosing in the production well or at the topside, calcite scaling can be prevented (with a site-specific dosage). In that case, the pressure does not need be kept elevated and the flow rates can be increased.

The results summarized above can be found in more detail in deliverable 2.2 and in Wasch, Shoeibi Omrani and Twerda (2019).

Besides the topside scaling, geochemical processes in the reservoir were assessed. The work on the reservoir was focussed on the possibilities of enhancing reservoir performance by optimizing the $CO_2$ content of the injected geothermal water. To achieve this, a reactive transport model was developed for the Greenwell site in the Netherlands. With a field-size reactive transport model, the pressure and temperature evolutions were predicted during production and injection, as well as the resulting chemical reactions and related changes to the pore space and permeability. The simulation results for the Greenwell site indicate that soft stimulation of the reservoir by carbonate dissolution could yield a large porosity increase around the injection well from 18 to 29 % and a permeability improvement from 750 mD to 3.75 D. This indicates that there is a potential for $CO_2$-content optimization to stimulate injectivity improvement. The technology has the additional benefit of reducing $CO_2$ emissions into the atmosphere. These results can be found in more detail in Wasch et al., (2020).

**Task 2.3 Application of the numerical tools on the technology of Injection temperature optimization** (objective number 4)

The work of task 2.3 was focussed on the development of the TOUGHREACT-Flac3d coupled thermo-hydraulic-mechanical-chemical (THMC) models. The coupling of thermal, hydraulic, mechanical and chemical processes is expected to be crucial in the performance of geothermal systems in terms of injectivity, productivity, heat recovery and potential environmental risk (e.g. induced seismicity). The coupled numerical models were applied to enhancing reservoir performance and assessing risks of seismic activity.

One of the key challenges in the production of geothermal energy is to overcome a decrease in injectivity or enhance the original injectivity. We developed coupled THMC models to assess the effectiveness of soft stimulation techniques for improving injectivity and reservoir performance, such as thermal stimulation by injection of additionally cooled water, with particular focus on the role of temperature changes. We used both the reactive transport simulator of TOUGHREACT (thermo-hydro-chemical coupling) and the coupled code of TOUGHREACT-Flac3D (thermo-hydro-mechanical-chemical coupling) to investigate the effects of the interaction between flow, mechanics, chemistry and thermal processes on the porosity, permeability and thermal fracturing near the injection well.

Based on the results of our models we derived the following main conclusions:

- The effect of the injection of cold fluids is significant and may promote thermal fracturing and permeability enhancement in the near-well region.
- An increased addition of $CO_2$ enhances the dissolution of calcite in the reservoir and increases the potential for soft-stimulation of the reservoir.
- These modelling results indicate that there is a potential for optimization of the $CO_2$-content and temperature of the injection fluid to improve injectivity.

In addition to the models above, we developed a new coupled thermo-hydro-mechanical workflow to model the effects of reservoir cooling on the induced seismicity potential of geothermal reservoirs. We used a relation between fault stressing rates and seismicity rates, which is based on so-called rate-and-state seismicity theory, to assess the evolution of seismicity in terms of the time-dependent frequency-magnitude distribution of seismicity. The workflow enables us to assess the spatio-temporal changes in the potential of fault reactivation and induced seismicity which is caused by the long-term progressive cooling of geothermal reservoirs.

The results summarized above can be found in more detail in the deliverable D2.3, Wasch et al., (2020), Gan et al., (2021) and Wassing et al., (2021).

## 2.3 Work package 3: Solve and prevent – Technology development and demonstration

WP3 focused on evaluating scaling prevention methods that do not involve the application of large amounts of chemicals (such as inhibitors) but instead on simple low-cost filtration techniques.

**Task 3.1 Testing and evaluating particle filters**

The HydroGeoFilt filter system that was developed for geothermal applications was tested under moderate geothermal conditions at a temperature of 50 °C at the thermal spa Oberlaa in Vienna, Austria and twice at the geothermal site Insheim, Germany (T = 45-62 °C). During those tests, it was shown that no corrosion or material changes of the filter components and no leakages were observed during the experiments. By using the HydroGeoFilt filter system, particles, added adsorption materials and flocculates could be efficiently filtered from the thermal water. In addition, back flushing by using the ultrasonic device was conducted at the geothermal sites Oberlaa and Insheim. The conducted onsite tests demonstrate that the HydroGeoFilt filter system was successfully installed and operated in the frame of bypass experiments for small-scale at moderate geothermal conditions. Hence, the HydroGeoFilt filter system was elevated to a TRL of 7. However, the filter efficiency and stability and the self-cleaning function of the filter system still have to be evaluated by long-term onsite tests. For the use at geothermal plants with higher temperatures and working pressures, the filter system still has to be improved. For effective particle removal the self-cleaning particle filters HydroGeoFilt and AMIAD-AMF that can be applied without disturbing the daily operation of the plant were tested. Both particle filters are equipped with a self-cleaning mechanism, require low energy for a cleaning cycle without chemical additives in its process and produce less than 1% waste water, which makes the technology particularly cost-effective. The details of the testing are reported in deliverable 3.1 “Report on stability and effectivity of particle filters in lab and field”.

**Task 3.2 Development, testing, and evaluating selective cation removal filter**

Within this task new methods for preventing or controlling scaling in geothermal plants were investigated. These methods do not involve the application of liquid additives such as inhibitors or acids into the thermal waters but the reduction of the concentration of scale-forming ions by the application of filter materials. Innovative cation removal technologies were investigated for the reduction of heavy metals in the fluid by chitosan, zeolites and iron oxide compounds. The cation filter materials were tested for stability and effectivity both at controlled conditions in the laboratory and, once proven to be efficient, at site-specific conditions in the field. Laboratory experiments comprised batch tests in an autoclave set-up and flow-through tests conducted in a fluid-flow monitoring system with a filter unit. The field test was performed in a bypass set-up directly at the geothermal demonstration field site in Insheim, Germany. Three different materials (zeolite, chitosan, and magnetite-coated quartz) were tested with regard to their stability at geothermal conditions and their adsorptions performance on copper, barium and lead ions. The influence of temperature, ionic strength in the fluid and the presence of Ca as a competitive ion was investigated. The tested materials (zeolite, chitosan, and magnetite-coated quartz sand) all showed good capacities to remove some of the investigated metals Ba, Pb, and Cu. Especially at low initial metal concentrations, adsorption of Pb and Ba was nearly 100% for zeolite in static batch tests. Lead could also be well removed from solutions even at higher concentrations and salinities. In contrast, only little Ba was bound to the respective surfaces when added at higher concentrations to the adsorbent material. Of the three tested materials, chitosan showed the highest adsorption capacities to bind Cu and Pb ions in the batch experiment. The influence of salinity on the adsorption process was also evident as a medium salinity of 1 M NaCl resulted in the highest metal adsorption. Another parameter that was considered in further tests was the potential competition of Ca that usually occurs at very high concentrations in saline brines with Ba or other metals for sorption sites. The effect of Ca on the performance of Pb and Cu adsorption on zeolite was stronger as compared to chitosan indicating that an application of zeolite in Ca-rich waters cannot be recommended, although more systematic experiments have to be performed in the future to determine the metal selectivity and effect of competing ions in thermal waters of complex composition. In dynamic flow-through experiments at elevated temperatures it was observed that the lead concentration was continuously reduced by zeolite to a sufficient extent. Chitosan, however, showed a better complexation performance at elevated temperatures when tested in static batch experiments as compared to the flow-through experiments.

Another tested technology was the FACT-concept (Filtration Assisted Crystallization Technology) whereas calcite is removed from the geothermal fluid. Finally, a series of laboratory core flooding experiments at reservoir pressure were performed to investigate the effects that injection of cation depleted brine may have on the properties of geothermal reservoirs that are either calcite or anhydrite cemented. In principle FACT might be appropriate to prevent calcite scaling by controlled crystallization on seeds during pressure release of the system to atmospheric pressure. Due to circumstances this has never been tested. During the project, it became clear that the operators are satisfied by operating the well at a certain pressure to prevent scaling. This way of operation is in practice much easier than implementing the FACT technology and therefore FACT is not competitive in these cases. It might be competitive in wells where calcite formation is a much larger problem, but in this project it is no option to investigate this further.

Core specimens of sandstone from the calcite cemented Gassum Formation and the anhydrite cemented Bunter sandstone Formation were flushed with either synthetic brine or synthetic cation depleted brine for 4-5 weeks. The core flooding experiments with cation depleted brine showed increased dissolution of calcite and anhydrite when calcite and anhydrite cemented core specimens are flooded with cation depleted brine. Increasing the temperature decreases the calcite dissolution due to lowered solubility of calcite at higher temperatures. For the calcite cemented Gassum Formation specimens, which show only a minor increase in the dissolution of calcite due to flooding with cation depleted brine, no effects on the mechanical strength were observed due to injection of cation depleted brine. Flooding the anhydrite cemented Bunter sandstone Formation significantly increased the dissolution of anhydrite, resulting in lower bulk modulus, shear strength and Young's modulus, which indicates the flooding with cation depleted brine results a weakening of the mechanical strength of the rock material. Work descriptions, results and discussions are summarised in deliverable 3.2 "Report on development, stability, and effectivity of cation filters in lab and field".

**Task 3.3 $H_2S$ corrosion prevention: Removal of $H_2S$ by $FeCl_2$ addition**

A new method to remove hydrogen sulphide from geothermal fluids during well operation was tested in situ at a geothermal site in Vienna (Austria). Ferric iron was added either as granulated iron hydroxide or as $FeCl_3$ solution into a reaction vessel containing the thermal water directly removed from the wells. From the container, the water would be pumped through a particle filter. Physicochemical parameters as well as sulphide were measured constantly over time before and after the filter. It was found that the sulphide was fully removed from the water by both iron additives. While the addition of $FeCl_3$ led first to the formation of black Fe(II) sulphide (FeS), which subsequently oxidized in presence of oxygen to Fe(III) hydroxide, no visible change of the granulated iron hydroxide was observed.

The application of the investigated method during operation of geothermal wells could prevent $H_2S$-induced corrosion and would eliminate the toxic effects of this gas. This technique has already been applied in a test phase at the geothermal site Oberlaa (A). To quantify and characterize the reactions during these procedures, the fluid monitoring device FluMo-1 (see WP1) was connected to an above–ground installation at the site before and after the filters and changes in physicochemical data (pH, redox, electric conductivity, $O_2$) were monitored. Simultaneously fluid and gas samples were collected and the composition of the thermal water determined especially with respect to iron and sulphate as well as for analysing released gases. This application will therefore move from TRL 7 to 8. Details of the research are published in: Regenspurg et al., 2020.

**Task 3.4 Corrosion and the effect of corrosion resistant alloys**
Parametric laboratory testing has been carried out to investigate the effect of lead in solution and its deposition on the steel in artificial brine solution, with varying concentrations of lead in solution. This has been done using electrochemical techniques, potentiodynamic polarisation and zero resistance amperometry. Also, the effect of oxygen ingress on corrosion resistant alloys (CRA) has been investigated. These studies showed that lead is more noble than steel with and without lead in solution, thus explaining the galvanic dissolution of steel. It also showed that while the temperature (25 and 70 °C) has no significant effect on the corrosion rate of carbon steel in lead-free brine it had a large effect in lead solution.
Due to use in the Margretheholm plant, the effect of a corrosion inhibitor was also investigated showing that the dosage of corrosion inhibitor has only limited effect. Linear polarisation resistance measurements showed that the efficacy of the inhibitor increased with time, likely due to more time to adsorb to the surface or consumption of the lead in solution. Investigation into the effect of oxygen ingress on the corrosion performance did not show a significant difference in open circuit potential or pitting potential with increasing amount of dissolved oxygen, because the alloy show bordline corrosion in the geothermal. Studying the effect of $CO_2$ on the coupling of carbon steel and CRAs (AISI 316L), reveals the presence of $CO_2$ will allow the stainless steel to function as a cathode in the coupling with carbon steel leading to a small increase in corrosion of the latter due to galvanic corrosion. More details of results obtained in task 3.4 can be found in deliverable D3.4 “Results of laboratory testing and on-site monitoring of corrosion in geothermal water”.

**Task 3.5 $CO_2$-(re)injection and pH control**
**and Task 3.6 Injection temperature optimisation**
The feasibility of two methods to enhance reservoir performance in geothermal systems was investigated: (i) Injection temperature optimization and (ii) $CO_2$ reinjection and pH control. Increased cooling of geothermal brine before injection in the reservoir will enhance carbonate dissolution in the reservoir but also may increase precipitation (of e.g. barite). Increasing the $CO_2$ content of the geothermal brine will decrease the pH and hence also enhance carbonate dissolution. Batch experiments were performed to assess the effect of these two methods on the reservoir. The results confirmed that exposing rock samples to the cooled geothermal water induces calcite dissolution. The results of the batch experiments also indicate (but inconclusively) that barite could precipitate.
A field test was designed to learn more about the effects of (i) increased cooling of the geothermal brine and (ii) changed topside pressure ($CO_2$ content) in the brine. In-situ monitoring with FluMo and gas sampling and analyses provided key information on the relationships between tank separator pressure and pH, gas content and $CO_2$ and $CH_4$ gas fraction. The monitoring of system performance, energy use and output is valuable for the optimization of geothermal operations. For example with over 10 ˚C more cooling, the geothermal energy output increased from around 5500 kW to 7000 kW, and the test showed that this can be done without operational issues.
After discontinuation of the FACT research in task 3.2, the remaining budget was relocated to increase the work on the field test with additional data analysis and model validation. In-situ monitoring with FluMo combined with water and gas measurements enables the validation of geochemical models to make more accurate predictions of scaling occurrence and prevention. To investigate the impact of the uncertainties in field measurements on the model outputs, an uncertainty quantification analysis was performed. In the analysis, 5000 sets of input parameters were generated and run with PHRREQC. The model developed in WP2 predicted 6.51E-05 mol/l calcite scaling, the new calibrated model predicts 1.34E-05 mol/l calcite, while the ‘best-match’ model of the uncertainty quantification yields 4.60E-05 mol/l calcite scaling (at a 2 bar tank pressure). This shows that using a different set of input values, even within a realistic range, can easily lead to predictions of a double amount of scaling. This sensitivity of the model highlights the importance of model validation with proper water and gas measurements.

## 2.4 Work package 4: Devise and disseminate
The goal of this work package is to provide design and operational best practices/guidelines;
- How could design choices or operational scenarios enhance production rates?
- How to tackle unwanted THMC changes (Thermo-Hydro-Mechanical-Chemical)?

- What is the impact of a certain measure on the integral cost (CAPEX/OPEX)?

WP4 of the PERFORM project was designed to integrate the results from the previous WPs and activities (WP1 to 3) and build a workflow for operational advice for a range of reservoirs, fluids and operating conditions. In addition, the overall dissemination of the PERFORM project's outcome was included in this work package.
WP4 contained three tasks.

**Task 4.1 Design and operation toolbox**
In the **task 4.1** the outcome of the data inventory from WP1, models from WP2 and improvements from WP3 were combined in a best practice document to assist operators' decisions to minimize scaling and corrosion in their geothermal assets. Best practice guidelines were prepared to match the different types of reservoirs, geothermal fluids and operating conditions. They will comprise practical advice for current and future geothermal operations that will help them to tackle operational problems tied to unwanted THMC (Thermo-Hydro-Mechanical- Chemical) changes such as low productivity/injectivity due to scaling and corrosion. The advice was derived from the insights of the previous three work packages. Direct feedback from the operators was incorporated in the best practice document based on the interviews which were held as an additional activity in WP4. The best practice document is publicly accessible on the PERFORM website (https://www.geothermperform.eu/). In addition to the best practice document, an interactive website application was developed to further support operators in estimating corrosion/scaling risks in their fields and in easy access to the learnings from PERFORM project. The application will be accessible on https://www.geothermperform.eu/.

**Task 4.2 Economic evaluation**
In order to assess the economic impact of the different mitigation measures, an economic evaluation tool was developed in **task 4.2**. The original model was developed in Geo-Elec project which was further modified in PERFORM to account for different scaling and corrosion mitigation measures and enable the users to estimate the impact of selecting a mitigation measure on different key performance indicators (KPIs) such as levelized costs of energy (LCoE) and Net Present Value (NPV). The mitigation/optimization measures which were added to the economic toolbox were degassing, acid jobs, inhibitor additions and filtering technologies. A site-specific economic evaluation was conducted by TNO to compare conventional techniques to optimize the flow rate with the new and optimized techniques. Two sites from the Netherlands and Denmark were selected to perform this economic assessment and validate the workflows. For this purpose, all the cost figures and subsidy schemes of the Netherlands and Denmark were collected and implemented in the economic toolbox. The outcome of the numerical demonstration (in cooperation with WP2) of the economic tool showed a possible decrease in the LCoE employing scaling inhibition techniques by 20% and filtering technology by 8%.

**Task 4.3 Dissemination**
In the **task 4.3**, in addition to the website and scientific publications of the PERFORM project, a workshop was organized for the operators of the low-enthalpy geothermal systems. The workshop was planned to disseminate the outcome of the PERFORM project and receive feedbacks on the potential operational challenges (broader than the operators in the PERFORM consortium), best practices and future steps. PERFORM project leads to several scientific publications and conference presentations which their list can be found https://www.geothermperform.eu/.

# 3 Deliverables

In Table 3 the overview of the deliverables is given. All public reports can be found on the website. Besides the reports the interactive web tool is available on the website.

Table 3 Overview of the project deliverables.

| WP | No | Description | Accessible? |
|---|---|---|---|
| 1 | D1 | A relational database with site-specific geothermal data at a supra-national level. | Yes, accessible via website |
| | D2 | A website for accessing and downloading data. | Yes, see www.geothermperform.eu |
| | D3 | Data evaluation work (addressing current problems at existing geothermal sites) and finding summarized in a report or scientific paper. | Yes, D1.3, public (available via website) |
| 2 | D1 | Paper on implementation of data and databases | Yes, D2.1, public (available via website) |
| | D2 | Report on model development and numerical modelling of $CO_2$-(re)injection and pH control and cation filtering for forecasting geothermal injectivity | No, Confidential |
| | D4-> D3 | Report on model development and THMC modelling for Injection temperature optimization. | No, Confidential |
| 3 | D1 | Report on stability and effectivity of particle filters in lab and field | Yes, D3.1, public (available via website) |
| | D2 | Report on development, stability and effectivity of cation filters in lab and field | No, Confidential (version of 19 Nov 2021) |
| | D3 | Report on evaluation of the $H_2S$ removal technique | Yes, D3.3, public (available via website) |
| | D4 | Report on $CO_2$ and galvanic corrosion | Yes, D3.4, public (available via website) |
| | D5 | Report on $CO_2$ injection and temperature optimization | No, Confidential |
| 4 | D1 | Report on best practices, toolbox for operational advice and overview of site specific costs and savings for new technologies and methods. | No, Confidential |
| | D2 | Workshop Economics | Yes |
| | D3 | Workshop Best Practices | Yes |
| | Extra | Best practice for geothermal plants to minimize scaling and corrosion | Public (available via website) |
| 5 | D5.8 | End Report to the GEOTHERMICA Secretariat | Confidential version (not accessible)<br>Public version |

# 4 Project impact

*Comment on the impact of the project, discussing the items below, if relevant for the project. Include a discussion of relevant market and policy developments and their potential impact.*

- *Demonstrating geothermal energy as a secure, sustainable, competitive and affordable energy source for Europe*

Within PERFORM a best practice guideline and an interactive web tool have been set up to asses corrosion and scaling as well as to suggest possible actions to prevent obstacles related to corrosion and scaling. Both results are based on the data and knowledge gathered in the project, and recommendations following from the project have already been demonstrated as effective to solve operational problems, e.g. at the geothermal site of Ammerlaan calcite scaling is avoided by increasing the operational pressure. Combining the technical and economical data and experience on an international level has improved and increased the applicability of the results. Examples of this integrated knowledge are e.g. the corrosion expertise from Force Technology from Denmark combined with operational economics from sites in the Netherlands. Based on the results, the geothermal operators in Europe can improve their decisions on exploiting their geothermal source in the best economic and sustainable way.

- *Demonstrating the significant role of geothermal energy within the energy system through novel concepts*

The removal of unwanted components from geothermal fluids is one crucial element within PERFORM to reduce operational costs by having less shut-down times for cleaning and replacing, while at the same time diminishing or avoiding wastewater. The method of $H_2S$ removal was successfully tested and is now being applied permanently at the geothermal site Oberlaa (Austria). The novel concept of cation filters showed promising results as well. The tested materials zeolite and chitosan showed good capacities to remove of the investigated metals Pb, and Cu. While lead was adsorbed well by zeolite especially at elevated temperatures. Chitosan showed good removal properties for lead and copper but cannot be applied at temperatures higher than 70 °C due to a limited thermal stability.

The pressure and level of outgassing and the cooling and injection temperature are operational settings that define the LCoE and energy output of the geothermal plant. The field tests and modelling work showed that increased cooling is a good concept for increasing the energy output but requires changes in legislation before it can be implemented. The experimental and modelling work showed that there is a significant potential for enhancing the geothermal injectivity by dissolving carbonate minerals in the reservoir rock. The rock composition data collected for the PERFORM database indicates that the potential is especially large for the carbonate rich Delft sandstone rocks. Increasing the $CO_2$ content in the injected water has the added benefit of reducing the emissions of greenhouse gasses and making geothermal more sustainable.

The development and validation of model tools enables more accurate simulations of scaling. This improves our ability to advise on scaling mitigations strategies. The development of THMC tools is an important step in the assessment of seismic risks by modelling of the combined thermal, flow, mechanic and chemical behaviour of the reservoir.

In general, the overall result of the project is a number of tools that will increase the probability of establishing successful geothermal doublets with a minimum of operational problems. In the same time, the tools supports as low a LCoE as possible in order to facilitate the delivery of geothermal energy at competitive costs to other renewable energy sources.

- *Strengthening the competitiveness and growth of European companies*

With the results of PERFORM, operators are able to make better decisions on their operation with the best practice and the interactive web tool. Besides, the novel technologies open up the possibility to market filter technologies to improve geothermal operation. In a next proposal the consortium with additional partners request a subsidy to further develop the investigated materials (zeolite and chitosan) and test and possible apply these materials under realistic flowing conditions at geothermal sites.

# 5 Collaboration and coordination within the Consortium

The consortium has been led according to the structure as presented in the Figure 1. The structure consists of a general assembly, an executive board and the work package leaders. Besides this there was an overall coordinator and three national consortium leaders that were interacting between the national partners and national funding authorities.

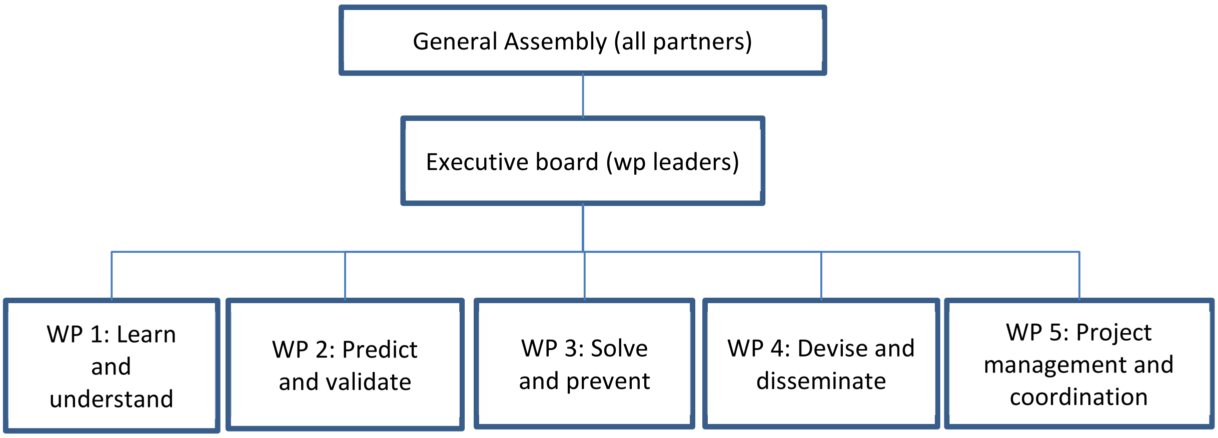


**Figure 1: Project management structure.**

The consortium collaborated in a good and constructive way. The atmosphere during the meetings has been constructive and all partners have been cooperating.

The advantage of the current trans-national consortium is clearly visible in the project.
For example in WP1, the input from all joining countries is incorporated in the study. The data in the database and the resulting discussion on geothermal issues have led to more insight on when certain issues can be seen than could be achieved compared to investigating from a national point of view. The set-up of a database and a website makes it possible to share and evaluate a comprehensive trans-national dataset that also forms the basis of comparing the performance of the different geothermal sites across borders.

Another example of the added transnational value is visible in WP3, where on site measurements in the Netherland (Ammerlaan) have been performed in a cooperation between Germany and the Netherlands (involved parties: TNO, HI and GFZ). The operating conditions have been varied and by that the $CO_2$ content and the temperature in the brine has been influenced. This process has been monitored by GFZ with samples taken and analysed by HI.

A third example is that the developed materials in PERFORM in Germany (for cation exchange) are relevant for sites outsides Germany as well. A possible follow-up of this could take place in the PERFORM II proposal that will be submitted in January 2022.

# 6 Dissemination activities

*List published project progress/outcomes such as brochures, media coverage, publications, patents, presentations etc. and make sure that these will be available through the project website as well.*

The publications can be found on the project website, https://www.geothermperform.eu/
As can be seen on the website, the publications are:

- Laura Wasch, Raymond Creusen, Florian Eichinger, Tanya Goldberg, Claus Kjøller, Simona Regenspurg, Troels Mathiesen, Pejman Shoeibi Omrani, Viola van Pul-Verboom, *Improving Geothermal System Performance Through Collective Knowledge Building and Technology Development*, European Geothermal Conference (EGC) 2019, 11-14 June 2019.
- POSTER: Improving Geothermal System Performance Through Collective Knowledge Building and Technology Development, L Wasch, R Creusen, F Eichinger, T Goldberg, C Kjøller, S Regenspurg, T. Mathiesen, P. S. Omrani, V. van Pul-Verboom, European Geothermal Congress, 2019.
- Kristensen, L., Dideriksen, K., Holmslykke, H.D., Kjøller, C., Larsen, U., Mathiesen, T., Dijkstra, H., Poort, J., Wasch, L., Omrani, P.S., Regenspurg, S.: *Learn and Understand. Knowledge database for understanding the current problems*. PERFORM WP1 Report, Deliverable 1.3, 2020.
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- ORAL PRESTATION and POSTER: *Integrated Scale Management for Geothermal*, Laura Wasch, Pejman Shoeibi Omrani, Aris Twerda, European Geothermal Congress, 2019.
  - Regenspurg S, Ianotta J, Feldbusch E, Zimmermann JF, Eichinger F., *Hydrogen sulfide removal from geothermal fluids by Fe(III)-based additive.* **Geothermal Energy 8, 21 (2020).**
- Regenspurg, S., Feldbusch, E., Byrne, J., Eichinger, F., Henker, A., Ianotta, J., Milsch, H., Sorwat J., Wasch, L., Zotzmann, J, (2020) *Prevention of scaling by quick removal of metals from the brine via adsorption* - Proceedings, World Geothermal Congress, 2020 Reykjavik.
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- Stoljarova, A., Regenspurg, S. Bäßler, R., Mathiesen, T. Braüner Nielsen, J., *Effect of lead and copper containing brine on steel materials for geothermal applications – A corrosion study*, Geothermics, Volume 91, 102024, March 2021
- Stoljarova, A., *Effect of lead on steel corrosion in geothermal systems*, Master thesis, 10 September 2020.
- Wassing, B.B.T., Candela, T., Osinga, S., Peters, E., Buijze, L., Fokker, P.A., van Wees, J.D., 2021. *Time-dependent Seismic Footprint of Thermal Loading for Geothermal Activities in Fractured Carbonate Reservoirs.* Front. Earth. Sci., 14 September 2021.
- Quan Gan, Thibault Candela, Brecht Wassing, Laura Wasch, Derek Elsworth, *The use of supercritical $CO_2$ in deep geothermal reservoirs as a working fluid: Insights from coupled*

*THCM modelling*. International Journal of Rock Mechanics and Mining Sciences, Volume 147, November 2021.

- Laura J. Wasch, Hester E. Dijkstra and Mariëlle K. Koenen, *Soft-stimulating Injection Procedures to Improve Geothermal Reservoir Performance*, Proceedings of the World Geothermal Conference 2020, held in Reykjavik, Iceland, April 26 – May 2, 2020
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- Simona Regenspurg (GFZ), Joy Ianotta (HI), *Evaluation of the $H_2S$ removal technique*, PERFORM, Deliverable 3.3, November 2019,
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