Final report

1. Project details

Project title	PERFORM - Forbedring af geotermiske anlægs drift gennem fælles vidensopbygning og teknologiudvikling
File no.	64018-0303
Name of the funding scheme	EUDP/GEOTHERMICA
Project managing company / institution	Geological Survey of Denmark and Greenland (GEUS)
CVR number (central business register)	55145016
Project partners	GEUS, Force Technology (National EUDP project) GEUS, Force Technology, TNO, GFZ, Hydroisotop, Green Well Westland, Ammerlaan Geothermie B.V, Wageningen Food and Biobased Research (trans-national GEOTHERMICA project)
Submission date	20 December 2021

2. Summary

English version:

The objective of the project was to improve geothermal plant performance. Main goals were: (1) to move from insights of a single doublet to collective and comprehensive knowledge across Europe and (2) to move from costly conventional approaches to cost-efficient deployment of next-generation technologies.

The work has focused on evaluation of capabilities to control mineral scaling, particles clogging, corrosion, and temperature/stress related effects of geothermal flow and injectivity. The project was structured as a four-step approach: (i) Building a database that integrates geological, geochemical, geomechanical and operational data with the aim to learn and understand reservoir performance and water-rock interaction processes; (ii) Predict and understand selected problems at geothermal plants e.g. by predictive geochemical modelling of thermo-dynamic processes (iii) Solve and prevent, including an approach for developing particle and cation filters as well as specific investigations of corrosion related problems; (iv) Dissemination and developing a best practice manual and a toolbox for operational advice.

Results of the project are expected to facilitate the geothermal energy generation worldwide. The knowledge database will continuously be updated with new data and shared via the project webpage where the best practice manual and toolbox are also available. The toolbox is designed to guarantee a maximum and an economical energy production, while the best practice manual focusses on advice to avoid scaling and corrosion during start-up and operation of geothermal plants. New data from corrosion, hydrogeochemical, and geomechanical experiments will, together with numerical models developed in the project, serve as examples for possible future risk minimization of geothermal plant operation. Developed particle and H_2S filter technologies are ready for implementation at geothermal plants, while cation removal filters will need more development before being operational.

Dansk version:

Formålet med projektet har været at forbedre driften af geotermiske anlæg. De vigtigste delmål var: (i) at opnå forøget forståelse for og viden om mulige årsager til driftsproblemer på geotermiske anlæg, samt (ii) at erstatte dyre, konventionelle og ofte usikre løsninger på driftsproblemer med omkostningseffektiv implementering af mere holdbare ”next-generation” teknologier.

Projektet har overordnet været delt i fire dele: (i) Opbygning af en database med det formål at skabe øget viden om sammenhænge mellem driftsproblemer og de fysisk-kemiske processer, der foregår i geotermiske reservoirer og anlæg. (ii) Beskrivelse af årsager til driftsproblemer på udvalgte geotermiske anlæg, bl.a. ved numerisk modellering af termodynamiske processer. (iii) Løsning og forebyggelse af driftsproblemer, bl.a. ved udvikling og demonstration af partikel- og kationfiltre og forsøg, som sikrer, at der ikke introduceres nye problemer i reservoiret med de nye teknologiske løsninger. (iv) Formidling og udvikling af en ”best practice” manual og en ”toolbox”, der kan bruges til operationel rådgivning med fokus på økonomisk optimering af geotermiske anlæg.

Resultaterne af projektet forventes at bidrage til øget geotermisk energiproduktion på verdensplan. Vidensdatabasen vil løbende blive opdateret med nye data og delt via projektets hjemmeside, hvor ”best practice” manual og ”toolbox” også er tilgængelige. ”Toolboxen” er designet for at opnå mest mulig og billigst mulig energiproduktion, mens ”best practice” manualen opstiller en række praktiske råd til at undgå scaling og korrosion under opstart og drift af geotermiske anlæg. Nye eksperimentelle data vil sammen med de numeriske modeller udviklet i projektet tjene som eksempler til brug ved fremtidig risikominimering i forbindelse med drift af geotermiske anlæg. De udviklede partikel- og H_2S-filterteknologier er klar til implementering på geotermiske anlæg, mens filtre til fjernelse af kationer skal udvikles mere, før de er operationelle.

3. Project objectives

The overarching objective of the trans-European PERFORM project was to improve geothermal system performance, lower operational expenses and extend the life-time of infrastructure by combining data collection, predictive modelling, innovative technology development, and in-situ validation. Specifically, the targets of the overall PERFORM project were:

- Creation of a collective knowledge database, enabling efficient evaluations of the causes for poor flow and injectivity;
- Establishing integrated models that will enable forecasting for scaling, productivity, and injectivity on short- and long- time scales supporting early warning and planning of mitigation measures;
- Development and demonstration of innovative technologies to prevent site-specific scaling, clogging and enhance injectivity, including recommendations for the deployment of technical solutions;

- An evaluation of injection temperature that apart for increasing flow will also increase the energy output.

In the Danish subproject, special emphasis was on the following objectives:

- Creation of a collective knowledge database, enabling efficient evaluations of the causes for poor flow and injectivity.

- Establishing improved hydrogeochemical models to support the improved early warning and planning of mitigation measures. Special emphasis was on establishing improved uncertainty evaluation of model results as well as providing the basis for constraining models by supporting experimental results.

- Supporting the development and demonstration of innovative technologies to prevent injectivity problems by providing access to Danish by-pass facilities at the Magretheholm site.

- Carrying out laboratory experiments and associated numerical modelling to ensure long term deployment of the innovative technologies without reservoir formation damage.

- Establishing improved knowledge about corrosion and material choice in the entire geothermal plant to enable economically optimal material selection in the future.

Based on the abovementioned objectives, the trans-European project has served two purposes from an energy technological development perspective. Development and demonstration of specific technologies supporting the overall objective of the project was mainly carried out in the trans-European project where the following technologies were developed and/or demonstrated at various scales:

- Novel self-cleaning particle filters
- H_2S filtration by flocculation
- Several types of cation filters

In the Danish sub-project emphasis was mainly on creating increased technological knowledge and insights with the aim to minimize future problems and optimized operation at geothermal production facilities. As such, the energy technology developed and demonstrated was merely geothermal energy production as a whole rather than single specific technologies. The technological improvements obtained in the Danish sub-project include:

- Establishment of a common web-based knowledge database resulting in improved understanding of geochemically related problems at geothermal production facilities
- Improved numerical geochemical models enabling better prediction of thermodynamic processes in geothermal energy systems, e.g. scaling problems. The numerical models can further support the prediction of mitigation measures such as implementation of filter technologies, changing operational pressure and temperature, etc. A major part of the work has focused on creating an operational tool to evaluate uncertainties associated with such numerical calculations with the purpose to minimize risks related to predictions.
- Improved understanding of driving processes for corrosion in geothermal plants and effects of mitigation measures such as correct material choice, addition of inhibitors, etc.
- Improved understanding of the influence on reservoir performance and integrity as a result of changing the chemical composition of the geothermal brine by the developed filter technologies.

A major part of the findings in the Danish sub-project has formed the foundation for the project's best practice manual for start-up and operation of geothermal plants as well as for the developed web-based toolbox available at https://www.geothermperform.eu/

4. Project implementation

In general, the project evolved according to the original plan in the sense that most planned activities in the Danish sub-project were carried out and associated deliverables were delivered and approved by the GEOTHERMICA office. However, two main non-expected obstacles caused the delay of several deliverables and milestones as well as an extension of the project period with six months, and further resulted in some milestones being achieved only partly. The two obstacles were:

- The COVID-19 pandemic
- The decision on not operating the Magretheholm nor the Sønderborg geothermal plants in the project period.

The COVID-19 pandemic resulted in delays of the overall timeline of the project since limited access to laboratory facilities delayed laboratory experiments, and in the trans-national part of the project, travel restrictions caused planned experiments at Dutch and German geothermal sites to be rearranged and delayed. In general, the international collaboration was somewhat affected by the pandemic situation and travel restrictions, although coordination meetings and workshops were generally successfully held as on-line events.

The closure of the Magretheholm and Sønderborg geothermal plants resulted in cancellation of the experiments planned at these two sites. Accordingly, the original project plan was changed as follows:

- Planned corrosion experiments in a by-pass set-up at the Sønderborg geothermal plant were changed to laboratory experiments. The experiments, however, improved our general understanding of the major factors controlling corrosion at geothermal plants.
- Testing of the developed particle filters was not carried out at Margretheholm as planned. However, this was only a minor part of the Danish sub-project as the only component of the Danish partners was to facilitate access to the Margretheholm site.
- Planned THMC modelling with the Margretheholm site as test case was deemed meaningless with an unknown future operational status of the Margretheholm geothermal plant. As a result, the activity was changed to collection of hard geomechanical data in relation to the experiments with focus on possible formation damage caused by manipulation of the chemical composition of the geothermal brine.

Four major milestones were defined at the initiation of the Danish sub-project:

M1: Database available through the website. A satisfactory explanation for the injectivity problems at 5 of the 7 geothermal sites in the project is reached. The milestone was fulfilled in January 2020.

M2: End of test of cation removal filters. At least one of the tested filters has proven to be applicable for solving current problems at a Danish site without causing new problems. This milestone was partly fulfilled in September 2021.

M3: End of corrosion tests. Cost-effective corrosion reducing initiatives suggested for at least one geothermal plant. This milestone was fulfilled in June 2021.

M4: End of the project. In 5 of the 7 geothermal plants in the project, the project outcome has helped to solve problems related to the operation, e.g. injectivity problems. This milestone was partly fulfilled at the project end date in October 2021.

Milestones M1 and M3 were fully achieved during the project while milestones M2 and M4 were only partly achieved during the project. Thus, the cation removal filters developed by the German partner, GFZ, were not developed to a stage where full-scale demonstration was possible. However, the development of the filters showed promising results in the laboratory, and if up-scaling and demonstration in an operational environment can follow in the near future, the filters may very likely enable the solution of problems related to galvanic corrosion, which is similar to the problems observed at e.g. the Margretheholm site. M4 was only partly achieved since we expect that the insights and technologies of the project will help solving problems at 5 of the 7 key plants of the project, but currently the advice and/or technologies have only to a limited extend been implemented at the key plants.

All milestones were delayed according to the original plan which was mainly due to the COVID-19 pandemic, but for M1, the delay was caused by the decision to include extra data in the database. Thus, the database currently includes data from 36 geothermal sites, including the originally planned 7 key plants.

Both the trans-national as well as the national Danish consortia collaborated in a good and constructive way. The atmosphere during meetings was constructive and all partners were cooperating in a constructive and supportive way to achieve the common goals of the project. Meetings were held in the trans-national project on a bi-monthly basis, and in the national Danish sub-project additional meetings were held when appropriate. Representatives from the national funding agencies were present at all general assembly meetings and work-shops held by the project. As part of the collaboration, FORCE Technology collaborated with the German partner, GFZ, to support the education of one M.Sc. student.

5. Project results

Four out of the five objectives of the national Danish sub-project (cf. Section 2) were obtained at the end of the project. The objective of supporting the development and demonstration of innovative technologies to prevent injectivity problems by providing access to the Margretheholm site could not be achieved due to the shutdown of activities at this site. This situation was not possible to foresee at the onset of the project. However, demon-stration of particle filters, corrosion measurements, and to some extend also cation filters was carried out at Dutch and German geothermal sites instead. Therefore, the missing access to the Margretheholm site was not crucial to the overall results of the trans-national project.

Apart from the missing access to the Margretheholm site, the project evolved without any major changes. However, some shifts in activities and timing did take place of which the most important were the delays in deliverables as mentioned above and the shift from hands-on THMC modelling at GEUS to getting hard data as input to the THMC models performed by TNO.

All changes have been approved by the involved national funding agencies, including EUDP, and the GEO-THERMICA Office.

The project was structured in 5 work packages (WP's) as shown in Figure 1. Below, the results of the technical work packages WP1-WP4 of the trans-national project are described for each WP with special emphasis on the results delivered by the national Danish sub-project.

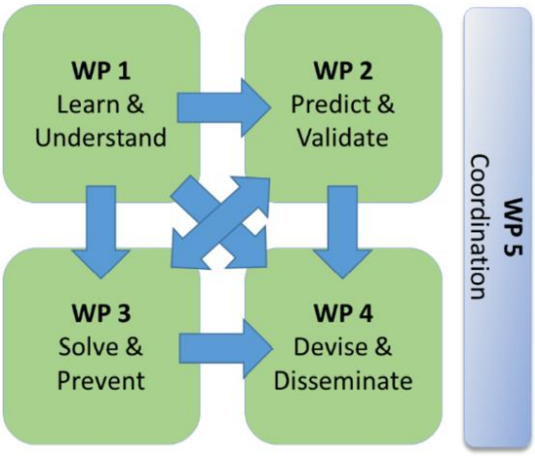

Figure 1: Work packages of the PERFORM project.

WP1: Learn & Understand

This work package was led by GEUS, and the majority of the results emerge from the national Danish sub-project. The results of the work package, including data collection, availability, and data evaluation, are described in detail in Kristensen et al. (2020). The main deliverables of the work package were a knowledge database and a website available at https://www.geothermperform.eu/. Major findings of the work package are summarized below.

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 was established. The database includes geological, geochemical, and geo-mechanical information as well as operational data from sensors at the plants. As part of the work in PERFORM, the data were analysed using a range of methods and tools.

Seven key geothermal sites shared detailed data with the project: Thisted, Margretheholm, and Sønderborg in Denmark; Groß Schönebeck in Germany; Honselersdijk and Pijnacker Nootdorp in the Netherlands; and Schlattingen in Switzerland. Less detailed data from additional sites were obtained partly from a Dutch database, partly from the Danish research project GEOTHERM, and partly from the published literature. The result is a database representing a variety of geothermal reservoir types and geological settings.

The collected data were analysed to check data 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 extend 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 apparently 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 the mill scale observed on left over tubing at the surface. This suggests that the injection problems at the Sønderborg site could stem partly from inadequately prepared well tubing, 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.

In general, the results show that operations based on hot, Cl^- rich formation waters are particularly challenging because of an increased potential for 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.

It is recommended that such knowledge 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. Therefore, the PERFORM website includes 4 major sections with common knowledge, assessments and data, focusing 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 main target group of the website and knowledge database are geothermal operators and their advisors who can quickly get an overview of the most common corrosion and scaling problems and possible solutions to avoid such problems. This is valid both when planning a new geothermal plant as well as when dealing with current problems – such as injectivity problems – at existing geothermal plants. Thus, the results of WP1 are expected to contribute to more economically viable and technically sustainable production of geothermal energy as the knowledge gained eventually will help in avoiding future problems related to scaling and corrosion at geothermal sites. Currently, the website has between 5-10 visits per day. However, up to two weeks following from public presentations of the project, the number of visitors increases to between 20-50.

Deviations from the plan: No data were supplied from the Oberlaa site (Austria), and thus the planned evaluation of data from Oberlaa was not possible. Collection of new data from the Margretheholm and Sønderborg sites (Denmark) was planned, but the data acquisition programme was reduced, as the production of geothermal water from the two sites halted during the period 2018-2021. However, data from other sites were obtained, via e.g. the Danish research project GEOTHERM that includes geochemical analyses of formation waters from several geothermal plants located in France, Germany and Sweden. The unintentional shut-down of the Danish plants meant that the field corrosion investigations were terminated. The activity has been replaced by additional corrosion testing in the laboratory.

WP2: Predict & Validate

This work package also contained major input from the national Danish sub-project. Specific contributions from the national Danish sub-project were the numerical model benchmarking analysis, speciation modelling to support WP1, and numerical hydrogeochemical modelling of experimental results in WP3. Regarding the latter, the original plan was to support only the interpretation of the reservoir rock experiments that were performed in Denmark to investigate for possible formation damage after cation filtration. However, the national Danish sub-project also supported interpretation and design of some of the filter experiments carried out by GFZ in Germany as part of WP3.

The benchmarking 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 supporting geochemical calculations with a qualitative uncertainty estimate. The target group of the benchmarking results is advisors to geothermal operators who can use the results to evaluate the uncertainty related to certain thermodynamic predictions, thereby enabling decision makers to de-risk their decisions – or at least be aware of the uncertainty of the technical calculations that support decisions.

Thus, 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. The benchmarking study tests the performance of 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. The results are presented as deviation plots for each database and a set of pressure, temperature, and salinity conditions. An example is provided in Figure 2.

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.

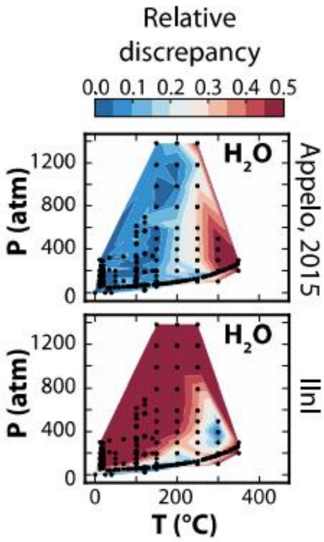

Figure 2: Example contour map of the relative discrepancy between calculations and measurements (RD) for CO_2(g) solubility in water using the Appelo 2015 Pitzer database and the llnl database. The Appelo 2015 Pitzer database employs the Peng-Robinson equation of state, whereas the llnl database uses the ideal gas law. The contour map is based on linear interpolation and RD from 0 to 0.5 is coloured according to the colour bar.

The results summarized above can be found in more detail in Deliverable 2.1 (Dideriksen et al., 2021), and will become available soon in a scientific publication which is currently under preparation.

Numerical modelling supporting the work in WP's 1 and 3 are an integrated part of these work packages, and as such are described under the results of these work packages.

Results from the trans-national project include the following which is targeted at geothermal operators and their technical advisors:

- Application of numerical tools on the technologies of CO_2-(re)injection and pH control.
- Application of the numerical tools on the technology of injection temperature optimization.

Deviations from the plan: There were no major deviations from the plan in the Danish sub-project. However, the planned THMC modelling for the Margretheholm site was replaced by experimental work due to the shutdown of the Margretheholm geothermal plant.

WP3: Solve & Prevent

The specific contributions of the Danish sub-project to this work package included increased knowledge about possible side effects from cation filtering on reservoir performance. In addition, the major part of the task regarding corrosion was carried out as part of the Danish sub-project. In both cases, the most important output was increased knowledge with the purpose to de-risk future geothermal energy production. Thus, the reservoir condition experiments pinpointed certain situations, where possible reservoir damage should be taken into consideration before applying cation filters, and for the corrosion study, the results have improved our general understanding of corrosion in geothermal plants as well as the pros and cons for several types of corrosion mitigation, thereby facilitating future material and mitigation choices. The target groups are in both cases operators and their advisors who will be able to make their technological choices based on an improved knowledge base.

The reservoir condition experiments included a series of laboratory core flooding experiments at reservoir pressure 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. 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 experiments and associated numerical modelling with cation depleted brine showed increased dissolution of calcite and anhydrite when calcite and anhydrite cemented core specimens were flooded with cation depleted brine. Increasing the temperature decreased 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. In contrast, 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 in a weakening of the mechanical strength of the rock material. Thus, overall the reservoir conditions experiments clearly illustrates the importance of thorough consideration about possible site specific risks for the geothermal reservoir – preferably prior to operation of a geothermal plant, but as a minimum in the initial start-up phase. Work descriptions, results and discussions are summarised in deliverable 3.2 "Report on development, stability, and effectivity of cation filters in lab and field".

With regard to corrosion, parametric laboratory testing was 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 was of specific relevance to Danish geothermal plants as galvanic corrosion by lead has been suggested to contribute to the injectivity problems encountered at the Margretheholm plant. The parametric laboratory testing was done using electrochemical techniques, potentiodynamic polarisation and zero resistance amperometry. Also, the effect of oxygen ingress on corrosion resistant alloys (CRA) was investigated with specific relevance to the injectivity problems at the Sønderborg geothermal plant.

The 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 (experiments performed at 25°C and 70°C, respectively) 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 borderline corrosion in contact with the geothermal brine. Studying the effect of CO_2 on the coupling of carbon steel and corrosion resistant alloys (AISI 316L), reveals that the presence of CO_2 will allow the stainless steel to function as a cathode in the coupling with carbon steel, thereby leading to a small increase in corrosion of the latter due to galvanic corrosion. More details of results from the corrosion studies can be found in deliverable D3.4 "Results of laboratory testing and on-site monitoring of corrosion in geothermal water".

Results from the trans-national project include the following targeted at geothermal operators and their technical advisors:

- Development of self-cleaning particle filters (HydroGeoFilt) and demonstration of these in a by-pass set-up at moderate geothermal conditions.

- Development of novel cation removal filters using chitosan, zeolite, and iron oxide compounds. The filters were generally tested at artificial conditions in a laboratory environment, but a single by-pass experiment at a geothermal plant was also conducted. The filter development was supported by numerical geochemical calculations in the national Danish sub-project.
- Development and test at real in-situ conditions of a H_2S-removal filter.
- Laboratory experiments and numerical modelling to investigate two methods to enhance reservoir performance in geothermal systems: (i) Injection temperature optimization and (ii) CO_2 reinjection and pH control.

Deviations from the plan: Within the work package no major changes occurred. However, due to national limitations of laboratory work and travel activities in 2020 resulting from the COVID-19 pandemic, some shifts in activities and timing did take place and were all approved by the national funding agencies as well as the GEOTHERMICA office. Further, the planned access to the Margretheholm and Sønderborg geothermal facilities were hampered by the shutdown of these plants during the project. The planned filter experiments were replaced by experiments at Dutch geothermal sites and the planned corrosion experiments were replaced by additional laboratory experiments.

WP4: Devise & Disseminate

This work package was carried out as a collaborative work package with contributions from all national sub-projects to the deliverables of the work package. The major deliverables were a best practice manual for start up and operation of geothermal plants, a web-based toolbox and an economic evaluation tool. The target groups were geothermal operators and their advisors.

With regard to the best practice manual, the outcome of WP1, WP2, and 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 comprise practical advice for current and future geothermal operations that will help to tackle operational problems tied to unwanted operational challenges such as low injectivity due to scaling and corrosion. Direct feedback from the operators were incorporated in the best practice manual based on interviews which were held as an additional activity in WP4. The best practice manual is publicly accessible on the PERFORM website.

In addition to the best practice manual, an interactive website application (the web-based toolbox) 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 is accessible through the project website.

The economic evaluation tool was developed to assess the economic impact of different mitigation measures. The original model was developed in the Dutch 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). 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 to compare conventional techniques to optimize the flow rate with the new and optimized techniques. Two sites, one from the Netherlands and one from 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 levelized cost of energy employing scaling inhibition techniques by 20% and filtering technology by 8%.

Dissemination activities included the website, the deliverable reports, presentations at national and international conferences and workshops, and scientific publications. Furthermore, a workshop organized for operators of low-enthalpy geothermal systems was arranged as part of WP4. 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.

Below, the dissemination activities are listed with contributions from the national Danish sub-project in *italic.*

- *Dideriksen K., Holmslykke H. D., Kjøller C. PERFORM WP2: Deliverable D2.1. Predict and Validate. PERFORM Work Package Report. Paper on implementation of data and databases. October 2021. To be submitted to Geothermics*.

- Dijkstra, H., Wasch, L., Regenspurg, S., Feldbusch, E., Iannotta, J., Poort, J. PERFORM WP3: Deliverable 3.5. Report on CO_2 injection and temperature optimization. November 2021. Confidential.

- Gan Q., Candela T., Wassing B., Wasch L, Elsworth D. The use of supercritical CO_2 in deep geothermal reservoirs as a working fluid: insights from coupled THMC modeling. International Journal of Rock Mechanics and Mining Sciences, Volume 147, November 2021

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6. Utilisation of project results

In general, the overall result of the project is a number of tools and technologies that will increase the probability of establishing successful geothermal doublets with a minimum of operational problems and a minimum of environmental impact. In the same time, the tools and technologies support as low a levelized cost of energy as possible in order to facilitate the delivery of geothermal energy at competitive costs to other renewable energy sources. Thus, the primary target group for the project results is the geothermal plants – not only in Denmark but across Europe.

The project results are timely, especially for the current Danish situation, where possibly up to 50 geothermal doublets may be established in Aarhus, Copenhagen and mid-Zealand within the next five years. In this context, the project results will facilitate the planning and design of geothermal doublets. It is expected that both the best practice manual as well as the toolbox available on the website can be used to investigate possible problems that may be encountered when establishing new geothermal facilities, and also to evaluate specific risks at specific geothermal locations. Furthermore, the developed uncertainty estimation tool for numerical calculations and the results from corrosion tests are expected to aid future operators in de-risking during the design phase by choosing the most economic and technically optimal mitigation strategies to avoid corrosion and scaling. Eventually, this may possibly mean that operators can save expenses related to establishment of additional injection wells where injectivity issues were previously expected. As each geothermal well comes with an expense of more than 100 mio DKK, the advantage of the project results is obvious.

Some of the specific technological solutions developed in the project are more mature than others. The particle filters and H_2S filter technology are developed to a fairly high TRL level and are ready for implementation at geothermal plants. In contrast, the cation filter technologies need further development to mature for implementation at operational conditions at a geothermal plant. Thus, until the TRL level of these filters is increased, the operators may need to choose more traditional technological solutions such as addition of corrosion inhibitors although this may not be the best choice – neither from a technological point of view nor from an environmental or economic point of view. However, both novel as well as more traditional options are provided in the PERFORM project tools.

For the more general perspectives regarding geothermal energy, Danish geothermal energy is of the low-enthalpy type, which renders electricity production non-profitable. However, with the widely adopted and well-established Danish district heating network, low-enthalpy geothermal energy has the best possible potential to cover more than 15% of the annual Danish heating requirement; in the larger cities such as Copenhagen, much more. The properties of geothermal energy makes it a companion technology to e.g. solar thermal collectors and incineration of biomass. Heat supply from geothermal energy will allow for district heating companies to convert from fossil fuel to multi-sourced energy systems, where safe and reliable base load from geothermal sources will be an advantage in a market with fluctuating market conditions on purchased commodities e.g. biomass in the form of woodchips and straw bales. A newly conducted study from Aalborg University has documented that combination of geothermal energy and district heating in Denmark is both economically and environmentally viable. With other renewable energy sources producing electricity, the geothermal energy supply to the local district heating systems is rather a supplement to other renewables than a competitor. Thus, in the broader perspective, the competitors are few in a society where we are exchanging previous fossil based energy sources for renewables.

Despite these obvious advantages, deployment of geothermal energy in Denmark has until now been challenged. Two out of three existing geothermal plants have been shut down due to injectivity problems that are possibly related to scaling and/or corrosion. Within PERFORM, however, the best practice guideline and the interactive web tool have been set up to assess 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 one Dutch geothermal site where calcite scaling was avoided by increasing the operational pressure. Combining the technical and economic 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.

7. Project conclusion and perspective

The overall conclusions of the project are:

- The more we invest in learning and understanding possible causes to problems at geothermal plants, the better we become to assess possible technical risks and, importantly, to minimize such risks.
- Basically, there are no technical showstoppers for utilization of geothermal energy in Denmark. However, it is of utmost importance that thorough technical investigations are carried out prior to establishment of a geothermal plant e.g. to avoid future problems related to corrosion and/or scaling.
- At existing geothermal plants with current operational problems, thorough investigation of possible causes to the problem(s) and consultation with professional advisors in due time provide good possibilities for mitigating problems and establishing a geothermal facility operating without major problems.
- The specific technologies developed in the project all have the potential to help solving possible problems related to scaling and/or corrosion. Some of the technologies are ready for implementation at geothermal sites while others need more development before being ready for full-scale implementation.

The conclusions above as well as a number of advice to operation of geothermal plants are provided in the project's best practice manual, and several tools for assessing possible problems at geothermal plants are made available from the project website.

We expect the project website and the tools developed in the project – including the best practice manual – to be used by geothermal operators and their advisors in planning and operation of geothermal plants in a variety of cases – from planning the data collection at a new site to deciding on mitigation actions for problems at currently operating sites. Specifically for Denmark, we expect that the knowledge gained in the project will support the growing interest for implementation of geothermal energy supply, and that the two Danish project partners will be invited as advisors to the future operators if current plans of up to 50 local geothermal doublets are realized. With this as the vision, we will also continue to maintain the website and update the database if operators or other projects share their data. Further, both GEUS and FORCE Technology will continue their dissemination activity by attending national and international conferences as well as through organized workshops for relevant stakeholders.

Overall, it is expected that the project results will facilitate the deployment of geothermal energy in Denmark. In some cases, the application of the specific technological solutions of the project may be implemented at specific sites, depending on the problem in hand and the development stage of the possible mitigation technology. For technologies not fully developed in the current project, we expect to apply for future funding to support the final development of these technologies.

8. Appendices

All deliverables, publications, and presentations produced as part of the project are available through the project web-site: https://www.geothermperform.eu/