

TOOLS FOR IMPROVING THE EFFICIENCY OF GEOTHERMAL OPERATIONS



REFLECT
REFLECT



Leaflet for operators: **TOOLS FOR IMPROVING THE EFFICIENCY OF GEOTHERMAL OPERATIONS**

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DOWNHOLE SAMPLER FOR HIGH-TEMPERATURE GEOTHERMAL WELLS

For what is this tool useful?



The Downhole Sampler can provide essential information on chemical composition from specific feed zones.

At which stage of the plant development should it be applied?

It can provide valuable input into characterisation of environmental properties and monitoring of geothermal systems throughout a project's lifetime.

For which geological setting?

It can be used in any type of geological settings, shallow (<1000 m) to deep (>3000 m), low (<150°C) to high temperature (200–450°C).

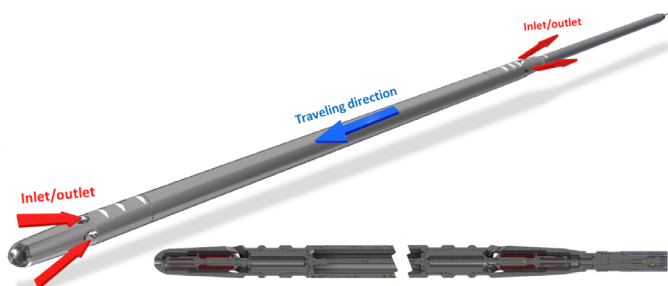


Figure 1. The REFLECT Downhole Sampler has been developed to be able to sample various phases (liquid, two-phase, steam) at low to high temperature/high pressure superheated/supercritical conditions in geothermal wells.

In the REFLECT project a downhole sampler and fluid transfer system for low- to high-enthalpy geothermal wells has been developed (Figure 1). The sampler is designed to tolerate harsh environments at high pressures and elevated temperatures, capable of sampling from individual feed-zones at specific depths giving information that is otherwise lost once the fluid flashes and/or mixes with shallower feed-zones while flowing up the well. The objective is to be able to use the sampler to sample various phases (liquid, steam and two-phase steam) at low- (<150°C) to high-temperatures (200–450°C) using a conventional well logging slick-line equipment and a lubricator pipe.

When deep feed zones of wells at high temperatures mix with colder inflow zones higher in the well, the local fluid conditions can cause severe corrosion and/or scaling in the perforated liner and production casing (Figure 2). Consequently, the lack of knowledge about fluid-properties of distinct aquifers leads to long term and high-cost geothermal utilisation problems. Furthermore, mixing can cause severe local scaling that can cause restriction in flow leading to loss in productivity where recurring expensive and risky workovers may be required. Downhole sampling of the fluid at depth provides information on the fluid composition, that enables optimal design of downhole and surface installations to prevent operational problems.

The downhole sampler has been designed in such a way that it is flexible towards different field conditions, i.e., the sealing mechanism can be adapted to the required temperatures and pressures, thereby lowering the cost of the sampling operation. A flow-through design has been selected as the most reliable principle for such a variable range of conditions (Figure 1). A special emphasis has been put on the selection of corrosion-resistant and leak-tight materials and parts suitable for the construction of the downhole sampler. A first proof-of-principle sampling test will be performed by the REFLECT team at a low-temperature well in the summer of 2023.

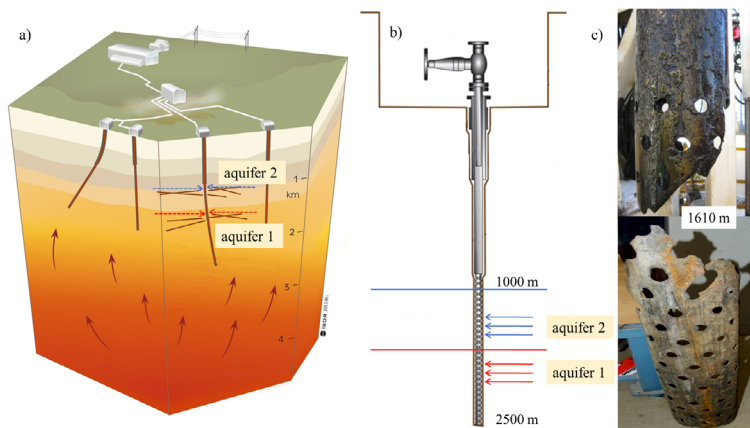


Figure 2. Schematic drawing of a high temperature geothermal system (a) and a well bore with two feeding aquifers (b) for demonstration of a liner corrosion (c) example at 1610 m depth within well KJ-39 (Krafla, Iceland). Extensive damage of the liner was caused by mixing between high temperature fluids from aquifer 1 (hot steam containing HCl gas) and aquifer 2 (colder instream) causing formation of HCl acid and corroding 12 mm liner down to 0 mm in few months.

EUROPEAN GEOTHERMAL FLUID ATLAS

For what is this tool useful?



Investors and operators can have data about the physical and chemical properties of geothermal fluids at a given site.

At which stage of the plant development should it be applied?

In the planning phase, knowledge on the fluid and reservoir properties reduces risks and makes the preparation easier.

For which geological setting?

The Fluid Atlas has data from different geological settings from the countries that were covered by data collection.

In the European Fluid Atlas (<https://www.reflect-h2020.eu/efa>), formerly existing and newly measured data of geothermal fluids collected from 21 countries are visualised (Figure 3). The different layers of the Atlas provide information on geography, geology and depth range, as well as the physical, chemical and microbial properties of fluids. Data of wells, rocks and reservoirs are also available. The focus is on fluids used for electricity generation ($> 100\text{ }^{\circ}\text{C}$), but also data from heat projects are included.

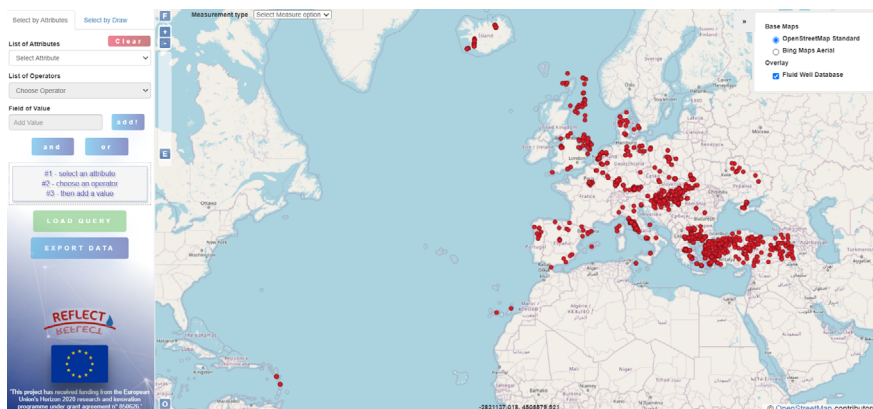


Figure 3. The Fluid Atlas is an online platform for querying and exploring a geothermal and geological database of 3000 wells, 4500 fluid samples and 500 rock samples.

For the Atlas, a free and open-source cross-platform is used, in which the geographic information system provides the environment to view, edit and analyse geospatial data (Figure 4). The interface includes query and filtering tools to explore the database with a map-based visualization.

The Fluid Atlas presents information to a wide range of sectors. Representatives of the scientific community (e.g. geochemists, chemists, microbiologists, geologists, physicists), the industry (e.g. geothermal operators, mining companies) and the public sector (e.g. environmental institutions) are all among the potential users.

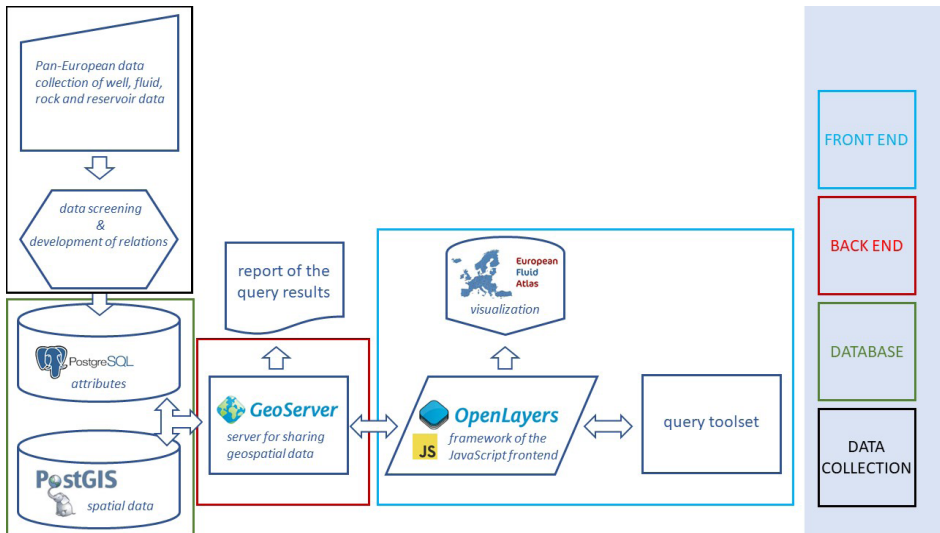


Figure 4. Diagram of the Fluid Atlas technology stack.

The Atlas provides a pre-drilling indication of what type of fluids can be expected and how to deal with them before drilling. Based on that, plant developers can assess and mitigate the expected risks. Knowledge about the distribution of geothermal fluids and their relation to geological and geographical areas allow investors to make more informed decisions about new sites for drilling wells. Data from the Atlas are also useful in all areas that require geochemical data and calculation for modelling at high salinities or temperatures.

Formerly existing and newly measured data – application examples of parameters

The Fluid Atlas contains existing and newly measured data including physicochemical parameters (pH, sp. el. conductivity and redox), main ions and trace elements. The data were compiled by the operators involved in REFLECT (Figure 5). For several sites also isotope data are available, which are also included. The plant operators conduct frequent hydrogeochemical monitoring. Therefore, the additional lab analyses, conducted during the project at the involved locations, represent an extension of the existing measurement network with respect to both the sampling sites and the in-depth analysis.

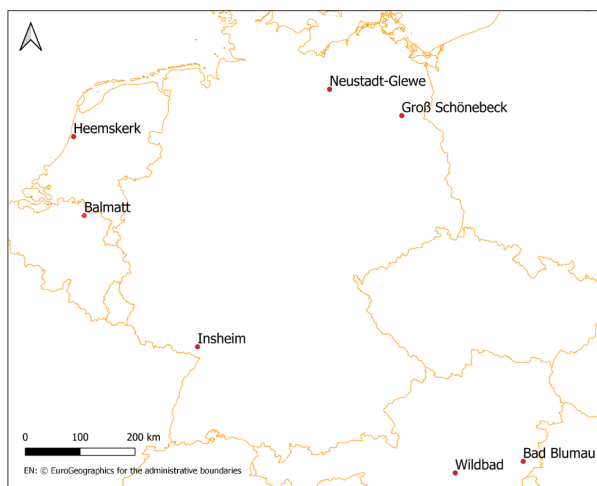


Figure 5. Location of the seven sampling sites in Austria, Belgium, the Netherlands and Germany.

With the support of the realised in-depth analyses, the fluids and their potential deterioration in the geothermal system are characterised and the occurrence of possible risks such as precipitation (scalings), corrosion, or degassing can be estimated, understood and hence be avoided in a targeted manner. Using isotope data, the age distribution and the origin and evolution of different dissolved constituents can be evaluated, being an important tool for the investigation of regional hydrogeological conditions.

Mineral Precipitations (Scalings)

In order to determine potential risks for the formation of scalings various parameters like Ca, Mg, Si, Ba, Sr, etc. were analysed at different locations in the plants and interpreted.

Corrosion

To estimate the potential corrosion processes of the metallic components in the plants different indicator parameters were analysed and interpreted on various positions. Thereby, hydrogen sulphide and hydrogen contents were measured as an indicator for corrosion processes. The $\delta^{34}\text{S-S}^{2-}$ values give information about the origin of sulphide (microbial, e.g. by sulfate reduction vs. geogenic).

Another indication of corrosive processes is provided by the occurrence of dissolved heavy metals such as Fe, Cu and Pb which can -with the presence of dissolved sulphide- react to heavy metal sulphide phases.

Degassing

With the help of dissolved gas analyses, degassing processes can be detected, provided that regular monitoring is carried out. In contrast to the formerly existing qualitative data, the dissolved gases were determined quantitatively by Hydroisotop GmbH.

Origin of dissolved constituents and age distribution

For the characterisation of the proportions of young groundwater and surface water in thermal water, ^3H can be added. Furthermore, ^{14}C concentrations, and $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotope signatures were measured to determine the groundwater age structure and climatic infiltration conditions.

To draw conclusions about the locality of the possible risk processes, samplings were carried out at different points in the geothermal system, for example before and after the heat exchanger.



PREDICTIVE MODELLING

For what is this tool useful?

The modelling tools aim anticipating reactivity of geothermal fluids especially the precipitation risks in wells and surface facilities.

At which stage of the plant development should it be applied?

The predictive modelling tools can be applied as soon as the chemical composition of the exploited geothermal fluids is known.

For which geological setting?

The modelling tools apply to every geothermal systems up to temperatures of 300°C.

In a geothermal system, brine is transported from aquifers – subsurface water reservoirs – to the surface, with the aim of extracting its thermal energy. However, the pumping and transport of these fluids toward the surface disturb the chemical equilibrium causing potential degassing and scaling. The deposition of solid scales can lead to the clogging of wells, reservoirs or surface facilities, reduction of flowrates within the wellbore and topside equipment, and impede the transfer of heat within heat exchanger systems, ultimately affecting the lifespan and economic viability of geothermal systems.

To avoid treating these deleterious physical and chemical reactions and their consequence on production operations, relevant numerical tools are used in order to predict these processes and to anticipate them before they occur.

In REFLECT, a numerical workflow was developed (Figure 6) in order to predict these chemical processes that could impact the geothermal facilities. It is first based on two numerical codes that can be selected to evaluate the precipitation risks:

- **porousMedia4Foam** is an open-source, multi-scale and multiphase package, where OpenFOAM® is coupled with PHREEQC to investigate hydro-geochemical interactions in wells. The flow, transport of species

and temperature are handled by solving equations implemented in OpenFOAM® whereas, the chemistry is exclusively handled by PHREEQC code. For the simulations, the code uses as input the chemical composition of the fluid and the exploitation conditions (i.e., the flowrates, pressures and temperatures) to determine the precise location and severity of scaling. The fluid reactivity can be calculated in simple geometry wells (1D) using a cross-section-averaged formulation (Darcy-like), but high-resolution modelling (2D and 3D) is also possible using Navier-Stokes-based Direct Numerical Simulations (DNS). This approach allows investigating the impact of turbulent flow mechanisms on the scaling formation at the junction of two well segments of different diameters.

- **Drift_Flux** is a modelling workflow used to simulate the fluid flow behaviour in the geothermal assets using Drift-Flux multiphase flow model and couples the fluid flow and chemistry-related processes. The model requires the geometry description, process boundary conditions (such as reservoir pressure and temperature and top-side constraints) and brine composition. The flow properties such as phase velocities and volume fractions and process conditions are being calculated by the Drift-Flux model. After the flow is calculated, the local information is used to calculate the scaling and saturation index at various locations of the geothermal asset to estimate the risk of scaling locally. Other flow-chemistry issues such as corrosion could also be estimated using this model, e.g. by tracking the pH value of the brine at different locations.

However, an accurate prediction of the scaling amount and location in the geothermal systems depends heavily on (1) characterisation of the geothermal fluid, which is impacted by the uncertainties in the fluid sampling and analysis and (2) interaction between flow hydrodynamics and precipitation. This is why a workflow was developed for uncertainty quantification in the fluid composition and its impact on scaling. This workflow will enable operators to make an optimum and robust decision about the operational settings and mitigation measures.

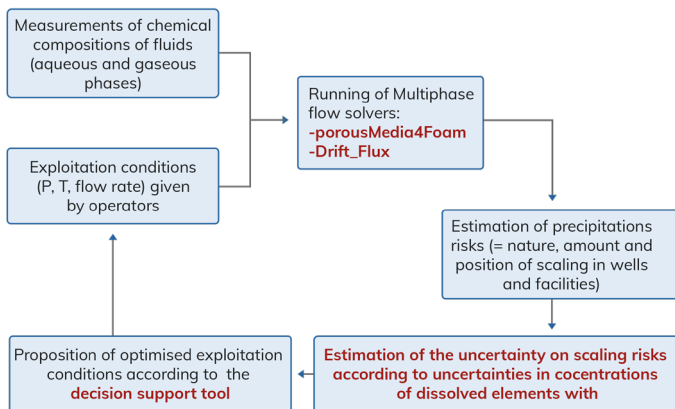


Figure 6. Workflow developed in REFLECT: predictive modelling of scaling processes using field data up to the optimisation of the geothermal fluid exploitation. In red, the numerical modules developed during the project.

DECISION MAKING TOOL

For what is this tool useful?



Robust optimisation tools are useful to find the best performance of geothermal plants, considering all unwanted flow-chemistry and operational upsets such as mineral precipitation risks.

At which stage of the plant development should it be applied?

This tool can be applied on the designing and risk assessment stage, and also during operational stage finding optimum controls.

For which geological setting?

This tool can be applied to any geological setting. Estimation over reservoir rock-fluid properties are needed as input.

A workflow has been developed for operational decision support under uncertainties using a robust optimisation algorithm to determine the optimum production decisions to obtain the best performance protocols for geothermal plants.

Robust optimisation is an optimisation process that incorporates uncertainty (Figure 7). Model-based optimisation workflows for the design and operation of geothermal systems would be incomplete if uncertainty is not accounted within the optimisation process. The Everest robust optimisation framework has been used, which applies the Stochastic Simplex Gradients (StoSAG) method.

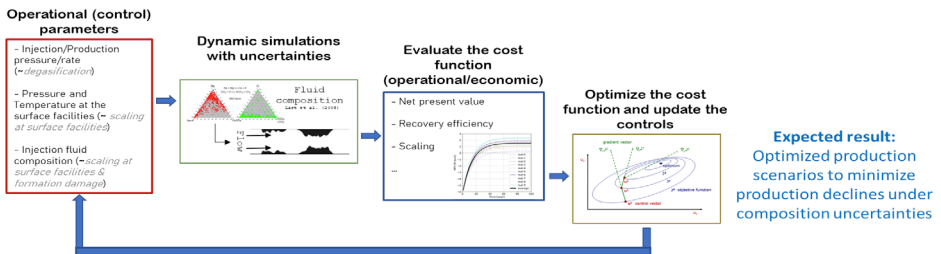


Figure 7. Optimisation workflow

In the workflow, the mean of an objective function is used - for a single strategy for controls - evaluated over an ensemble of several discrete scenarios describing the known uncertainty. The numerical models developed within the REFLECT project have been used to describe the geothermal fluid and heat transfer in the geothermal plant with brine composition uncertainties.

The developed workflow was demonstrated in a case study of optimum temperature control of the geothermal plant, downstream of the heat exchanger, which suffers from barite precipitation. The optimum operation point that gives the highest COP is the outlet temperature that gives the highest temperature drop across the heat exchange, while maintaining the temperature of the system high enough to avoid mineral precipitation. Several deterministic and robust optimisation experiments have been run to show how the optimisation workflow can be used to find the optimum operational range of temperatures.

The results demonstrate that a single value for the control of temperature in the heat exchangers will not provide the optimum for the plant and the mean of the optimum values for each realisation will provide an improved strategy for the plant. An optimum range of temperatures where the system would lead to an acceptable COP were looked at. This problem was formulated as a weighted multi-objective optimisation

problem where it was tried to optimise the COP of the lower and upper outlet temperatures of the range while also optimising the temperature difference between the upper and lower limit.

Two optimisation experiments were run where it was optimised only an optimum value vs. an optimum range (Figure 8). This tool can be further extended to different production and operation challenges to support the decision of operators while considering different uncertainties which can impact the decision.

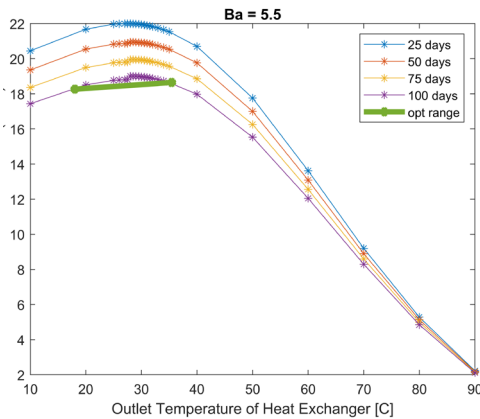


Figure 8. COP vs. outlet temperature at different times for a barite concentration of 5.5 with an acceptable range for outlet temperature between 18 and 35 C to have a COP above 18. In this case, the optimum range for the outlet temperature is between 18 and 35 C.

RISK MAP

For what is this tool useful?



The risk map and numerical tools are powerful to tackle uncertainties in fluid composition, to accurately predict scaling and improve scaling mitigation.

At which stage of the plant development should it be applied?

It provides operational advice to investors and operators during both the design and operation of geothermal plants.

For which geological setting?

It was demonstrated for Dutch sandstone geothermal reservoirs. However, risk maps could be made for any scaling case and reservoir type.

The main objective of the risk map is to assess scaling risks where no data yet exists. The REFLECT Fluid Atlas provides a unique opportunity to access regional fluid data and to use that data for regional scaling risk assessments. A risk map can advise future operators on how to best design and operate their geothermal systems to prevent scaling.

A workflow is defined to create a risk map:

1. Develop a conceptual geochemical model for the scaling issue. Include input on fluid composition, pH and dissolved gasses, such as collected in the REFLECT Fluid Atlas.
2. Determine the base for the risk map, i.e. the chosen parameter to spatially extrapolate model results. This could be the reservoir temperature, pressure or geological formation.
3. Define areas where the chosen parameter is approximately uniform and make a geochemical model for each area.
4. Simulate reservoir conditions for each model and include assumptions such as equilibrium with calcite or quartz in the reservoir.
5. Simulate the production of the reservoir fluid and the pressure and temperature changes in the geothermal plant. Calculate the scaling tendency (dissolution or precipitation) of the mineral of interest for specific operational conditions.
6. Assign a risk to the scaling tendency by comparing it to a critical saturation index. For a scaling risk to be high, the critical saturation index must be exceeded so that the mineral is sufficiently supersaturated to overcome kinetic inhibitions and starts to precipitate.
7. Plot the assigned risk for each area on the base map.

The risk map workflow was demonstrated for calcite scaling in the geothermal doublets in the West-Netherlands Basin (Figure 9). Calcite scaling occurs when the reservoir fluid is depressurized during production and the naturally dissolved CO_2 escapes the fluid, causing the pH to rise. To accurately predict calcite scaling, the CO_2 pressure and fluid pH must be precisely known. This is challenging for the high temperature, pressure and salinity geothermal fluids.

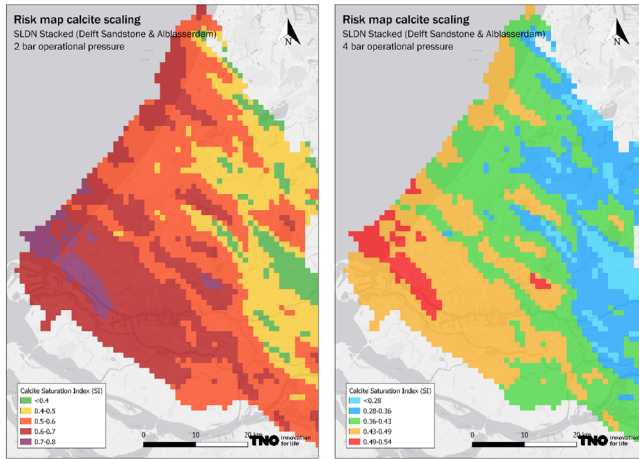


Figure 9. Risk maps for calcite scaling, predicted for operational conditions of 2 bar (left) and 4 bar (right).

A new model tool was developed to deal with these uncertainties. Assuming calcite equilibrium in the reservoir, a site specific linear function was found between pH and CO_2 partial pressure. The relation originates from the principle that with a fixed calcite saturation index (SI of 0 in the reservoir), a higher pH requires a lower CO_2 partial pressure and vice versa to retain equilibrium. This function is very powerful to deal with natural variations and uncertainties in fluid data, since with any combination of pH and CO_2 partial pressure, the same value for the scaling tendency is computed. This means that uncertainties in scaling predictions related to these parameters are reduced to almost zero.

Maps were made for the predicted calcite scaling. Scaling risks were defined by how much the calcite SI deviates from a defined critical SI of ~ 0.6 . With a low top side pressure of 2 bar, the scaling risk is high for most of the West-Netherlands Basin. With a higher pressure of 4 bar, most of the West-Netherlands Basin has a low scaling risk indicating that a 4 bar pressure is high enough to prevent calcite scaling. Only the high reservoir temperatures in the South-West would require a higher system pressure.

This demonstration illustrates how risk maps and improved model tools can improve scaling prevention and are an important step towards better operational practices and enhanced geothermal energy production.

Redefining geothermal fluid properties at extreme conditions

Pictures in the cover (from left to right):

- Los Azufres Geothermal Plant, Chris Rochelle
- European Union, 2008
- Insheim Geothermal Plant, Jörg Uhde



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