

## Demonstration of Soft Stimulation Treatments in Geothermal Reservoirs

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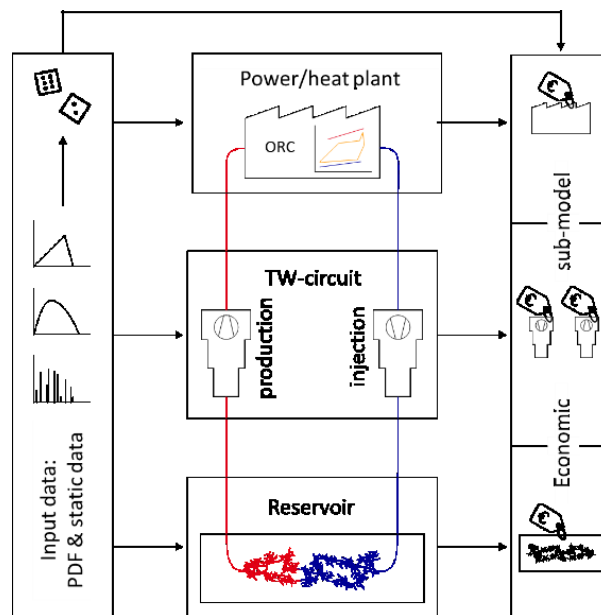
### INTRODUCTION

Enhanced geothermal systems (EGS) allow a widespread use of the enormous untapped geothermal energy potential. EGS measures are generally intended to improve productivity (or injectivity) of a geothermal reservoir by increasing the overall transmissivity of the reservoir rocks. This goal is envisaged by various methods that are dependent on the geological system, comprising the rocks, the rock structures, the tectonic situation as well as the stress field (Huenges et al. 2018). Besides the controlled enhancement of the reservoir, the sustainable operation of the system presents a challenge, as newly opened fractures may close again with reduced reservoir pressure and because of chemical interaction with the fluid, which may lead to precipitation and reduced permeability (see e.g. Brehme et al 2017). Another challenge lies in the side effects of hydraulic treatments, as the high fluid pressures applied and the large fluid volumes injected in such treatments sometimes induce seismic events that can be felt at the surface or even provoke damage and jeopardize the public acceptance of a project (see Lee et al 2019). These issues are addressed by the DESTRESS project (Demonstration of soft stimulation treatments in geothermal reservoirs). The project aims to demonstrate a concept-based approach to develop an EGS that takes the site-specific geological requirements into account. DESTRESS has three overall objectives: i) increase transmissivity of the reservoir, ii) maintain productivity of the system and iii) minimize the level of induced seismicity. The concepts are based on experience in previous projects, on developments in other fields, mainly the oil & gas sector, on scientific progress made on topics such as fluid-rock interaction, the improved determination of the stress field and on the analysis of induced seismicity.

For the demonstration in various geological environments representative for large parts of Europe (representing ~80 % of rock types and adequate settings), the DESTRESS concept will be applied at several sites. In general, we will use a “soft stimulation” approach. Soft Stimulation is a collective term for geothermal reservoir stimulation techniques that aim to achieve enhanced reservoir performance while minimizing environmental impacts including induced seismicity. Soft stimulation includes techniques such as cyclic/fatigue stimulation, multi-stage stimulation, chemical stimulation and thermal stimulation. This implies a stimulation treatment with minimized environmental hazard, to enhance the reservoir performance in several geological settings covering granites, sandstones, and other rocks, and systems where operations have caused significant reduction in productivity due to mineral precipitation. In all cases, risks will be managed at the specific sites with a demonstration of the reduced environmental footprint, and lessons learned will be disseminated to the public (see Hofmann et al 2018, Hofmann et al 2019). Risk management will also include the demonstration of non-standard risk monitoring or tools controlling performance. The business cases will be shown with cost and benefit estimations based on the proven changes of system performance. All the steps included in the DESTRESS approach are designed to be transferrable to other sites, such that the concepts can become the basis for a standardized procedure in the development of EGS projects.

### BUSINESS CASE

The application of soft stimulation techniques will have an impact on geothermal energy production cost and public acceptance. The techno-economic evaluation includes the investment decisions. Therefore, a structured approach for decision making in project development and operation was investigated. Following the single steps of the decision analysis approach, a techno-economic methodology was developed (Reith et al 2018, Welter 2018) with uncertainty integrated into the modelling. Based on this methodological structure it was possible to implement risk factors, and the uncertainty that comes with them, into a techno-economic simulation tool called Integrated Geothermal Energy Model (IGEM) (Figure 1). Risk mitigation measures were identified and quantified with respect to soft stimulation technique based on relevant technical and non-technical factors (Welter et al 2019). The quantification is based on widely-used economic key performance indicators. The application of IGEM allows to determine future trends and to draw up a road map and further recommendations.



**Figure 1: Model overview on the integrated geothermal energy model capable of investigating the impact of soft stimulation measures on technical and economic key performance indicators; PDF = probability distribution function; TW = thermal water.**

### RISK MANAGEMENT FOR SOFT STIMULATIONS

In the framework of DESTRESS, risk management for deep geothermal energy deals with risk governance during soft stimulation operations of geothermal reservoirs for both chemical and hydraulic stimulations as well as for sustainable operations such as long-term exploitation (Baujard et al., 2017; Baujard et al., 2018). Thus, a series of risk assessment and workflows have been achieved for both soft chemical stimulation (Peterschmitt et al., 2018) and for seismic risk related to hydraulic stimulation (Grigoli et al., 2017). Such methodology aims to provide a reliable decision tool to operators to estimate environmental risk like induced seismicity following reservoir operations. Thus, an Adaptive Traffic Light Systems (ATLS) has been developed and tested with real and synthetic datasets (Grigoli et al., 2018; Mignan et al., 2019). It considers, in a probabilistic way, data such as real time induced seismicity and geomechanical model.

In parallel to risk assessment, several acceptability studies have been conducted in various EU countries (France, Germany, the UK), in which different methodologies have been applied (Chavot et al., 2018). Most of them were implemented in areas where geothermal stimulations had been performed or are planned: in France (Soultz, Rittershoffen (Figure 2), Northern Alsace, Strasbourg area), in Switzerland (Basel, Geneva, Haute Sorne, St Gallen) and in the UK (Chavot et al., 2019; Ejderyan et al., 2019). Some dedicated work related to stakeholder engagement has been conducted with European industrial developers.



**Figure 2: Soft stimulation operations at Rittershoffen geothermal site in the Upper Rhine Graben where injectivity was improved by a factor 4 (Baujard et al., 2017).**

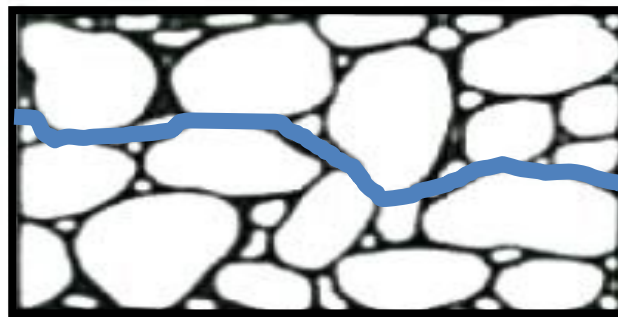
Finally, the risk management was also studied by investigating risks related to stimulation or sustainable exploitation of geothermal resource by using non-standard monitoring techniques. Sensors have been deployed for investigating buildings' vulnerability during geothermal exploitation (Soultz-sous-Forêts, Rittershoffen). A set of 500 buildings was surveyed in an area of around 130 km<sup>2</sup> (Megalooikonomou et al., 2018; Pittore et al., 2018). The analyses performed comprised the data collected in the field around the operational power plant of Soultz and the geothermal plant of Rittershoffen as well as experimental work and numerical modelling activities on CWI (Coda Wave Interferometry) reproducing the mechanical and acoustic behavior of a typical reservoir rock (Azzola et al., 2018a, b). A specific analysis for characterizing the present-day stress field in the Rittershoffen geothermal wells has been done (Azzola et al., 2019).

### APPROACHES FOR SOFT STIMULATION – GENERAL

Specific challenges of the different European settings require technological approaches foreseen in the DESTRESS concept with a dedicated treatment procedure. Initially, DESTRESS planned five fixed geothermal sites to perform soft stimulation treatments: Klaipeda, Westland, Soultz-sous-Forêts, Pohang, Haute-Sorne (Huenges et al 2018). While implementing the project and planning the stimulations, various obstacles occurred and the further availability of the sites in Klaipeda, Westland, Pohang and Haute-Sorne was not valid. This caused a significant reduction of possibilities to execute the foreseen experiments. Fortunately, the project consortium managed to find a substitution for Klaipeda > Mezöberény (Brehme et al 2020), Pohang > Geldinganes (Hofmann et al 2020) and Haute-Sorne > Bedretto (Meier et al 2020).

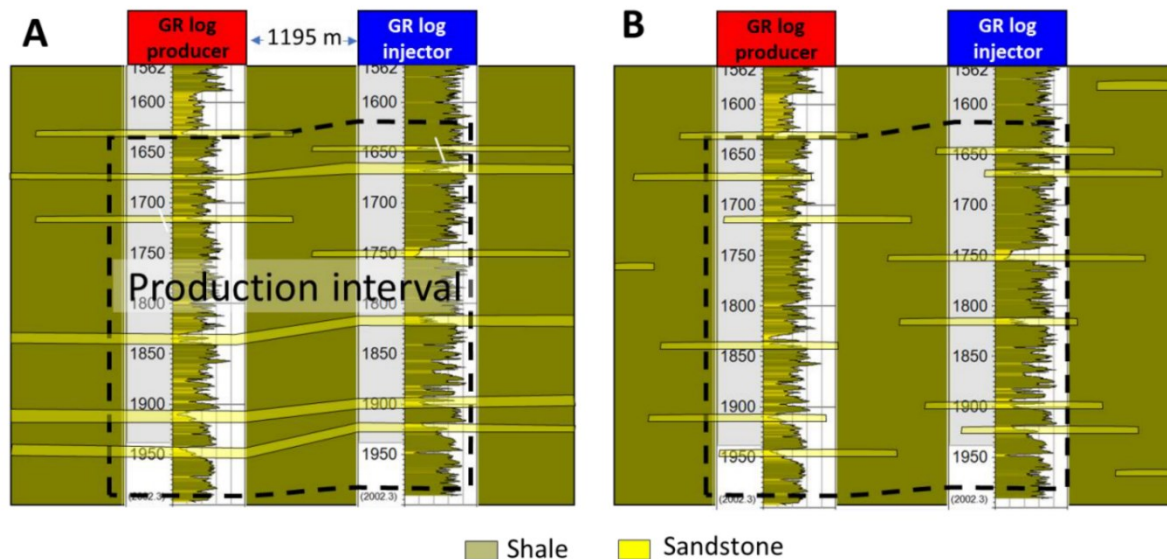
### APPROACH FOR SANDSTONE FORMATION WITH FORMATION DAMAGE

At the Klaipeda site, in sandstone, the analysis indicates that a complex interaction of physical, chemical and biological processes during operation led to the reduction of injectivity in one of the wells (Brehme et al. 2018). Each process that affects injectivity may require a special measure to enhance the production and fulfill environmental constraints. Therefore, Brehme et al. (2017) developed an iterative approach, the so-called Feedback Adjustment Procedure. This sequence of treatment, analysis, feedback, ranking of induced processes and final measures leads to the adequate treatment for soft rock reservoirs, such as sandstones. The foreseen treatment could not be applied at the Klaipeda site due to economic obstacles of the site owner. Therefore, the methodology is applied at the Mezöberény site in Hungary (Figure 3). The foreseen combined hydraulic-acidization treatment is presented by Brehme et al (2020) in this issue.



**Figure 3: Conceptual Chemical Stimulation with acidisation to remove obstacles in pores (e.g. carbonates and fines) (foreseen in Mezöberény)**

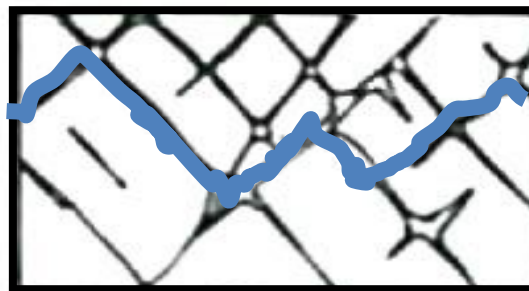
The knowledge about the setup of the Mezöberény site is limited to historical data with short-term tests of the geothermal system. Analysis suggests several reasons for injection -triggered occlusion, i.e. mineral precipitation, fines migration, microbiology, well completion and permeability as well as connectivity of the reservoir layers. Figure 4 shows two possible scenarios for reservoir layer connectivity in the target section of Mezöberény (Brehme et al 2020). Both scenarios, (A) given connectivity or (B) not given connectivity due to geological set-up or formation damage, should be treated chemically to remove occlusion patterns. The temperature of the Mezöberény production horizon is 110°C, which allows to also perform a thermal stimulation. The combination of a chemical stimulation with a thermal stimulation promises an increased effect of the stimulation leading to an increased permeability after each stimulation type.



**Figure 4: Options for the underground of Mezöbereny site with 2 wells based on the given gamma-ray logs. A) with a connected production and B) not connected in the underground.**

#### APPROACH FOR GRANITE FORMATION WITH FORMATION DAMAGE

The creation of the deep hot reservoir in Soultz-sous-Forêts began in 1999, making use of existing local geological knowledge from the former local oil industry. Four deep wells were drilled: GPK-1 to ~3600 m depth and GPK-2 to GPK-4, all from the same well pad, to >5000 m, these wells being deviated to separations of ~700 m at depth. The project was designed with well GPK-2 producing brine at ~150 °C from fractured granite, with wells GPK-3 and GPK-4 used for reinjection at ~70 °C. However, well GPK-4 has underperformed; the principal activity planned for DESTRESS is its remediation via soft stimulation to achieve a soft chemical stimulation of a Soultz-sous-Forêts geothermal well GPK-4.



**Figure 5: Conceptual chemical stimulation with acidisation to weaken strength of particles (e.g. calcite or illite) in contractions of fractured rocks (Soultz-sous-Forêts)**

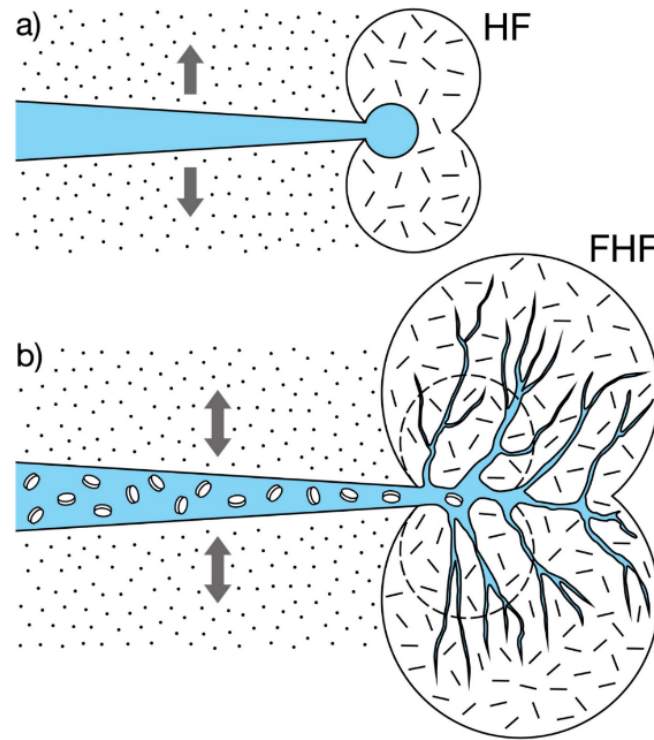
The purpose is to provide stimulation to improve the hydraulic performance of the Soultz-sous-Forêts deep well GPK-4 (Figure 5). However, well integrity issues have to be taken into consideration. Therefore, a preliminary evaluation proposes to inject a total of 100m<sup>3</sup> of acids for the three fractured zones to be distributed according to the mineral composition occurring the natural fractures (more carbonates for Zone at 4924 m). For operating, the chemical injection is foreseen for three different depth-sections by means of focused injection with coiled tubing by starting with the deepest one.

#### APPROACHES FOR CRYSTALLINE BASEMENTS

##### *Cyclic stimulation*

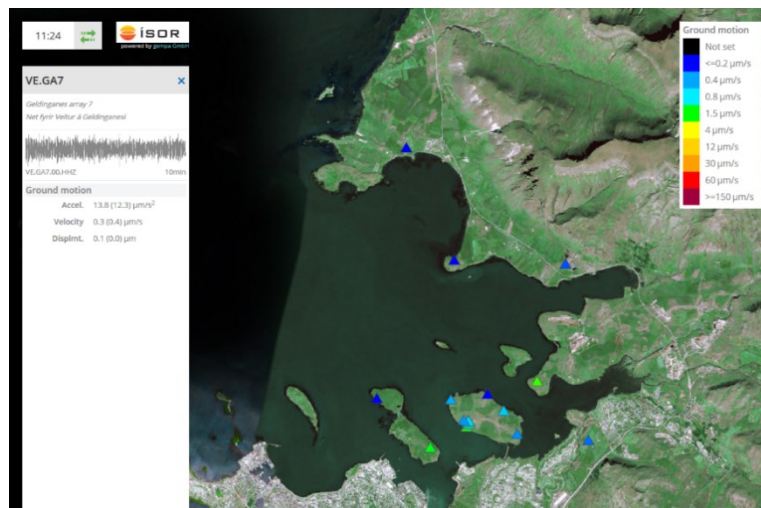
The idea of a soft stimulation differs from a conventional hydraulic fracturing with monotonic injection of high-pressure fluid (Figure 6). The new treatment can be called fatigue hydraulic fracturing, i.e. the fluid is injected in pressure cycles with increasing target pressure, separated by depressurization phases for relaxing the crack tip stresses (Zang et al 2018). Effectively, larger permeability is created at lower pressure by many extra generated microfractures and wash-out at the fracture tip as shown in Figure 6b. In order to demonstrate the effect of such cyclic hydraulic treatments in granites, granodiorites and/or in tight sandstones, this procedure became a crucial part of DESTRESS. This treatment method aims at reducing seismic and environmental risks and providing plannable results of the stimulation. So far, the DESTRESS treatment in the Pohang well PX-1 showed that applying the cyclic stimulation and an adapted traffic light system (Hofmann et al 2018) kept the seismic level under the given threshold of M2. It is important to note that Lee et al (2019) investigated the effect of induced seismicity in the context of the M5.5 Pohang earthquake in 2017 and concluded that injection in PX-1 induced seismicity, but in a spatially and hydraulically

distinct volume of rock, and it is not believed to have played a role in triggering the damaging earthquake. Nevertheless, the effect of the stimulation on productivity in PX-1 was poor so far because the second well PX-2 was in another hydraulic regime and only a side track to the seismic cloud around PX-1 would have led to a success. A number of research activities of the DESTRESS participants are ongoing to explain the large earthquake, e.g. Meier et al. (2020). Westaway and Burnside (2019) considered the possibility that hydrochemical “corrosion” of the granite by the injected surface water contributed. As the project in Pohang was stopped after the M5.5 event, Geldinganes was chosen for the demonstration as described by Hofmann et al (2020).



**Figure 6: Synoptic view of the fracture process zone resulting from a) conventional hydraulic fracturing with monotonic increase of injection pressure (HF), and b) fatigue hydraulic fracturing with frequent phases of depressurization and oscillating pulses during pressurization phases (FHF). In (b), rock chips removed from fracture faces through high-frequency vibrations (secondary pump) and washed out to the fracture tip allow a change in the local stress field in depressurization phases of the FHF treatment. A larger fracture process zone is created (b) compared to the case with continuous fluid injection in the conventional hydraulic fracturing (a) (Zang et al. 2018).**

The stimulation treatment in Geldinganes, a peninsula north of Reykjavik is foreseen for autumn 2019 and will be accompanied by an extended online seismic monitoring program (Figure 7).

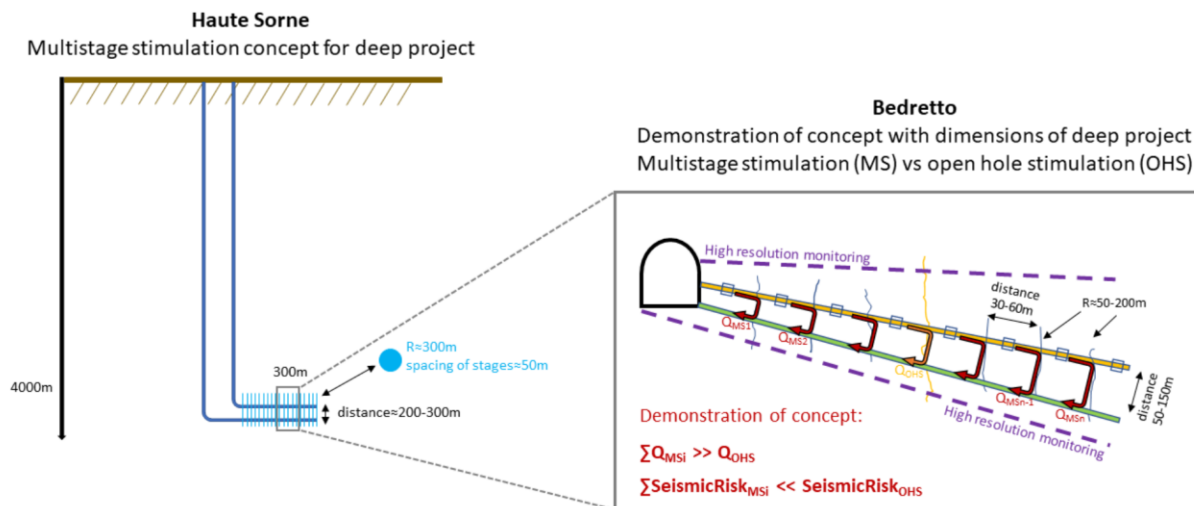


**Figure 7: Seismic monitoring stations "online" in the frame of the DESTRESS project (<http://veitur.isor.is/stationview/#>). All these stations are reporting to ISOR in real-time (200Hz).**



### Multi-stage stimulation

We assume that an economically viable EGS project in a randomly fissured crystalline rock is more probable with an efficient method for sectioning and successfully stimulating individual sections (Figure 8). This shall lead to a reduction of the seismic risk. These technologies exist in other industries, namely oil and gas, but must be adapted to and tested for geothermal operating conditions. The advantage of the multi-stage system, compared to the single-stage system, becomes obvious if one compares the vertical single-stage open hole system with the multi-stage system. Individual stimulations were performed in several sections of a deep borehole in Helsinki and they showed seismicity under a given threshold (Kwiatek et al 2019). However, the data do not show an improvement of hydraulic properties so far and zonal isolation seems not yet to be reached. The Bedretto project of DESTRESS will be focused on demonstrating solutions to overcome such obstacles, e.g. applying new zonal isolation techniques (Meier 2020).



**Figure 8: Concept for multistage stimulation demonstration in the Bedretto underground lab. The findings will help to bring the delayed Haute-Sorne site project or others later to a success.**

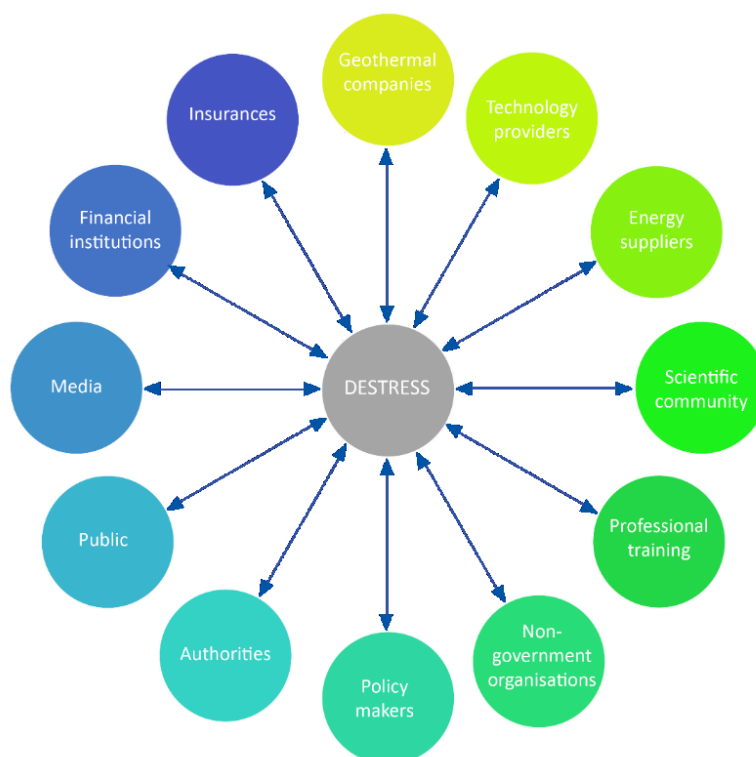
### INTELLIGENT TOOLS CONTROLLING PERFORMANCE AND ENVIRONMENT

Components of best practice workflows for assessing the effects of chemical and hydraulic stimulations have been developed. For chemical stimulation, focus has been on the use of image analysis techniques for characterizing mineralogical and chemical components, as well as porosity and permeability characteristics of rock samples, as crucial input for the assessment of the effectiveness of chemical stimulations (Kong Xiang-Zhao, Jin Ma, and Martin O. Saar pers. Comm. 2019, and UoG,Rob Westaway pers. Comm., University of Glasgow X-CT Scanning and Image Analysis 2019). For hydraulic stimulation, focus has been on the use of both computationally fast models and dedicated computationally more demanding modelling tools. The aim is the assessment of permeability enhancement and induced seismicity during hydraulic stimulations. Models have been applied for the Pohang EGS site and summarized (Candela et al 2019; Wassing et al 2019, and Fokker and Wassing 2019). Model results show that in addition to the effects of pore pressure diffusion, the mechanical processes of poroelasticity and stress transfer (by creep or through the interaction of smaller earthquakes) can have an effect on seismicity potential during stimulations.

Additionally, components for best practices and workflows for technical and environmental performance monitoring have been set up; e.g. GFZ has successfully applied Distributed Acoustic Sensing (DAS) at the EGS Site of Groß Schönebeck (Krawczyk et al 2019, Henniges et al 2019). Furthermore, a best practice guideline “Good Practice Guide for Managing Induced Seismicity” was prepared. New techniques for real-time detection of induced seismicity have been developed and tested (Grigoli et al 2018a) and, of course, there is still ongoing work on the large magnitude EQ in Pohang (Grigoli et al 2018b).

### DISSEMINATION

The dissemination strategy of DESTRESS includes promotion and maintenance of an efficient, proactive, and open communication within DESTRESS and with interested stakeholders (Figure 9). To this aim, the DESTRESS group constantly published latest news on the project website ([www.destress-h2020.eu](http://www.destress-h2020.eu)) and distributed them via newsletters. A constant growth of visitors and readers proves a success of these measures. In addition, DESTRESS supports and promotes various internal and external events. The project group successfully established a site-access program for interested stakeholders and published a series of best-practice reports on the website. Therefore, non-experts in the respective field get an easy access to complex aspects of geothermal heat extraction: Decision Analysis, Geochemistry and Hydrochemistry, Well Construction, Risk Assessment, Pulse Testing, Environment, Hydraulic, Chemical and Thermal Stimulation, Induced Seismicity Management, Well Testing and Reservoir Characterization, In-situ Stress Estimation in Geothermal Reservoir, and others in future.



**Figure 9: Relevant stakeholders and professional societies for improved stimulation technologies in geothermal wells, which were included and coordinated as part of a communication strategy.**

## CONCLUSIONS

The aim of achieving enhanced performance of geothermal reservoirs while minimizing environmental impacts requires specific stimulation concepts based on the geological setting and the needs of the plant operation. DESTRESS delivers recommendations on a broad field of aspects concerning soft stimulation. This includes risk management consisting of risk assessment and strategies for risk mitigation, monitoring, governance and public acceptance. Furthermore, DESTRESS presents good practices for applying the treatments and evaluating specific costs, installing good-practice workflows and tools for monitoring and controlling performance and environment with the overall goal of achieving good practices for improving and developing sustainable productivity and injectivity of geothermal reservoirs. The demonstrated practices for stimulation of geothermal reservoirs are applicable for various geological settings achieving an optimized performance with minimized impact on environment.

The DESTRESS project still continues. At this point of the project life cycle, our results confirm the practicability of soft stimulation, which must be designed based on local requirements. Other sites will be further included in the project to demonstrate our approach and to assess both, the environmental and financial downs and upsides of EGS developments.

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