Deliverable 2.3: Practitioner's guidelines concerning synergies and standardization needs

WP 2: Business case - key performance indicators-based analysis

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Practitioner's guidelines concerning synergies and standardization needs

Wellhead with pipeline for stimulation. © EnBW

Authors

Elif Kaymakci (EnBW), Dr. Sören Welter (EnBW), Christian Bos (TNO), Alexandre Richard (ésg), Dr. Thomas Kölbel (EnBW),

Table of Contents

List of Figures

List of Tables

Nomenclature

Abbreviation

Symbol	Explanation	Unit
CHP	Combined heat and power	-
ESP	Electrical submersible pump	-
EUR	Euro	€
E&P	Oil and Gas industry	-
FBHP	Flowing bottom hole pressure	bar
FTHP	Flowing tubing head pressure	bar
IRR	Internal rate of return	-
KPI	Key performance indicator	-
LCOE	Levelized Costs of energy	€/kWh$_{el}$
LCOH	Levelized cost of heat	€/kWh$_{th}$
LSP	Line shaft pump	-
MC	Monte-Carlo	-
MD	Measured depth	m
NPV	Net present value	€
IRR	Internal rate of return	
OH	Overheating	-
ORC	Organic Rankine Cycle	-
PBT	Pay-back time	-
PDF	Probability distribution function	-
PH	Preheating	-
SHE	Shell and tube heat exchangers	-
TDS	Total dissolved solids	g/l
TVD	True vertical depth	m
TW	Thermal water	-
TWC	Thermal water circuit	-

Indices

Abbreviation	Explanation
a	Apparent / outside
WM	Working medium
out	Output value
Bypass	CHP in parallel connection
in	Input value
el	Electrical
geo	Rock, soil, formation
hydro	Hydrostatic

i	Sumindex; inside
I to IV	State points with heat exchanger
is	Isentrop
Cond	Condensator
crit	Critical
PP	Power plant
Pump	Feed-; Production-; Injection-pump
TW	Thermal water
Loss	Energy- / Temperature loss
at-rest	steady state
1 to 10	State points in the working medium cycle
2009	Year 2009
2013	Year 2013
2016	Year 2016

Latin formula symbols

Abbreviation	Explanation	Unit
$\dot{V}$	Volume flow	m^3/s
$\dot{m}$	Mass flow	kg/s
a	Thermal conductivity	m^2/s
C	Costs	EUR
c_p	Specific heat capacity	$J/{kg*K}$
d	Diameter	m
H	Water level	-
I_0	Investment costs	EUR
k	Heat transition coefficient	$W/{m^2*K}$
p	Pressure	Pa
s	Drilling distance (measured depth)	m
S_x	Standard deviation population	EUR; m²
T	Temperature	K; °C
Z	Interest on construction period	EUR
z	Vertical depth (true vertical depth)	m

Abstract

In this report, an attempt is made to translate the DESTRESS project results on soft stimulation techniques (ref. DESTRESS tasks 2.1, 2.2, 2.3) to the business environment (i.e. investment decision support). A standardized business case assessment method is proposed for the geothermal community and other interested parties.

In our report we also describe some observed differences between the geothermal and E&P business models. Whereas, by and large, E&P companies see their business activities as a high risk/high reward venture, geothermal project developers often have to cope with a limited project portfolio, or even a single project approach, i.e. at least for low enthalpy projects. Together with a high risk / low reward business perspective, this may lead to cost minimization and, hence, reduced data acquisition activities. The geothermal industry is generally highly dependent on the success of single wells (high risk). The industry would therefore probably much benefit from pooling their data and knowledge, thereby leveraging the lessons learnt (cost cutting, value of information, well success rate, etc.) for the benefit of all. With a better organization and sharing of data and experience, synergies between different geothermal projects can be achieved to reduce the risk of single experiments. With a standardized business opportunity assessment methodology, the cases studied by different operators would become more comparable, thereby increasing the value of information sharing and reducing the investment risk.

With this in mind, guidelines for technical and economic feasibility studies of geothermal projects, including soft-stimulation techniques, are presented in this report. This report focuses on the topics of uncertainty evaluation to identify the main risk factors, and on the integrated techno-economic evaluation. It uses the principles of Decision Analysis (DA) and the Decision Gate (DG) process, as commonly applied in the E&P industry, as this provides a systematic approach to assess business opportunities.

First, the architecture of the techno-economic model and the equations of the basic modules developed in DESTRESS are presented. The DESTRESS techno-economic model consists of three main parts: the reservoir, the thermal fluid cycle and the heat or power plant, respectively. The power plant is implemented as an Organic Rankine Cycle. The model enables the assessment of power only, heat generation only, as well as combined heat and power (CHP), whether configured as a parallel or serial process.

Apart from this technical/economic focus on geothermal power and heat, lessons learnt from the E&P industry in technical questions are also presented, as they may be of benefit to the geothermal industry. An example is the data acquired in the exploration phase. The E&P business typically uses 3D-seismic surveys, whereas typically in geothermal exploration only 2D-seismic is used. In production operations, the E&P industry may even use 4D-seismic to monitor the flood front, but as far as we know this is not used commercially by the geothermal industry to monitor the cold/hot waterfront. An important opportunity for the geothermal industry is to leverage the E&P lessons learnt on well stimulation results, as geothermal operations are highly dependent on well

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

1   Well Stimulation

1.1   Fields of application and intended effect of stimulation techniques

1.1.1   Introduction

Well stimulation to increase a well's productivity or injectivity is a standard technique that has been applied for many decades, especially in the oil and gas exploration and production (E&P) industry. But not only the E&P industry has benefited from well stimulation techniques, also the geothermal and water industries have applied it for many years.

In general, well stimulation has proven so beneficial that it has developed into a mature technical science, where theory, engineering, predictive modelling, planning and logistics, monitoring of results and side-effects, application domains etc. have colluded to increase the chances of success, and to increase the expected improvement in productivity or injectivity.

The principle of well stimulation is that the formation's rock permeability around the completed well interval is enhanced, relative to the original permeability. Below, we mention three reasons to consider well stimulation. 1) One may imagine that with radial (i.e. cylindrical) flow from the reservoir to the well, the streamlines of the fluids moving through the reservoir converge as they approach the well, and that congestion of the streamlines may occur in the wellbore's vicinity. This congestion may result in increased "friction", which may be substantially reduced by enhancing the permeability around the wellbore.

But 2) also removing "formation damage", i.e. permeability destruction around the wellbore, as a result of drilling the formation with drilling mud, is a major reason to consider well stimulation. Drilling mud invariably contains solids (such as clay minerals) that while drilling invade the pores of the virgin rock and sediment in the pores at some distance away from the wellbore. Although the mud normally is designed in such a way to minimize solids invasion into the rock's wellbore vicinity (due to a "*mudcake*" plastering the wellbore), some damage typically cannot be avoided. Formation damage around the wellbore may also result from production operations, e.g. "fines" migration (solids being dragged by the fluids to the wellbore vicinity) leading to pore blockage, or geochemical deposition due to changing P and T conditions.

A third reason is 3) that the rock's original permeability is so low that commercial production cannot be achieved. In such cases, not only the permeability of the wellbore vicinity is to be enhanced, but also a wider drainage volume around the well.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs
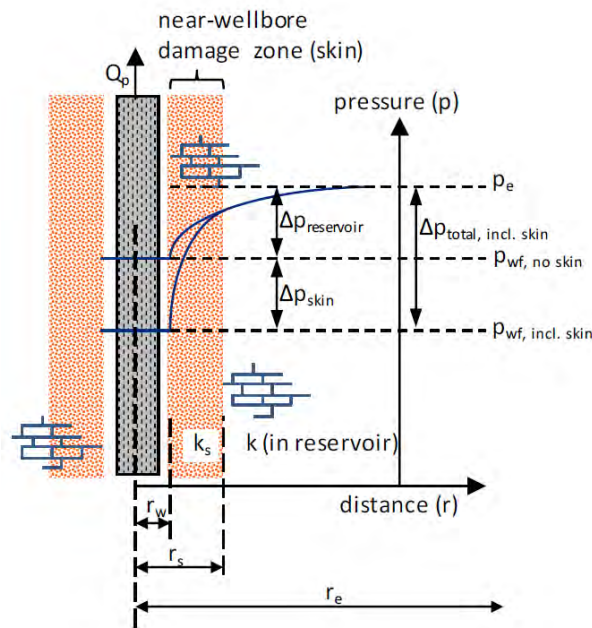
Figure 1: Skin damage around wellbore (IF Technology , 2016)

In the last case, such stimulation techniques involve larger volumes to be injected at higher pressures than stimulation measures that are targeted at the wellbore vicinity only. But even when commercial production can be achieved at some relatively low permeability, stimulation measures may significantly enhance the productivity of the well, and thereby the economics.

1.1.2   Deciding whether or not to simulate a well

Well stimulation measures are typically costly and may even be counterproductive when inappropriately applied. Therefore, proposing a stimulation measure requires careful consideration. The risks are: 1) The stimulation measure does not result in the expected improvement in productivity / injectivity; 2) the stimulation measure fails otherwise, potentially even leading to the loss of the well; 3) the stimulation measure has serious undesired side-effects, such as induced seismicity with possible damage at the surface, or environmental pollution because of the induced fractures or acids not being constrained by the hydrocarbon reservoir / pay zone, but affecting also adjacent (shallower) formations.

Considering these risks before implementing the stimulation measure is crucial to a company's reputation and economic success of stimulation. But first of all, let's investigate what information an operator can acquire to predict whether a well would benefit, and if so, how much, from stimulation?

The classes of information that impact on assessing the possible well stimulation effect are:

- *Pre-stimulation productivity / injectivity index*, as established by a (long-term) production test.
- *Skin factor* of well, as established by Pressure Transient Analysis, i.e. a pressure build-up or fall-off test, where the well is produced (injected) for some time and suddenly shut-in. The skin factor, i.e. a dimensionless number indicating the relative change in permeability in some undefined zone around the wellbore, can be determined by the early-time vs. late-time pressure information.
- *Permeability of the rock*: above some threshold value, it makes no sense to stimulate the well by hydraulic fracturing, as the fracture initiation pressure will never be achieved.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

- *Rock mineralogy (geochemistry) and depth*: these influence the geo-mechanical properties of the rock, and therefore the sensitivity to hydraulic and chemical stimulation.
- *Log information*: well logs give information on porosity (various logs), permeability (various logs), geo-mechanical properties (sonic log). Also, the presence of natural fractures may be detected by the logs. Surrounding rock properties will also be important to assess whether the induced fractures, or injected chemicals, will be contained within the targeted formation (and e.g. not break through the caprock).
- *Reservoir geological interpretation*: the 3D sedimentology / stratigraphy, and the structural geology (notably proximity to faults, existence of natural fracture networks, etc.) around the well may provide crucial information on whether a stimulation measure could be successful.
- *Well completion*: the mechanical status of the well tubulars and installed equipment is important to understand the suitability of certain stimulation techniques. Operating conditions such as the design pressures etc. need to be within the specs of the equipment.
- *Local and regional analogue knowledge / empirical evidence*: knowing how earlier stimulation jobs done in analogue wells is crucial information, as there are no deterministic rules to predict the effect of a stimulation measure: uncertainty on the final result remains typically high. One should allow for learning and experimenting at the local scale.

Finally, the type of stimulation measure considered is important. One may distinguish here:

- Acidizing
- Acid-fracking
- Fracking
- Massive hydraulic fracking

The above stimulation measures can be implemented as single-stage or multiple-stage jobs. The former stimulates only one interval of the borehole, while in the latter case several disjunct intervals are stimulated using intra-well separation packers that hydraulically isolate the various intervals.

1.1.3   Work process for selection & design of well stimulation treatments
The following technical work process needs to be followed for preparing and executing the well stimulation. Part of the text below refers to a 2016 report by IF Technology (IF Technology , 2016).

1. Candidate selection
   - Improving new wells or existing wells
   - Skin analysis – separating skin caused by damage from other sources of skin
2. Treatment selection
   - Defining cause of damage
   - Identifying suitable treatments
3. Preliminary treatment design
   - Fluids and additives recommendation
   - Placement and diversion method
   - Pumping schedule
   - Flow (diversion) simulation modelling
   - Design evaluation
4. Execution of the well stimulation job
   - Final detailed design
   - Work plan

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

- Permits
- HSE
5. Post-job analysis
   - Productivity improvement
   - Re-run flow simulation
   - Long-term, short-term analysis / monitoring

In these technical guidelines, no economic considerations are included. Nevertheless, typical economic go-no go milestones for the process could be chosen after the process steps: candidate selection, treatment selection, and preliminary treatment design.

- After the candidate selection the difference in productivity before and after the treatment can be estimated and therefore the extra benefits after improving the wells can be estimated.
- After the treatment selection the monetary investment of the selected treatment can be roughly estimated.
- After the Preliminary treatment design, the work can be tendered and costs for the well stimulation job can be determined.

Figure 2 below depicts the sequence and details of these elements and their mutual dependence.
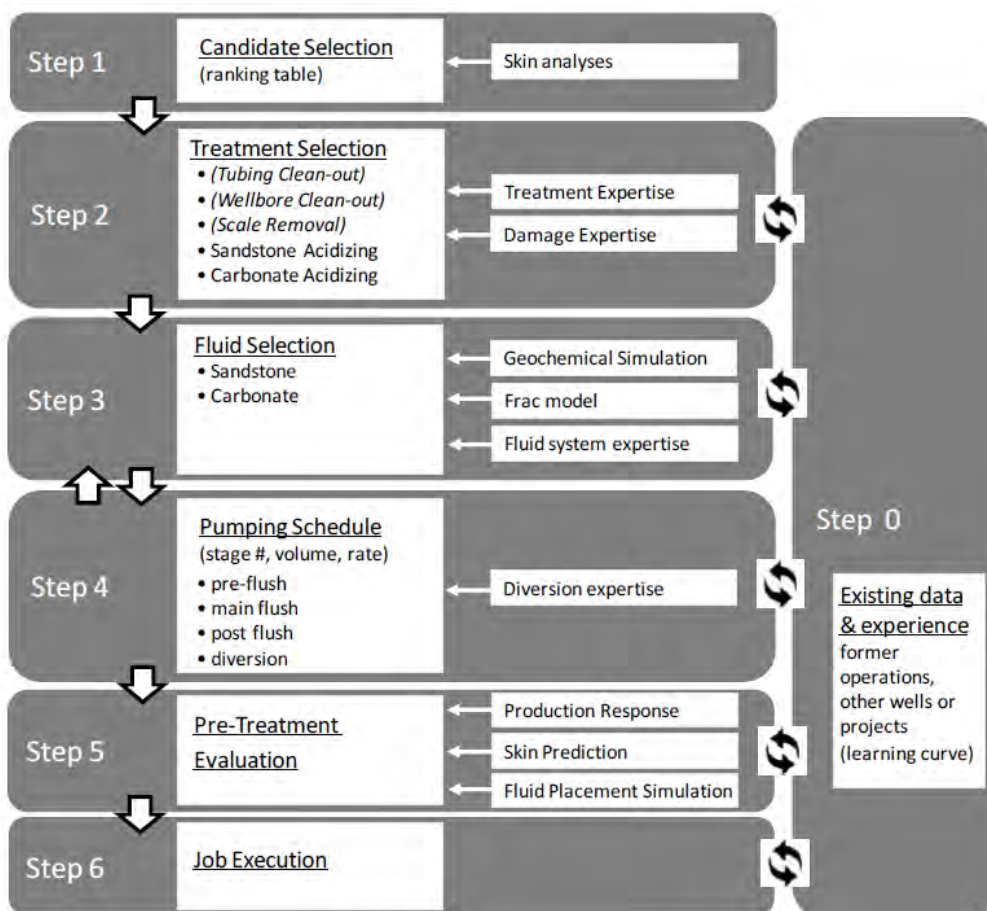
Figure 2: Workflow for selection and design of well stimulation treatments (IF Technology , 2016)

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Demonstration of soft stimulation treatments
of geothermal reservoirs

*Step 1 - Candidate selection (*Figure 2*)*

The candidate selection could account for two situations:

1. improving the productivity of existing wells because of suspected damage;
2. improving the productivity of new or existing wells by effectively improving the "natural" permeability.

1. Improving existing wells because of suspected damage

In time, well productivities could decrease because of clogging mechanisms in the near-wellbore zone (near-wellbore damage). Also, the productivity of newly drilled wells could be less than expected because of near-wellbore damage e.g. by blocking drilling fluids remnants. When considering well stimulation the following damage analysis should be worked out. For candidate selection the existing data should be analyzed, and parameters should be calculated:

- Measure the actual PI/II
- Determine the permeability of the reservoir
- Calculate the ideal PI/II
- Calculate the WIQI (Well Inflow Quality Indicator)
- Calculate S_{dam} (skin due to wellbore damage)
- Whether the wells are a candidate for well stimulation depends on the expected improvement which is reflected by the WIQI (Well Inflow Quality Indicator). If WIQI < 0.9, the treatment could affect the well productivity significantly.
- The expected damage which is reflected by the S_{dam}. If S_{dam} >5, the treatment could improve the well productivity significantly.

2. Improving existing or new wells focusing on improving the "natural" permeability

Operators will also consider improving the well performance by creating artificial, additional permeability (effectively improving the "natural" permeability). In that case the "natural" PI or II should be calculated, followed by the expected improvement in PI or II. The expected PI after well stimulation should be significantly higher than the "natural" PI. It is mainly an economic consideration whether the well is a candidate for well stimulation: does the extra production/injection after the well stimulation justify the extra investment.

Sand control: If sand production is expected in new wells or if sand control is a problem in existing wells, the well could also be considered to be a well stimulation candidate, as a Frac and Pack treatment (also known as skinfrac treatment) could solve this problem.

Skin or damage analysis

The analysis of the skin damage focuses on:

- quantifying the skinfactor (S);
- defining which part of the skin is related to near-wellbore damage (S_{damage}).

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

Using the terms and definitions as described in chapter 4 the skinfactor (S) can be calculated after performing specific well tests. It should be considered by reservoir specialists if (simplified) analytic models can be used or if more difficult 3D or 4D modelling is required in this stage. This depends on the complexity of the reservoir e.g. variation of specific the reservoir parameters (temperature, depth of top/bottom reservoir, thickness of reservoir and/or permeability and well trajectory) as also the existence of sealing or non-sealing faults but also on the availability of data e.g. production data and well test data.

After determining the total skin, it should be analyzed which part is related to the near-wellbore damage. Skin is in fact the sum of a series of components that together make up the skin factor determined in a pressure build-up test. This is often overlooked and S_{total} is used for the decision to stimulate a well. This may lead to unsuccessful treatments. For instance, treating a well with an insufficient number of perforations or a limited completion interval, will not have the desired result.

Figure 3 below shows the most common skin components:

$S_{total} =$

S_{dam} skin caused by damage

$+ S_{perf}$ skin caused by perforation

$+ S_{turb}$ skin caused by turbulation

$+ S_{dev}$ skin caused by deviation

skin caused by gravelpacks $+ S_{gravel}$

skin caused by stimulation $+ S_{stim}$

skin caused by natural fracs $+ S_{fiss}$
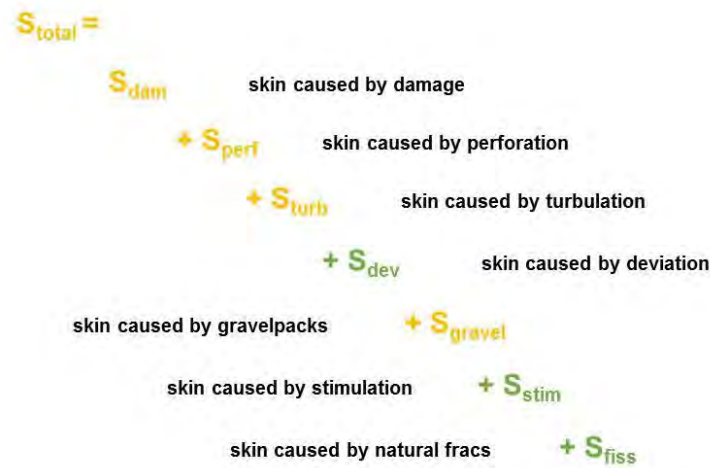
Figure 3: Origin of skin (yellow = add'l inflow resistance; green = reduced inflow resistance)

Again, it is important to realize that only the damage skin (i.e. the zone around the wellbore where the original formation permeability is impaired due to drilling fluids and rock flour invading the wellbore vicinity) can be removed or bypassed by stimulation. All other components are not affected by stimulation. In geothermal wells the turbulence skin is insignificant.

Step 2 - Treatment selection (Figure 2)

The first choice that has to be made is whether to treat the well with acid or carry out a fracture treatment as the main and most common treatment techniques used in the conventional well stimulation market. The procedure is shown in Figure 4 and Figure 5 for existing and for new wells, respectively.

The basic principle is that low permeability reservoirs need a fracture treatment, not an acidizing treatment. There are a few exceptions:

- If the reservoir height is limited, say, less than 10 m a fracture may be a waste of materials because a fracture is likely to grow out of the zone. The only option then becomes an acidizing treatment.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

- If the damage is insoluble or the formation is incompatible with acid a (small) fracture may be more effective.

Acidizing is a good stimulation method in moderate to high permeability reservoirs, which show substantial damage (skin) in the near-wellbore region. The damage is removed by injecting acid below fracturing pressure. The impairment may originate from drilling or completion operations, for example due to the invasion of drilling or completion fluids, or it may be caused by the production process (or in case of injection wells, by the continuously injected fluids), for example by oil residues or moving fines. Hydraulic fracturing is successfully applied in low to moderate permeability reservoirs, whereby the productivity is improved from effectively increasing the wellbore radius. It can be applied in almost any formation, although commonly in carbonate reservoirs acid fracturing is applied.
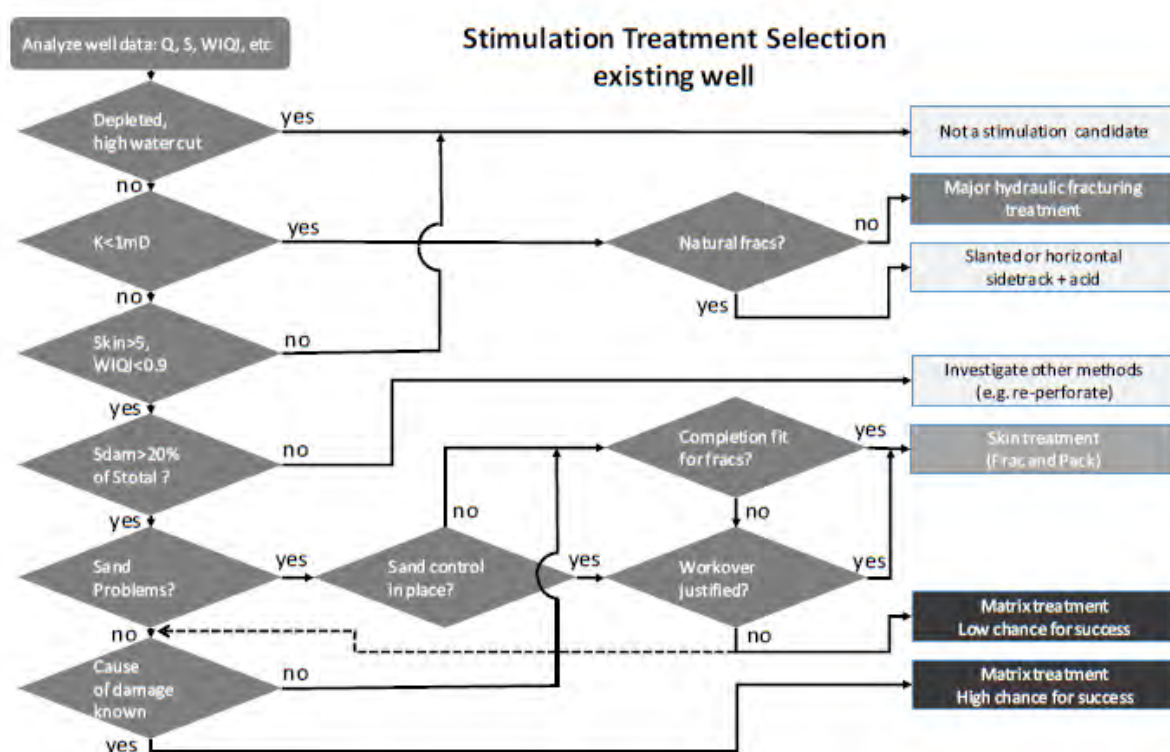
Figure 4: Candidate selection chart for existing wells (IF Technology , 2016)

New wells

To improve the capacity of new wells that will be developed, it can be decided to use stimulation treatments on beforehand. In Figure 5 a typical stimulation treatment selection chart for new wells is given. It is assumed that drilling and completion methods that will be used for new wells are optimal, so no skin/wellbore damage is foreseen (different from existing wells, Figure 5). For the new wells the stimulation is only used to improve the "natural" permeability and therefore the capacity of the well. Which stimulation technique to be used depends mainly on the permeability of the reservoir and is then decided on beforehand.

Two different scenarios for new wells:

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

- After drilling and testing the capacity of a new well could be worse than expected. In this case the selection chart for an existing well (Figure 4) should be used, because the skin/wellbore damage could be the reason of the capacity reduction.
- If a specific drilling mud is used, it could be concluded on beforehand to remove it using a acid treatment. This treatment is actually focused on an optimal drilling & completion method instead improving the "natural" permeability (first decision step in Figure 5 is "no").
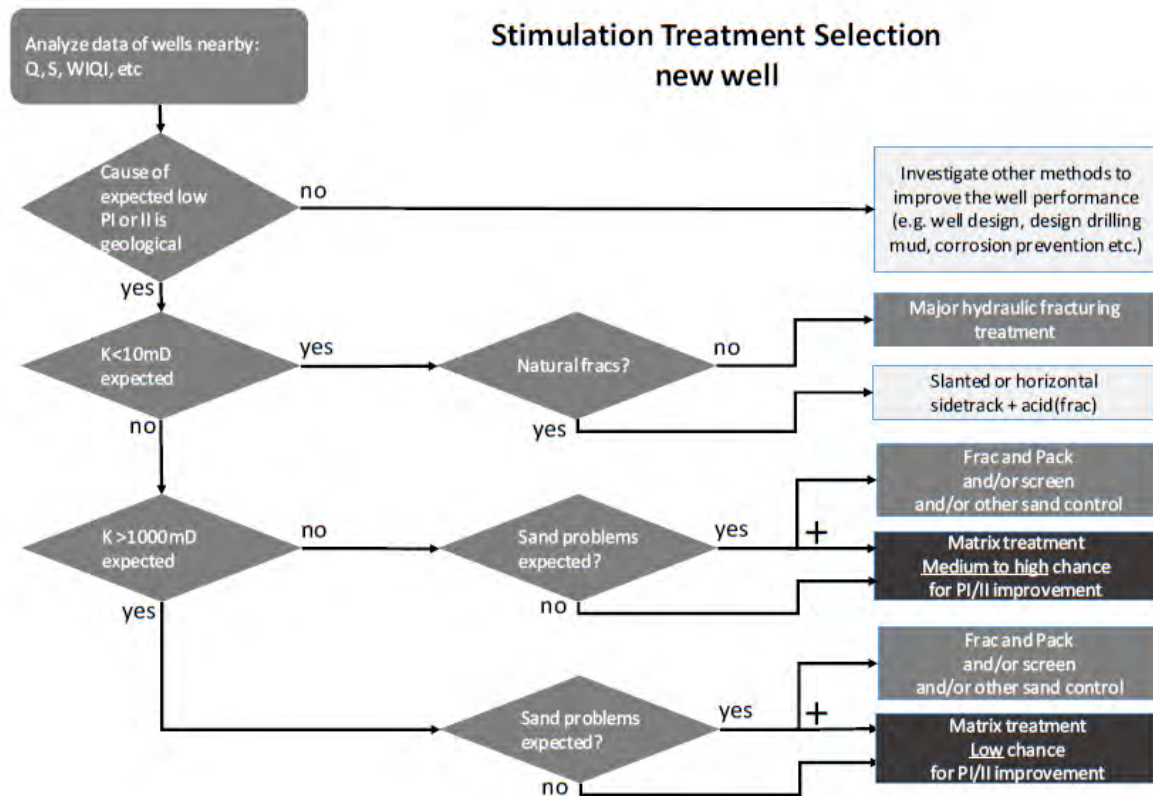
Figure 5: Candidate selection chart for new wells (IF Technology , 2016)

Step 3&4 – Preliminary treatment design (Figure 2)

This topic involves:

- fluids and additives recommendation
- pumping schedule
- (diversion) simulation modelling

In fact, this is an iterative process. If after the modelling step the results are not satisfactory, the process goes back to re-formulate a pumping schedule, followed by a next round of modelling.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

Step 5 – Treatment design evaluation (Figure 2)

Before executing the treatment and finalizing on the design it is useful to evaluate the potential benefits of the treatment. For matrix acidizing this can be done by assuming that the damage skin becomes zero or slightly negative.

Step 6 – Execution of the well stimulation job + documentation (Figure 2)

The operational aspects will not be further discussed in this report. Formalizing past experience in order to enable learning is extremely important, as well stimulation is by and large a highly empirical science. Predictive physics-based models are of limited value due to the many unknowns, both in the reservoir properties, and in the cause-effect relationships. At most steps it is important to include experience and information from projects and well treatments in the area, perhaps from other operators. When executing a treatment, it is crucial that the results and experience – both positive and negative – are properly documented for future treatments.

1.1.4 Soft stimulation

The normal operating window (P, T, chemistry) of a standard well stimulation technique may coincide with a relatively high probability that adverse side-effects will be observed. Some examples are:

- Massive hydraulic fracturing (MHF) or regular hydraulic fracturing in consolidated, low-permeability reservoirs may result in direct seismicity that is felt at surface and that causes damage to buildings and infrastructure.
- Induced fractures may result in hydraulic communication to nearby fault planes, thereby changing the stress regime and/or natural friction within these fault planes. This may suddenly unleash the potential energy of the rock, resulting in seismicity that is felt at surface.
- Induced fractures may propagate and break through the caprock, thereby providing a conduit for injected and reservoir fluids to the overburden, potentially even leading to shallow aquifer contamination.
- Well stimulation may result in hydraulic conduits directly around the wellbore, resulting in the loss of zonal isolation.

The intended effects of soft stimulation are to reduce such undesired side-effects. Soft-stimulation techniques being investigated are, for example:

- When starting the hydraulic stimulation job and putting hydraulic pressure on the formation, rather than exposing the rock quickly to the Fracture Initiation Pressure (FIP), which will create a shock wave through the formation, the formation may be gradually "fatigued" by exposing it slowly and gradually to increasing pressures below the FIP. When the fracture is initiated, the shock wave will then be much reduced, resulting in a lower seismicity.
- An acid-wash or acid-frac, instead of a regular hydraulic stimulation job, may also much reduce the FIP and, hence, the seismicity resulting from the shock wave.

1.2 HSSE&SR

Safety, environment, health, security, and social responsibility are all interlinked. It becomes particularly visible that these are linked when there is a major accident. For example, an accident in the system occurred after wrong decisions made by unskilled people may lead to a polluted area with consequences on the local population. In order to avoid these incidents, secured design of installations,

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

creation of skilled and healthy teams, good planning of necessary measures and so forth have to be ensured. Avoiding such incidents is definitely not only the responsibility of health, safety, and environment (HSE) or health, safety, security, environment, and social responsibility (HSSE & SR) teams, but of all employees.

1.2.1 Health, safety, security

The safety aspects of an operation should never be endangered. Safety instructions have been enhanced from experiences originated from past incidents. The potential of many of these incidents to seriously injure personnel and damage expensive equipment were immense. Hydraulic fracturing treatments or whatsoever type of soft stimulation techniques can never be acknowledged as a success if there is an incident during these stimulation practices resulting in personnel's injury, loss of equipment or harm the nature. The inherent risk of coping with high pressures within hydraulic fracturing treatments can be enormously diminished if simple safety procedures pursued (Economides & Nolte , 2000).

First of all, each personnel who works on site must wear proper safety equipment in order to diminish the risk of any injury or lost-time incident. The minimum level of safety equipment to be worn on site should consist of hard hats (helmets), hard-toed shoes and safety glasses. Depending on the situation, other equipment may also have to be worn. This other equipment may consist of hearing protection (ear plugs), googles, fire-retardant fabrics and filter masks. Using safety equipment is the easiest step that generates safe and secure environment on site.

Next, safety meetings are important. To ensure that all personnel on site are aware of possible dangers and necessary procedures relevant to the treatment, safety meetings have to be conducted. It has to be assured that all personnel working on site understands her or his role in the treatment, as well as the individual responsibilities in case of an emergency. A head count should be done for the personnel on site. In case of an emergency, an escape route and meeting point should be agreed upon where everyone will gather. Personnel who are not having a direct role in the treatment should not be allowed to access dangerous areas on site during the actual operations.

Everyone should be informed about the unique dangers of each treatment. The fluids being pumped can be highly flammable. Therefore, all possible safety problems and concerns should be brought to the attention of all employees.

Maximum pressure limits should be set, and the high-pressure pump operators must know these limits. A test should be performed in the pressure treating line up to the wellhead valve under a pressure that is slightly above the foreseen fracturing pressure. It should be ascertained whether the pressure rating of the wellhead exceeds the treating pressure. This is important because a wellhead isolation tool will be needed to isolate the wellhead in case the wellhead pressure rating is lower than the foreseen treating pressure.

It is crucial to have a pretreatment safety meeting to give final instructions to all personnel. A well-organized safety meeting is necessary to make the treatment an operational success without a risk to human safety.

There should be at least two valves at the wellhead in order to ensure that well control is constantly maintained. Above the main wellhead valve there should be a frac or master valve. In case of a failure of one of the valves for holding the pressure, the other one can immediately be closed to control the

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

well. For safety purposes, the main wellhead valve should preferably be flanged to the casing head, instead of using a threaded connection. If a threaded connection is required, the threads conditions need to be thoroughly controlled for thread wear and appropriate taper.

A barrier tape should be used around the storage tanks of flammable fluids and they should be located at least 150 ft. from the wellhead. Locating the flammable fluids in this way helps minimizing the fire exposure of the wellhead in case problems occur during pumping.

Smoking on site is absolutely forbidden. All personnel should check matches and lighters after they have arrived on site to avoid lighting up unintentionally. Fire-fighting equipment should be on site and ready to be operated. Small fires can be avoided in this way before they spread and become a major disaster.

The most commonly used gases in foamed and energized fluids are N_2 and CO_2. They provide a good source of concentrated energy to help quick and complete post-treatment cleanup during flowback after a treatment. However, there are potential hazards related to the use of N_2 and CO_2. When the fluid leaves the flowline during flowback, the gas phase expands quickly. To prevent a loss of flowback efficiency and ensure personnel safety, this quick energy release must be checked. Another possible danger caused by these gases that is sometimes overlooked is asphyxiation. N_2 and CO_2 may accumulate in low areas and replace breathable air. Personnel should know and avoid these areas and always stay windward. One person should only be allowed to stay in the well area during flowback operations (Economides & Nolte , 2000).

1.2.2   Environmental concerns on soft stimulation

This chapter addresses environmental hazards that are attributable to well stimulation. Hazards that are attributable to well stimulation are mainly consisting of human exposures to well stimulation chemicals through unintentional or intentional release to water, air or soil by transport or treatment processes. Environmental hazards directly attributable to well stimulation is due to the use of large types and quantities of stimulation chemicals. Stimulation chemicals comprise both hydraulic fracturing and acidization chemicals that are intentionally injected to improve reservoir productivity. Due to the large number of chemicals that are used in well stimulation fluids, it may be difficult to quantify their risk to the environment and to human health.

Environmental concerns that are particularly related to soft stimulation include:

- Spills of chemicals at the surface
- Surface water quality degeneration from wastewater disposal
- Ground water quality degradation
- Induced seismicity

In the following some of these potential environmental hazards of soft stimulation techniques shall be given in detail.

1.2.2.1   Potential impacts of soft stimulation techniques on drinking water resources

Stimulation fluids and additives (chemicals)

In hydraulic fracturing, fluids (chemicals) are used to initiate and extend fractures, carry proppant and place proppant in the fractures. Fluids usually consist of three parts: the base fluid – typically water, the additives – a single chemical or a mixture of chemicals and the proppant. Chemicals are used for

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

the purpose of adjusting the pH, increasing viscosity and limiting bacterial growth. Chemicals usually amount to a small percentage (2% or less) of the total volume of the injected fluid (EPA, 2015).

Hydraulic fracturing fluids have the potential of resulting in incidental discharges, such as spills or leaks while mixing and pumping of chemicals or on-site storage. A spill may contaminate drinking water resources through several mechanisms. These mechanisms are over-land flow to nearby surface water, soil contamination and possible transport to surface water, penetration and contamination of subjacent ground water. There are 151 cases of spills characterized by the EPA (the US Environmental Protection Agency). It is reported by the EPA that fluids (chemicals) may reach surface water in 13 scenarios, whereas they can contaminate the soil in 97 scenarios. The EPA also reported that none of the spills of hydraulic fracturing fluids have reached ground water. According to the experts, the infiltration of spilled fluids into the soil and then leaching into ground water might take some years. Therefore, it may not be yet possible as yet to conclude whether a spill has reached any ground water level or not (EPA, 2015).

Depending on the relative importance of each of these contamination mechanisms, the potential impacts of hydraulic fracturing chemical additives may occur quickly, be delayed for a short or longer time, or have continuous effect in the long run. To quote a rare example, in Kentucky, surface water was affected by a spill soon after hydraulic fracturing fluid penetrated into a creek. It reduced the water's pH and increased its electrical conductivity (Papoulias & Velasco , 2013)

Waste Disposal and Wastewater Management

Hydraulic fracturing generates extensive volumes of produced water that need management. This produced water and any other water generated during hydraulic fracturing is called with a single term "wastewater". The more hydraulic fracturing activity increases, the more wastewater volumes can sharply increase. Potential impacts of these fluids and chemicals from spills are highly depending on the characteristics of the spills as well as the transport and toxicity of chemicals that are spilled.

Potential effects of hydraulic fracturing wastewater on water resources are recognized in several articles ((Vengosh et al. , 2014) (Olmstead et al. , 2013) (States et al. , 2013) (Vidic et al. , 2013) (Rozell & Reaven , 2012) (Entrekin et al. , 2011)). The exposure of drinking water resources to the effects of hydraulic fracturing wastewater depends definitely upon the characteristics of the wastewater, the method of discharge and the processes applied if the wastewater is treated. The hydraulic fracturing wastewater is mostly either injected into a disposal well or reused for other hydraulic fracturing jobs. There are several mechanisms through which potential impacts of hydraulic fracturing wastewater on drinking water resources may occur, including (EPA, 2015):

- Insufficient treatment of hydraulic fracturing wastewater before discharging into a receiving water
- Incidental discharge while transport
- Leakage from wastewater storage pits
- Illegal discharges of wastewaters
- Improper management of residual elements arise from treatment
- Discharge of treated hydraulic fracturing wastewater directly from centralized wastewater treatment or indirectly from public treatment facilities

When investigating the potential impact of hydraulic fracturing wastewater on drinking water resources, it is important to know whether wastewater constituents have health effects, whether they

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

are regulated drinking water contaminants, or whether they may increase regulated contaminants. Some constituents that are known to arise in hydraulic fracturing wastewater are given in the following.

Potential impacts of treated hydraulic fracturing wastewater to drinking water resources may occur when hydraulic fracturing wastewater is incompletely treated and discharged into surface water. Concentrations of total dissolved solids (TDS), bromide, chloride, and iodide in receiving bodies might increase due to incompletely treated hydraulic fracturing wastewater. Most particularly, bromide and iodide are precursors of disinfection byproducts (DBPs) that may originate if organic carbon exists in drinking water or wastewater treatment plants. In drinking water treatment plants, certain types of DBPs need to be monitored, because some are very toxic and may cause cancer (EPA, 2015).

Also, radionuclides can be found in improperly treated hydraulic fracturing wastewater from certain shales. A recent study performed by the (PA DEP, 2015b) found high radium concentrations and gross alpha and gross beta in effluent samples from several centralized wastewater treatment facilities that receive oil and gas wastewater. They were also encountered at lower concentrations in effluents from public treatment facilities that receive oil and gas wastewater. These are the examples of radionuclides contamination from oil and gas well stimulation wastewater, however, the same contamination may occur from geothermal well stimulation wastewater, because techniques of well stimulation on oil and gas and geothermal industry are similar. In other words, hydraulic fracturing wastewater from certain shales may also occur in geothermal well stimulation (EPA, 2015).

1.2.2.2 Induced Seismicity within Enhanced Geothermal Systems (EGS) applications

Enhanced Geothermal Systems (EGS) have a significant potential in contributing to the world energy inventory. However, the impact of induced seismicity or microseismicity caused by EGS operations is a controversial issue being an obstacle in the development of EGS operations. At least two EGS projects worldwide have been delayed or cancelled because of the impact of induced seismicity. Even though microseismicity has had a few or zero negative effects on operations or neighboring communities, public concern about the amount and magnitude of the seismicity related to current and future EGS operations still remains (Ernest et al., 2007).

There are two reasons why EGS technology is being developed. One is to make the uneconomic hydrothermal systems productive by improving their underground conditions via stimulation, and the second one is to create underground hydraulic continuity resulting in a hydrothermal system.

Seismicity has been so far linked together with several human activities, i.e., mining/rock removal ((McGarr, 1976) (Richardson & Jordan, 2002)), fluid extraction in the oil and gas industry ((Segall, 1989) (Grasso, 1992)) and fluid injection ((Raleigh et al., 2002) (Seeber et al. , 2004)). Fluid injection seems to be one of the most common reasons that make way for induced seismicity. It was nearly a century ago suggested by (Hubbert & Rubey, 1959) that an increase in pore pressure would decrease the effective strength of rocks and weaken a fault by this means.

In most cases of main EGS stimulation techniques including hydraulic fracturing, fluid injection or acidization, there is information that these operations induced seismicity. Hydrofracturing is by definition a form of induced seismicity and has been extensively used in the oil and gas and geothermal industry to create permeability in compact rock formations. Fluid injection with sub-hydraulic fracture pressures can induce seismicity, as reported in a few numbers of EGS projects ((Mauk et al., 1981) (Ludwin et al., 1982) (Sherburn et al., 1990)). In these geothermal fields low-pressure injection was implemented, and the induced seismicity events were mostly of low magnitude. The largest recorded

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

earthquake happened at The Geysers field in Northern California in the 1980s with a magnitude of 4.6 (Ernest et al., 2007).

There are a number of different mechanisms that have been counted as cause in the occurrence of induced seismicity in geothermal operations. These causes are given below.

Increase in pore-pressure

Increased fluid pressure can decrease static friction which then may ease seismic slip if a deviatoric stress field exists. The local stress field drives the seismicity in those cases, but an increase of the pore-pressure may trigger an existing fracture. The pore pressure increase needed to shear properly aligned joints might be very low and therefore many seismic events occur as the pressure moves away from the wellbore in a direction of maximum main stress. One obvious mechanism that can increase pore pressure locally, thereby causing high seismicity around injection wells in a geothermal field, is fluid injection. Fluid injection can go beyond the rock strength at higher pressures and thereby can create new fractures in the rock that may cause seismic events (Ernest et al., 2007).

Decrease in temperature

Contraction of fracture surfaces in a process named thermoelastic strain may occur by means of interaction of cold fluids with hot rocks. Cold fluid – hot rock interactions may cause fracture creations and seismicity directly associated with thermal contraction. Researchers found out non-shear components indicative of contraction, tensile failure or spalling mechanisms in some instances (Ernest et al., 2007).

Change in volume due to fluid production and injection

The reservoir rock may compact or be stressed, since fluid is produced from or injected into an underground resource. These volume changes may shock the conditions of the local stress. As geothermal systems are commonly located in the faulted regions under high stress, this shock may lead to a seismic slip in or around the geothermal reservoir. A similar anomaly happens in mines when solid material is removed underground (Ernest et al., 2007).

Change in chemistry of fracture surfaces

Geochemical changes may occur in fracture surfaces when external fluids are injected into the formation and thereby the friction coefficient of those surfaces change. Small seismic events would happen more likely if the friction reduces. It is hypothesized by (Pennington et al. , 1986) that even large seismic events may occur more often if seismic barriers grow.

1.2.2.3   Summary of Environmental Public Health Hazards and Risk Factors

Current practices and regulatory schemes for well stimulation enabling geothermal energy development to bring about potential environmental public health risks associated with well stimulation activities. Table 1 summarizes all environment and human health relevant hazards identified within the DESTRESS project.

Table 1: Summary of hazards identified within DESTRESS Project.

Phase	Risk factor	Description of cause	Description of effect
Transport and Storage	Leakage in flowback reservoir	Leakage through corrosion or mechanical damage	Environmental contamination

Transport and Storage	Accidental disperse of hazardous materials (acids, fuel, flowback) on public ground	Traffic accident	Environmental contamination, delay
Transport and Storage	Casualties through traffic	Traffic accident on public streets or on site	Dead or injured people through an accident
Transport and Storage	Loosing hazardous material during unloading	Accidents or untrained staff	Environmental contamination and injured staff
Transport and Storage	Delay in delivery of equipment for waste management	Traffic jam and not enough storage space	Waste management doesn't work --> environmental contamination
Transport and Storage	Leakage in storage tank (all liquids)	Leakage through damaged container	Environmental contamination
Injection	Induced seismicity exceeding threshold	High pressure within formation triggers seismicity	Losing public acceptance, surface damage, losing permission depending on the regulations, Project shut down
Injection	Ground water contamination	Injection water migrates towards higher formation	Loss of Project or extra costs for cleaning and closing
Injection	Interruption while proppant frac	Operational disruptions, pump failure	Proppants block the well, workover is needed
Injection	Well damage	Injection pressure damages casing cement, poor cement job, through shearing process	Workover (squeeze job) is needed, delay (1 month), groundwater contamination if damage close to surface, loss of hole
Injection	Accident with the pumps on the surface	Mechanical failure (pressure issues)	Injured people, delay, replacement of pump
Injection	Lost in hole (packer or other equipment)	Tubing string breaks, instability of the well	Packer gets stuck, fishing or workover is necessary, delay
Injection	Casualties through pipe failure	High pressure pipe failure	Through high pressure coupling breaks --> staff gets injured
Reaction	Fluid-rock interactions	Interactions including reactions with proppants, wrong selection of acids (concentrations of acids), inhibitors, proppants	Clogging of well, reduction of permeability, loss of project
Reaction	Fluid-fluid interactions (thermal brine and chemicals)	Interactions including reactions with proppants, wrong selection of acids (concentrations of acids), inhibitors, proppants, microbiological processes, oxygen entrance	Clogging of well, reduction of permeability, corrosion, H_2S and other gasses production
Reaction	Induced seismicity (with time delay after injection)	High pressure within formation triggers seismicity	Losing public acceptance, surface damage, losing permission depending on the regulations, Project shut down
Reaction	Unwanted subsurface hydraulic connections	Too effective stimulation, wrong doublet design (wrong orientation), highly conductive fault planes	Connectivity between geothermal reservoir and unwanted layers, contamination

			of/through geothermal brine, loss of project
Reaction	Increase in gas content	Connection to gas reservoir	Reduction of effective permeability due to free gas in the reservoir, deepening the well, side-track
Production	Blow out	Due to gas migration	Closing the well, loss of Project, injuries/fatalities
Production	Gas kick	Due to gas migration	Producing methane instead of geothermal brine, closing the well, loss of Project, injured people
Production	Producing corrosion products	Reaction between casing, acids, thermal brine	Toxic gases, casing failure (lifespan)
Production	Producing acids before reaction	Ineffective use of acids	Getting acids on surface, ineffective stimulation, redoing stimulation
Production	Acids not reaching near wellbore area	Too high-pressure result in acids going into new fractures instead of stimulating near well area	Ineffective stimulation, not reducing skin factor, environmental contamination
Waste Mtg. and Decommissioning	Not getting license for brine disposal into surface water bodies	Not fulfilling the governmental obligation	Extra cost for storing and treating flowback, environmental contamination
Waste Mtg. and Decommissioning	Violation of regulations	Regulatory violations through incorrect treatment of flowback and incorrect reporting	Stop of operations, delay, environmental contamination
Waste Mtg. and Decommissioning	Casualties (acids treatment)	Pipe or device failure	Injuries through contact with acids, contamination of soil
Waste Mtg. and Decommissioning	Inappropriate basin volume	Volume of wastewater / flowback is higher than expected, basin is too small	Delay, stop in production, additional treatment, environmental contamination

1.2.3   Effect of stimulation measures on public acceptance

The perception of geothermal energy is either quite positive or comparatively uncertain by the society and awareness is less than the other renewable energy resources ((Moser & Stauffacher, 2015) (Stadelmann-Steffen & Dermont, 2016)). In democratic systems, public acceptance is very important because citizens may have a direct influence on policies that support geothermal energy development via legal schemes or referenda. Especially residents who live in close vicinity of potential geothermal power plant sites might protest these projects. The acceptance of the geothermal energy technologies can be highly impacted as these projects typically carry a low-probability high-consequence risk (Knoblauch et al., 2018).

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

A survey was conducted within the DESTRESS Project to investigate the opinions and perception of the public on deep geothermal energy in urban and rural areas. The results of this survey are published in Deliverable D3.3: Risk governance strategy report. For further information reference is made to this report.

Four regions in total are examined in the survey, three near Eurometropolis of Strasbourg (EMS) and one in northern Alsace, France. The survey has been divided into six different parts and one of them is about the perception of risks occurring in deep geothermal energy developments. In this part of the survey, it is intended to analyze the impacts of drilling and exploitation of deep geothermal energy including stimulation techniques on public acceptance (Chavot et al., 2019).

There were several questions in the survey related to risks and the first question was an open-ended one: "What are the risks of the exploitation of deep geothermal energy?" Quite spontaneous comments were received from the respondents about risks. The number of people interviewed was 268. The risks mentioned by the respondents were (Chavot et al., 2019):

- Cracks in homes - by 14.5% of the respondents
- Seismic activity or earthquakes - by 11.1% of the respondents
- Slow ground deformation - by 10.5 % of the respondents
- Incidents occur during drilling - by 8.7% of the respondents
- Potential groundwater pollution - by 7.5% of the respondents
- Other types of pollution - by 4% of the respondents

These risks were often mentioned by the residents in Wissembourg and Vendenheim. While the projects are quite well accepted in Wissembourg, the local project in Vendenheim is much debated. Therefore, it can be concluded that the opposition to geothermal energy is not always linked to the knowledge of the public on risks of deep geothermal energy development (Chavot et al., 2019).

In order to gain insight into whether respondents believe that deep geothermal energy development may cause risks, they were asked several close-ended questions. These close-ended questions were related to seismic activities, ground deformation, noise, groundwater pollution, soil pollution and radioactive pollution. The positive replies of the local residents to the question "Whether deep geothermal exploration may cause different types of risks or not?" are given below as percentages (Chavot et al., 2019):

- Surface deformation? "Yes" by 65% - 85% of the respondents depending on the region
- Seismic activities? 51% - 75%
- Groundwater pollution? 41% - 66%
- Soil pollution? 36% - 57%
- Noise? 24% - 47%
- Radioactivity? 4% - 14%

Surface deformation was mentioned more than the other risks by the people who were aware of the local projects. Other sources of risk, i.e., awaking natural Alsatian seismicity while drilling, a return of a deep bacterial life, rising oil, a local volcanic phenomenon was seldom mentioned (Chavot et al., 2019).

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

Besides, the benefits of geothermal energy development that were mentioned during the interviews were plentiful. However, the participants discussed frequently that geothermal production plants should be built at a certain distance from populated areas. This shows that there is a high level of awareness on the induced risks (Chavot et al., 2019).

2 Lessons learnt from the Oil&Gas industry that can be extrapolated to the geothermal industry

2.1 Exploration

It is common to see exploratory programs dedicated to deep geothermal energy only dealing with 2D reflection seismic technology ((Richard et al., 2016) and Figure 6). However, in the oil industry and for several decades, the relevance of 3D seismic acquisitions has been shown because it has led to a significant drop in dry wells.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs
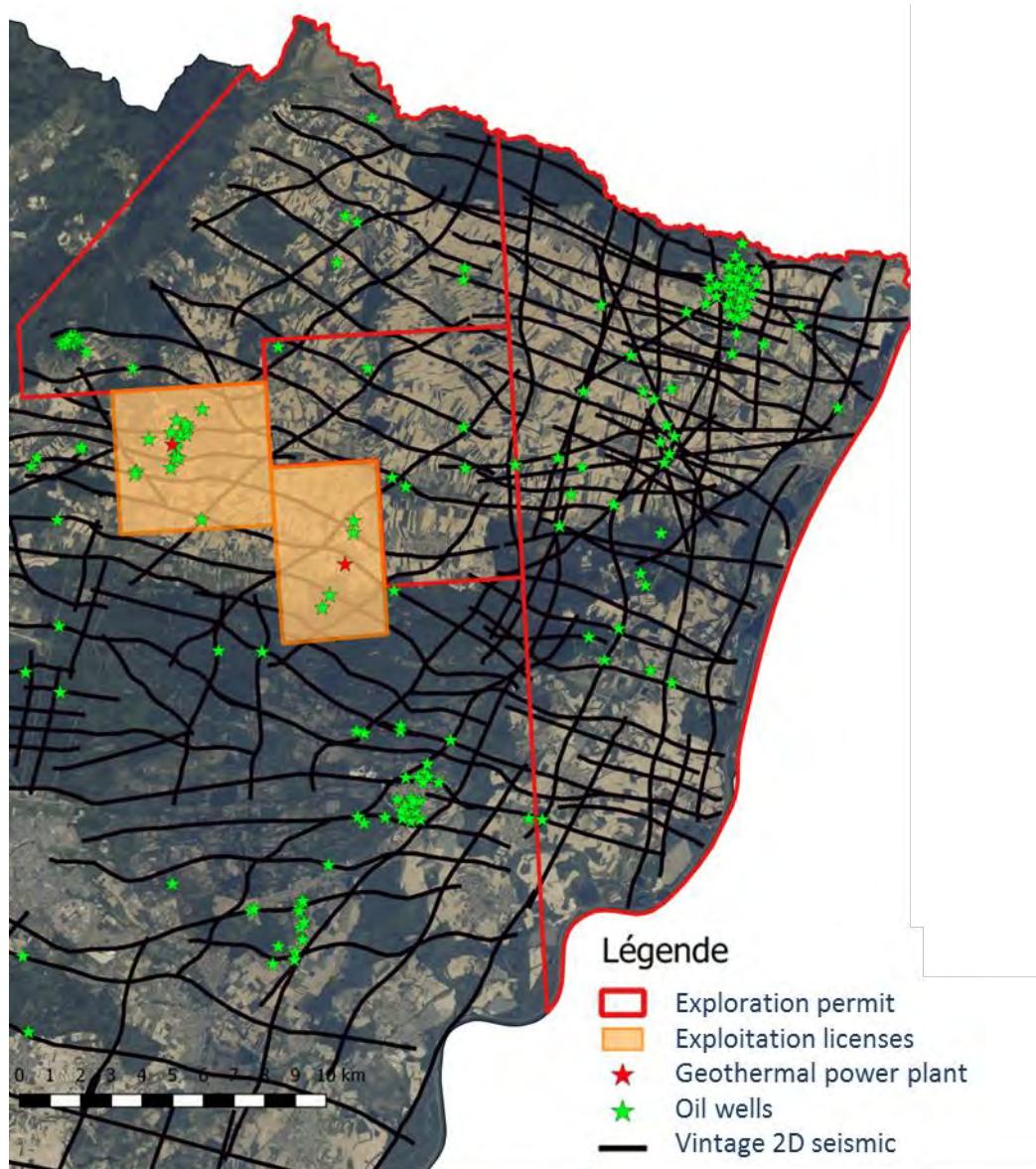
Figure 6: Context of the exploration in the Northern part of Alsace (France).

If certain European countries have carried out 3D seismic campaigns for the exploration of geothermal deposits, no acquisition of this type had been made in mainland France.

As part of the development of these exclusive research permits, Strasbourg Electricity has undertaken to carry out a large-scale 3D seismic study, 180 km², in order to obtain detailed imagery of the entire geological structure of the subsoil. Having contiguous exclusive research licenses, a significant economy of scale could be obtained by pooling the share of exploration on each license (Richard et al., 2019).

Before really being able to benefit from this upscale, several months of work were necessary in order to mitigate the strong noise level acquired on such noisy onshore acquisition. We benefited from the state-of-the art processing workflow from CGG Massy to tackle all the challenges we faced (Toubiana et al., 2020) (Richard et al., 2020)

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

2.1.1   Technical description of the lesson learnt

The first result for the geothermal industry is that this exploration by 3D seismic proved to be a success with the imagery of the last known reflector (the top of the granite) as well as the imagery of faults within the crystal structure of the basement. These structures are the targets in the upper Rhine graben.
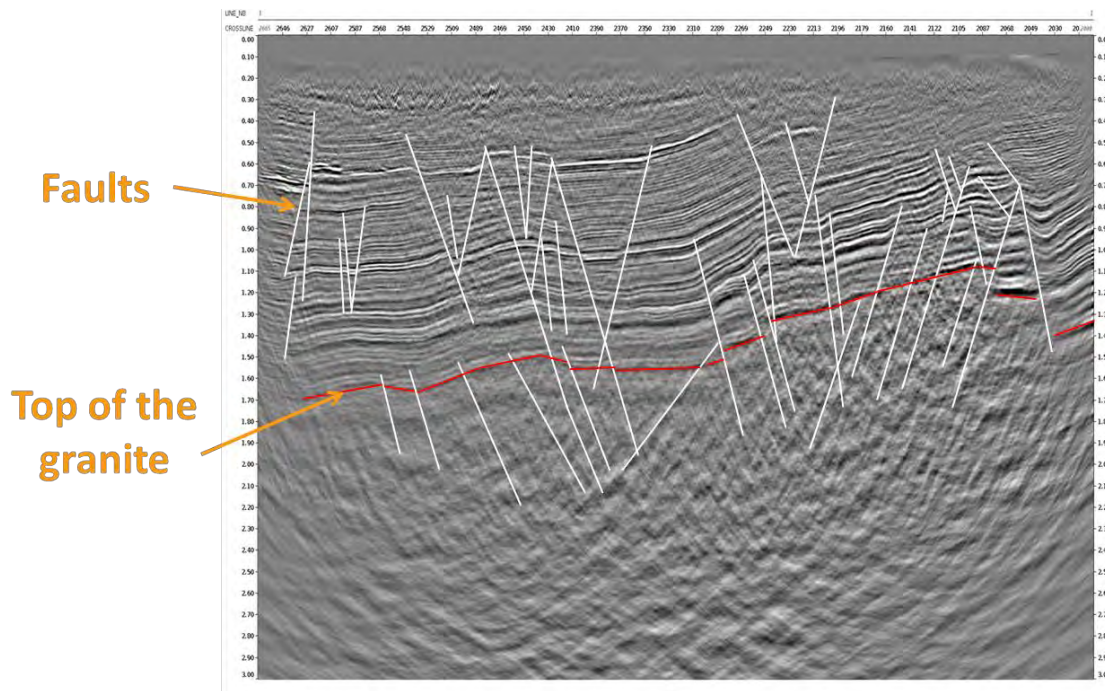
Figure 7: 2D line extracted from the 3D seismic cube. Faults are now visible from sedimentary layers to the granite.

Consequently, the acquisition parameters used both for the acquisition geometry and for the seismic source can be used for exploratory programs under similar geological conditions.

In particular, wireless data recording technologies as well as seismic sources such as vibrators may be selected. In addition, given the variety of environments encountered (crops, meadows, cities), we can say that the mission optimization techniques we used were efficient. In that way can be mentioned the so-called preplanning and all the computerized monitoring of the entire project (Figure 9).

In terms of administrative "strategy", this large-scale seismic acquisition project (180 km²) has highlighted the importance of filing an exploration permit largely encompassing the area of geothermal interest. Indeed, the perimeter of acquisition is inevitably reduced with a significant surface due to the constraints of processing algorithm (Figure 8).

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs
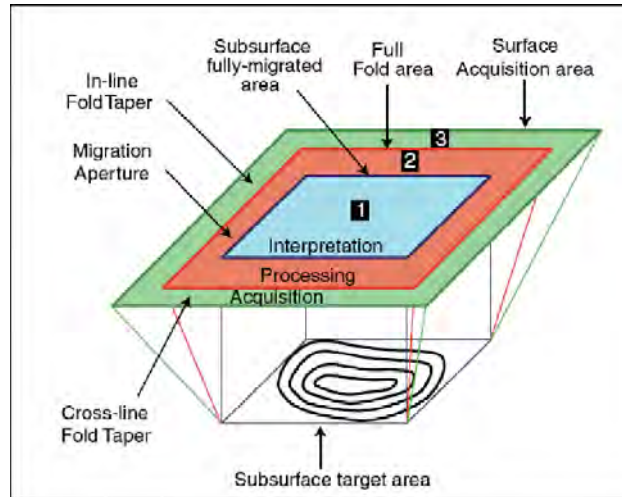
Figure 8: Effect of fold coverage and migration aperture on the dimension of the final interpretation cube (Chaouch and Mari, 2006).

Monitoring a project of this scale requires almost complete computerization of all surface aspects that may impact the acquisition. Consequently, all agricultural fields (over 13,000), all roads and all networks have been vectored (Figure 9).
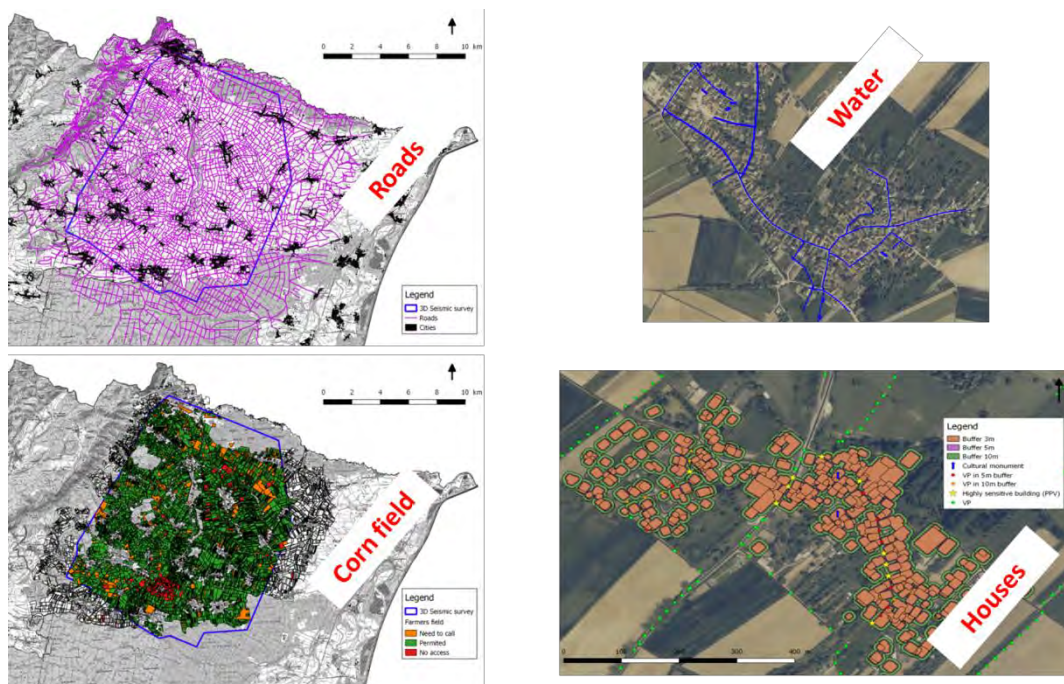
Figure 9: Computerized monitoring of the acquisition. All roads, water network, fields and houses were geographically located to optimize the acquisition and reduce the disturbance for citizens.

2.1.2   Techno-economic effect of lesson learnt

Exploratory projects are often the first field contacts with the population living on geothermal research permits. Consequently, beyond the technical challenge represented by the exploratory programs, it is also an important vector of communication with the population.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

It is well known that a poor acceptability can have very serious consequences on the future of a geothermal energy project (see Basel, St. Gallen, Landau, Port au Pétrole de Strasbourg, Mittelhausbergen, Schaidt, etc.). However, an effective and inexpensive communication strategy can easily be used as part of an exploration project (Figure 10). In addition to television news (2 regional reports and 1 national report for 3D seismics in Northern Alsace), radio news (2 broadcasts for 3D seismics in Northern Alsace) and papers (3 regional publications for 3D seismics in Northern Alsace), the organization of intercommunal meetings (3 for 3D seismics in Northern Alsace) and public meetings (2 for 3D seismic in northern Alsace) play a major role in the overall acceptability of a geothermal energy project, for a maximum budget of around 10 k€.

Figure 10: Part of all the communication that highlighted for free our 3D seismic acquisition (TV and regional newspaper).

When exploration permits are contiguous, it is possible to reduce exploration costs by acquiring seismic data on all permits at the same time, saving fixed costs such as mobilization / demobilization, permitting, basic living costs etc. (Figure 11). As part of this 3D seismic project in northern Alsace, the externalities saved amount was around 500 k€, i.e. almost 10% of the full project cost.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs
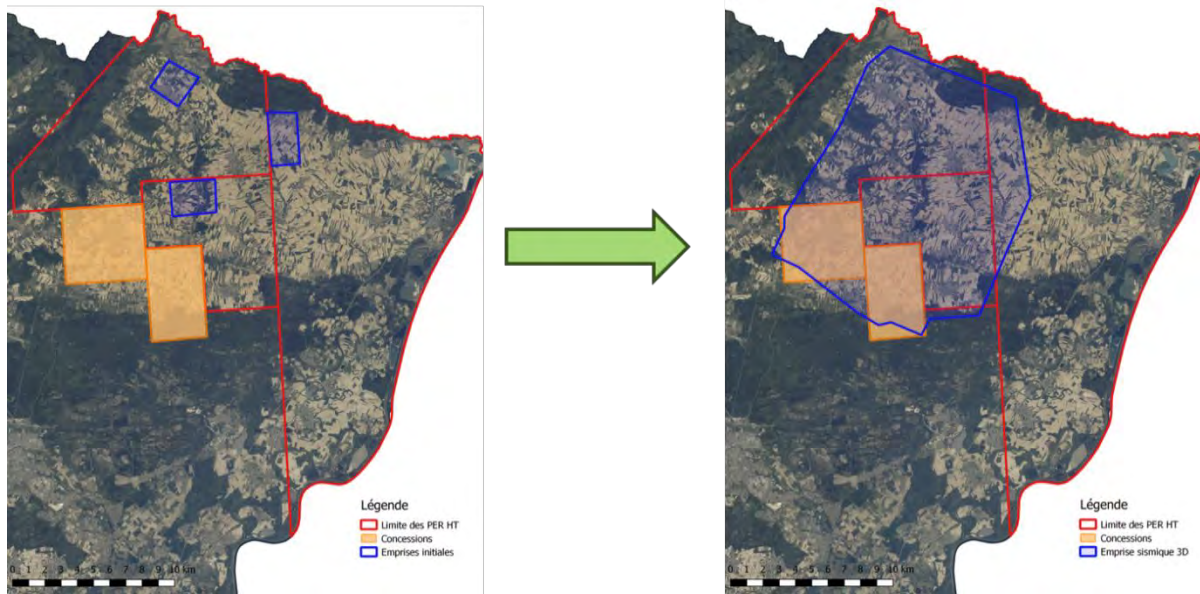
Figure 11: Cost reduction by sharing exploration over several licenses at the same time.

The technical success of this project and the clear imagery of the faults in the crystalline basement augur a major reduction in the geological risks associated with deep geothermal projects. Such risk reduction will most likely result in a reduction of around 5-10% in the amount of the insurance contract for the drilling phase.

Furthermore, the most important economy lies in the fact that 3D seismic allows to reveal enough faulted structures so that it is possible to design a project of 2 doublets from the same platform. The benefit of pooling surface infrastructure leads to an effective gain of almost 10 m€.

And finally, the extended scale of the seismic acquisition of Electricity of Strasbourg made it possible to submit 3 projects of each 4 wells to the authorities, yet therefore at 12 the number of wells to be completed (Figure 12). It is obvious that negotiations with possible assemblers and drillers will allow reductions of up to 15%.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs
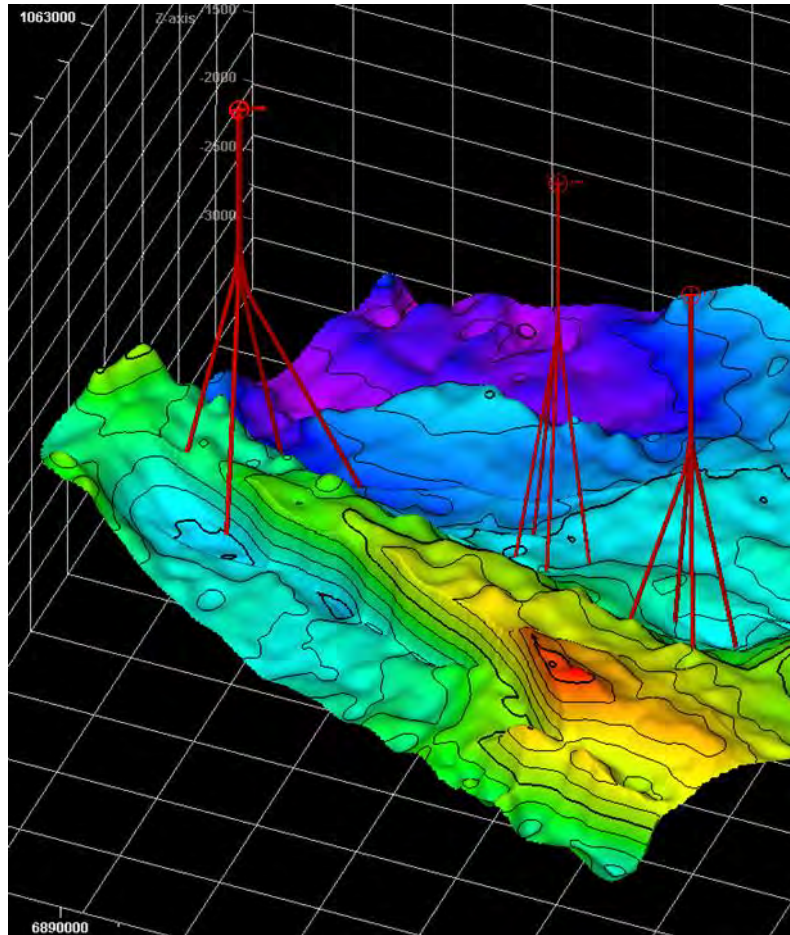
Figure 12: 3 projects of 4 wells were designed. Thanks to the 3D exploration done by Electricity of Strasbourg.

2.2   Data management

A geothermal power plant is equipped with around 300 sensors from pressure gauge to the valve opening state indicator. The industrial operation of a power plant also requires monitoring of equipment and regular reporting. The other major problem in the context of data management is the supervision software, which can vary from one plant to another. Thus, a data management homogenization project was launched and deployed on the Rittershoffen and Soultz-sous-Forêts power plants by the ESG teams.

The objective is threefold:
- To have a unique system to collect, store and classify all type of data
- To have a user-friendly reporting tool to save time
- To have "Artificial Intelligence" ready platform

The project entered its operational phase with the deployment of the various OPC servers allowing the connection of the various IT entities and the supervision servers of the power stations.
All historical data from the 2 sites will be integrated into the database.
The implementation of this software overlay will significantly improve the efficiency of reporting operations which can be extremely time-consuming and above all will allow us to compare, quickly and easily, all of the data pushed into the database.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

2.2.1 Technical description of the lesson learnt

It will not be possible to enter into the details of the deployment of this technology (Figure 13) within the two plants (Soultz-sous-Forêts and Rittershoffen) for obvious cybersecurity reasons. On the other hand, it can be mentioned that the most complex work lies in exchanging data with the ancillary installations (the ORC turbine at Soultz-sous-Forêts) and the client (Roquettes Frères for the Rittershoffen power plant). Indeed, securing transfers between these entities and the main Fieldbox server has proven to be particularly difficult.
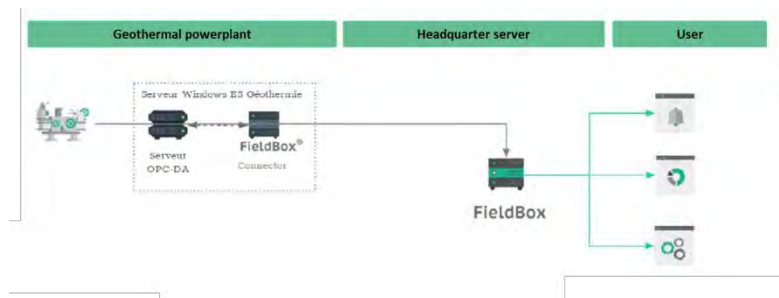
Figure 13: Simplified diagram of the operation of the sharing of operating data from geothermal power plants in Northern Alsace.

2.2.2 Techno-economic effect of lesson learnt

As the Fieldbox system is not yet fully functional, it is not possible for us to objectively quantify the economic gain of this technology. On the other hand, we had integrated the following elements into our business plan:

The automation of all the reports (Figure 14) and all the reports represents a saving of about 2000 h / year (technician time) and 240 h / year (engineer time).

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

Figure 14: Examples of automatic reports for the exploitation monitoring and for the reporting to the authorities.

2.3   Monitoring systems

In deep geothermal energy, and in the French case, the legislation requires environmental and technical monitoring of power plants and doublets. Commonly to do this, few seismological sensors (five per project) and punctual monitoring (each three years for injection well and each six years for production well) are provided by operators. But in order to improve our monitoring, the ESG teams tested new monitoring methods using fiber optic. Three objectives for three deployments forming a 3D geometry (Figure 15):

- 500m fiber around the power plant
- 200m fiber on the concrete hosting the drilling machine
- 150mx2 fiber in a shallow well (150m deep)

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Demonstration of soft stimulation treatments
of geothermal reservoirs
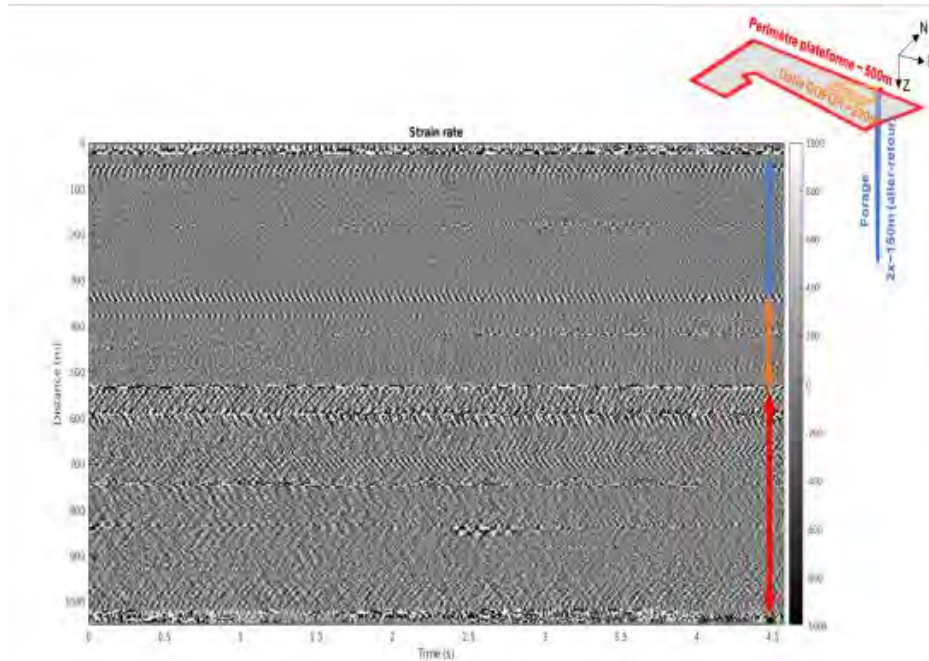
Figure 15: Deployment geometry of the 3D layout of the fiber optic experiment.

The first objective was to compare the noise level on the different deployments. Then a passive monitoring was recorded during several days in order to test the seismic noise correlation on data acquired by optical fiber and in a second time to possibly detect microseisms. Terabytes of data are now in processing step!

As part of a deep geothermal project, usually made up of at least 2 wells, the drilling machine remains on the platform for several months. The advantage of the optical fiber placed into the concrete is to monitor the state of stress of the concrete slab and anticipate possible concrete failure that can be dramatic for a project.

Shallow drilling was also used to determine velocity laws in the shallow layers of the subsoil. This data can be particularly useful for the construction of a velocity model in order to correct static errors in the context of the relocation of microseismic events. It can also be used as an antenna to detect possible microseismic events.

2.3.1   Technical description of the lesson learnt

The deployment of optical fibers was relatively easy, and no particular problem happened. The implementation of monitoring was also quick. On the other hand, it is on the side of data management that the challenge is greatest. Indeed, the monitoring technology via optical fiber is found to be extremely carnivorous in storage space due to the very fine sampling, both spatially and temporally and for a wide frequency range. It will be necessary to finely tune the acquisition parameters so as not to have mind-boggling amounts of data which will be very difficult to analyze.

2.3.2   Techno-economic effect of lesson learnt

The environmental monitoring rules impose the shutdown of geothermal installations in order to control the integrity of the casings of the injection and production wells, respectively every three and six years. The fiber optic deployment project along the casing of geothermal wells will aim to allow continuous monitoring of deformations and the detection of leaks due to casing rupture. Logging operations represent an average of one week and cost approximatively 100 k€.

2.4   Differences in business aspects between geothermal and E&P operations

Although the technique of providing a conduit from reservoir to surface in principle is the same for the E&P and the geothermal industry, the differences in the commercial perspectives between the two often dictate a different practice. These differences are caused in essence by

1) The generally more *local* scope of geothermal projects relative to E&P operations. In contrast, the E&P industry tends to have a more international or at least petroleum-basin / province portfolio-type of approach than the geothermal industry. These results in a different attitude towards *information gathering*: The E&P industry can more easily multiply their benefits from learning through (local) experiments, as they are in a better position to extrapolate the lessons learnt to their (world-wide) portfolio of projects, as compared to the geothermal industry.

2) By and large, the E&P business can be characterized by a *high-risk / high reward* business proposition. The geothermal industry tends to be rather *high-risk / low reward*, which from a business point of view is much less attractive. Hence, cost-minimization and short-term benefits are more important than for the E&P industry. The high risk of the geothermal industry is also related to the previous point: because they tend to me more locally focussed, the possibilities of risk reduction due to portfolio effects and regional / international upscaling of know-how are less evident.

3) The low-enthalpy geothermal industry (i.e. heat-sales only) will generally have to negotiate long-term sales contracts in order to safeguard security of demand. Long-term contracts are often tailored such to provide a rather marginal return on investment, whereas in case of an open market governed by exchanges (such the oil markets, or electricity markets) there is more flexibility to earn money by arbitrage. Heat is not an easy product to sell at an attractive profit margin.

Considerations such as above tend to result in operational differences between the E&P and geothermal industries in terms of data acquisition. Examples are:

- To economize costs, the standard logging suite in geothermal wells is generally less extensive than in E&P wells.
- Drilling deeper than the targeted horizon to explore for risky business opportunities below the pay zone is seldom done by the geothermal industry.
- During production operations, production logging tools to better understand the vertical flow profiles (fluids, enthalpy) and associated commercial optimization opportunities are seldom applied.
- Seismic interpretation for geothermal prospect development is often based on earlier (vintage) E&P seismic, which is re-processed for the geothermal horizon. New seismic acquisition if often too expensive.
- Well stimulation jobs in geothermal operations are often required to obtain a minimum commercial production rate, whereas in E&P operations the wells are typically already commercial pre-stimulation. The probability of having a non-commercial well in a known productive geothermal field is much higher than having a non-commercial well in a known productive oil field. On average, E&P wells would only gain from stimulation, whereas stimulating a geothermal well still has a relatively high probability of not resulting in commercial rates. This also impacts on the data acquisition required for designing a stimulation job.

An important difference between geothermal and E&P operations is also the chemistry of the produced hot water, with the negative impact this may have on operating expenses and well/facility downtime. Oil and gas wells, although certainly also subject to scale deposition in the tubulars and surface equipment, tend to be less vulnerable for flow assurance problems than geothermal wells. This also pertains to skin build-up around the production and injection wells.

2.5 Updating single experiment knowledge

2.5.1 Technical description of the lesson learnt

As already suggested in the previous section 2.4, having a more or less localized focus, rather than a (regional / international) portfolio approach, limits how new knowledge and experience can be generalized and exploited at some later stage. As the subsurface is generally poorly known (in terms of limited knowledge on the reservoir properties, but also in terms of the often poorly understood physical cause-effect relationships), predicting the effects of a new experiment is to be based on (generalized) analogue data and empirical evidence, i.e. if one wishes to optimize the design of a well, of a stimulation job, or even a reservoir management plan.

However, in case of limited experiments, as one may expect from the local focus of a geothermal operation, obtaining convincing statistical information may not be possible. In general, new information is to be merged with the existing information in order to update and improve one's knowledge on some relationship. Apart from theoretical relationships, empirical relationships can be as important or even more important (such as in the case of well stimulation) to validate and calibrate any performance prediction made.

The performance of sparsely sampled, heterogeneous systems with highly non-linear physical relationships, such as the subsurface, cannot be predicted without some prior knowledge on the system's properties and the system's constitutional relationships. Moreover, with so much uncertainty, the performance prediction should in principle be done probabilistically. This problem is exacerbated by the fact that the accuracy of the data (measurements, calibration points) is often poor, amplifying the uncertainty that is already there. Using *a priori* information on the reservoir properties and on the physical constitutional laws and updating these based on new experiments (new data) is typically done using Bayes' Theorem on conditional probabilities. This formalism ensures that all existing information (i.e. on physical laws, measured properties, measured performance) is combined and modelled such as to compute the comprehensive *a posteriori* uncertainty on some prediction.

It is postulated that geothermal systems can take less advantage of such comprehensive modelling techniques than oil producing systems. Major contributors to uncertainty in geothermal predictions are the uncertainties in geochemical and geomechanical behaviour, which in oil and gas operations typically is less relevant. Moreover, E&P typically has more information and more calibration data points than in geothermal operations.

Being less capable of narrowing down the uncertainties in a geothermal reservoir's performance prediction, as compared to the E&P industry, may lead to relatively higher 'technical risks' (i.e. the project-specific risks associated with the 'technical uncertainties', also known as 'endogenous risk'; an example is the rock's poorly known permeability, or the doublet's poorly known cold-water breakthrough time and, hence, enthalpy production). For the geothermal industry, this may easily lead to an unacceptable risk/reward ratio. The typical approach of de-risking the commerciality of low-enthalpy geothermal projects is to negotiate a long-term contract with the heat consumer (e.g. a housing corporation) in which a heat-sales tariff is agreed that meets a minimum IRR hurdle rate over

the lifetime of the geothermal installation. The IRR hurdle rate is then set at a level that there is a high probability of recovering the costs, even in case of adverse technical conditions. This is commercially less risky than being exposed to market forces and variable sales prices.

In conclusion, in case of large technical uncertainties (poorly known system properties, poorly known cause-effect relationships, uncertainty on the accuracy of measurement data, no or limited availability of analogues for estimating the technical performance of the new doublet being considered), updating one's (limited) knowledge with a single experiment is fraught with problems of statistical representativeness. With limited experience of earlier projects, these problems will remain and will translate into commercial risk. Nevertheless, a properly designed database is to be set up and maintained in order to de-risk subsequent projects.

The data from a new experiment (e.g. drilling a well, logs, cores, geochemical analyses, fluid analyses, production testing the well, stimulating the well, scaling problems, new reservoir simulation studies, new economic studies, etc.) are to be documented such that they can be merged with the existing data, and that the previous statistical correlations can be updated. Gradually, the predictive power of the fundamental relationships and the calibrated empirical data will result in less uncertainty in a next geothermal doublet's predicted performance.

2.5.2 Techno-economic effect of lesson learnt

Eventually, the updated technical data will be used to populate a so-called '*integrated asset model*' (IAM, i.e. a model that intricately couples the geological / physical / technical / operational planning / economic aspects). This IAM also relates future information (such as physical state variables like enthalpy produced, market information) to decision-making, by computing decision metrics also known as Key Performance Indicators. New information, to be revealed in future, can be modelled, and may lead to responsive measures such as new operational or investment decisions. The IAM can also be run probabilistically, thereby quantifying the impact of input data uncertainty on output uncertainty. For example, the sensitivity analysis, which is a direct result from the probabilistic computation of the IAM, may show that the IRR hurdle rate is very sensitive on the uncertainty in the breakthrough time of the cold water into the production well. This may provide an indication to conduct a new '*Value of Information*' study on additional geological/reservoir simulation studies in order to reduce the uncertainty in this breakthrough time: if this uncertainty can be narrowed down, then the probability of not meeting the IRR hurdle rate can be reduced by x%, resulting in an investment risk reduction of y%.

Many alternative approaches may be followed, but the investor should somehow attempt to relate new information to uncertainty reduction and translate this into commercial risk reduction.

3 Standardization of techno-economic assessments

3.1 Introduction

In this chapter, guidelines are given on conducting techno-economic assessments of geothermal energy projects, including soft stimulation techniques. Within this framework, model input and output parameters that are required by the investors to assess geothermal energy project opportunities are identified. The parameters include a wide range of factors, e.g. expensive and long exploration and resource identification, or different types of conversion technologies that affect the risk assessment. A key barrier in developing a geothermal energy site is the high level of uncertainty that exists in its costs and expected technical performance. These uncertainties remain high, even though the heat

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

recovery and costs have been estimated by several analogue studies. As part of the DESTRESS project, a series of state variables and Key Performance Indicators (KPIs) are computed in the techno-economic model developed to compare alternative investment options with the integration of uncertainty in developing a geothermal field (see also DESTRESS deliverable D6.5). The output of the model and the comparative difference between alternative development options should help decision-makers to further mature a project until final investment decision.

First of all, a standardized Decision and Risk Analysis process shall be conducted for complex decision-making problems under uncertainty. Subsequently, the techno-economic model will have a central role in the Decision Analysis process. Techno-economic assessment models should be designed in such a way that for each alternative decision they can capture the impact of technical and economic uncertainties on the asset's future performance.

In the following, the key parameters shall be given that drive the techno-economic assessment of some geothermal investment opportunity.

3.2 Methodological background

The technical-economic evaluation of a project performed for investment decisions can basically be found in every business. Considering any type of uncertainty including the ones caused by risk factors in the investment decision analysis process of geothermal projects is very important. For this reason, the possible uncertainties are taken into consideration within the techno-economic evaluation of the DESTRESS project. The structure of how to define uncertainty in projects is given with the Decision Analysis approach. In other words, Decision Analysis is used as methodological approach in DESTRESS project to identify risk factors and integrate uncertainties into the technical-economic evaluation.

3.2.1 Decision Analysis Process

The Decision Analysis (DA) process is the main building block of a company's project maturation (Decision Gate process) and asset life-cycle processes.

The DA process provides information to the Decision Gate (DG) process and both of them lead the physical and economic development of a subsurface asset. The objective of the DG process is to phase the capital commitment from project initiation to final investment decision, and only commit a next DG-phase's capital when sufficient clarity has been obtained to proceed. Keep in mind that different companies may have their individual variants on these processes. Different types of decisions and data will be available depending on the project maturity and the asset's life-cycle phase. Besides, different tools, either qualitative or (semi-) quantitative, will be used for the assessment. The targeted technical-economic model has a role in the different steps of the Decision Analysis process. The output parameters of the model (time-series, and time-integrals also known as Key Performance Indicators) allow decision makers to compare alternative development options and decide which options are to be further investigated, eventually leading to final investment decision (FID).

Several types of decisions can be made in an early phase of a project with the technical-economical model developed in DESTRESS. These decisions are generally related to a relatively immature geothermal asset that is in its early life-cycle phase. Some examples of such decisions are:

- Explore or not a mapped, but undrilled prospect or not
- Appraise or not a mapped, drilled resource. If so, establish the number and sequence of appraisal wells.

- Note: the targeted DESTRESS tool will not model spatial heterogeneity of the reservoir. Hence, the tool will not help in optimizing the location of a new well. However, the effect of spatial heterogeneity in terms of reinjected cold-water breakthrough into the production well can be modelled in the DESTRESS tool, i.e. if a 3D reservoir simulation study has been done.
- Select concept in developing the appraised resource and understand economic feasibility of geothermal resource. This includes the decisions on:
  - Number, sequence, spacing/pattern and timing of development wells to be drilled (production, injection, number of well clusters)
  - Well design: depth, diameters, completions, vertical lift
  - Types and frequency of well stimulation jobs to be done
    - Soft stimulation vs. conventional stimulation + associated costs.
    - Impact on skin factor remediation + impact on post stimulation job skin buildup.
  - Type of energy to be utilized
    - Pure Heat Generation Plant (HP)
    - Combined heat and power generation plant (CHP)
    - Pure power generation plant (PP)
  - Technical configuration of surface facilities to be installed

In order to make adequate decisions in maturing a project, investors (decision-makers) need the following information:

- How the decision alternatives were framed: the project team is to select a range of different alternatives that are supposed to be the most relevant for the investment opportunity.
- For each alternative, they need to know:
  - The value (including the option value) and its top drivers;
  - The risk and its top drivers;
  - What combination of outcomes would cause the investors to change their choice?
- They would like to be convinced that the calculated uncertainty range reasonably captures the range of possible outcomes.
- They like to have confidence that their decision is robust under a range of possible assumptions.
- They like to be sure that all projects / alternatives have been evaluated on a consistent basis, and the evaluation tool is based on sound principles. Also, they would like to know how the evaluation tool has performed in the past and which potential pitfalls the tool may have.

Therefore, the role of the DESTRESS technical-economic model in the Decision Analysis process is crucial. The model should be designed in such a way that it can adequately capture the impact of a decision on the asset's future (technical and economic) performance.

The Decision Analysis (DA) approach consists of the following steps (Howard & Abbas, 2016):

- › Clear articulation of the decision to be made
- › Framing
- › Recognition of a decision hierarchy
- › Development of alternatives
- › Identification of uncertainties

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

›   Valuation, including probabilistic analysis
›   Sensitivity analysis
›   Interpretation and communication
›   Assessment of decision quality (DQ)

The last step of the Decision Analysis process is establishing the Decision Quality. It is actually a review on the recently concluded Decision Analysis process to assess whether it had sufficient quality.

Criteria for Decision Quality are:

›   Appropriate frame
›   Meaningful, reliable information
›   Creative alternatives
›   Clear values and trade-offs
›   Logically correct reasoning
›   Fostering corporate learning and working towards "best practices"
›   Commitment to action

Figure 16 depicts the steps of the Decision Analysis process:
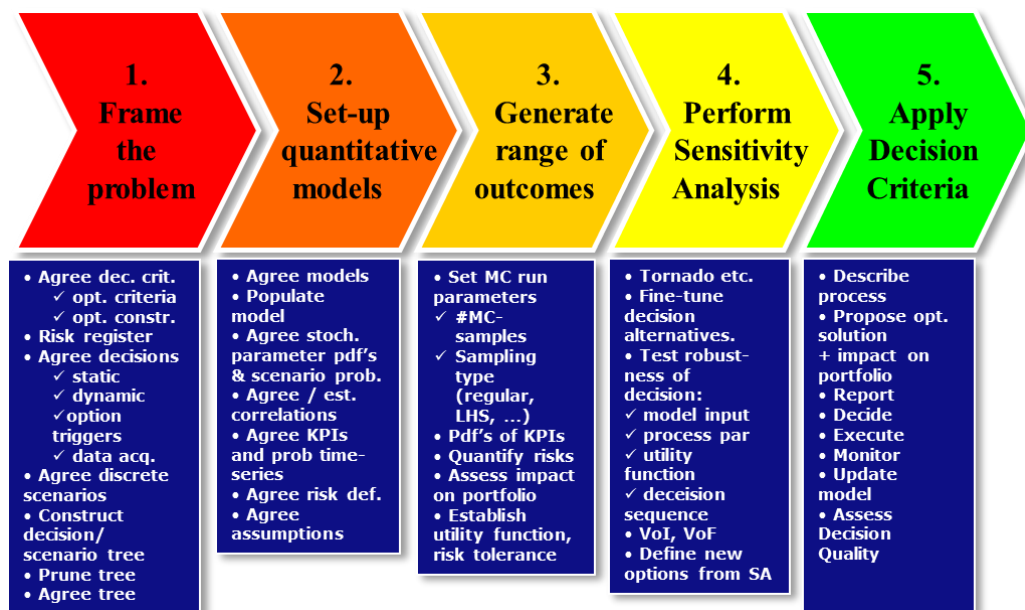
Figure 16: Steps in the Decision Analysis (DA) process

Each Decision Analysis step consists of several sub-processes. In these sub-processes uncertainty /decision areas and process parameters must be defined. Steps 2, 3 and 4 are conducted using the DESTESS technical-economic model. During these steps, quantitative calculations are prepared and carried out. The DESTRESS project focuses on soft stimulation; therefore, the technical-economic model is designed to be able to compare the techniques of conventional vs. soft stimulation of geothermal wells. This comparison should be framed in the Decision Analysis Step 1.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

3.2.2 Integration of uncertainty into technical-economic evaluations

Uncertainty in a parameter in principle causes an infinite number of possible scenarios. To circumvent this, a defined number of discrete scenarios may be selected, and/or input parameters may be assigned a probability density function that is to be sampled by the Monte Carlo process.

The scenario technique is frequently used to integrate uncertainty into the technical-economic evaluation of an investment decision. Some companies reduce the uncertainty space to three discrete scenarios to characterize the uncertainty in a parameter. These scenarios are (Gleißner, 2015):

› Best case: The most favourable realistic possibility of realization
› Worst case: The most pessimistic realistic scenario
› Base case: The most probable scenario

Investment decisions are then based on the range of possible outcomes, although often there is no quantification of the probability of occurrence of a discretized scenario. The value of information may increase, if the information is provided via empirical data or expert elicitation. In Figure 17b shows the case when the probability of occurrence is also known besides the value of a certain scenario.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs
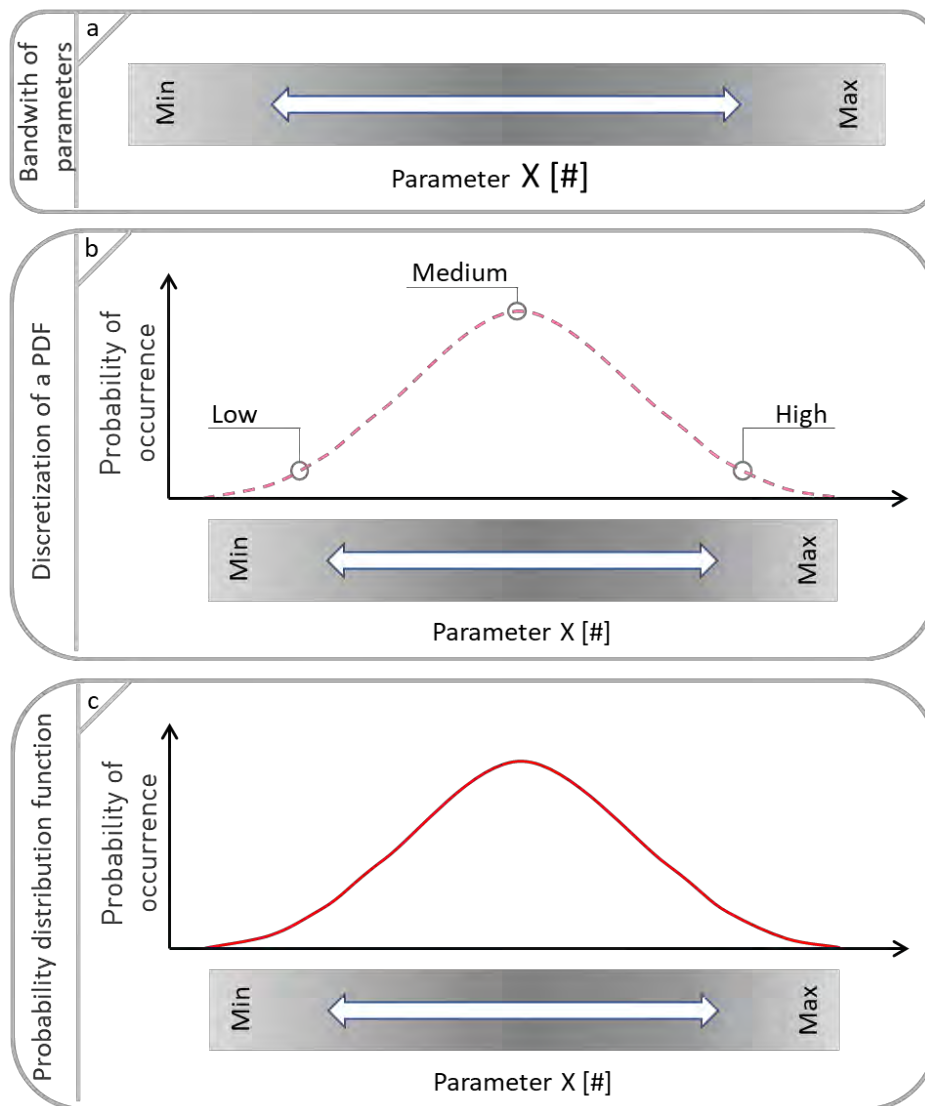
Figure 17: Uncertainty on the realization of a parameter in technical-economic modelling

Through a continuous probability distribution function as depicted in Figure 17c, it can be possible to decide on a discretized unbiased scenario among the infinite number of possible realizations (Gleißner, 2015). The scenario technique can be examined with simple spreadsheets, while binominal or continuous probability distribution functions (Figure 17a and Figure 17b) need a Monte-Carlo-Simulation.

For more information on uncertainty within technical-economic evaluations please see the published report of DESTRESS Deliverable 2.2: "Key performance indicator analyses based on Monte Carlo simulation".

3.2.3   Risk Analysis Process

The identification and quantification of risk factors was published in (Reith, Hehn, Mergner , & Kölbel, 2017) and shall be summarized in the following. Figure 18 shows an overview of the quantitative risk assessment process. The first step of the risk analysis process is the "Definition of scope and objectives". Then the identification of risk factors, prioritization and quantification take places respectively. Prioritization is carried out in order to limit the quantification effort.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs
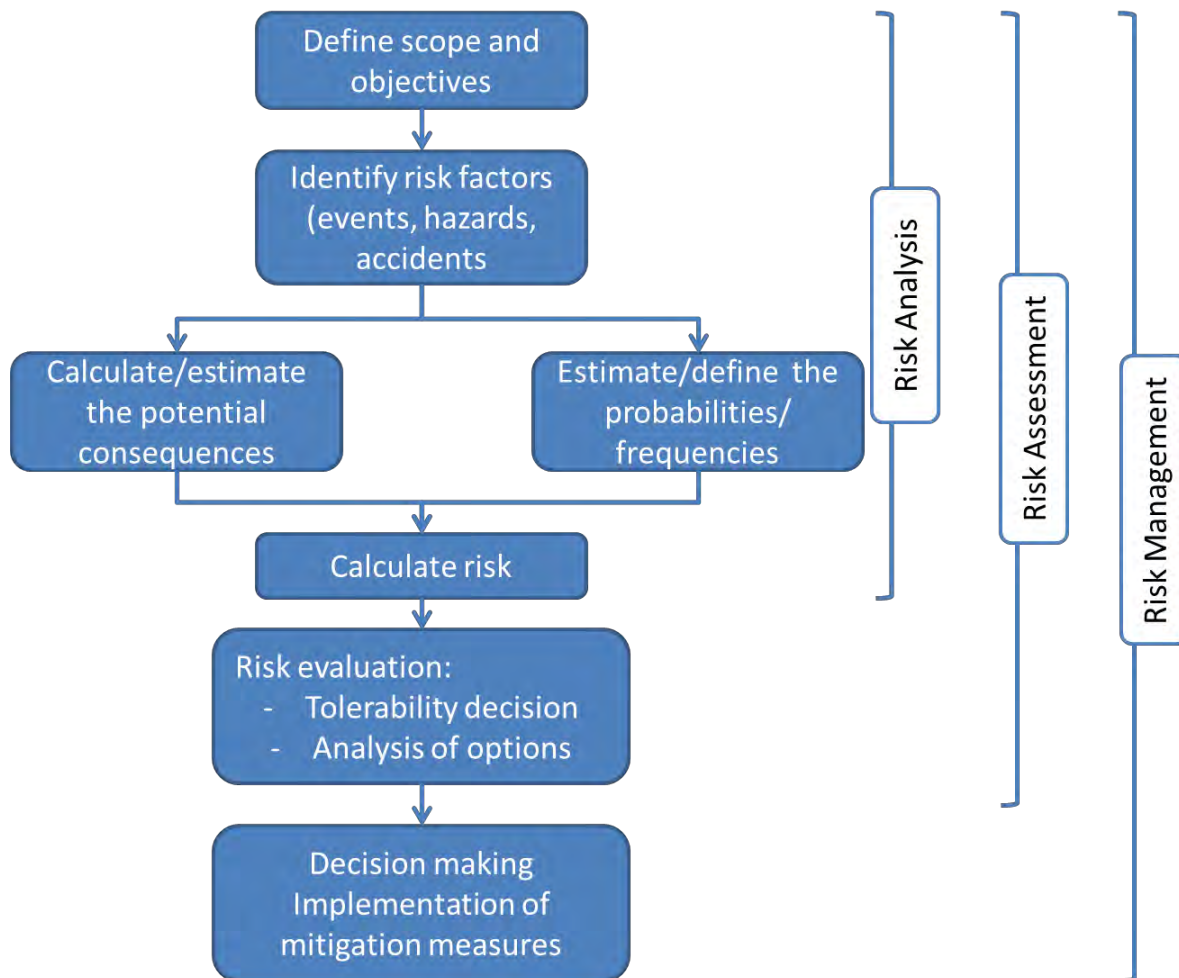
Figure 18: Quantitative risk assessment process (Abrahamsson, 2002) (Reith, Hehn, Mergner , & Kölbel, 2017)

Risks factors can either stem from accidents related to certain operations like handling of hazardous materials during chemical stimulation or can be site-specific like the impact of local geology on operations. As the focus of the DESTRESS project is the evaluation of soft stimulation techniques, site specific effects are not included in the investigations.

A structured approach is presented by (Reith, Hehn, Mergner , & Kölbel, 2017) to identify the risk factors. This approach is based on expert elicitation which is designed to make the identification of risk factors easier. The outcome of an expert elicitation is a "risk inventory". This risk inventory is a database of risk factors including name, description of cause and description of effect for each identified risk factor.

The prioritization of risk factors, in (Bos & Wilschut, 2011), is done by a sensitivity analysis on modelling results. However, in DESTRESS project, the prioritization of risk factors is done before the technical-economic modelling and the prioritized list of risk factors are integrated into the model. This provides a first overview on the risk factors without modelling effort.

The quantification of risk factors or uncertainty should rather be done with empirical data or and analytical correlation. Such empirical data is rarely available (Reith, Hehn, Mergner , & Kölbel, 2017). A deep literature review on the quantification of the prioritized risk factors is given in the DESTRESS Deliverable 2.2: "Key performance indicator analyses based on Monte Carlo simulation" – Chapter B.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

In the literature review, it is found that geothermal reservoir stimulation is comparably a chartless technology and therefore limited empirical data exists for building stochastic models The parameters that have influence on the prioritized risk factors are usually uncertain and highly depend on the local, physical-geological conditions or culture. Therefore, an accurate quantitative stochastic assessment of the risks is proved not to be feasible.

For further information on the risk assessment process please see the published reports of DESTRESS Deliverable 2.1: "Systematic preparation of the techno-economic evaluation of soft stimulation" and Deliverable 2.2: "Key performance indicator analyses based on Monte Carlo simulation".

3.3   DESTRESS techno-economic assessment procedure

In this section, the procedure followed to carry out the techno-economic assessment within the scope of DESTRESS including uncertainty is presented. A technical description of the energy utilization system, including model design, built-in models, sub-models and economic characteristics/correlations are discussed.

3.3.1   Objective of DESTRESS Model

The purpose of the DESTRESS techno-economic model is to feed the Decision Analysis (DA) process and thereby support the project maturation. Project evaluation tools, such as the targeted DESTRESS tool, can help maturing a project along the DA process, which drives the physical and economic evaluation of an asset. The DESTRESS geothermal project evaluation tool is mainly aimed at assessing projects in which uncertainties are large and the prediction of the physical processes cannot be obtained precisely. Thus, the tool should particularly be applicable and useful in case of limited information on geothermal reservoir and comparing development options. The detailed computations of physical processes in the three spatial dimensions with important spatial heterogeneities and the detailed time-steps are not aimed to be considered in the DESTRESS tool. The latter computations would be pertinent in case of availability of more detailed data and in case of more detailed decisions such as locating a next well to be drilled, or the detailed design of a production facility.

The DESTRESS techno-economic model processes physical, technical, economic and planning data into deterministic and probabilistic time-series of heat production, electricity production and cash flows, and into Key Performance Indicators (KPIs), which can be used as decision criteria. Examples of KPIs are: NPV, IRR, LCOE, maximum exposure, GWh_{th} and GWh_e sales, Unit Technical Cost, CO_2 emissions to the atmosphere avoided, etc.

3.3.2   Assumptions and main considerations

The DESTRESS techno-economic model is designed in accordance with the following concepts:

- Only analytical equations are used in the model. This is because they are fast to solve and allow more comprehensive analysis of uncertainty and can holistically integrate physics, planning aspects and economics. Iterative calculations within a time-step are avoided as much as possible.
- Modelling of detailed spatial heterogeneity is not possible. The reservoir is represented as a zero-dimensional point. The reservoir-averaged physical property is used for each well and the state variables are assumed to be constant in a modelling time-step.
- The system's state variables are computed per time step in the physical variables domain and converted into the time domain using the planning assumptions (i.e. timing of a new well, of a workover). The time-step used in the model is 1 year. Stabilised conditions are assumed per time-step.

- Hydraulic properties i.e. skin factor, II, or PI of production and injection wells can be specified per well.
- The initial static situation of the reservoir is considered as "Heat in Place".
- There is no material balance modelling in case of steady-state inflow (i.e. in case of geothermal doublet).
- Conductive heat flow in the reservoir during the asset's productive life is not considered. Instead, convective heat flow related to the production / injection of water by the wells is modelled.
- Decline of produced water temperature in production wells, i.e. after the breakthrough of the (cold) injected water is represented by a simple analytical function, which can be derived from a separate 3D thermal reservoir simulation study.
- The drainage area per well is assumed to be the area of the reservoir divided by the number of wells. (Semi-)steady-state radial well inflow equation, both for producers and injectors.
- The skin factor for producers and injectors is computed per time-step at given a build-up rate. It is re-set at its given starting value after a well stimulation job.
- Vertical Flow Performance (VFP) is done by computing Δp and ΔT between bottom hole and tubing head as a function of the production rate, well/tubing geometry, and absolute value of pressure & temperature at the upstream end.
- Thermodynamics of surface facilities is done by enthalpy and entropy calculations to transfer energy to a binary cycle, evaporate the working medium of the binary cycle and convert steam into electricity. These calculations are done for a defined number of state points.
- The planning variables are:
  - Timing of geophysical / geological survey, CAPEX, drilling expenditures, CAPEX of the facility, well workovers, stimulation jobs, etc.
  - Timing of first production
  - 2 different automatic stopping criteria:
    - If there is decline on production rate, the field is shut-in when Net Cash Flow has been below zero for more than *n* consecutive years
    - The field is shit-in when flowing bottom hole pressure of production well is lower than the minimum required value.
  - An automatic mandatory monitoring including OPEX begins after the field is permanently closed in. Finally, the field is decommissioned including the associated decommissioning CAPEX.
- The geothermal asset is assumed to be stand-alone for tax purposes, i.e. the DESTRESS model does not consolidate the asset being studied into a corporate portfolio of assets.
- Discounted Cash Flow analysis (DCF), with a fixed discount rate in included.
- Fiscal regimes of specific countries are included through an adaption of the interest rate. A method by (Konstantin, 2013) for the determination of interest rates including taxes is used.
- Depreciation is not included in the calculations....
- Different types of government subsidies, i.e. premium tariff for electricity are taken into account.
- The tool is based on the Monte Carlo sampling
- Multiple discrete uncertainty scenarios are not taken into consideration by the model.
- Decisions, continuous uncertainties and deterministic assumptions are clearly distinguished.
- Histograms of KPIs and probabilistic time-series of state variables are computed by the model.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

3.3.3 History of the DESTRESS techno-economic model

The DESTRESS techno-economic model is developed by the DESTRESS-partners University of Glasgow (UoG), Netherlands organization for applied scientific research (TNO) and Energie Baden-Württemberg (EnBW) based on the techno-economic model used in (Welter, 2018).

One of the main development approaches of the DESTRESS techno-economic model is the use of Monte-Carlo-Simulations. When analytical approached fail or can only be applied with extensive effort, the use of Monte-Carlo-Simulations is pretty powerful option for solving problems. The Monte-Carlo method is used for quantitative analysis in varied scientific disciplines. They are often used to integrate uncertainty into models. The integration of uncertainty that comes from parameters and risk factors into the DESTRESS techno-economic modelling is done with the Monte-Carlo method. Another new approach developed in the DESTRESS techno-economic model is in power plant modelling. UoG and EnBW applied the Monte-Carlo approach for the optimization of the power plant designs, while a heuristic optimization is used by (Welter, 2018) for the identification of an optimal power plant design. The solution space was limited with the heuristic optimization by changing only one parameter in a defined step size. However, in the power plant modelling presented in the DESTRESS techno-economic model the solution space is enlarged by manipulating five parameters at different state points of the power plant. The Monte-Carlo approach is used for two different reasons in the DESTRESS techno-economic model. These are the integration of uncertainty and the simulation and optimization of power plant designs. In order to limit the computational effort these are technically separated in the actual code but integrated in the main model.

3.3.4 The DESTRESS techno-economic model architecture

The model is designed in five different parts in MATLAB. Figure 19 depicts an overview of the model. The technical models are presented in the middle of Figure 19. The physical state of the thermal water is exchanged between the single models.
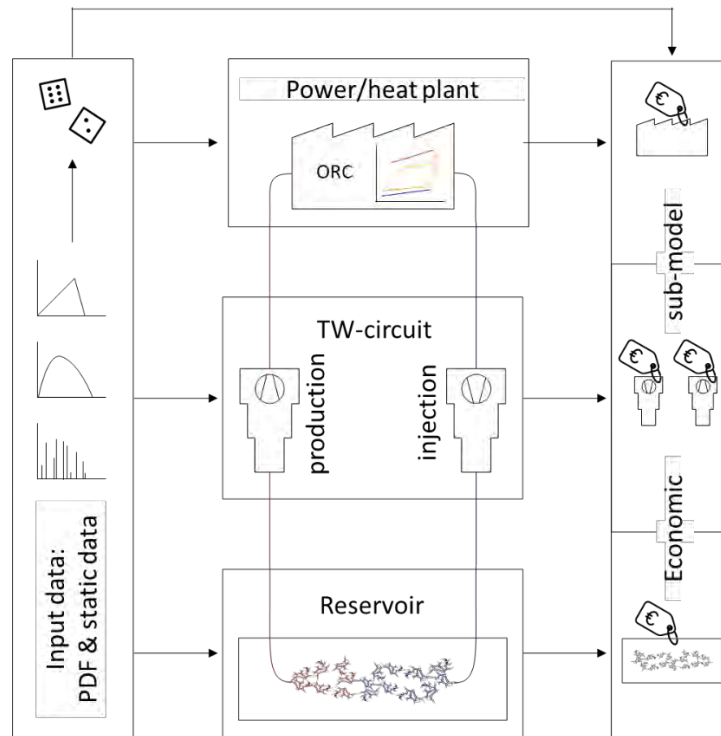
Figure 19: The DESTRESS techno-economic model overview

A closed-loop is simulated starting from the reservoir model. This includes:

- Drawdown in the production reservoir
- Temperature and pressure reduction in the production wellbore
- Energy utilization in the power/heat plant
- Pressure and temperature changes in the injection well
- Up arching in the injection reservoir
- Pressure coupling with production reservoir.

The technical models are feeding data into the economic model. In the economic model, different cost engineering approaches are used to calculate costs, earnings and different key performance indicators. Uncertainty mainly caused by risk factors is integrated into the model by using risk associated costs.

The built-in models (technical & economic) are described in detail in the following chapters.

3.3.5 Built-in models and characteristics/correlations

3.3.5.1 Different options of geothermal energy usage considered in the model

Five different geothermal energy usage options are considered in the DESTRESS model.

1. Pure power generation: All produced geothermal fluid is used for electricity generation with an Organic Rankine Cycle (ORC) plant.
2. Pure heat supply: All produced geothermal fluid is used to supply heating for an application, e.g., a district heating system or an industrial process.
3. Combined heat and power generation (CHP): Both electricity and heat are produced. Two different configurations are available:
   a. CHP in series: A geothermal power plant is combined by a direct-use heat application in series. Geothermal heat is first converted into electricity and the remaining heat in

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

the geothermal fluid after leaving the power plant is used to supply to a direct-use heat application.

b. CHP in parallel: A geothermal power plant is operated in parallel with a direct-use heat application. The produced geothermal water is split into two streams to provide heat to a power plant and direct-use heat application at the same temperature.

3.3.5.2   Reservoir model

The reservoir model is introduced in this chapter. An introduction to basic analytical equations that are used in the reservoir model, and the general frame conditions of the model together with the input data shall be given. Also, the effect of stimulation is quantified.

The main principles are considered in the reservoir model:

- The material balance equation
- The stabilised radial inflow equation for vertical wells completed on a porous and permeable reservoir

In the material balance the reservoir is represented a single zero-dimensional tank. The evolution of the average pressure is a function of the net volume withdrawn from the reservoir, the compressibility of the fluid and rock. Also, hydraulic communication to remote volumes away from the main reservoir may have an impact on the reservoir pressure.

In the well inflow equation, it is described how a vertical well produces fluids as a function of a pressure difference applied between the reservoir and the bottom of the well. The flow rate is a function of variables such as reservoir permeability, skin factor, fluid viscosity, drainage area diameter and well diameter.

The related equations are available in the reservoir engineering literature (Krusemann & de Ridder, 2000).

The general frame conditions of the model are categorized as follows:

Production and injection wells are identical: the reservoir is assumed to be homogenous and skin factors, FBHPs are assumed to be identical in all wells.

Pressure vs. rate-constraint: The reservoir produces rate-constrained (i.e. a flow rate is given to the simulation model) until a pressure-constraint, i.e. a maximum drawdown/build-up in a well, is violated. The pressure constraint then takes over and the flow rate is re-calculated. The flow rate is given, together with the maximum pressure constraint. If the rate, given the minimum FBHP or the FTHP, does not violate the pressure constraint, then the given rate applies. Else, the pressure constraint applies.

Flow regimes of the reservoir (Darcy vs. fracture-dominated flow): two approaches are available.

- The flow rate is calculated with the fundamental equations and reservoir parameters (Darcy flow – can be applied when the flow is matrix dominated)
- The flow rate or the PI / II are user-defined (can be applied when the flow is fracture-dominated)

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

Stimulation effects: to model the gradual decline in well productivity / injectivity as a result of geochemical precipitation or fines migration, a dynamic skin build-up rate can be defined that result in the wellbore or wellbore vicinity a clog. A well's rate will gradually decline if Δskin is positive. This decline in well productivity / injectivity can often be improved with the well stimulation. The number of stimulation job frequency can be defined by user. This treatment can be applied to all wells and thus they provide the Δskin or Δ II/PI. As a result of this improvement, there will be an increase in production or injection rate. The OPEX of this workover is automatically accrued to the cash-flow.

In accordance with the two approaches for the flow regimes, the effect of stimulation can be modelled by defining a post-stimulation change in the skin factor or by defining a change in the PI or II. This effect of stimulation is applied to all wells (injection / production) evenly, since all wells are assumed to be equal.

Degradation in reservoir performance: the overall performance of the reservoir can get worse resulting from the cooled water injection, because the cooled water injection may trigger the geochemical precipitation of minerals in the pores or fractures. The approaches available in the literature are not implemented in the DESTRESS model because of the simulation complexity of data.

Temperature decrease in production well: the temperature decrease in the production well can be modelled in the DESTRESS tool by defining a breakthrough time for when the cooled injection water reaches the production wells. The calculation of the breakthrough time is presented by (Schulz & Jobmann, 1989) with an analytical approach.

3.3.5.3 Thermal water circuit model

Thermal water circuit summarizes all parts of a geothermal system that connect the geothermal reservoir to the surface power plant. A thermal water cycle consists of production wells, connecting lines, pressure retaining devices, filters, slop pits, heat exchangers and injection wells (Hoth, Seibt, Kellner, & Huenges, 1997). Production and injections pumps can also be considered as part of the thermal water circuit if they are used in the power plant.

With the given temperature and pressure values of the thermal water in the reservoir, the inlet pressure and temperature of the power plant are determined. Similarly, the temperature and pressure values of the thermal water while re-entering the reservoir are determined based on the values at the power plant output. The calculation of the thermal water pressure and temperature are explained in this chapter. In the calculation, production & injection wells, pumps and heat exchangers are taken into account. The other parts of the thermal water circuit such as connecting lines, retaining lines, overhead filter and sloping pits are neglected.

Knowledge of the well geometry is required in the determination of the pressure and temperature of the thermal water in the well, since pressure losses and heat transfer in wellbore and surroundings are influenced by the diameter and angle of the well. The geometry of the wellbore and temperatures in the subsurface are specified by the user. Figure 20 illustrates a vertical and deflected hole.
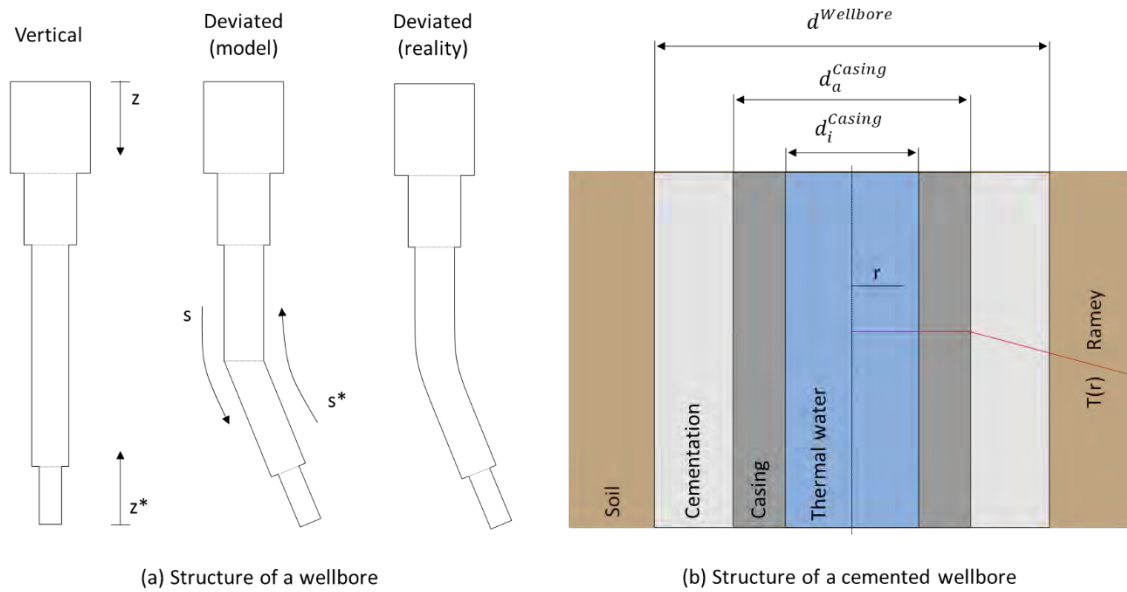
(a) Structure of a wellbore   (b) Structure of a cemented wellbore

Figure 20: Schematic structure of production and injection wellbore

In Figure 20a, z means the vertical depth (true vertical depth, TVD) and s describes the measured depth (measured depth, MD) which is the drilled distance. The calculation of pressure and temperature of the thermal water in the well is done in sections. In Figure 20b, a schematic representation of a section of a cemented wellbore is shown.

To determine the course of the thermal water pressure and temperature in the borehole, the water level "at-rest" is first calculated. It is calculated by dividing the prevailing reservoir pressure with the density of thermal water that is assumed to be constant along the well.

$$H_{TW}^{at-rest} = \frac{p_{reservoir}}{\rho_{TW}*g} \tag{1}$$

The water level is used to determine the pump position. Then, the pump position is used to determine the pressure and temperature increase caused by the pump to the correct wellbore section.

The thermal water pressure at the outlet of each wellbore section ($p_{TW,out}$) is obtained by means of the equation below.

$$p_{TW,out} = p_{TW,in} + \Delta p_{hydro} + \Delta p_{loss} + \Delta p_{pump} \tag{2}$$

The change in hydraulic pressure is determined according to:

$$\Delta p_{hydro} = \rho_{TW} * g * \Delta z \tag{3}$$

The pressure losses due to friction are given as (Oertel & Reviol, 2015) (Schlagermann, 2014):

$$\Delta p_{loss} = \frac{1}{2} * \rho_{TW} * u_{TW}^2 * |\Delta s| * \left(\frac{\lambda}{d_i^{casing}} + \zeta \right) \tag{4}$$

The thermal water density ρ_{TW} is assumed to be constant in sections, i.e. it varies over the length of the hole. $|\Delta s|$ describes the length of the pipe section as the absolute value of the difference of the measured depth. λ, represents the pipe friction coefficient and ζ, the drag coefficient.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

The pressure loss in the filter is defined as:

$$\Delta p_{loss}^{filter} = \frac{1}{6} * \rho_{TW} * u_{TW}^2 * \lambda * \frac{|\Delta s|}{d_i^{casing}} \tag{5}$$

with u_{TW} the velocity of the thermal water which sets itself at the nominal mass flow in the wellbore.

The thermal water temperature at the outlet of each wellbore section ($T_{TW,out}$) is obtained by means of the equation below.

$$T_{TW,out} = T_{TW,in} + \Delta T_{HE} + \Delta T_{pump} \tag{6}$$

with $T_{TW,in}$ inlet temperature, ΔT_{HE} the temperature difference as a result of the heat transfer to the ground and, if applicable, ΔT_{pump} the temperature difference generated by the pump.

In the DESTRESS techno-economic model, Ramey's (Ramey, 1962) approach is used to determine the temperature profile of a fluid injected into a borehole (ΔT_{HE}).

$$\Delta T_{TW} = T_{TW,in} - \frac{dT_{geo}}{ds} * \Delta s - T_{geo}(z = z_{out}) + \frac{dT_{geo}}{ds} * F(t) - \left[T_{TW,in} + \frac{dT_{geo}}{ds} - T_{geo}(z = z_{out}) \right] *$$
$$e^{\frac{-\Delta s}{F(t)}} \tag{7}$$

ΔT_{TW} represents the change of the thermal water temperature through a section in dependence with the measured depth (MD) s and the observation time t. T_{geo} is the temperature in the rock surrounding the borehole and z_{out} is the depth where the outlet of the respective section lies. $F(t)$ is a time function and can be determined by the following equation:

$$F(t) = \frac{\dot{m}_{TW} * c_{p,TW} * f(t)}{2 * \pi * \lambda_{geo}} \tag{8}$$

f(t) can be calculated by using the equation below:

$$f(t) = -ln\left(\frac{d_a^{casing}}{4 * \sqrt{a_{geo} * t}} \right) - 0{,}29 + \frac{\left(d_a^{casing} \right)^2}{4 * a_{geo} * t} \tag{9}$$

Another development compared to the technical model in (Welter, 2018) is on the production pump. Two technical solutions are on the market. In the past only electrical submersible pumps (ESP) were considered in techno-economic, whereas line shaft pumps (LSP) showed increasing relevance especially in the Upper Rhine Graben. For the determination of the temperature increase by friction losses within the production pump, a distinction is made between submersible pump (ESP) and line shaft pump (LSP).

$$\Delta T_{loss}^{ESP} = \frac{\Delta p_{pump} * (1 - \eta_{is} * \eta_{mot})}{\rho_{TW} * c_{p,TW} * \eta_{is} * \eta_{mot}} \tag{10}$$

$$\Delta T_{loss}^{LSP} = \frac{\Delta p_{pump} * (1 - \eta_{is})}{\rho_{TW} * c_{p,TW} * \eta_{is}} \tag{11}$$

η_{is} represents the isentropic efficiency and η_{mot} the motor efficiency of the pump. The specific heat capacity $c_{p,TW}$ and the density of the thermal water ρ_{TW} are calculated as described in (Francke, 2014).

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

3.3.5.4 Surface plant-technical model

A single-stage Organic Rankine Cycle (ORC) plant type is modelled within the power plant model. The pure provision of electricity, the simultaneous provision of electricity and heat (CHP - combined heat and power) are considered in the surface plant technical model. The flow diagram of the power plant mode (ORC) that is implemented in the technical model is shown in Figure 21. In CHP design, heat extraction can be connected in parallel or in series, or a combination of both (Eyerer, et al., 2017).
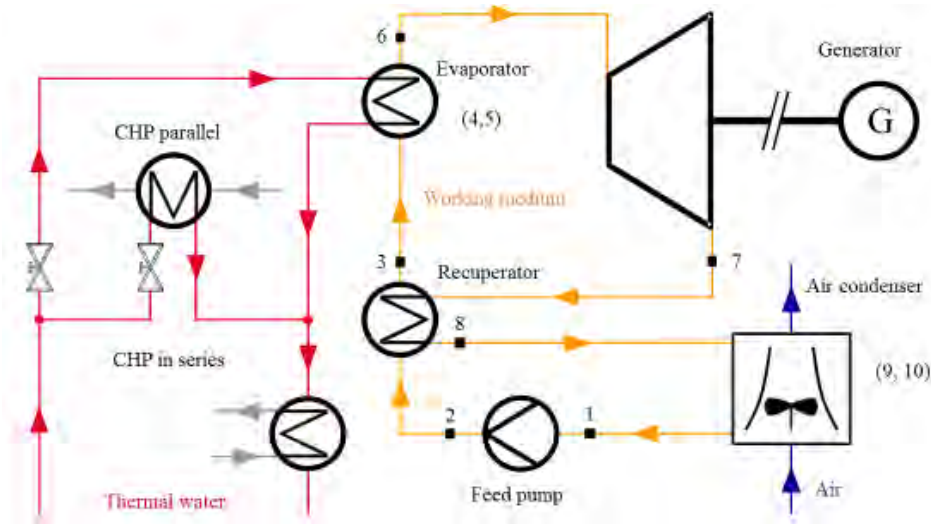
Figure 21: Schematic depiction of ORC with CHP

The power plant is consisting of the components of working medium feed pump, recuperator (optional), evaporator, turbine, generator and air condenser. Only air-cooled type condenser is considered in the model. A heat exchanger (HE) in parallel and series connection is provided. The changes of state (condensation, vaporization etc.) of the working medium between the state points shown in Figure 21 are determined within one of the sub-models named "BasicCycle.m".

Table 2: Overview of Monte-Carlo parameters power plant

Parameters	Upper limit	Lower limit
p_1	$0{,}5p_2$	$p(X = 0, T_{air,in})$
p_1	If $\quad T_{TW,in} - \Delta T^{min} < T_{crit} - \Delta T^{min}$ $\quad\quad p(X = 1, T = T_{TW,in} - \Delta T^{min})$ Else $p(X = 1, T = T_{crit} - \Delta T^{min})$	$1{,}5p_1$
T_6	$T_{TW,in} - \Delta T^{min}$	$T(X = 1, p_2 * \zeta_{evap} * \zeta_{cond})$
$\Delta h_{7,8}$	Pinch-analysis	$0 kJ/kg$
$T_{TW,out}$	$T_{TW,in} - 50K$	$55°C$

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

The working medium cycle (BasicCycle.m) MATLAB routine is evaluated based on the process parameters given in Table 2. For determining the temperatures, enthalpies and entropies of the working medium for the ten state points shown in Figure 21 the NIST database is used (Lemmon, Huber, & McLinden, NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties REFPROP, Version 9.1, 2013). A pressure drop of 2% is assumed in all heat exchangers (Chacartegui, Sanchez, Munoz, & Sanchez, 2009). The feed pump and turbine are modelled in the working medium cycle considering a firmly defined isentropic efficiency of 80% and 85% respectively and an efficiency of 96% for the motor and generator is assumed (Schlagermann, 2014).

In case of installation of a recuperator in the system, the "RecuperatorQuick.m" routine is mapped. Within this routine, state points 3 and 8 change with the recuperated heat. The heat exchangers are considered in detail to calculate the required heat exchanger area. The evaporator, condenser, recuperator and the heat exchanger or exchangers for heat extraction at CHP are simplified and modelled as shell-and-tube heat exchangers (SHE), which are operated in counter-current mode.

In modelling the evaporator MATLAB routine (Evaporator.m), as input variables, pressure, temperature and enthalpy of the working medium at inlet and outlet of evaporator as well as the composition of the working medium and properties of the thermal water at power plant inlet are required. The minimum permissible temperature of the thermal water after the evaporator must also be known ($T_{TW,out}$ -see Table 2) that is defined by the lower limit of the Monte Carlo parameters. As output, the heat transfer surfaces for preheating (A_{PH}), evaporation (A_{EV}) and overheating (A_{OH}), as well as the working medium mass flow are calculated. Furthermore, the mass flow rate of the thermal water required for combined heat and power generation in parallel connection and the temperature of the thermal water after the evaporator for both cases with and without heat extraction in parallel are calculated as the model output variables. The mass flow rate of the working medium and thermal water (for CHP parallel connection) are determined by using the temperature profiles of thermal water and working medium according to the pinch-analysis methodology (Kemp, 2007). The specific heat capacity of the thermal water $c_{p,TW}$ is assumed to be constant over the considered temperature and pressure range in all calculations. Based on the approach used in (Welter, 2018), this simplification is implemented.

For the condenser, the "Condenser.m" MATLAB routine is used to determine the condenser surface areas. Knowing the working medium mass flow rate as outcome of the evaporator routine simplified the procedure of the condenser routine. The heat transfer from the working medium flow to the air flow in the condenser is calculated according to the pinch-analysis methodology (Kemp, 2007). The air has different states in the condenser and these states are determined using the NIST database (Lemmon, Huber, & McLinden, NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties REFPROP, Version 9.1, 2013). For the fluid air, state equations of (Lemmon, Jacobsen, Penoncello, & Friend, 2000) are used. The viscosity and thermal conductivity of air that is provided by (Lemmon, Jacobsen, Penoncello, & Friend, 2000) are used. It is considered that the cooling air shall not heat up by more than 10K. The calculation of the fan power is done based on the manufacturer data (Systemair, 2018) and a valid EU directive (EU, 2009). The input variables of the condenser routine are the temperature, pressure and enthalpy of the working medium at state points 8 to 10, as well as the composition and mass flow rate. Besides, the inlet temperature and pressure of the air flowing through the condenser jacket, as well as the minimum temperature difference. As an outcome of the energy balance around the condenser, the mass flow rate and outlet temperature of the air. Also, the condenser surface areas and the fan power are determined.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

In the recuperator MATLAB routine, the temperature, pressure and enthalpy at the state points 2, 3, 7 and 8 as well as the composition of the working medium are used as input variables to determine the heat exchanger area. The recuperator model is the simplified version of the evaporator and condenser model.

The heat exchangers that are used for extracting heat and supplying pure heat correspond to the preheating section of the evaporator. For the outgoing and return flows in the heat network, constant temperatures of 70°C and 45°C are assumed respectively. If the pure heat supply application is regarded as the only option for the geothermal energy system, then no working medium circuit is implemented in the model. In this case, only one heat exchanger is considered for transferring heat to the network. Similarly, if the pure power generation application is regarded as the only option for the geothermal energy system, the heat exchanger routine needs therefore to be neglected.

3.3.5.5   Economic model

All the geothermal system properties required for economic evaluation that are determined in the technical sub-models and given in the corresponding economic sub-models (see Figure 19). For instance, the heat exchanger surface areas and the power of the components that are determined in the power plant technical sub-model are relevant to the cost estimations. In the economic sub-models, the capital investment and operational costs of the power plant, thermal water cycle and reservoir are determined. Based on these economic and technical parameters that are determined in the sub-models, the "Levelized costs of electricity" (LCOE) are calculated and used for the technical-economic evaluation of the overall system. The LCOE are calculated with the equation below.

$$LCOE_{net} = \frac{I_0 + Z + \sum_t^{tmax}(1+i)^{-t} * (C_{Operation} - R)}{\sum_t^{tmax}(1+i)^{-t} * \tau v * P_{el,net}} \qquad (12)$$

with I_0 as the investment costs and Z as the interest during the construction period. Due to the time lag between the start of the construction and the commissioning of the power plant, the investment costs are incurred before the start of the period under consideration (t_{max}). They are referenced to the beginning of the period under consideration by means of the construction period interest rate Z. The calculatory interest rate i of 7%, including income taxes, is estimated using the method of (Konstantin, 2017). For a detailed description of this procedure, please see (Welter, 2018). The average annual operating costs are described with $C_{Operation}$. The parameter R is used in the CHP mode and represents the annual income from the secondary product, e.g., if the main product is electricity, then R is the secondary revenue from selling heat. Furthermore, v symbolizes the annual full load hours for power generation at the power plant and $P_{el,net}$ its net electrical output, meaning the power fed into the grid minus its own consumption. Revenues only accrue in the power plant part but not in the thermal water circuit or reservoir part.

$$I_0 = I_0^{Powerplant} + I_0^{TWcircuit} + I_0^{Reservoir} \qquad (12)$$

$$Z = Z^{Powerplant} + Z^{TWcircuit} + Z^{Reservoir} \qquad (14)$$

$$C_{Operation} = C_{Operation}^{Powerplant} + C_{Operation}^{TWcircuit} + C_{Operation}^{Reservoir} \qquad (15)$$

$$R = R_{Powerplant} \qquad (16)$$

The calculated annual costs and revenues are modified over the period under consideration with the aid of nationally resolved producer price indices (EUROSTAT, 2018a) or consumer price indices (EUROSTAT, 2018b) in order to consider price increases over the period under consideration.

In the case of a system has fixed electricity remuneration, it might be more economical to purchase the electricity instead of using the one produced in-house for its own- electricity consumption. For this case, the gross LCOE should be calculated according to equation below.

$$LCOE_{gross} = \frac{I_0 + Z + \sum_t^{tmax}(1+i)^{-t} * (C_{Operation} + C_{Electricity} - R)}{\sum_t^{tmax}(1+i)^{-t} * \tau v * P_{el,gross}}$$ (17)

The costs of the purchased electricity $C_{Electricity}$ are calculated with the electricity meter.

In the case of pure heat generation, the "Levelized costs of heat" (LCOH) are calculated.

$$LCOH = \frac{I_0 + Z + \sum_t^{tmax}(1+i)^{-t} * (C_{Operation} + C_{Electricity} - R)}{\sum_t^{tmax}(1+i)^{-t} * \tau v * \dot{Q}}$$ (18)

with V for the full load hours of the heat generation of the power plant.

As far as possible, the module costing technique is used in the calculation of the investment costs I_0 that is developed for estimating the costs of chemical plants (Turton, Bailie, Whiting, Shaeiwitz, & Bhattacharyya, 2013). The method is also widely used for energy plants, such as ORC plants in (Welter, 2018), (Schlagermann, 2014), (Astolfi, 2014), (Collings, Yu, & Wang, 2016), (Wang, Li, Li, & Wu, 2015) and (Toffolo, Lazzaretto, Manente, & Paci, 2014). In (AACE, 2016), it is stated that such cost estimations may differ from real costs by around -20% to +30%. The investment costs I_0 of the "Power/heat plant (ORC)" are approximated by using the methodology according to (Turton, Bailie, Whiting, Shaeiwitz, & Bhattacharyya, 2013). The operating costs of the "Power/heat plant", in contrast to the investment costs, are incurred continuously during operation and are reported as annual costs. They are influenced by price increases as well as interest rate effects. Price increases are included using the arithmetic mean of consumer price indices between 2010 and 2017 (EUROSTAT, 2018a). Several assumptions are made for the operating costs of the geothermal power plant: insurance costs against electronic and machine breakdowns, maintenance and repair costs and costs for other operating resources accounts for 0.6%, 3%, and 1% of the investment costs, respectively. Business interruption insurance accounts for 0.6% of the annual income. In addition, personnel costs are assumed to be EUR 130,000 per year for plants with a thermal output of less than 30 MW and personnel costs of around EUR 180,000 are assumed for larger plants. These assumptions are based on the values used in (Welter, 2018).

The module costing method (Turton, Bailie, Whiting, Shaeiwitz, & Bhattacharyya, 2013)) is not used to calculate the price of the components of the thermal water circuit, due to the lack of suitable correlations. Instead, correlations according to (Welter, 2018) and (Schlagermann, 2014) are used to determine the various cost items. In relation to the thermal water circuit, the costs for maintenance, insurance and other operating costs are considered as operating costs.

The investment costs of the reservoir are estimated on the basis of (Welter, 2018) and (Schlagermann, 2014), whose cost information is largely derived from expert knowledge in the geothermal sector. The operating costs of the reservoir are incurred for the seismic monitoring of the reservoir. These costs are estimated at around EUR 40,000. The costs of liability insurance are estimated around 90,000 EUR

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

per year. The public relations need to be maintained during operation and approximately EUR 40,000 per year are required for that ((Welter, 2018); (Schlagermann, 2014)).

Besides the main technical models "Power/heat plant", "Thermal water circuit" and "Reservoir" a special focus is put on the approaches for stimulation costs and the line shaft pump, as these correlations didn't receive much attention in techno-economic modelling for geothermal energy systems, yet.

Stimulation Costs

All costs associated with stimulation are listed in Table 3. The cost categories and items are formed based on the actual soft stimulation jobs carried out in different demonstration sites of the DESTRESS Project.

Table 3: Overview of Stimulation Costs

Cost Category	Cost item	Cost Type
Mob / Demob & Rig up / Rig Down	Mob / Demob	I_0
	Rig Cost	I_0
	Rig-up / Rig-down Equipment	I_0
	Rental of Equipment	I_0
	Coiled tubing	I_0
	Pumps	I_0
	BOP	I_0
	Storage Tanks	I_0
	Downhole tools	I_0
	Cross-over	I_0
	Crane	I_0
	Cleaning of Equipment	I_0
	Packers	I_0
	Packers Transport	I_0
	Packer Personnel	I_0
	Perforation subs.	I_0
	Fuels	I_0
	Transport liner	I_0
	Personnel	I_0
	Transport of Equipment	I_0
Chemical	Water Supply	I_0
	Chemicals	I_0
	Additives	I_0
	Solids	I_0
Cleaning/Waste Management	Water Disposal	I_0
	Disposal of Fluids	I_0

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

	Cleaning of Equipment	I_0
	Rental of Equipment	I_0
	Personnel	I_0
	Storage Tanks	I_0
Stimulation Treatment	Risk Assessment	I_0
	Stimulation	I_0
	Equipment	I_0
	Rental of Equipment	I_0
	Reaming	I_0
	Add Work	I_0
	Running CT String	I_0
	Mud Pump	I_0
	Pumping Services	I_0
	Personnel Costs for Fracking	I_0
	Crew Costs	I_0
	Water Filter	I_0
	Consumables	I_0
	Lab & Workshops	I_0
	Fuels	I_0
Supervision / Planning	Permitting	I_0
	Legal Administration	I_0
	Financial Administration	I_0
	Site Supervision	I_0
	Technical Planning	I_0
	Data Analysis	I_0
	Personnel	I_0
Logging / Wellsite Preparation	Road Construction	I_0
	Infrastructure	I_0
	Well Head	I_0
	Well Head Assembly	I_0
	Logging	I_0
	Crane for Logging	I_0
	Testing	I_0
	Site Assessment	I_0
	Sampling	I_0
	BHTV/Temp/NPHI/gamma	I_0
	Excavator	I_0
	Drill Pad	I_0
Others	Seismic Monitoring	I_0

	ATLS (Advanced Traffic Lights System)	I_0
	Geophonchain	I_0
	ISOR / Survey Service	I_0
	Seismic monitoring	$C_{Operation}$
	Maintenance	$C_{Operation}$
	Liability insurance	$C_{Operation}$
	Public relations work	$C_{Operation}$

Some cost functions presented by (Reith, Hehn, Mergner , & Kölbel, 2017) based on the experience of projects in France are also used in the economic model.

For detailed cost information, please see the published report of DESTRESS Deliverable 2.2: "Key performance indicator analyses based on Monte Carlo simulation".

Line Shaft Pump Costs

Most of the downhole production pumps are installed at depths below 300 m in central European conditions i.e. the Upper Rhine Graben. Under these types of operating conditions, the only available LSP on the market is ITT GOULDS LSP. The first oil lubricated downhole geothermal LSP in Europe was operated in 2007 in Landau, in 2012 in Insheim, in 2016 in Rittershoffen and Soultz-sous-Forêts. Capital expenditures (CAPEX) of LSP of the Rittershofen geothermal heat plant was investigated in detail by ES-Geothermie. CAPEX in euros is estimated via the formula below. The cost of strainer, pumps, lubstring, production column, discharge wellhead, wellhead thermal compensator, surface pump supporting, electrical motor, frequency driver, lubrication system and connection, installation preparation, installation at depth and start-up is included in this CAPEX.

$$CAPEX(z, P_{hydro}) = 470000 + 700 \times z + 225000 \times (\frac{P_{hydro}}{450})^{0.67} \tag{19}$$

with z the setting depth in meters and P_{hydro} the hydraulic power of the pump in kW.

The operating costs of LSP are mainly consisting of its electrical consumption. Oil bearing consumption and maintenance of surface equipment are the other operating costs. The oil for lubrication represents an operational expenditure of nearly 16 k€ per year including oil recycling. During geothermal plant shut down every 4 months, motor and line shaft must be uncoupled and coupled during start-up procedure. Therefore, crane and maintenance operations are required, representing about 6 k€ per shut down over 1 day. The surface mechanical seal must be replaced every two years, which costs about 6 k€ for the spare part. Bearings of the electrical motor also must be replaced every 5 years during a long shut down period. The costs of such an operation are nearly 15 k€. Based on this data, annual OPEX of downhole geothermal LSP can be estimated with formula below.

$$OPEX(T_{operating}, P_{elec}, P_{hydro}) = \frac{P_{hydro}}{0.7} \times P_{elec} \times T_{operating} + 28000€ \tag{20}$$

with P_{elec} the electrical consumption of the pump in kW.

Key Performance Indicators (KPIs)

Key Performance indicators pay an important role in the techno-economic investigations. Multiple KIPs are usually used by decision makers to assess a decision alternative. Below, the main KPI that are used for the economic evaluation in this report are listed.

- Levelized costs of energy (LCOE)
- Internal rate of return (IRR)
- Net present Value (NPV)
- Payback-Time (PBT)
- Net electrical power $P_{el,net}$
- Gross electrical power $P_{el,gross}$
- Thermal power P_{th}
- Investment costs

All KPIs are calculated dynamically. The term dynamic is often simplified to a consideration of the inflation. But dynamic means the discounting of a series of payment. Whether calculations are done with or without inflation depends on investigated time frame as well as techno-economic evaluation rules of organization that investigates a project (Konstantin, 2013). Investigated time frame of an evaluation must be defined individually. One could either orientate oneself on legal/political, technical or economic frame conditions. The development of renewable energies in Europe was highly supported by the legal/political schemes. One of these schemes is feed-in-tariff that is valid in the course of a defined time frame. There is currently a feed-in-tariff system in France that is valid for 15 years, while renewable energies are supported in Germany with feed-in-tariff system over 20 years (Ravier, 2019) (Bundesministerium für Justiz und Verfassungsschutz, 2018). The feed-in-tariff is defined individually per power plant (225 €/MWh for Soultz) in France; whereas in Germany there is a general feed-in-tariff of 252 €/MWh (Ravier, 2019) (Bundesministerium für Justiz und Verfassungsschutz, 2018). From a techno-economic point of view, time frame of a geothermal project is defined based on useful lifetime of cost-intensive components of overall power/heat plant. A period of 30 years is unanimously chosen for geothermal projects in the literature ((Hondo, 2005), (Frick, Kaltschmitt, & Schröder, 2010) and (Schlagermann, 2014)). Therefore, a period of 30 years as time frame is considered in this report to ensure comparability with other investigations.

4   Conclusions

In this report, an overview is presented on some major presumed differences between the E&P industry practice and the geothermal industry practice. The topics addressed include:

- Data acquisition
- Well stimulation practice
- Exploration and 3D seismic data acquisition
- Public acceptance
- Integrated Asset Modelling
- Investment Decision Analysis
- Updating of knowledge

The main difference in practice, in our opinion, is caused by the difference in the commercial perspective between the two industries. The geothermal industry seems more of a "high risk / low to medium reward" and local/regional type of business proposition, whereas the E&P may be qualified

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

as "high risk / high reward", with a strong international focus. The impact this has on decision-making could be significant. We suspect that the E&P industry has a more long-term value maximization type of approach, with the geothermal industry focusing more on short-term cost minimization. Apart from the difference in nature of the two industries (hydrocarbons production vs. heat or electricity production), this will have an impact on what type of data is acquired, how the data is analyzed, how investment decisions are made, and how the day-to-day practice is run.

In this report, we suggest some possible changes in practice that in the future may become beneficial to the geothermal industry as they would gradually move from a "high risk / low to medium reward" with a local / regional business focus, to a more "high risk / high reward" international focus.

Apart from differences between the E&P industry practice and the geothermal industry practice, a procedure on conducting technical and economic feasibility studies of geothermal projects including soft-stimulation techniques is presented. The architecture of the DESTRESS techno-economic model, model equations and cost correlations are provided. The techno-economic model developed in DESTRESS combines cost correlations with technical models of reservoir, thermal-water circuit and surface plant to assess the technical and economic performance of a geothermal power plant. Besides, uncertainty caused by risk factors of soft stimulation measures is integrated into the techno-economic modelling by following the single steps of the decision analysis approach.

The techno-economic model described in this report has more efficient algorithms compared to the model in (Welter, 2018) based on which it is developed. While maintaining the general structure, selected correlations are updated to map the reality intimately. New cost functions are introduced in the economic model, e.g. the representation of LSP and the updated stimulation cost functions. The model given in (Welter, 2018) is restricted to the German geothermal market; however, evaluation of different geothermal sites with the techno-economic model presented in this report is possible.

The main task in Work-Package 2 is the overall improvement of techno-economic evaluation in geothermal energy provision. This goal is reached by the development steps of the DESTRESS techno-economic evaluation model. These development steps are:

- The decision analysis approach
- The integration of risk factors into techno-economic modelling
- Power plant optimization with the Monte-Carlo
- The possibility to simulate heat, CHP and pure power provision in one model (consistent evaluation)
- New approaches in cost engineering

The DESTRESS techno-economic model has room for improvement by future research, even though it has many advantages over existing technical-economic models. Several future research questions can be derived from the investigations presented in this report:

- The focus of DESTRESS is on risk factors; however, future model developers could identify and implement uncertain model parameters
- Cost engineering models applied in the DESTRESS techno-economic model must be adapted to current market developments.
- The air condenser in the ORC is designed as a shell and tube heat exchanger in the model, although it has a different geometry. Therefore, the geometry of air condenser could be adapted to improve the technical simulation.

DESTRESS
Demonstration of soft stimulation treatments
of geothermal reservoirs

- Uncertainty increases the risk for possible investors. Further uncertainties could be integrated into techno-economic model to have a more robust configuration.

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Demonstration of soft stimulation treatments
of geothermal reservoirs

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Project Lead	GFZ German Research Centre for Geosciences Telegrafenberg 14473 Potsdam (Germany) www.gfz-potsdam.de/en/home/
Project Coordinator	Prof. Ernst Huenges huenges@gfz-potsdam.de +49 (0)331/288-1440
Project Manager	Dr. Justyna Ellis ellis@gfz-potsdam.de +49 (0)331/288-1526
Project Website	www.destress-h2020.ch
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