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# Risk factors within techno-economic evaluation of soft-stimulation measures

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## ABSTRACT

Stimulation treatments are often the only means to meet economic and sustainability requirements for a geothermal project. Nevertheless, stimulation is expensive, due to varying natural conditions not always successful and sometimes coupled with negative environmental impacts. The “soft stimulation” concept applied within the DESTRESS-project aims at minimizing environmental impact and increasing success rate. Thereby social acceptance and economic efficiency shall be increased to enable market uptake of EGS. Market uptake is inseparably linked with a promising business case. Besides the application of soft stimulation measures DESTRESS therefore also puts a focus on the techno-economic evaluation including risk factors (e.g. uncertainty in technical parameters). The present paper will show the methodology and first results of the integration of risk factors into techno-economic modelling. Inspired by the decision analysis approach, probabilistic evaluation based on risk factors can improve project evaluation by supporting investment decisions through a statistical data basis. For the integration of risk factors an integrated simulation model is developed that maps the whole geothermal circuit process (production – utilization – injection) technically and economically on a highly detailed level. First results presented in this paper include risk factors of soft stimulation measures, the integration of risk factors into the simulation as well as the representation of the technical effects of soft stimulation. The research leading to these results has received funding from the European Union’s Horizon2020 Research and Innovation Program under grant agreement No 691728 (Project DESTRESS).

## 1. INTRODUCTION

In December 2015, the community of nations agreed at the Paris climate conference, binding under international law, on a limitation of anthropogenic climate change. The Paris climate agreement entered into force at the $4^{th}$ of November 2016. The aim is to limit global warming to a maximum of 2 °C compared to the pre-industrial level. Exploited in a closed loop cycle, geothermal power can provide renewable energy with only limited environmental impact. To access the whole potential of geothermal energy besides hydrothermal also petrothermal reservoirs have to be developed. In Germany e.g. 95 % of the technical potential of geothermal power is stored in petrothermal reservoirs (Paschen et al, , 2003). Petrothermal reservoirs normally show an economical unattractive transmissibility. Therefore measures have to be applied that enhance the natural structures to a level that is economically viable. So called enhanced geothermal systems (EGS) are intended to improve productivity (or injectivity) of a geothermal reservoir by increasing the overall transmissibility of the used reservoir. An enhancement can be achieved by various measures depending on the geological setting. Important criteria for the selection of a specific method are the rocks, the rock structures, the tectonic situation as well as the stress field. Besides the initial enhancement of the system the sustainable operation poses another challenge to the profitability of a geothermal power plant. Existing or enhanced fractures may close again due to reduced reservoir pressure. Precipitation through fluid rock interactions can have a similar effect on the transmissibility of the reservoir.

Initial as well as sustainable stimulation measures are facing public acceptance issues. During hydraulic stimulation high well head pressures are applied and large fluid volumes are injected. This can cause seismic events big enough to be felt at the surface. Not only since the seismic events in Basel and St. Gallen (Deichmann, Giardini, 2009; Moeck et al., 2015) the public discussion on seismicity is slowing down the development of geothermal projects in central Europe. The same is valid for chemical stimulation, which has also become a public topic in the course of fracking bans in multiple European countries following the shale gas development in the USA. These issues will be addressed by the DESTRESS research project. The project aims at developing EGS taking into account the site-specific geological requirements. Thereby three main goals shall be achieved. The initial transmissibility shall be increased and maintained while seismicity and other environmental impact shall be minimized. The market uptake of the investigated measures is inseparably linked with a promising business case. On the one side stimulation measures are sometimes the only mean to make a natural geothermal reservoir economically viable. On the other side stimulation is expensive, due to varying natural conditions not always successful and sometimes coupled with negative environmental impacts that could cause an erosion of public acceptance. Therefore it is important to follow a comprehensive approach in project evaluation and decision making. This includes up- and downsides but also the uncertainty on risk factors. Risk factors can be found in technical parameters (e.g. permeability, temperature gradient), costs (capex/opex), legal and social issues (time delays, permits etc.). Additionally uncertainty in modelling is often overlooked, as technical parameters in equations (e.g. parameterization, upscaling uncertainty) or the framing of the uncertainty space could cause uncertainty in modelling results.

The techno-economic evaluation of energy provision is not only an important task for project developers but also for energy economy research and public bodies. Efficiency and effectivity are in this context targets that should not only be strived for from a technical point of view but should include an economic component. Also in geothermal energy techno-economic evaluations have been performed since many years. Thereby two main research questions can be separated. While on the one hand a comprehensive investigation of geothermal energy in general is in the focus, there are also studies that are investigating single technical or economic details and their effect on the techno-economic performance. Optimization possibilities can be found in all parts of geothermal power conversion. (Held et al., 2014) investigated the effect of multi-well field management at the EGS-plant in Soultz based on a detailed finite-element model of the reservoir. They were able to show a superiority of multi-well systems on a techno economic basis. Other authors like (Reith, 2015) investigated the reservoir exploration as access to the source of geothermal energy from a techno-economic point of view. The author compared different drilling concepts and found multilateral wells to be the best strategy for reservoir development. But he emphasized that the calculations were done without considering risk factors. A purely technical investigation of this issue can also be found in (Sanyal et al., 2007a). Many publications also deal with the selection of working fluids as one of the main parameters determining the conversion efficiency. Noteworthy are e.g. (Kang et al., 2015), (Li et al., 2014) or (Heberle and Brüggemann, 2016). All mentioned authors put a special focus on zeotropic mixtures. (Heberle and Brüggemann, 2016) can show for a source temperature of 150 °C that the zeotropic mixture isobutene/isopentane performs the best of all investigated working fluid mixtures from a techno-economic point of view. Another option for increasing the operation efficiency is a supercritical cycle. (Astolfi et al., 2014) found that configurations based on supercritical cycles are able to further decrease levelized costs of electricity. Besides the conversion efficiency the operation of a geothermal power plant poses additional challenges to research and operators. (Lecompte et al., 2014) raise awareness to the part load operation of ORC-cycles. Combined heat and power provision as another option for optimizing the techno-economic performance of a plant is investigated by (Heberle et al., 2011) or (Van Erdeweghe et al., 2017). In general a reduction of levelized costs of electricity through the provision of heat can be observed. For all presented publications economic modelling translates technical data into economic figures. The bare-module-costing approach (Turton et al., 2013) enables a detailed modelling for most aspects besides drilling costs. For this important part of total costs, different approaches based on drilling length or time per job are used (Lukawski et al., 2014; Yost et al., 2015). Drilling costs are one of the most sensitive parameters of techno-economic evaluation in geothermal energy provision (Guth, 2011). Therefore uncertainties have more severe effects than in other cost items (Yost et al., 2015; Weimann, 2011). Recently this important field of research was investigated more closely e.g. by (Silverman et al., 2014; Yost et al., 2015; Lukawski et al., 2016). The multitude of research fields touched by the above mentioned publications shows the interdisciplinary character of geothermal energy provision. Therefore an integrated evaluation including production reservoir, production wellbore(s), energy conversion, injection wellbore(s) and injection reservoir in a closed loop approach is needed. This situation has already been addressed in the past. Next to multiple approaches focused in one single project, (Olasolo et al., 2016) identified and described two approaches that have been developed continuously with a focus on EGS projects. Parallel to the development of the Soultz-sous-Forêts EGS project (Heidinger et al., 2006) developed the HDRec software package to evaluate economics as a part of the scientific work at the French site. Because of constraints of HDRec mainly in terms of programming language and new technical developments (Heidinger, 2010) presented EURONAUT for evaluating, hydrothermal, EGS, doublet or multi-well systems. A similar development can be observed with the MIT-HDR model that was originally created on simulation models dating back to the 80's. This model was extensively used in (Tester et al., 2006) for investigating the technical potential of EGS in the USA as well as doing techno-economic evaluations of current and future EGS applications. Major steps forward in modelling have been done for the economics of well drilling as well as in energy conversion. Based on this (Beckers et al, 2014) further developed economic correlations for well drilling and completion, resource exploration and power conversion. Additionally new key figures were introduced as levelized costs of heat. (Yost et al., 2015) state that geothermal projects are facing several technical and financial uncertainties. (Sanyal et al., 2007) mapped these uncertainties through a Monte-Carlo-simulation on capital costs of drilling, stimulation, power plant and surface facilities, O&M costs, interest rate and inflation rate. This enables a probabilistic evaluation of LCOE. The probabilistic techno-economic evaluation shows an increasing attention also in other fields of energy provision as can be seen in (Lee et al, 2017; Welkenhuysen et al, 2017). (Daniiöidis et al., 2017) evaluate a geothermal district heating project including uncertainties. Their probabilistic approach maps the initial reservoir state, geological and operational conditions as well as economic uncertainties. In an evaluation of ex-post and ex-ante key figures it becomes obvious that the evaluated projected is only economic in 50% of all simulated cases. These results form a statistically sound basis for an investment decision.

The preliminary literature research revealed, a gap in research that shall be closed in the course of the DESTRESS project. Integrated techno-economic models are the most appropriate to the interdisciplinary character of geothermal energy provision. Integrated models are available, but still have room for further development. EURONAUT (Heidinger, 2010) e.g. needs an update on economic as well as technical issues. GEOPHIRES (Beckers et al., 2014) as another well developed software package is not directly applicable to the European markets. These and other software packages lack the possibility of probabilistic evaluation, which is especially true for minimally invasive stimulation measures as they are proposed by the DESTRESS consortium. It becomes obvious that technical, economic and social risk factors of stimulation measures are neither investigated in detail nor mapped in integrated techno-economic models. Therefore a current integrated model (Reith, 2018) will be enriched by DESTRESS research results and other developments in techno-economic modeling of geothermal energy provision. The overarching research goal is the evaluation of minimal invasive stimulation measures under consideration of technical, economic and social risk factors.

Hereinafter chapter 2 explains the methodological background of the decision analysis approach that forms the framework of the techno-economic research in theDESTRESS project. Additionally the applied risk assessment approach is explained with a special focus on prioritization of risk factors through the risk map and the conditional-value-at-risk approach. Chapter 3 will be used for the introduction of the used model, giving a general overview with a special focus on the mapping of uncertainties. Afterwards chapter 4 will show first results and further research goals.

## 2. BUSINESS CASE EVALUATION SUPPORTED BY PROBABILISTIC STATEMENTS

Market uptake of enhanced geothermal systems is inseparable connected to the economic application of stimulation measures. The Basel (Switzerland) EGS-project (Häringer et al., 2008; Mignan et al., 2014) showed that stimulation measures on their current technical level are still connected to technical, economic and also social uncertainties. One lesson learned from the Basel project cancelation is that the public won't tolerate noticeable environmental effects as induced seismicity. Therefore DESTRESS investigates minimal invasive so called "soft stimulation" approaches that shall minimize the environmental footprint. "Soft stimulation is a collective term for geothermal reservoir stimulation techniques. It aims to achieve enhanced reservoir performance while minimizing environmental impacts including induced seismicity. Soft stimulation includes techniques such as cyclic/fatigue, multi-stage, chemical and thermal stimulation" (DESTRESS, 2016).

A company willing to sustainably operate an EGS-plant close to densely populated areas therefore will have to include uncertainties and risk factors into their techno-economic decision process. Decision analysis as a structured approach of comparing different alternatives is able to integrate risk factors into the evaluation process and allows within its normative approach the selection of the best possible alternative. Figure 1 gives an overview of the methodological approach of decision analysis. The methodological approach starts with framing the problem. As a first step possible decision alternatives, the goal of the investigation as well as the investigated system has to be defined, which includes a spatial and temporal definition of the investigation frame. First ideas on the technical and economic representation of the investigated system should be developed. This mainly serves as a basis for a qualitative investigation of sensitivities, uncertainties and risk factors. Therefore different techniques from strategical management like mind map, dependency structure analysis and relevance analysis can be applied. These techniques serve as tools for the identification and prioritization of input parameters (Reith et al., 2017). -Through the qualitative nature of this step subjectivity should be minimized through employing a group of experts from different fields (Laux et al., 2012; Almeida et al., 2015; Bos, Wilschut, 2011). As a second step, setting-up the model means defining a programming language as well as further clarification of the frame conditions. This includes, based on the framing process, an in-advance planning of input/output variables and finally the development of the model. The Monte-Carlo-Simulation has proven itself as a valuable methodology to combine deterministic and stochastic input variables. The type of input variables (deterministic/stochastic) thereby also decides on the evaluation process. For a stochastic survey the use of decision criteria like the μ-rule or the (μ,σ)-rules are possible (Laux et al., 2012). With respect to the frame conditions the identified decision alternatives are then investigated with the developed model. The defined key performance indicators afterwards serve as evaluation basis for the different alternatives. Lastly, a revision of the results shows their significance and reveals possibly necessary adaptions. In the revision step the gained results are verified. The conformity of the results with the frame conditions should be validated. Conducting a quantitative sensitivity analysis often is a valuable step to evaluate the results and maybe adapt the frame conditions. Loops over the previous steps can become necessary to improve the quality of the decision. Afterwards the decision can be taken based on the criteria defined in the framing process.

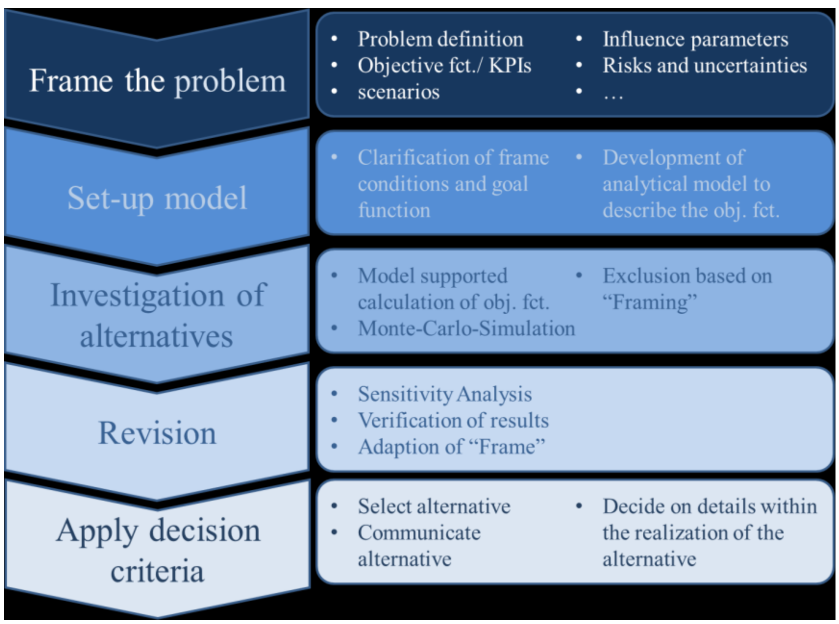



**Figure 1: Decision analysis steps (Own representation based on: Laux et al., 2012; Almeida et al., 2015; Bos, Wilschut, 2011)**

Part of the framing step is the risk analysis. The semi-quantitative approach presented here, consists of identification, prioritization and evaluation of risk factors. Risk factors are features, events or processes that could prevent/enable a project to reach its goals. The uncertainty caused by these risk factors is later mapped in the techno-economic model. Practical limitations in modelling (e.g. computing time, physical complexity …), the size of the uncertainty space or simply the availability of data limit the risk analysis process (Abrahamsson, 2002). Figure 2 shows the risk analysis process as it has been executed for the presented study. An ideal basis for risk assessment would be a detailed database with information on frequency and effect (preferably monetary) of risk factors. In geothermal energy such a database is not publically accessible. Therefore the presented approach mainly relies on expert knowledge. The so called "educated guess" is a group interview technique often applied in identification, prioritization and evaluation of risk factors. Especially in cases of unavailability of data or for rare events this methodology delivers a sound data basis (Bos, Wilschut, 2011). An expert elicitation also forms the basis for the first step of the risk analysis as shown in Figure 2. (Holthaus, 2007; Jakoby, 2013) demand for a structured approach when identifying risk factors. They suggest e.g. in-/outflow graphs. The presented study used a project plan with the different project phases to have a structured approach and to ease the identification process. The amount of identified risk factors is strongly linked to the frame conditions of the investigated question and the expert group doing the identification. The group should be inhomogeneous and consist of experts from all relevant fields.

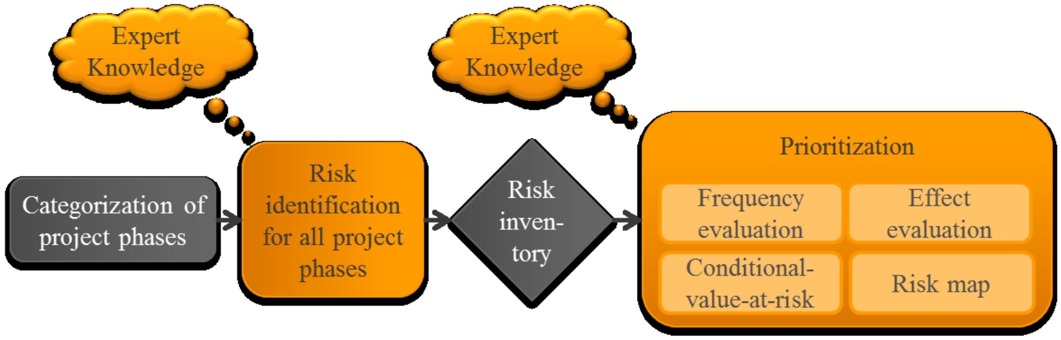



**Figure 2: Risk analysis consisting of identification and prioritization of risk factors**

It is impractical or even impossible to evaluate all identified risk factors in a model based approach (Bos, Wilschut, 2011). Therefore, before applying complex simulation models, risk factors have to be prioritized. A structured approach for the prioritization step is the so called risk or heat map. The effect of a risk factor is shown as a function of the frequency of occurrence in a two axis diagram. Risk factors are prioritized based on the combination of highest probability of occurrence and highest effect. The weakness of this tool lies in the reduction of the frequency distribution of a risk factor to one single value for the probability of occurrence and the connected effect (Ale et al., 2012). The uncertainty on the concrete effect of a risk factor is described by a probability distribution function (PDF). By reducing the information to a binominal distribution a lot of the information gets lost. The strength of a risk map on the other side is the easy and understandable presentation of results as well as the possibility to filter risk factors without an in-deep modelling. To use the risk map a value for probability and effect have to be found that represent the PDF of a risk factor.

Risk as an integrative key figure can either be defined broad or narrow (see Reith et al., 2017). (Bos, Wilschut, 2011) use the narrow definition and define risk as probability of occurrence times undesired impact. As undesired, one can define all manifestations of a PDF of a risk factor, that are worse than a defined base case. Although an improvement compared to the base case is desirable, most project developers will rather be interested in the downside of uncertainty. From this interest situation the probability value in a risk map can easily be identified by expert elicitation. For given risk factors and base case, experts are asked to estimate the probability of receiving results worse than the base case. Figure 3 shows the described methodology for a fictive normal distribution of a temperature gradient.

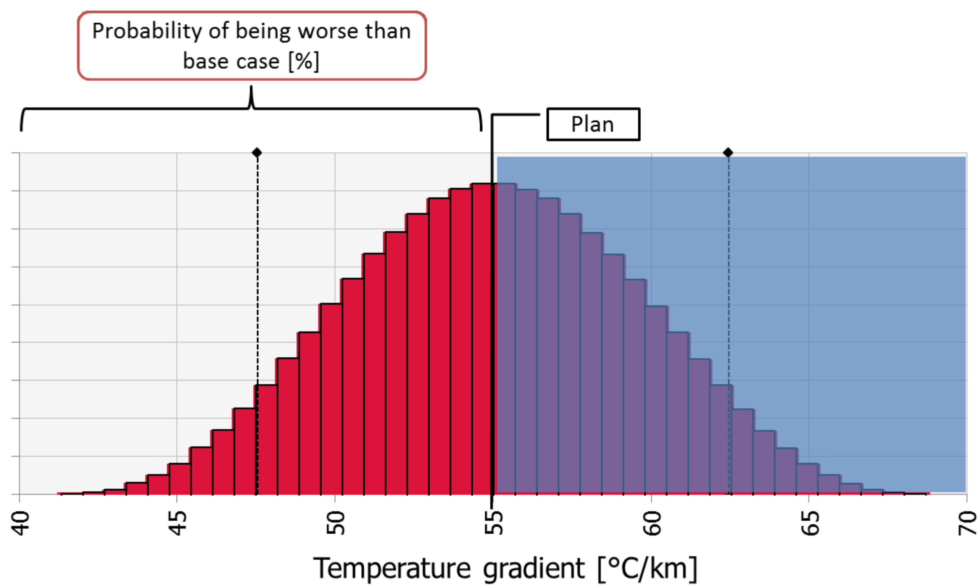



**Figure 3 Methodological approach for the the determination of the porbability of occurence for a risk map conform evaluation**

While a binominal probability for the risk map tool can be derived out of the interest situation of decision makers, a sound binominal value for the effect of a certain risk factor is more difficult to determine. (Brünger, 2011) introduced the conditional value at risk (CVaR) approach from financial mathematics into the risk map methodology. The CVaR describes the expectation value of a loss of an investment above or below a defined percentile (see formula (1)).

$$\alpha \in (0,1);\ CVaR_{\alpha} = E\big(X \big| x > Plan(X)\big)$$

In addition to the already defined base case, an additional deterministic low case and an assumption on the possible form of a probability distribution between these two cases has to be defined. Based on this information one can calculate the CVaR as stated in equation (1). The expectation value below the base case is a sound statistical key figure, which represents the nature of the unknown probability distribution through a value that can be used as binominal distribution. The prioritization of risk factors within the "risk map"-tool is conducted by assuming the CVaR to be the effect of a binominal distribution. Figure 4 shows the above explained methodology for the example of a temperature gradient. Based on expert elicitation, two deterministic cases (base, low) are defined. A base case with 55 °C/km and a low case with only 40 °C/km are defined by expert elicitation. Following the law of large numbers, with a growing number of random experiments the distribution function of experimental results tends towards a normal distribution. Therefore in Figure 4 a normal distribution was used. For this normal distribution between 40 °C/km and 55 °C/km the expected value can be calculated.

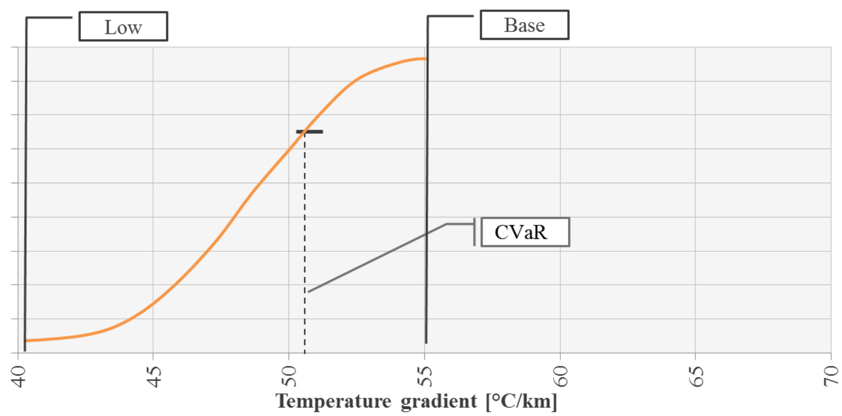
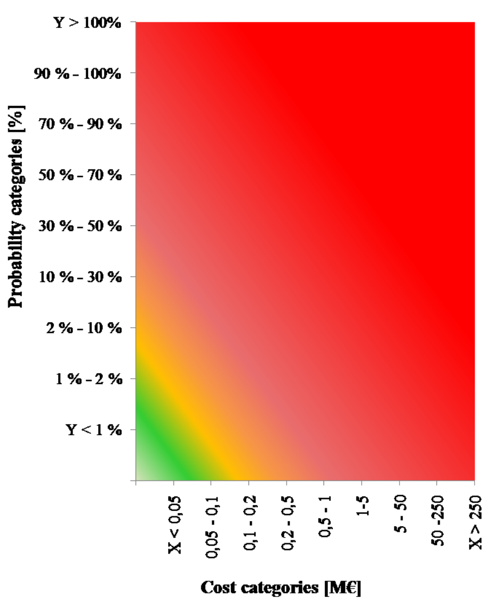



**Figure 4: Example for the application of the conditional-value-at-risk approach**

Based on the aforementioned methodology (see Figure 3 and Figure 4) risk factors can be prioritized in the "risk map" shown in Figure 5. The axes are clustered in categories that are also shown in Figure 5. The categories were chosen based on the requirements of an evaluated project. Other distributions are also conceivable (e.g. logarithmic) but should fit to the evaluated case and should allow an easy understanding for the involved experts. As mentioned before, for the prioritization of risk factors the negative side of uncertainty is more interesting. Therefore the effect is measured in costs caused by risk factors. For non-integer results as the average of an expert elicitation the numeration of the categories can be used to map the results. The risk factors on the most upper right corner of the risk map have to be prioritized. Following the Pareto-principle, the top-10 risk factors have shown to be a good basis for an in-deep evaluation.




| Financial evaluation | |
|---|---|
| 1 | X < 50 T€ |
| 2 | 50 T€ < X < 100 T€ |
| 3 | 100 T€ < X< 200 T€ |
| 4 | 200 T€ < X< 500 T€ |
| 5 | 500 T€ < X< 1 M€ |
| 6 | 1 M€ < X< 5 M€ |
| 7 | 5 M€ < X< 50 M€ |
| 8 | 50 M€ < X< 250 M€ |
| 9 | X > 250 M€ |

| Probability evaluation | | |
|---|---|---|
| 1 | Y < 1 % | Rarer than 1 in 100 projects |
| 2 | 1 % < Y < 2 % | Rarer than 1 in 50 projects |
| 3 | 2 % < Y < 10 % | Rarer than 1 in 10 projects |
| 4 | 10 % < Y < 30 % | Rarer than 1 in 3 projects |
| 5 | 30 % < Y < 50 % | Rarer than 1 in 2 projects |
| 6 | 50 % < Y < 70 % | Rarer than 2 in 3 projects |
| 7 | 70 % < Y < 90 % | Rarer than 9 in 10 projects |
| 8 | 90 % < Y < 100% | Rarer than each project |
| 9 | Y > 100% | Several times within each project |

**Figure 5: Risk map and evaluation categories**

For the prioritized risk factors a PDF has to be found. For technical input parameters like permeability PDF's are sometimes published in literature (see e.g. (Stober and Jodocy, 2009)). PDF's showing costs of risk factors as effect or rather soft/regional risk factors like public acceptance normally have to be constructed by expert elicitation as no data is publically available. Following the ideas published in (Kaplan and Garrick, 1981) the real but unknown PDF of a risk factor can be approximated by a discrete PDF. Through the definition of several discrete cases expert elicitation can be used to identify effect and probability of each case. Sorted in a distribution function it is possible to approximate a real PDF. Figure 6 shows on the example of a normal distributed temperature gradient the explained methodology. Four cases are defined that can be evaluated by experts. Relative to the base case, the uncertainty connected to the risk factor "temperature gradient" is mapped to the negative as well as to the positive side. The decrease of the expected temperature gradient is investigated more detailed so that minimal expectations for an economic operation of a plant can be defined. Based on the PDF's of the prioritized risk factors the impact of uncertainty on the techno-economic key figures can be simulated through a probabilistic, techno-economic model that is presented in chapter 3.

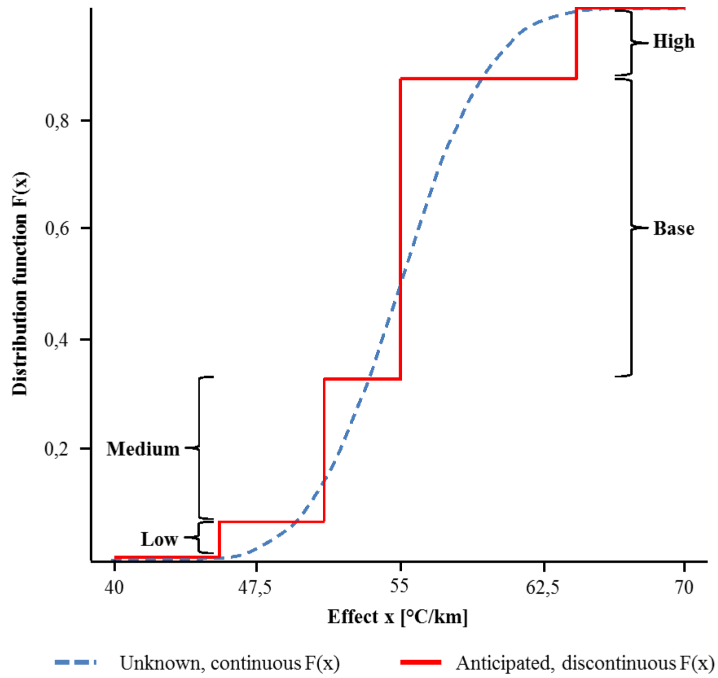



**Figure 6: Anticipation of continious distribution function by discrete distribution function (own figure)**

## 3. TECHNO-ECONOMIC EVALUATION OF GEOTHERMAL POWER AND STIMULATION MEASSURES

Deep geothermal plants are characterized by a complex cycle process. From the production of thermal water as source of energy, to the above ground energy conversion to the re-injection of the cooled thermal water, multiple interactions have to be considered. For this reason, an integrated simulation model is further developed within the scope of the present work. All areas of geothermal energy supply are mapped technically and economically, which enables an evaluation of technical measures.

Figure 7 shows the merging of various sub-models into an integrated model for the techno-economic simulation and analysis of the electricity and heat supply from low enthalpy areas considering risk factors. Starting from producing brine out of the aquifer to the transport in the thermal water circuit, the cooling of the brine in the power plant up to the reinjection of the thermal water into the aquifer, the technical sub-models simulate all technical process steps. Additionally the integrated model includes the economic sub-model and the evaluation of risk factors. Thereby a detailed technical-economical description takes place along the whole process. The technical simulation is carried out for a quasi-stationary state at defined state points. Uncertainties caused by risk factors are integrated into the overall model with the help of stochastic procedures. The economic sub-model enables a systemic evaluation of the technical model results based on the electricity production costs. Investment costs, maintenance and operating costs are determined on the basis of technical input parameters.

In the context of the present work approaches, methods and functions are developed, adapted from literature or further developed and finally bundled into an integrated model. The various sub-models are implemented in MATLAB®. Interfaces exist for the substance database REFPROP® (Lemmon et al., 2013). REFPROP® is used as part of the power plant model as it provides validated data on a wide variety of substances and mixtures over a wide range of states and can be integrated into MATLAB® through a direct interface. The investigations of stochastic influences will also be implemented in MATLAB® to have an identical data basis and to minimize couplings to other software solutions. The proposed integrated overall model contains both non-linear causal relationships and discrete decision variables, so that optimization using linear optimization methods would not be effective. Heuristic optimization approaches are able to integrate the above-mentioned framework conditions and to approach an optimal solution with manageable computation times. However, the claim of optimality is thus abandoned (Domschke, Scholl, 2006; Fink, Rothlauf, 2006). Parameter variations can be used, for example, to approximate optima in the power plant or reservoir model.

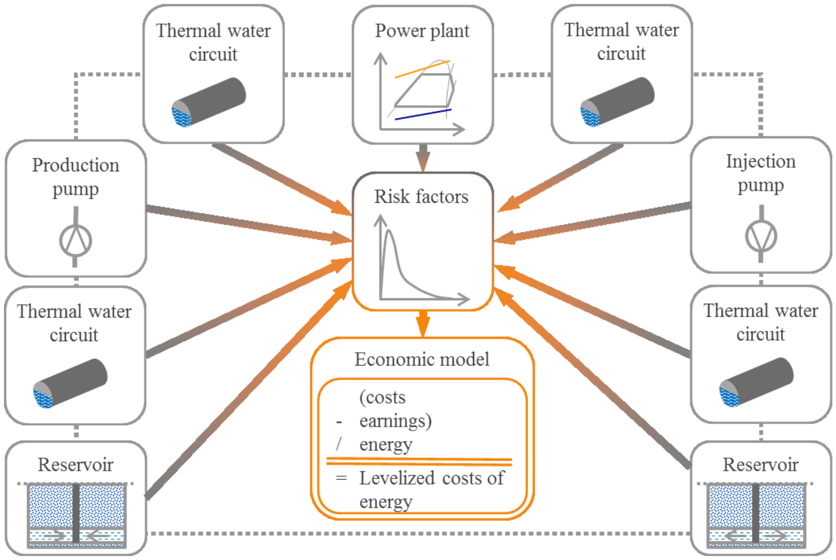



**Figure 7: Combination of different sub-models into an integrated, techno-economic model**

**Reservoir simulation**

(Reith, 2018) was able to show that the hydraulic connection between reservoir and wellbore has a considerable effect on the overall techno-economic performance of a geothermal plant. For the evaluation of stimulation measures the representation of hydraulics is particularly important. On the contrary the physical modelling has to fit for purpose especially when doing a Monte-Carlo-Simulation. Hydraulic, thermal and chemical stimulation measures mainly focus on improving the connection between wellbore and reservoir. Through drilling residues the near wellbore area can be contaminated by drilling mud or cement. The contaminations can cause an additional pressure loss $\Delta P_S$, the so called skin-effect $s_F$, that can be expressed as shown in equation (2) (Tareke, 2002). Thereby $\Delta P_T$ is the total pressure loss meassured in a pumping test, $\Delta P$ the natural pressure diffusion described by the law of mass conservation, Darcy's law and the equation of state.

$$\Delta P_T = \Delta P + \Delta P_S$$

The additional drawdown $\Delta P_S$ caused by the skin factor is proportional to the flow rate and can be described by equation (3) (Krusemann, de Ridder, 1994). In equation (3), $s_F$ represents the dimensionless skin factor, Q the brine flow rate and T the transmissivity of the reservoir.

$$\Delta P_s = s_F * \frac{Q}{2\pi T}$$

Within the presented model $\Delta P$ is calculated by the Theis equation (see (Krusemann, de Ridder, 1994)) for vertical wells. Deviated wells are mapped by the approach presented in (Williams, 2013) with the Theis equations as underlying basement. For multilateral wells the mathematical approach of superposition is used on the Williams' approach.

**Thermal water circuit and thermal water pumps**

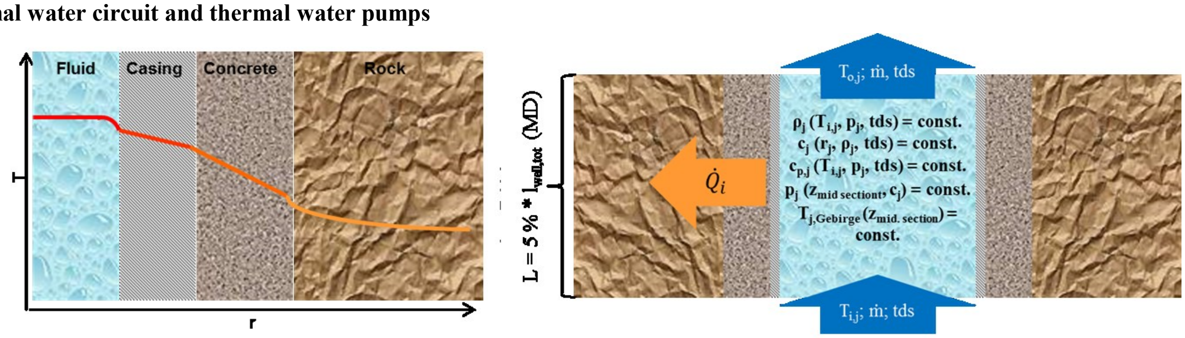



**Figure 8: Calculation of temperature losses in sections for the thermal water circuit**

The thermal water circuit above and below ground level is modelled as a multilayered hollow cylinder with heat losses to the formation or the air. Between the different layers a perfect coupling is assumed. Physics of the thermal brine are considered by the model presented in (Francke, 2014) for a one phase flow. Pressure losses are described according to the Bernoulli equation. Technical components, wall roughness and flow type are considered based on literature values (see Reith, 2018). Temperature and pressure increase in the thermal water pumps is also considered within the simulation. To map the assumption of a one phase flow and to represent the operation conditions of existing binary power plants an operation pressure above 20 bars is assumed to reduce degassing.

**Power plant**

The DESTRESS project demonstration sites are situated in so called low enthalpy areas. Relatively low temperature and pressure at the wellhead within these geological plots make binary systems necessary for energy conversion. The binary systems for heat, power or combined heat and power (CHP) provision are simulated for defined state points in a steady state observation based on energy balances of the individual power plant components. It is assumed that there is an adiabatic cyclic process. By considering isentropic efficiencies, finite strains, and pressure losses in the heat exchangers, the simulation approaches reality. Besides pure working fluids, zeotropic mixtures are also investigated to improve the energy conversion efficiency. Heat provision is compared to power provision technically easy to realize but from an operational point of view heat demand curves have to be followed by the geothermal power plant. Therefore heat demand curves are integrated in the techno-economic model.

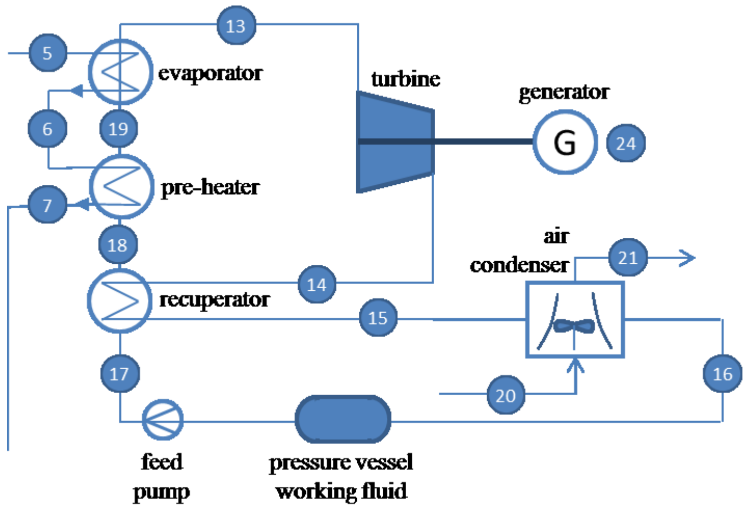



**Figure 9: Simulation of power plant process for defined state points**

**Economic model**

For the evaluation of technical measures economic key performance indicators (KPI) like internal rate of return (IRR) or present value (PV) can be used. The origin of these KPIs is in business administration. In energy economics a KPI with a background in economics has become widely used. Levelized cost of energy (LCOE) can be calculated either for electricity or heat as well as for CHP. Different energy provision technologies or technical measures for the same technology can be compared based on technical performance and costs without the uncertainty of future energy prices. Equation (4) gives the LCOE formula following the VDI 2067 norm. The investment costs $I_0$ are accumulated to a fixed point of time t = 0 by the construction period interests (CPI) while the demand related cost $C_{dr}$, the operation related costs $C_{or}$, the other costs $C_{other}$ and the earnings E are discounted for the economic life time of the project $t_{eco}$ with a given interest rate i. Following the methodological approach of LCOE the provided energy also has to be discounted to t = 0. Dividing costs and earnings by the provided energy one derives the LCOE

$$LCOE_{net} = \frac{I_0 + CPI + \sum_{t_{eco}=1}^{t_{eco}=n} \frac{C_{dr,t_{eco}} + C_{or,t_{eco}} + C_{other,t_{eco}} - E_{t_{eco}}}{q_{t_{eco}}}}{\sum_{t_{eco}=1}^{t_{eco}=n} \frac{W_{el,net,t}}{q^{t_{eco}}}}$$

$$with$$

$$q = 1 + i$$

To be able to map the effect of technical measures on economics, a detailed economic sub-model is necessary. In literature this problem is solved by a parameter-dependent cost calculation approach, which is originating from the chemical industry. (Turton et al, 2013) present the so called module-costing approach. The total costs of an installation are estimated on the basis of the costs of its main components and the aggregation of the individual components in the overall system is assessed by additional factors. The individual components are scaled in relation to characteristic quantities and adapted to the technical parameters derived from the process simulation by means of addition factors for e.g. material and pressure. This approach has been followed for all components where literature data is available. If necessary, adaptions specific to geothermal energies were done. If no literature data for the module costing approach was available, own cost functions were developed or taken from literature.

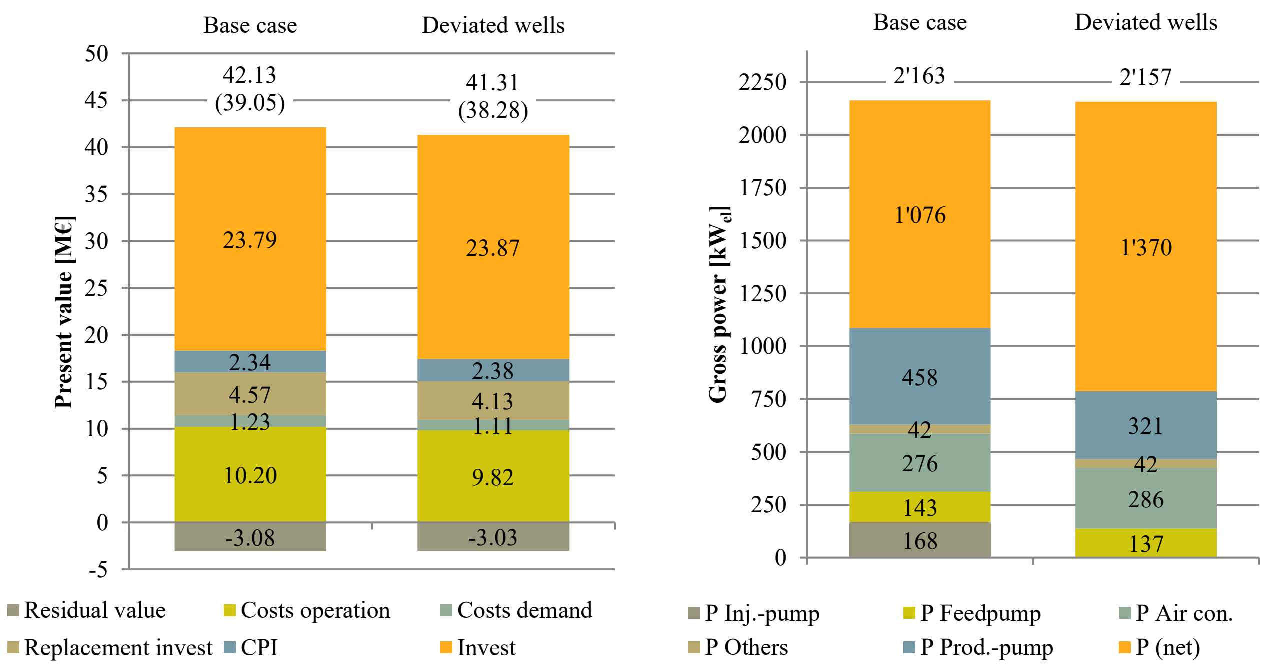
**4. RESULTS**

(Reith, 2018) validated the technical parts of the model presented in chapter 3 on published data of existing power plants. Therefore, among others measured data gathered at the geothermal research power plant Bruchsal (Germany) was used. Hereinafter a fictive geothermal plant in the style of the Bruchsal geological and technical frame conditions is constructed to show general deterministic findings on reservoir connectivity and utilization factor of geothermal energy. The location of the plant is about 20 km northeast of the city of Karlsruhe (Germany) on the east side of the Upper Rhine Graben. The geological structure of the Upper Rhine Graben is characterized by an above-average temperature gradient, in addition to its strongly split structure, especially at the lateral edges of the valley. Thereby it represents a geological structure that is also used through the DESTRESS sites Rittershofen and Soultz-sous-Forêts. General frame conditions of the fictive plant at the Bruchsal site are given in Table 1.

**Table 1: Frame conditions of the fictive geothermal plant at the Bruchsal site – base case**

| Name | Unit | Value |
|---|---|---|
| Volume flow thermal water | $m^3/s$ | 0.085 |
| Reservoir temperature production | °C | 132.8 |
| depth production well | m | 2542 |
| Reservoir temperature injection | °C | 119.0 |
| depth injection well | m | 1877 |
| Number of wells | # | 2 |
| Reservoir exploration method | - | Vertical drilling |
| Power plant entrance temperature | °C | 125.9 |
| Working fluid | - | R236fa |
| Total desolved solids (GB2) | g/l | 125 |

The effect of stimulation measures on the connection between wellbore and reservoir will be modelled in detail within the DESTRESS project. The results for modelling as well as the experimental proof for the different stimulation measures and sites will be available in the course of the DESTRESS project. Besides stimulation measures a better connection between reservoir and wellbore can also be achieved through different exploration methods. Compared to reservoir exploration through vertical wells, as assumed in the base case presented in Table 1, deviated wells increase the reservoir connection area of the wellbore. Figure 10 shows the results of the techno-economic evaluation of an exploration with deviated wells compared to vertical wells (base case).

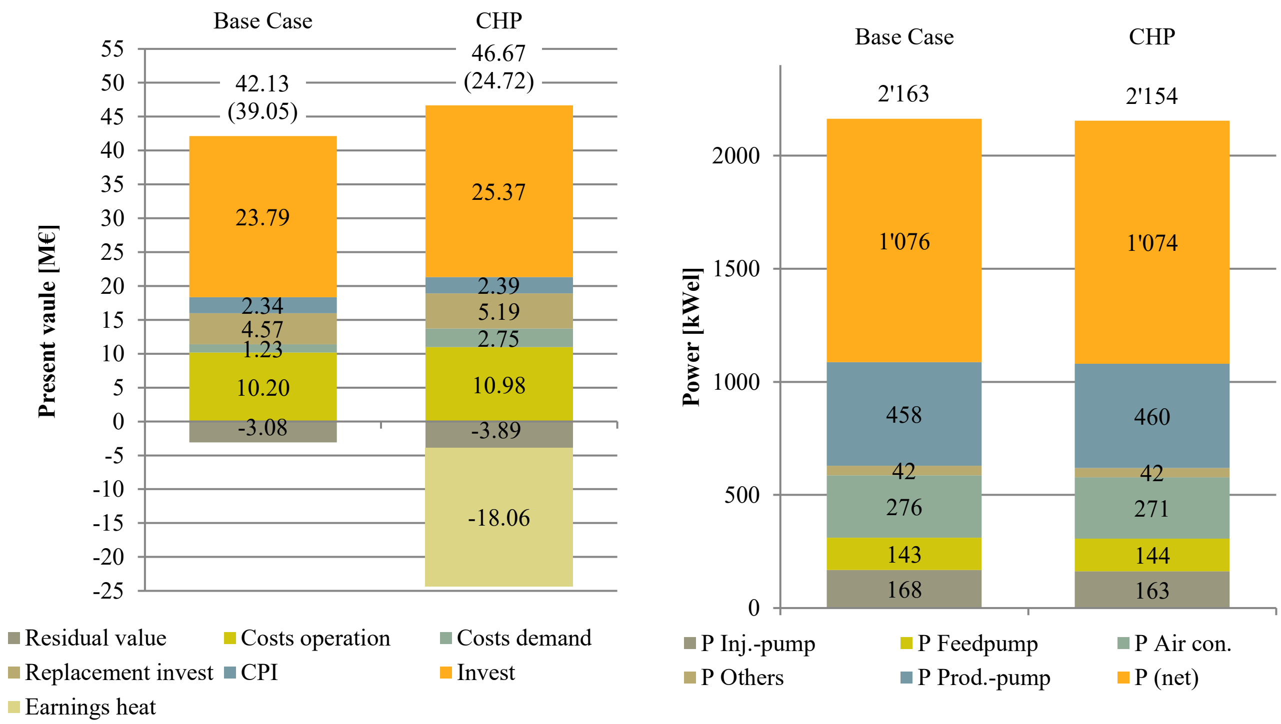



| | Present value [M€] | Δ-% | Net power [kW$_{el}$] | Δ-% | Levelized costs of energy [€/kWh] | Δ-% |
|---|---|---|---|---|---|---|
| Base case | 42.13 | | 1’076 | | 0.21 | |
| Deviated wells | 41.31 | -1.9% | 1’370 | 2.,3% | 0.16 | -23.0% |

**Figure 10: Techno-economic evaluation of exploration with deviated wells compared to vertical wells (base case)**

Figure 10 shows the present value and the net electrical power as economical and technical key performance indicators for the effect of deviated wells compared to the base case. The present value only shows a slight decrease of 1.9 %. In contrast to this overall trend, power plant costs are increasing by 1.8 % and exploration costs increase by 9.15 % because of longer wells. This contrary trend is surprising because exploration costs have the highest share in total investment costs (42.9 %). At the same time a significant reduction of around 30 % in thermal water pumps (less power) and thermal water circuit (no above ground connection pipeline) compensates the cost increase. While economically there are no major changes, the technical simulation shows a considerable increase of the net power observed KPI by 27.3 %. The model simulates a hydraulic coupling between production and injection well. The deviation of the wells increases the connection area between wellbore and reservoir. This leads to a reduction of the power demand for injection and production pumps. In the overall techno-economic evaluation, the decrease of the parasitic losses leads to a reduction of LCOE by 23 %. Thereby it is possible to show that expenses for an improvement of reservoir connection like stimulation measures can be justified in a techno-economic evaluation.

The exact opposite can be observed, when investigating CHP for increasing the utilization factor. In Figure 11 it can be seen that the net power only shows negligible changes through the integration of CHP, while the present value is increasing by 10.8 %. Thereby the increase in present value is mainly due to the additional investment in a heat plant. At the same time the earnings through heat provision reduce the expenses by 18.06 M€. In total, the initial increase turns out to be a reduction by -36,7 % if one includes residual value and earnings. Although the gross, net power and parasitic losses don't change considerably the provided electrical and thermal energy shows considerable changes as shown in Figure 11. Over the investigated operation period of 30 years, the simulated geothermal plant provides 815 $GWh_{th}$ of heat. The provided thermal energy adversely affects the provided electrical energy. In comparison to the base case a reduction of around 30 % can be observed. The described developments finally lead to a decrease of the LCOE by 17.5 %.




| | Present value [M€] | Δ-% | Net power [$kW_{el}$] | Δ-% | LCOE [€/$kWh_{el}$] | Δ-% | Discounted .el. energy [$GWh_{el}$/30a] | Δ-% | Discounted th. energy [$GWh_{el}$/30a] |
|---|---|---|---|---|---|---|---|---|---|
| Base case | 42.13 | | 1'076 | | 0.21 | | 189 | | - |
| CHP | 46.67 | 10.8% | 1'074 | -0.2% | 0.17 | -17.5% | 131 | -30.4% | 816 |

**Figure 11: Techno-economic evaluation of CHP compared to a pure electrical energy provision (base case)**

The above presented investigations on the improvement of reservoir connectivity and the increase of utilization factor show for a deterministic investigation that there is considerable improvement potential in geothermal energy provision. Within the DESTRESS project these investigations will be enriched by a detailed investigation of stimulation measures as well as a probabilistic methodological approach.

The basis for the probabilistic methodological approach is the identification and evaluation of uncertainties. As presented in chapter 2, for the DESTRESS project this shall be achieved through risk factors. Within the risk identification process shown in Figure 2 thirty-seven risk factors were identified through expert elicitation. The bandwidth of risk factors is thereby very broad. Starting from organizational issues like delays or problems with permissions, also technical and social risk factors like the interaction between rock and fluid or public acceptance were identified through expert elicitation. To enable a fit for purpose evaluation of risk factors a preliminary prioritization was conducted. The results of the prioritization process are shown in Table 2. As being most important for the probabilistic evaluation of stimulation measures in Europe, the experts identified public acceptance. Next to public acceptance risk factors connected to political or permission issues could have an important impact on the success of the project. The expert elicitation also identified induced seismicity as one of the main risk factors causing uncertainty in geothermal projects applying stimulation measures. From a technical point of view the effectivity of stimulation measures also was an important issue. Thereby no as well as unwanted chemical/physical effects could severely affect the project. The presented risk factors will be further evaluated in terms of their PDF in the course of the DESTRESS project. Through the PDFs of the prioritized risk factors the uncertainty in the techno-economic model will be mapped.

**Table 2: Prioritized risk factors for soft stimulation meassures**

| # | Phase | Risk | Description of cause | Description of effect |
|---|---|---|---|---|
| 1 | ALL Phase | Public Acceptance | Citizen groups or NGO's being against the project (impact of accidents occurred in other Project sites) | Loosing permission, strong delay, loss of bankability (after planning before drilling) |
| 2 | Project Development | Lack of information | Lack of information in engineering →extra data needed for planning the stimulation, | More/additional measuring effort → redesign based on the new information, |
| 3 | 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 |
| 4 | ALL Phase | Change in legislations | Accident occurred in another project, additional extensive seismic monitoring and precautions etc. needed | Losing permission, strong delay, not receiving permission |
| 5 | 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 |
| 6 | Injection | Loss of effectivity | Injection pressure damages casing/cement | Not achieving the expected permeability increase, loss of project (becomes uneconomic) |
| 7 | 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 |
| 8 | 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, production $H_2S$ and other gasses |
| 9 | ALL Phase | Political Instability | Change in the government on all levels of politics that could affect the project | Losing permission or get extra official requirements |
| 10 | Project Development | Lost in hole (measuring tool) | Logging with loss of tool, purely related to soft stimulation and the additional data needed | Workover or fishing needed, Losing the well, delay |

## 5. CONCLUSION

In this paper we presented a software tool and a methodological approach for the probabilistic evaluation of geothermal energy provision with a focus on low-enthalpy resources. First an introduction into decision analysis as methodological framework for the evaluation of soft stimulation was given. Within the decision analysis approach a probabilistic evaluation is possible. The uncertainty within a model is mapped through single parameters, so called risk factors. The identification and prioritization of risk factors has been explained in detail. Thereby the risk map as a tool for the prioritization of risk factors was presented. The risk map enables an easy prioritization of risk factors. At the same time, through the binominal input parameters the probabilistic information on a risk factor gets lost. Therefore an approach was presented that enables the prioritization of risk factors on a sound statistical basis. For this purpose the conditional value at risk approach is used. Additionally an integrated techno-economic model was presented to evaluate the effect of stimulation measures on the basis of levelized costs of energy. The closed loop approach of the presented simulation model maps all parts of a geothermal plant. Starting from the production reservoir, through the thermal water circuit to the energy conversion and the injection reservoir a detailed, technical simulation is performed. In the future the simulation results are used to calculate expenses and earnings connected to the investigated geothermal plant. Within the paper the general structure was presented as well as important technical and economic correlations were given.

The integrated techno-economic model was used on two case studies to show the effect of an improved hydraulic connection between wellbore and reservoir as well as the effect of enhancement of the utilization factor in geothermal energy. Although the exploration method was changed from vertical to deviated wells, the improvement of hydraulic connectivity didn't have major effects on the investment costs. The more important effect was revealed by the technical model. The efficiency of the system increased as the effort for production and injection of brine was reduced . The decrease of parasitic losses through thermal water pumps led to an increase of the net power. Combined provision of heat and power increases the utilization of the available energy. As the model is backed by load duration curves, part and full load situations are investigated. Therefore the design of the power plant (net power) changes only slightly. However, the provided thermal energy reduces the total electrical energy considerably. The additional costs for the provision of heat are over compensated through the earnings from heat sale, so that CHP turns out to be a good measure for the techno-economic improvement of geothermal energy. Under the investigated technical and geological circumstances the hydraulic reservoir connection improves the LCOE relative to a defined base case by 23.0 % while CHP enables an improvement of 17.5 %.

The results presented in this paper clearly depend on the hydraulics of the reservoir, temperature and salinity of the brine, the energy conversion as well as multiple other technical and economic correlations, parameters and assumptions. For the evaluation of the techno-economic performance of soft stimulation measures a probabilistic analysis will play an important role to map the uncertainty connected to the investigated techniques. Therefore the presented risk factors will play an important role in the future work. Besides results on the evaluation of PDFs for soft stimulation future work will show improvements in the techno-economic modelling and statements on the techno-economic evaluation of soft stimulation measures.

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