Maury *et al. Geothermal Energy* (2022) 10:26
https://doi.org/10.1186/s40517-022-00238-y

Geothermal Energy

RESEARCH Open Access

Development of a risk assessment tool for deep geothermal projects: example of application in the Paris Basin and Upper Rhine graben

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Abstract

This paper presents the development of a tool to perform risk assessment for deep geothermal projects. The tool is aimed at project developers to help them present their project to local authority, decision-makers and financers so they can highlight how they take into account risks and consider mitigation measures to minimize them. The main criteria for this tool are the simplicity of use, the quality of presentation and flexibility. It is based on results from the H2020 GEORISK project that identified risks that apply to geothermal projects and proposed insurance schemes all over Europe. A characteristic of this tool is that it considers all the categories of risks that a project may face, including geological, technical, environmental risks as well as risks related to the social, economic and political contexts. The tool can be customized: selection of risks in a list that can be completed, adaptable rating scheme for risk analysis, possibility to choose the best display for results depending on the user needs. Two case applications are presented, one in the Paris Basin considering a doublet targeting the Upper Trias, a geological layer that presents some technical challenges; and one in the Upper Rhine graben targeting a fault zone, where the risk of induced seismicity must be carefully considered. A posteriori risk assessment highlights the main issues with these types of projects, and the comparison between the two cases emphasizes the flexibility of the tool, as well as, the different ways to present the results depending on the objective of the analyses.

Keywords: Risk assessment, Risk matrix, Deep geothermal, Upper Trias, Paris Basin, Upper Rhine graben

Introduction

Deep geothermal energy production represents in Europe 3.5 GWe for geothermal electricity (139 powers plants) and 5.7 GWth for geothermal district heating (350 geothermal heating systems in operation) (EGEC 2021). In the context of reducing the energetic carbon footprint and of increasing the part of renewable energy sources, deep geothermal energy represents a high potential in Europe. Indeed, development of geothermal energy is a necessity to pursue the national objectives for decarbonation (e.g., the French

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multi-year energy plan targets an increase in geothermal energy production for heating from 2 TWh in 2020 to 4 TWh in 2028). The main levers to achieve this are better resource identification and assessment, cost reduction, and minimization of the risks associated with the development of deep geothermal energy projects.

Among these levers, robust risk management and mitigation will help improve geothermal project success, attract investors and improve trust. Risk is a barrier to geothermal uptake, specifically during the development phase where the investments are large and the risks important, especially in unknown contexts (Immolauer and Ueltzen 2021). Several definitions of risk exist; here we mean an event preventing the proper development of the project considering the economic, geological, technical, environmental, political and social points of view (Le Guénan et al. 2019). An event often has multiple causes and consequences. It is necessary to understand all of them in order to estimate the risk properly. For instance, induced seismicity is a risk event. It can be provoked by different causes: perturbations due to drilling, stress changes due to fluid circulations, variation of fracture resistance due to geochemical phenomena, etc. It may have technical and environmental consequences and engender public opposition. These aspects can lead to the termination of a geothermal project, with strong economic consequences (Basel, Switzerland: Häring et al. 2008; Californië, Netherlands: Heege et al. 2020; Vendenheim, France: Schmittbuhl et al. 2021). However, when well-managed, successful projects can be realized (Helsinki, Finland: Ader et al. 2020; Rittershoffen, France: Gaucher et al. 2020).

The ISO 31000 standard about risk management describes the process and is not prescriptive about the method. Thus, each developer can have its own risk management method which lead to much diversity. In the field of geothermal energy, published risk analyses are often focused on a specific phase or category of risk. Gombert et al (2021) give an inventory and risk assessment with likelihood and severity of the main environmental risks that have occurred in deep geothermal projects for the past 70 years. Some authors proposed specific tools to assist risk assessment of geothermal project. Nador (2018) proposed a transnational toolbox in the framework of the DALINGe Interreg program. This toolbox is composed of three parts: (i) a tool for benchmarking geothermal projects with the definition of relevant indicators (14) that cover 5 topics: management, technology and energy, environmental, social and economic; (ii) a decision-tree which classifies the project according to the UNFC-2009 (Geothermal Working Group 2016) at different stages of their life; and (iii) a risk mitigation scheme with the definition of potential damages (19) and proposed risk mitigation measures. A'Campo and Baisch (2020) developed a tool for ultra-deep geothermal EGS projects. The entrance data are the classification of the project parameters such as gas content, mudweight or reservoir pressure from very high to very low values. A threat that can generate an event is then ranked according to this classification. From this, the likelihood of an event is estimated by multiplying the ranking of a threat by the relative contribution of this threat to the event. The advantage of this tool is that the risk is well defined from the characteristics of the site. However, a good technical knowledge is necessary to implement it and it is based on a small number of projects so further validation is needed even if changes are possible for advanced users to account for it. Another aspect of their method is that they separate the seismic risk from other risks, using an existing tool to rank seismic risk. In

the same way, a risk analysis has been performed for the stimulation phase of a deep geothermal project in the framework of the H2020 DESTRESS project (Peterschmitt et al. 2018). However, even if this approach explains the process to make it reproducible, it remains project specific in the sense that the risks identified are specific to each project.

In view of the existing methods to perform a risk analysis and in the framework of the H2020 GEORISK project (H2020 Georisk project 2021), we identified the need to propose a risk assessment and mitigation tool that would deliver a complete view of the project risks, with ranking of the risks and identification of technical mitigation measures. The result is the development of a risk assessment tool (https://www.georisk-project.eu/georisk-tool/) that aims to be helpful for project developers to appreciate their project with confidence in a holistic approach and it would help them communicate with stakeholders about the risks. This tool: (i) provides a comprehensive—and editable—list of risks considered for all phases of a project; (ii) integrates different ranking levels as it is often project dependent (based on the level of knowledge); (iii) allows to realize several consecutive risk ranking for a same project with several plots; (iv) is downloadable as an excel sheet: https://github.com/ThomasLeGuenan/Georisktool/releases/tag/v2.1. To add flexibility, instead of a list of risks valid for only one phase or a particular geological context, we chose to provide a global list of risks that can serve as a base for any type of geothermal project. Likewise, the ranking of the different risks and their consequences may depend on a project, so we opted for a user-dependent ranking. The ranking is semi-quantitative with score, but the tool also proposes a prototype of the risk register using probabilities with the aim to go towards a fully quantitative risk analysis. In the following sections, the tool is presented and two examples of application are given on typical projects in the Paris Basin and the Upper Rhine Graben (URG). In the last section, a discussion is given about the benefits and limitations of this toolbox.

Presentation of the tool

Risk management according to ISO31000

The developed tool is loosely based on the principles of ISO31000[1] For clarity, we recall here some vocabulary as defined in the norm. According to the norm, risk assessment is a part of risk management and is composed of the following steps:

- Risk identification
- Risk analysis
- Risk evaluation.

The main outcome of the risk identification step is a list of risks. These risks are "scored" (qualitatively or quantitatively) in the risk analysis step, commonly with probability and magnitude of loss. The risk evaluation step serves to guide decisions: are the risks acceptable or should mitigation measures apply?

The proposed tool provides guidance for each of these steps.

[1] The document can be previewed at this address: https://www.iso.org/standard/65694.html.

Purpose

Risk management has two main purposes. The first one is compliance, mostly of regulations, but that can also include company rules, norms, etc. In compliance risk assessment, the goal is to compare the predicted level of risk to a pre-determined level. An authority is typically in charge of reviewing a submitted risk assessment and to accept it or not. The acceptability of the risk is thus determined by this authority, mostly based on rules, laws, regulations, norms, etc. In this case, the risks considered are often predetermined (i.e., they correspond to something considered by the regulation), and the assessment is standardized.

The other purpose of risk management is more of a proactive nature, when decision-makers use it in order to guarantee a sufficient performance, and to limit the possibility of losses.

In this second version of risk management, the risk is dependent on each decision-maker, and on the objectives of each project, the context, etc. Thus, the level of acceptability of risk—the risk tolerance—is dependent upon the preference of the decision-maker. For instance, a large energy company, which invests a small part of its capital into a new energy project, might be willing to accept more risk than a municipality. Recalling the steps of risk assessment, risk analysis is mostly based on 'objective' elements; i.e., the risk level will be the same whether the decision-maker is a large company or a small municipality. For instance, the result of the analysis could be that the target power would be achieved with a confidence of 75%. It is at the risk evaluation stage that things will differ: the large company may decide that the risk is acceptable and would continue with the project and start drilling, whereas the municipality would think that 75% is too risky and would not continue the project unless it can acquire new data or find an insurance.

The tool is mainly developed for this second version of risk management. Therefore, the main criteria for this tool are the simplicity of use, the quality of presentation, and flexibility. This is to ensure the tool can be used by developers of a variety of geothermal projects, and the results communicated with the decision-makers (e.g., investors, bankers), whether they are "literate" in risk management or not. Of course, the main goal of this tool is to improve the success rate of geothermal projects, by encouraging a proportionate implementation of risk mitigation measures.

Tool design

The main target users of the Georisk tool are project developers. The tool takes into account all risks identified within the GEORISK project (Le Guénan et al. 2019, Le Guenan 2021). A first list of risks was established based on previous European projects or reports dealing with risks and geothermal energy: the GEOELEC project (Fraser et al. 2013); the DARLINGe project (Nador et al. 2018); the GEOWELL project (Lohne et al. 2016); and a report from the French institute INERIS (Gombert et al. 2017).

The GEORISK partners shared their related references, reaching more than 70 documents (see Le Guénan et al. (2019) for the full list). The list was ranked by priority and analyzed for improving the register. This included general documents on the development of geothermal energy (GWG 2016; Hirschberg et al. 2014), regional case studies

(Daniilidis et al. 2016; Ganz et al. 2013; Heijnen et al. 2015; Kousis 1993; Mendrinos et al. 2010), papers and reports on risk mitigation or risk management (Deloitte 2008; Ganie et al. 2012; Matek 2014; Ngugi 2014), on risk assessment (Antics and Ungemach 2010; IFC 2013), on economic risk (Reif 2008), on Enhanced Geothermal Systems (EGS) (Beardsmore and Cooper 2009), and on exploration (Harvey 2014). In addition, some partners added risks to the register based on their own experience.

In the first version of the risk register, the proposed model for risk identification was a typical cause—> event—> consequences model. However, as the initial purpose was to have a list as exhaustive as possible, the list became very large, due to many repetitions. As an example, an event with three possible causes, and two types of consequences would have to be repeated six times for each unique pair of cause–consequences.

The model for identification was thus simplified to only the main events, and the list was reduced to around 50 individual items. Possible causes and consequences were mentioned in the description. The drawback is that it does not consider complex risk scenarios with an event A as a precursor of an event B. This list is intended to be used as a checklist, where potential redundancy is possible, but where comprehensiveness is the main criteria.

As part of the GEORISK project, the partners, as well as external stakeholders through dedicated workshops, gave feedback on a first version of the tool. This allowed to provide features which better correspond to the intended use case (Le Guénan et al. 2021):

- The list of risks is editable and can be tailored to the case study.
- Both the scales for risk analysis and the criteria for risk evaluation can be adapted.
- The visuals were improved and more options were provided, focused on helping the user to quickly prioritize the highest risks.
- The possibility to run a second analysis puts more emphasis on risk mitigation.

Description

The risks were organized according to their cause into six categories:

- Category A: external hazard,
- Category B: risks due to uncertainties in the external context,
- Category C: risks due to internal deficiencies,
- Category D: risks due to subsurface uncertainties,
- Category E: technical issues,
- Category F: environmental risks.

Identifiers (ID) were generated according to this classification for each risk. For a description of each risk, the reader is referred to the online risk register (https://www.georisk-project.eu/georisk-tool/), containing a short description of each risk, the phase where it can occur, and the possible mitigation measures. For the sake of the risk analysis tool, we decided to elaborate a clustering of risks, corresponding to the type of expertise needed. The idea was to prepare the discussion and communication with different stakeholders depending on their field of expertise. The following clusters were proposed:

- "Managerial and social-economic" with 16 risks,
- "Operation and geology" with 21 risks,
- "Drilling" with 17 risks.

Table 1 shows the risks and their associated ID/category. An additional category called "new risk" also exists to allow the project developer to add other potential risks, which would not be covered in the existing categories.

The four steps needed to perform a risk assessment with the tool are presented in Fig. 1.

Step 1: risk identification

The first step in the process is the selection of the risks. By default, all risks identified within GEORISK project are selected, but it is possible to exclude some of them from the analysis or add some risks that can be project specific. To exclude a risk, the user must put a 0 in the pre-screening column. Each new risk can be assigned to one of the three categories already defined or put in the "new risk" category. An ID is associated to each risk (Table 1), which makes the final plots easier to read.

Step 2: elaboration of rating scales and risk matrix

Once the risks are preselected, a rating scheme must be defined (step 2). Both the likelihood of a risk and the consequence severity (damage) must be considered. In order to define a rating scale (either for likelihood or for damage), the user can set:

- The number of discretization levels. The default value is 4 levels for both scales.
- The multiplicative factor (MF) between each level. The default value is 10 for both scales.
- The maximum value of the interval for the first level (denoted MV). The default value is 0.0001 (probability 0.01%) for likelihood and 1 k€ for damage.

A damage/likelihood level i is then between:

$$\begin{cases} MF^{i-2} * MV & if\ i > 1 \\ 0 & if\ i = 1 \end{cases} and \quad MF^{i-1} * MV.$$

Figure 2 shows the default rating tables. It is possible to define some qualitative description of the levels for easier understanding (yellow boxes in the right column).

Care must be taken in the design of the ranking to obtain a meaningful risk matrix (e.g., Baybutt 2018). We chose to use logarithmic scales for the risk matrix because the damage and likelihood levels vary by orders of magnitude (Baybutt 2016; Duijm 2015). Contrary to what is often done (e.g., Dethlefs and Chastain 2012; Peterschmitt et al. 2018), considering the logarithmic scales, we estimate the risk as the sum of the likelihood score and the damage score instead of the product (Duijm 2015). This is valid when keeping the multiplicative factors close for damages and likelihood.

In addition to the rating tables, there are two possibilities for the construction of the risk matrix: (i) to use the default risk matrix by defining two acceptability thresholds (from acceptable to moderate or from moderate to unacceptable), or (ii) to build its own

Table 1 List of risk sorted by topic. The ID of each risk is indicated

Topic	ID	Description
Managerial and social-economic	A-1	External natural hazards damaging the infrastructure
	A-2	Anthropogenic hazard damaging the infrastructure
	B-1	Changes in policies, laws, taxes and regulations put development/economy in jeopardy
	B-2	Lack of financing for the next phases
	B-3	Low social acceptance put barrier to development
	B-4	Public opposition against nuisances from the exploitation
	B-6	Lack or loss of clients
	B-8	Significant changes of energy costs
	C-1	Low financing for work leading to low safety standards
	B-5	Unanticipated delays and costs in operations (materials, services, maintenance)
	C-2	Suboptimal design of well leads to reduced flow rate
	C-3	Best practices not applied (data acquisition, modeling, decision-making, design of wells / plants, construction)
	C-4	Unsuitable contracts (roles and responsibility not clearly defined) leading to suboptimal performance or exploding costs
	C-8	Organization is not experienced/financially robust enough for the challenge
	B-9	The research or exploitation permit is changed in favor of another resource
	C-9	Demand analysis and forecast are inaccurate
Operation and geology	D-1	Flow rate lower than expected (reservoir)
	D-2	Flow rate degrades over time
	D-3	Temperature lower than expected (reservoir)
	D-4	Temperature degrades too quickly
	D-5	Pressure lower/higher than expected
	D-6	Pressure is changing during the operation in an unexpected way
	B-7	Neighboring operators cause negative changes to the reservoir parameters
	D-7	Fluid chemistry/gas content/physical properties are different from expected
	F-6	NCG[a] Production
	C-5-a	Human error leading to failure during work (including either insufficient background and/or regulations)
	D-8	Fluid chemistry/gas content/physical properties change
	D-9	Target formation is missing in the well (unexpected geology, insufficient exploration)
	D-10	Target formation has no/insufficient fluid for commercial production
	D-11	Geological lithology or stratigraphy is different than expected
	D-12	Excessive scaling in the geothermal loop
	D-13	Excessive corrosion in the geothermal loop
	D-14	Particle production ("sanding")
	D-15	Hydraulic connectivity between wells is insufficient for commercial use
	D-16	Re-injection of the fluid is more difficult than expected
	D-17	Degradation of the reservoir (structure, properties, deteriorating whole-scale further commercial utilization)
	F-8-a	Loss of integrity of surface equipments (leakage from the tanks, pipeline, heat-exchanger, etc.)

Table 1 (continued)

Topic	ID	Description
Drilling	E-1	Fluid losses leading to severe technical issues
	C-7	Damage to the well/reservoir while drilling or testing
	E-2	Wellbore instability
	E-3	Trajectory issues (deviation from target)
	F-8-b	Loss of integrity of surface equipments (leakage from the mud pit; well head, etc.)
	F-7	Loss of integrity of the wellbore (connection of well fluid with surface; inter layer fluid connection, etc.)
	C-6	Wrong choice of stimulation fluids or techniques damaging the reservoir/well
	E-7	Issues in transporting/handling radioactive sources for logging
	E-8	Technical failure of the equipment
	E-9	Well casing collapse
	F-1	Blowouts
	F-2	Fluid communication between different formations due to ineffective isolation of the well
	F-3	Induced seismicity (above sensitivity level)
	F-4	Surface subsidence or uplift
	F-5	Toxic emissions due to gases and fluids produced in situ
	C-5-b	Human error leading to failure during work (including either insufficient background and/or safety regulations)
	E-5	Technical failure/difficulties during drilling (due to any additional causes that were not mentioned)

[a] NCG non-condensable gas

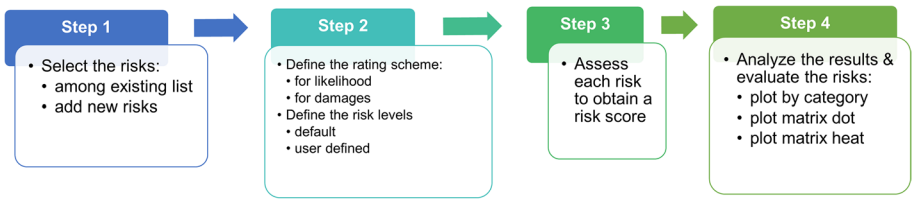


Fig. 1 Steps to perform to realize a risk analysis with the risk register tool. Each step corresponds to a different tab in the tool

rating table by completing the risk matrix with 1 (acceptable), 2 (moderate risk), 3 (unacceptable risk). Figure 3 shows an example of the risk matrix using default construction or user rating table. The second option allows giving a different weight between damage and likelihood. This can be used, for instance, to account for risk aversion of the decision-maker. We recall that risk aversion plays a role only at the risk evaluation stage (when decisions about the risks are made) and not at the risk analysis stage (which consists of assigning a score for damage and likelihood). In this case, a high damage, low probability risk will be perceived as less acceptable than a low damage, high probability

A

Damage rating table			
Damage level	The damage level is comprised between:		
	Minimum value	Maximum value	
1	- €	1 000 €	*Very low damage*
2	1 000 €	10 000 €	*Low damage*
3	10 000 €	100 000 €	*Medium damage*
4	100 000 €	1 000 000 €	*High damage*

B

Likelihood rating table			
Likelihood level	The likelihood level is comprised between:		
	Minimum value	Maximum value	
1	0.00%	0.01%	*Not likely to occur*
2	0.01%	0.10%	*Mild chance of occurence*
3	0.10%	1.00%	*Moderate chance of occurence*
4	1.00%	10.00%	*High chances of occurence*

Fig. 2 Default values for **A** the damage and **B** the likelihood rating tables

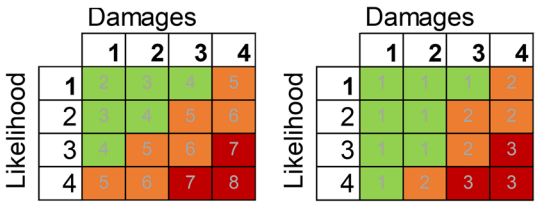


Fig. 3 Examples of risk matrix implementation. Left: default construction and acceptability thresholds of 5 and 7. Right: user own rating table

risk. We strongly suggest that when presenting results, the risk matrix is shown as its design is user-dependent.

Step 3: risk ranking

Step 3, after selecting the risks and defining the rating tables and risk matrix, is the risk ranking step. For each risk selected in step 1, the likelihood and the damage level must be rated according to the ranking selected in step 2. From this rating, the risk score is automatically estimated according to the matrix construction chosen in step 2. An icon indicates whether the risk is acceptable, moderate or unacceptable according to the rating calculated. An expert or a working group of different experts should perform this rating. Indeed, for a risk assessment considering all three categories proposed in the tool, experts from different backgrounds are needed. If necessary, a dedicated risk analysis tool can be used as an input for some risks (e.g., use of a dedicated method for induced seismicity risk analysis in the Upper Rhine Graben example below). A second assessment can be performed later on, on the same sheet, which can be useful for taking into account mitigation measures, for example, or to assess a different phase of the project.

Step 4: results analysis and risk evaluation

Once the analysis is done, various plots presenting the results are displayed. It can show for each of the three (plus one) categories the ratings in bar chart format. This is helpful

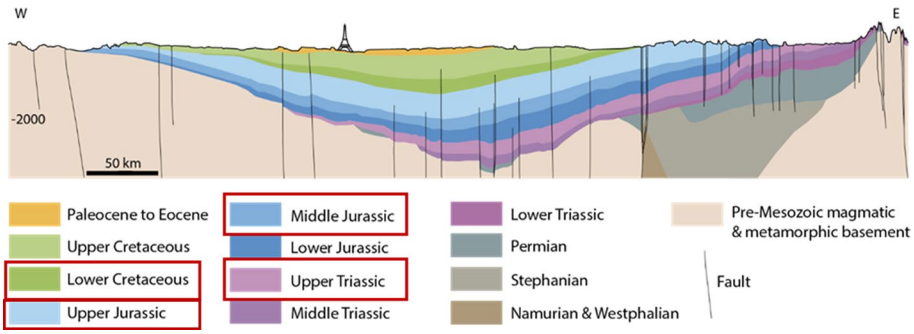


Fig. 4 Main geological units for geothermal application in the Paris Basin

to show which risks are above the selected threshold and the relative contribution of the likelihood and damage. A matrix plot for up to 12 risks can also be displayed with different display options. The choice of the plot will depend on the aim of the risk assessment: identifying the problematic risks (bar chart) or showing an overview of the project (matrix plot) for example.

Case studies

To demonstrate the ease of use of the tool and its applicability in different contexts, we show how it can be used in two application examples. These examples highlight the different features that can be used with this tool and how the results can be presented depending on the objective of the risk assessment.

Example of application in the Paris Basin

General context

France has a leading position in Europe for geothermal district heating. Deep geothermal projects are mainly targeting the Paris Basin (Hamm et al. 2016; Lopez et al. 2010). Four main lithostratigraphic units exhibiting aquifer properties are identified in the Paris Basin (Fig. 4): (i) the Lower Cretaceous sand formations (Albian and Neocomian); (ii) the Upper Jurassic (Lusitanian) and Middle Jurassic (Dogger) limestones; (iii) and the Upper Triassic sandstones formation. The Dogger, the Albian and the Neocomian aquifers are currently identified as the most promising targets below the urbanized Paris area for deep geothermal projects. In the case of the Albian aquifer, it is also a strategic resource for drinking water and all geothermal well targeting this formation should be able to be used for drinking water usage in case of emergency. The Triassic sandstones formation has had limited development for deep geothermal energy recovery so far but has proven to have important geothermal potential in the Paris area. The Lusitanian limestones have not been targeted so far, but were tested in some wells during drilling operations as the formation is crossed when targeting the Dogger.

Since 1970, 199 wells have been drilled in the Paris Basin, with 180 targeting the Dogger limestone aquifer and 13 the Albian–Neocomian sands. In 2020, 85% of the 2 TWh of geothermal heat produced in France is produced for district heating networks in Paris area (from Sybase database presented in Hamm et al. 2019b). The Paris area has favorable conditions, subsurface geothermal resources plus important surface needs that

allowed the development of deep geothermal projects. However, in order to meet the objectives of the French pluriannual energy plan, new challenges are emerging like:

(i) defining new priority development areas in other geological formations (e.g., Trias) little exploited so far or exploited in other basins (e.g., Aquitaine Basin);
(ii) developing and increasing exploration phases like 2D high density or 3D seismic methods at local scale to better define high-potential locations and increase the probability of success (Darnet et al. 2020);
(iii) using adapted well architectures (e.g., subhorizontal or multilateral well architecture) to increase the well productivity/injectivity depending on the initial evaluation (EGEC 2021; Hamm et al. 2016; Lentsch et al. 2021).

In this context, the Georisk tool represents an opportunity for developers to build a thorough risk analysis in the early phase of a new project and also during project implementation. This is particularly important for the permitting procedure related to both exploration and exploitation of geothermal resources for depths over 200 m. The developers have the choice between two procedures:

– a Research Authorisation (AR) more appropriate for area already geologically well known. The lease is attributed by the Departmental authority for a 3-year period,
– an Exclusive Research Permit (PER) more appropriate in areas where there is less geological knowledge. The lease is granted by the Ministry of Environment for a period of 3 to 5 years.

Whatever the procedure chosen, the project must be well documented in order to be presented and evaluated by the local public authority. Furthermore, experts from the French Geothermal Guarantee Fund, which grants the *"Short-term"* and "*Long-term*" guarantees (Bommensatt et al. 2015), will also evaluate the project-related risks. The "*Short-term*" guarantee fund covers the risk of the non-existence or the insufficiency of the geothermal resource in terms of flowrate and/or temperature at the end of the drilling phase. It also covers the additional costs of drilling or development phases in case of "geological difficulties". The "*Long Term*" guarantee fund covers geological hazards and geothermal risks likely to affect the subsurface and surface installations specific to the exploitation phase. It concerns exclusively equipment specific to the exploitation of geothermal energy directly in contact with the geothermal fluid, as well as the thermal power linked to the flow rate, and the temperature of the extracted geothermal water.

The "short-term" guarantee is compulsory to benefit from additional grants from the Renewable Heat Fund (Bommensatt et al. 2015), a financial mitigation tool for deep geothermal installations producing renewable heat in France. Thus, to obtain these guarantees, the Georisk tool can provide a thorough risk assessment and help experts and decision-makers to make a decision on the project and propose preventive or corrective risk mitigation measures if necessary.

Risk assessment for a typical case in the Upper Triassic formation

Here we apply the tool in the case of the development of a new project in the Trias sandstones aquifer in the Paris area. As mentioned above, first attempts for geothermal

exploitation were made in the early 1980's but these proved unsuccessful: the deep layers proved hotter but less productive than the overlying Dogger aquifer. Among the three projects targeting this formation, only one, located in the southwestern part of the sedimentary basin, was commissioned; it ran for no more than a year due to reinjection-related problems. However, deep Triassic aquifers in the center of the Paris Basin, at depths between 2000 and 2500 m and with temperatures up to 120 °C in some areas, are still considered a possible target for geothermal heat production. The main difficulty to overcome is the nature of the aquifer, which consists of fluvial deposits with permeable sand bodies that are relatively narrow and disconnected. Its properties (i.e., porosity and permeability) are thus more heterogeneous and discontinuous than those of the Dogger limestone aquifer. Numerous works have allowed a better characterization of the Trias (Bouchot et al. 2012; Bugarel et al. 2018; Hamm and Lopez 2012; Sengelen et al. 2021). In 2019, a new geothermal operation in Paris area has targeted the Upper Triassic sandstones with the aim to produce from the Trias layer and to reinject in the overlying Dogger layer to avoid injection issues. The reinjection of the geothermal fluid into the same geological horizon is a regulatory obligation (Article 17-2 of the Ministerial Order of 14 October 2016) for any new geothermal project in France operating in an open loop on the basis of a doublet of boreholes (producer/injector). However, derogations may be granted in very specific cases, clearly justifying the reasons and arguments for reinjecting the geothermal fluid outside the producing formation (e.g., other horizon, surface). Unfortunately, the Trias target has been abandoned in favor of the Dogger due to technical drilling issues. Indeed, in order to maximize the flow rate, the borehole diameter should be greater than 8″1/2 (classical diameter in the Dogger reservoir), necessitating the use of an Expandable Liner on the upper section overlying the reservoir target and, consequently, the use of a widener to set and cement this liner. During this operation, the widener was blocked and the decision was taken to abandon the Trias objective.

For the risk evaluation, we kept 35 risks among the default 54 proposed including: 7 in "Managerial and Social-economic" category, 17 in "Operation and Geology" category, and 11 in "Drilling" category. We made this selection based on the specificities of the Paris Basin, as, for example, it is within a temperate climate and calm geological context, so natural hazards are not relevant in this case. In the same way, a change in exploitation permit, once attributed, is not possible in France. Figure 5 shows the preselected risks and their ranking from the risk assessment. For this example, the default rating tables are used (see Fig. 2). The risk matrix is the user own rating table with the following rating: (i) unacceptable risk (level 3) for the combination of likelihoods and damages of (3,4), (4,3) and (4,4); (ii) moderate risk (level 2) for the combination of likelihoods and damages of (1,4), (2,3), (2,4), (3,3) and (4,2); and iii) acceptable risks (level 1) for the other combinations (see Fig. 3, right matrix). This choice corresponds to a moderate level of risk aversion from the decision-maker. This first assessment shows that among the 35 risks identified for implementing a new doublet in the Upper Triassic sandstones, 15 represent moderate risks and 5 unacceptable risks that can endanger the economic and technical viability of the project. Figure 6 plots for each identified risk, the likelihood and damage levels in bar charts (one graph for each risk category) and highlights risks that are moderate according to the risk matrix elaboration.

	Description	Likelihood	Damage Level	RI	
2	Lack of financing for the next phases	1	4	5	
3	Low social acceptance put barrier to development	2	2	4	
4	Public opposition against nuisances from the exploitation	3	2	5	
5	Unanticipated delays and costs in operations (materials, services, maintenance)	3	4	7	
2	Suboptimal design of well leads to reduced flow rate	2	3	5	
3	Best practices not applied (data acquisition, modelling, decision making, design of wells / plants, construction)	2	4	6	
4	Unsuitable contracts (roles and responsibility not clearly defined) leading to suboptimal performance or exploding costs	1	2	3	
1	Flow rate lower than expected (reservoir)	4	4	8	
2	Flow rate degrades over time	3	4	7	
3	Temperature lower than expected (reservoir)	1	2	3	
4	Temperature degrades too quickly	1	2	3	
5	Pressure lower/higher than expected	3	3	6	
6	Pressure is changing during the operation in an unexpected way	3	3	6	
7	Fluid chemistry/ gas content / physical properties are different from expected	2	2	4	
8	Fluid chemistry/ gas content / physical properties change	2	2	4	
10	Target formation has no/insufficient fluid for commercial production	3	3	6	
11	Geological lithology or stratigraphy is different than expected	1	1	2	
12	Excessive scaling in the geothermal loop	3	3	6	
13	Excessive corrosion in the geothermal loop	3	3	6	
14	Particle production ("sanding")	2	3	5	
15	Hydraulic connectivity between wells is insufficient for commercial use	3	4	7	
16	Re-injection of the fluid is more difficult than expected	3	4	7	
17	Degradation of the reservoir (structure, properties, deteriorating whole-scale further commercial utilization)	2	3	5	
3-a	Loss of integrity of surface equipments (leakage from the tanks, pipeline, heat-exchanger, etc.) [Operation&Geology]	2	3	5	
1	Fluid losses leading to severe technical issues	1	2	3	
2	Wellbore instability	1	2	3	
3	Trajectory issues (deviation from target)	2	3	5	
7	Loss of integrity of the wellbore (connection of well fluid with surface; inter layer fluid connection; etc.)	2	3	5	
6	Wrong choice of stimulation fluids or techniques damaging the reservoir/well	2	3	5	
8	Technical failure of the equipment	2	2	4	
9	Well casing collapse	1	3	4	
1	Blowouts	1	3	4	
2	Fluid communication between different formations due to ineffective isolation of the well	2	1	3	
5	Toxic emissions due to gases and fluids produced in-situ	3	2	5	
5	Technical failure/difficulties during drilling (due to any additional causes that were not mentioned)	2	3	5	

Fig. 5 Risks that were identified and assessed for their likelihood and damage levels for the Paris Basin case (yellow: managerial and socio-economic risks, blue: operation and geology risks and green: drilling risks)

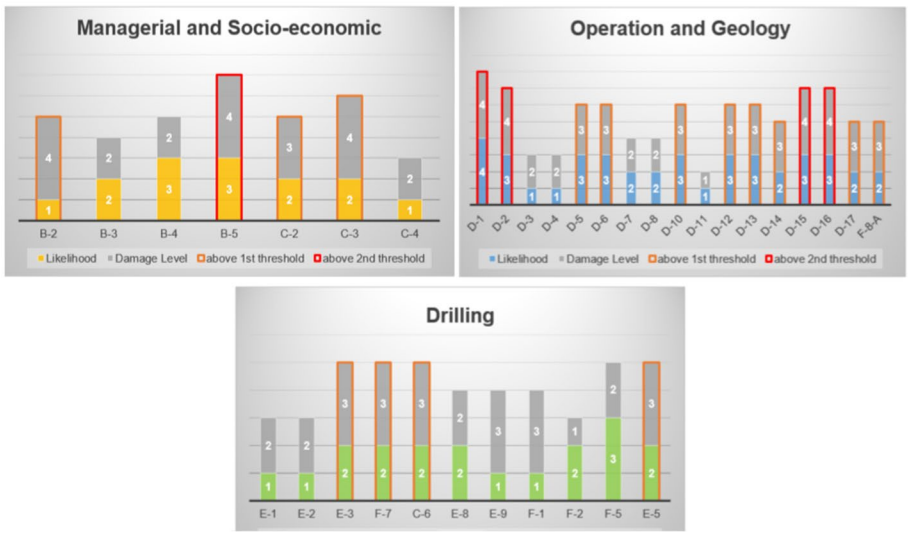


Fig. 6 Graphical representation (bar charts) of the different risks for each category (highlighted in red the unacceptable risk and in amber the moderate risks). The risk ID corresponding description is given Fig. 5

Figure 7 shows another possible risk representation with the risk matrix plot (named PlotMatrix_Heat in the Excel tool). In this case, the risks are represented with their ID in each cell of the risk matrix and colored according to their risk index. Several risks can be in the same cell if their rankings are similar. For example, 8 risks have been assessed with an identical likelihood of 2 and damage level of 3.

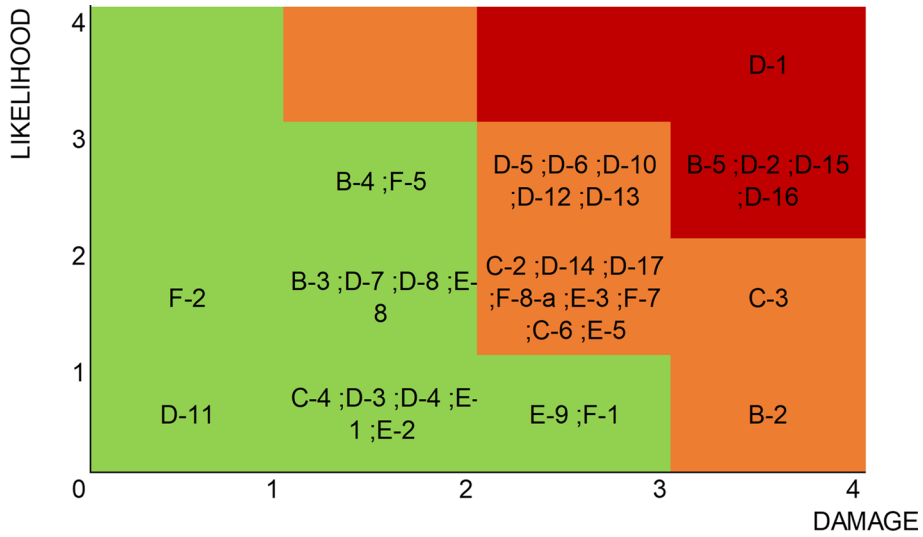


Fig. 7 Matrix plot for the different risks identified for the project

Once the risk assessment is done (for a thorough risk analysis, different experts are needed to cover the different topics of the project implementation), the moderate and unacceptable risks can be reevaluated by applying mitigation measures. The Georisk tool proposes for each risk some mitigation measures, by giving a link on the Excel spreadsheet to the online risk register (https://www.georisk-project.eu/georisk-tool/), that an operator can apply to reduce the assessed risks. Nonetheless, the proposed mitigation measures are not exhaustive. It is up to the project developer to take into account current knowledge and existing best practices in order to mitigate the potential risks. In this example, the unacceptable risks are: flow rate lower than expected, flow rate degrades over time, insufficient hydraulic connectivity, reinjection of the fluid more difficult than expected, and unanticipated delays and costs in operations. Four of them are in the "Operation and Geology" category. The operator can refer to existing guidelines to help mitigate them as for example the "Good practice guide for lessons learned from deep geothermal drilling" published by BRGM and ADEME (Agency of Environment and Energy management) (Hamm et al. 2019a). In the specific project described above, the reason for not exploiting the Trias aquifer and retreating to the Dogger aquifer was due to technical failure during drilling (risk E5 due to the dysfunction of the widener). This risk is assessed here as moderate, but can have an important impact on the decision to pursue the specific target. In this case, the operator could have done a sidetrack, but in order to limit the risk of losing completely the well, the decision was taken to use Dogger as a fallback solution. Even if a posteriori analysis has some bias (knowledge of previous failure has probably influenced the assessments), this example illustrates that moderate or unacceptable risks must be carefully taken into account as they can have an important impact on the project implementation.

Example of application in the Upper Rhine Graben

General context

The URG is part of the broader Rhine graben that encompasses geothermal operations in France and Germany. Geothermal investigations started in the Rhine graben in the 1980s at Cronenbourg (France) and Bruschal (Germany) to exploit the Triassic cover (Vidal and Genter 2018). Then a European research project for the Hot Dry Rock technology was conceived at Soultz-sous-Forêts (France) to exploit the granitic basement (Genter et al. 2010). The next projects (e.g., Rittershoffen in France, Landau or Insheim in Germany) were established following lessons learned from Soultz-sous-Forêts project and targeted a fault at the interface between the basement and the sedimentary cover (Vidal and Genter 2018). Nowadays in France, Soultz-sous-Forêts and Rittershoffen are producing electricity and heat for industrial use, respectively. The installed capacity is 26.5 MW_{th} for Rittershoffen and 1.8 MW_e for Soultz-sous-Forêts.

One of the issues regarding development of deep geothermal projects in the URG is the possible occurrence of induced seismicity and, if it happens, how to manage it. Some induced seismicity occurred at Soultz-sous-Forêts (max magnitude M2.9 on 2003), the Basel project (Switzerland) was stopped following a Ml3.4 event in 2003 (Evans et al. 2012), and the Vendenheim project (France) was also stopped following a Ml3.6 event in 2020 (Schmittbuhl et al. 2021). Additionally, opposition to deep geothermal projects emerged in French side of URG in 2014 (Chavot et al. 2018).

Risk assessment for a typical project

Here we apply our methodology to a typical cogeneration project in the URG, targeting a fault zone at the interface between the basement and the sediments. We suppose stimulations will be realized to reach the intended flow rate. Since heat will be produced, we suppose the project is close to a city or town. We aim to show how our tool can be used to take into account the seismic risk in addition to the other risks that can prevent the project from being successful. We perform our analysis as if we were at the beginning of the project, before drilling. First, a seismic risk analysis is done using the GRID method (Kraft et al. 2020; Trutnevyte and Wiemer 2017), as an additional input to the experts' estimation. The GRID method was developed for Switzerland and so would need some modification for a proper application to geothermal operations in France but it can still give a first approximation of the seismic risk level. GRID classifies a project according to a four-level scale (from 0 to 3) considering seismic hazard, vulnerability, and social concern. It recommends tailored risk governance according to the level a project reaches. The indicators related to social concern are based on findings from Chavot et al (2019) supposing an unbound project. The ranking for each indicator is shown in* MERGEFORMAT Table 2 with the justification associated to the ranking. According to our results, at its beginning, such a project falls in class II, combining technical criterion and reach class III if the social criteria is considered. As a comparison Basel project was classified in level III even without social concern.

For the full risk assessment, we kept 37 risks among the default 54 proposed including: 12 in "Managerial and Social-economic" category, 17 in "Operation and Geology" category, and 8 in "Drilling" category.

Table 2 GRID analysis applied to a URG project. For each indicator its evaluation is shown along with the corresponding score and its justification when necessary, based on representative cases

	Class	Rating	Justification
Seismic hazard concern			
Depth of the reservoir	> 3 km	2	3 to 5 km depth
Cumulative injection volume during stimulation	> 10,000 m^3	2	Soultz 2000 stimulation 23400m^3 (Cuenot et al. 2008)
Daily injection or extraction volume during operation	1–10,000 m^3/day	1	Soultz 2000 stimulation up to 50 L/s (Cuenot et al. 2008)
Rock type	within 500 m from the crystalline basement	1	
Separation between background and induced seismicity	Seismic zone 2 in SIA	1	correspondence with global seismic hazard map
Fluid injection pressure	0.3–10 MPa	1	mandatory upper limit of 10 MPa
Distance to known and potentially active faults with length greater than 3 km	< 2 km	2	reservoir is a fault zone
Total		**10**	
Concern about secondary hazards, exposure and vulnerability (within a radius of 5 km)			
Local site amplification	No building or infrastructure on soft soil	0	
Exposed population	Urban (≥ 20,000 inhabitants)	2	
Industrial or commercial activity	High activity	2	
Importance of buildings and infrastructure	No building or infrastructure of class II or III	0	
Infrastructure with considerable environmental risk	non concern	0	
Unreinforced cultural heritage	< 5% buildings listed as important local, regional or national heritage sites	0	
Susceptibility to secondary hazard	very low	0	
Total		**4**	
Social concern			
Potential for concern in the general population	Exist	1	
Vulnerable or strongly opposing stakeholders	Exist	1	
Negative experiences with similar projects	Exist	1	Basel case
Lack of trusts in the project operators or authorities	Exist	1	
Benefits to the local community	Direct benefits with or without local compensation	0	
Total		**4**	

We keep the standard rating table and the recommended risk matrix for our analysis. As a consequence of our seismic risk analysis, we assign a value of 3 (moderate chance to occur) to the seismic risk likelihood (technical ranking of GRID method corresponding to a mild chance of induced seismicity to occur) and a damage level of 4 (high damage) considering the social concern score in GRID analysis and reparation paid for Basel case (Baisch et al. 2009). Our risk evaluation yields two unacceptable risks and seventeen

ID	Description	Likelihood	Damage Level	RI
A-2	Anthropogenic hazard damaging the infrastructure	1	1	2
B-1	Changes in policies, laws, taxes and regulations put development/economy in jeopardy	1	3	4
B-2	Lack of financing for the next phases	1	4	5
B-3	Low social acceptance put barrier to development	4	2	6
B-4	Public opposition against nuisances from the exploitation	4	2	6
B-6	Lack or loss of clients	2	3	5
B-8	Significant changes of energy costs	1	3	4
B-5	Unanticipated delays and costs in operations (materials, services, maintenance)	3	4	7
C-2	Suboptimal design of well leads to reduced flow rate	2	2	4
C-3	Best practices not applied (data acquisition, modelling, decision making, design of wells / plants, construction)	2	4	6
C-8	Organization is not experienced / financially robust enough for the challenge	1	3	4
C-9	Demand analysis and forecast are inaccurate	1	3	4
D-1	Flow rate lower than expected (reservoir)	3	2	5
D-3	Temperature lower than expected (reservoir)	2	2	4
D-5	Pressure lower/higher than expected	3	3	6
D-6	Pressure is changing during the operation in an unexpected way	3	3	6
D-9	Target formation is missing in the well (unexpected geology, insufficient exploration)	1	4	5
D-10	Target formation has no/insufficient fluid for commercial production	3	3	6
D-11	Geological lithology or stratigraphy is different than expected	1	1	2
D-15	Hydraulic connectivity between wells is insufficient for commercial use	2	3	5
E-1	Fluid losses leading to severe technical issues	1	2	3
C-7	Damage to the well/reservoir while drilling or testing	2	3	5
E-2	Wellbore instability	2	2	4
E-3	Trajectory issues (deviation from target)	2	3	5
F-8-b	Loss of integrity of surface equipments (leakage from the mud mud pit; well head and etc.) [Drilling]	2	2	4
F-7	Loss of integrity of the wellbore (connection of well fluid with surface; inter layer fluid connection; etc.)	2	3	5
C-6	Wrong choice of stimulation fluids or techniques damaging the reservoir/well	2	2	4
E-7	Issues in transporting/handling radioactive sources for logging	1	2	3
E-8	Technical failure of the equipment	2	2	4
E-9	Well casing collapse	1	3	4
F-1	Blowouts	1	3	4
F-2	Fluid communication between different formations due to ineffective isolation of the well	2	3	5
F-3	Induced seismicity (above sensitivity level)	3	4	7
F-4	Surface subsidence or uplift	1	3	4
F-5	Toxic emissions due to gases and fluids produced in-situ	3	2	5
C-5-b	Human error leading to failure during work (including either insufficient background and/or safety regulations) [Drilling]	1	2	3
E-5	Technical failure/difficulties during drilling (due to any additional causes that were not mentioned)	2	3	5

Fig. 8 Risks that were identified and assessed for their likelihood and damage levels for the URG case (yellow: managerial and socio-economic risks, blue: operation and geology risks and green: drilling risks)

moderate risks for the project (Fig. 8). One unacceptable risk is related to unanticipated delays, a risk that was also highlighted in the Paris basin and is common in a major project such as a deep geothermal project. Mitigation measures can include a time and/or cost buffer in the planning and regular report should be established to monitor this risk. The second unacceptable risk is related to induced seismicity. It is generally accounted for in URG projects, from a regulation point of view, that forbid injection pressure above 10 MPa and imposing two thresholds on magnitude or peak ground velocity above which increased vigilance is recommended and operations must be stopped, respectively. This is associated with a monitoring network composed of four stations. However, in addition, operators must design processes to deal with induced seismicity operationally (how they will react if an increase in seismicity occurs, for example). Figure 9 shows the risks that can be related to induced seismicity, either as a cause, a consequence, or a coincident risk. Among them, anthropogenic hazard damaging the infrastructures is rated as acceptable since there is few impact on infrastructure related to induced seismicity. Change in policies law is also rated as acceptable since it seems unlikely and few examples exist in France but the recent example of Vendenheim project (Schmittbuhl et al. 2021) shows it can occurs. The risk "public opposition against nuisance" itself was rated as high chance to occur since opposition appeared, in French URG, in 2014 (Chavot et al. 2019), but its impact was estimated as mild, since once the authorisation to drill is validated, the company can proceed. This example highlights the complex interactions between risks and the importance of reassessing them as a project progresses because once one risk is realized it changes the likelihood and possibly damage of other risks.

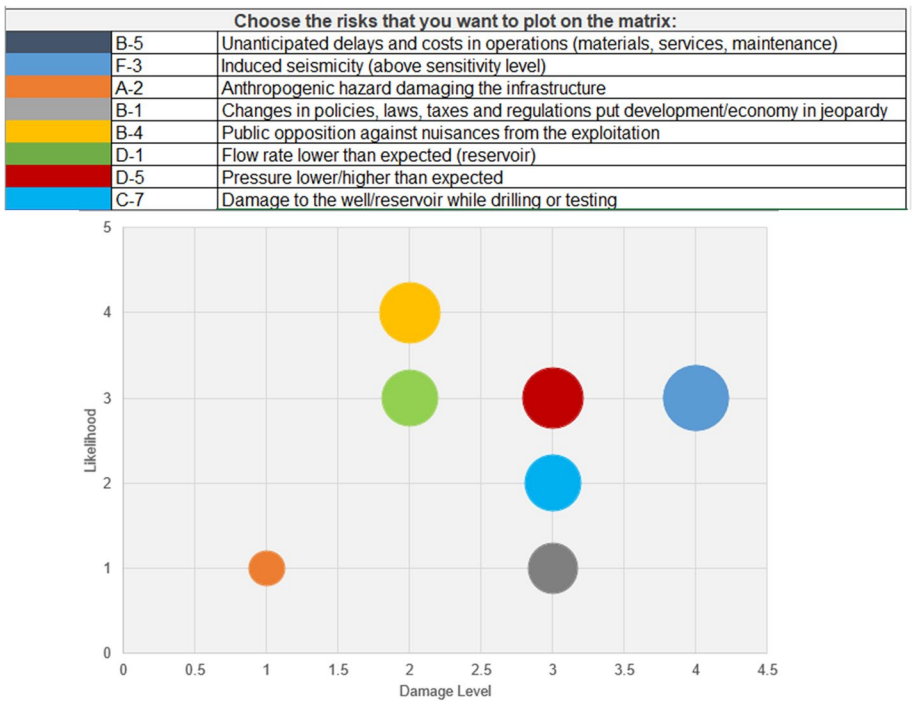


Fig. 9 Matrix dot plot showing the risks related to induced seismicity risk for the URG case. Size of point is representative of the risk index (likelihood + damage level)

Discussion

Novelty and purpose of the tool

This tool was developed for project developers to help present their project risks to insurance companies and investors in a comprehensive and easy to understand way. It is a middle ground between an application of good practices without any analysis behind and a complex tool as developed by A'Campo and Baisch (2020). The main question to answer while developing such a tool is what makes a good risk management tool. Two directions are possible: either describe in as many details as possible each risk relevant to the project and the sequence of event to identify all possible way leading to its realization and all possible mitigation measure, or be as exhaustive as possible in the identification of risk to consider all possible situations.

The first option has the advantage of yielding project parameters upon which to act or to monitor. However, it is a very project-dependent approach and is difficult to provide a tool available for all possible project configurations.

The second option, the one we chose, encourages the user to consider all kinds of situations that may not have been thought of and yields an easy-to-use tool, even for a non-specialist. To overcome the short description of risks, we provide, in the tool, a link to more in-depth descriptions explaining the cause, phases where the risk can occur, and possible mitigation measures. The tool also needs to be very flexible to be adaptable to different project configurations, which is why we developed several options such as adding a new risk or selecting a personalized rating scheme. The other drawback of this option is that the analysis, as rather simple, does not lead to an immediate operational decision on risk but it prompts the users to consider the risk management and to include

it in their decision-making process. A way to make the risk analyses more thorough is to plug in a more in-depth risk analysis on sensitive topics as was done in the Upper Rhine Graben example. Such analyses can be added a priori if the risk is identified from the beginning as important, or a posteriori.

Impact of the tool

All the features correspond to the criteria of simplicity, communication, and flexibility that were the purpose of this tool. The case studies can illustrate those aspects of the tool. However, we acknowledge that the main impact of this tool should be measured in reduction of risk. There is no scientific way of measuring this impact a priori (Hubbard 2020). The only rigorous way to do this would be to make statistics based on a high number of projects using the tool and comparing them to a representative number of projects not using the tool. We can, however, put forward that the tool follows, and gives guidance to the various steps of risk assessment based on ISO 31000. In particular, the possibility to adapt the risk analysis rating and the acceptability thresholds encourages users to use best practices. This is an improvement over an intuitive approach to risk assessment or management. For the risk analysis phase, dedicated approaches can be used as an input as was done for induced seismicity risk in the URG example.

Flexibility of the tool

This tool is the result of brainstorming between partners to produce a collective tool, usable by different kinds of experts. As explained in the presentation of the tool, dedicated workshops were organized in order to gather feedback from the projects partners as well as interested stakeholders. The current version of the tool integrates these feedbacks (Le Guénan et al. 2021) in order to have a tool as flexible as possible.

The separation into three categories of risks allows the user to focus on a specific topic. For example, if one needs to consider the potential risks of the construction phase for insurance purposes it is possible to filter out the risks that are not relevant for this phase. It is also an advantage to separate the analysis by expertise domains, as a person is rarely an expert on all three categories.

The application of the tool a posteriori on an example of a deep geothermal project in the Paris area shows the importance of a proper risk assessment and the need to have a good knowledge of the different risks that a project can face. As seen in the example discussed above, it is necessary to have a good idea of the different risks that can occur and that are project-specific. In this particular example, the feedback from other operations in this specific geological formation has allowed to have a more precise knowledge of the potential risks and their likelihood and damage levels for the risk assessment. In this example, there was a specific design of the geothermal doublet with the production well targeting the Trias and the reinjection well the Dogger. This configuration allowed the anticipation of a fallback solution (production in the Dogger) in the case where the targeted Triassic formation could not be exploited (characteristics of the resource insufficient, technical issue…). This allowed to significantly reduce the risks of a total failure.

The comparison between the risk assessment in the Paris basin and the URG reveals that on one hand, the problematic of flow rate lower than expected is an unacceptable risk in the Triassic formation in the Paris basin case (high likelihood and high damage) but is moderate in the Vendenheim case (moderate likelihood and low damage) because it is something expected and accounted for (stimulations program). On the other hand, damage to the reservoir while drilling/testing are not considered in the Paris basin while they are important for the URG. This highlights that the geothermal system type and exploitation design play an important part in evaluating the risks associated with a project and should be considered carefully. The Georisk tool can be applied to other kinds of geothermal operations such as volcanic play type or field exploitation. The difference will be in the risk considered and their ratings. In volcanic play type, for example, risk such as subsidence may need more attention (generally reinjection is limited in these kind of contexts) as well as NCG emission. For exploitation in fields, more attention is needed on the impact of neighboring installations.

Qualitative vs quantitative analysis

From the point of view of risk analysis, we provide all the necessary tools to adapt the ranking to different contexts. The definition of the rating as well as the risk matrix construction can be user-defined. Guidance in the risk matrix design is given in order to help users avoid common pitfalls in using risk matrices. For instance, the use of a logarithmic scale corresponds to current best practices (Baybutt 2016). However, this remains a qualitative/semi-quantitative tool with a ranking that is primarily defined from expert opinion. Considering the stakes in developing deep geothermal projects, it is recognized that quantitative risk assessments (QRA) should be favored (Hubbard 2020). A prototype for a QRA tool has thus been proposed (Le Guenan et al. 2020), but there is clearly a compromise to be found between the rigor of the analysis and the ease of use from users who may not be fluent in quantitative risk language (such as probability distributions). We propose to use the qualitative tool for a quick overview of all the risks faced by a project, and to spend more resources in quantitatively analyzing the top (e.g., top 10) risks.

Conclusion

The exploration phase and the drilling of a first well in deep geothermal is a critical phase. Risks are important, in particular in area not well known due to lack of geological and hydrogeological knowledge or existing geothermal or other wells in the area. Risk assessment is therefore an upfront step in order to minimize or prevent their occurrence. The Georisk tool developed under the H2020 GEORISK project helps developers to perform a good practice risk assessment, including risk identification, analysis and evaluation. The 54 potential risks predefined cover a large specter of risks that can be encountered by a geothermal project in different geological contexts all over Europe and help the developer to identify the risks more likely to occur for their specific project. At this stage of development, the tool remains qualitative even if each damage and likelihood level corresponds to a certain cost predefined during the risk analysis. The main strength of the tool is that it provides an accessible, yet rigorous platform for presenting and communicating risks to decision-makers.

Acknowledgements
The authors thank the GEORISK partners for the feedbacks during the creation of the tool. The authors are very thankful to both reviewers for their constructive and insightful comments that helped improve the manuscript.

Author contributions
All authors contributed to the development of the risk assessment tool and reviewed the manuscript. JM: main redactor for presentation of the tool; VH: main redactor for example of application; TLG: project manager and primary developer of the tool; AL: secondary developer of the tool. All authors read and approved the final manuscript.

Funding
This work was supported by the H2020 GEORISK project (2018–2021) aimed at developing risk insurance schemes all over Europe to cover risks associated with the development and the operation of deep geothermal projects. This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 818232.

Availability of data and materials
The list of references reviewed by the GEORISK project partners to produce the risk register is available in Le Guénan et al (2019). The risk assessment tool can be downloaded here: https://github.com/ThomasLeGuenan/Georisktool/releases/tag/v2.1.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 7 April 2022 Accepted: 27 October 2022
Published online: 16 November 2022

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