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Risk Assessment of HSE risks of Ultra Deep Geothermal Energy and Enhanced Geothermal Systems in the Netherlands

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ABSTRACT

Ultra-Deep Geothermal Energy (UDG), characterized by a depth larger than 4 km and temperatures above 120 °C, has the potential to play an important role in fulfilling the high temperature heat demand in the Netherlands. In the long term the possibilities for conversion of geothermal heat to sustainable electricity can also be considered. Enhanced Geothermal Systems (EGS) are usually required with UDG. The various hazards and risks associated with UDG and EGS in the Netherlands have not yet been thoroughly identified and no comprehensive guidelines exist in the Netherlands for UDG. This study provides an overview of the Health, Safety and Environmental (HSE) risks of UDG and EGS in the Netherlands. Both surface and subsurface risks are covered, with a specific focus on subsurface risks in the Dutch geological, technological and seismotectonic context. The main challenge for UDG and EGS is the lack of knowledge of the deep subsurface and the lack of experience in exploiting UDG wells. A potential target play is the Dinantian limestone, which is likely to be present in different parts of the country. The risk analysis is based on expert elicitation and known risks from analogue cases abroad. The first result is an overview of the risks and a visualization following the bowtie method. The second result is a project classification scheme which allows the geothermal operator and supervising authority to get insight in the project-specific risks and the most appropriate measures. The results can be used to develop strategies for risk management and mitigation by regulators and geothermal operators both in the Netherlands and abroad.

1. INTRODUCTION

The Dutch society faces a major challenge regarding the sustainability of its energy supply. This challenge is formulated in the Energy Agreement ('Het Energieakkoord'). This agreement sets a target of 14 % renewable energy in 2020 in the final energy demand, which is expected to grow to 20 % in 2023 in the total energy mix. Ultra Deep Geothermal energy (UDG) and Enhanced Geothermal Systems (EGS) are promoted by the Ministry of Economic Affairs and Climate Policy and Energie Beheer Nederland (EBN) as a source of sustainable heat. There is approximately 90 PJ of industrial heat demand per year in the temperature range between 100 and 250 °C. After 2030 there will be a functional heat demand of about 75 PJ from the industry [Schepers and Aarnink (2020), Gasunie (2018)]. In June 2017, the 'Green Deal' was signed between the Ministry of Economic Affairs, seven project consortia, Energie Beheer Nederland (EBN) and the Dutch Geological Survey (TNO) in order to obtain more knowledge on UDG and realize pilot projects [EBN, TNO and consortia (2018)]. These pilot projects are mostly still in a feasibility stage.

In the Netherlands there is no experience with UDG and EGS yet. For UDG and EGS no risk inventory is currently available and the mining law is not yet suited for UDG and EGS projects. The main challenge for UDG and EGS is the lack of knowledge of the deep subsurface and the lack of experience in exploiting UDG wells: the uniqueness of the well is a barrier to effective learning in the exploration and development process [Denninger et al. (2015)]. In addition, differing characteristics of UDG projects compared to conventional geothermal projects in the Netherlands induce enhanced or additional risks.

This study provides a comprehensive overview of the health, safety and environmental risks of UDG and EGS in the Netherlands. Economic risks, reputational risks or public acceptance risks are excluded from this study. Both surface and subsurface risk are covered, with a specific focus on underground risks in the Dutch geological, technological and seismotectonic context. Surface risks include the risk associated with the surface installations of the geothermal heat production (wellhead, separator/degasser, filters, heat exchangers, pumps). The risks associated with geothermal heat distribution networks or geothermal powerplants are excluded from the scope of this study. Risks have been inventoried for all project phases excluding the abandonment phase. This study addresses the additional or enhanced risks in comparison with the known risks of conventional geothermal projects already carried out in The Netherlands. In addition, a qualitative project specific risk classification scheme has been developed. The result can be used to develop strategies for risk management and mitigation. This study is aimed to assist the Dutch State Supervision of Mines in their advisory role to the Ministry of Economic Affairs and Climate on aspects of health, safety and environmental impact regarding geothermal developments.

2. BACKGROUND

This section provides an overview of the current geothermal practices in The Netherlands, UDG and EGS developments in The Netherlands and the available knowledge and data.

2.1 Current geothermal practices in the Netherlands and UDG/EGS definitions

Conventional geothermal energy has been developed in the Netherlands since 2007 [NLOG (2018)] and is defined as the production of warm water from a sedimentary reservoir at a depth between 0.5-4 km. Conventional geothermal systems produce water with a temperature of 50-120 °C. In 2018 there are 22 conventional geothermal systems in the Netherlands reported to have an exploitation permit [NLOG (2019)]. Several risks that are associated with conventional geothermal energy include soil- or groundwater pollution, induced seismicity, co-production of Naturally Occurring Radioactive Materials (NORM), staff accidents and occurrence of a blow-out [Dutch State Supervision of Mines (2020), DAGO and Platform Geothermie (2018)]. In 2017, the State Supervision of Mines has expressed concerns about the control of health, safety and environment risks within the Dutch geothermal sector. Concerns were mainly attributed to inexperienced staff, usage of inferior materials and limited financial reserves [Dutch State Supervision of Mines (2017)]. Today, improvements have been made by sharing and learning from knowledge and experiences, advanced designs of wells and surface installations and development of industry standards such as the 'VGM-zorgsysteem' and 'Leidraad Putontwerp Geothermie' (expected 2020) by the Dutch Geothermal Association of Operators [DAGO (2018)].

In the Netherlands, geothermal systems at a depth larger than 4 km are considered ultra-deep. Temperatures can range from 120 - 250 °C. Potentially UDG temperatures are high enough to generate electricity. However, the current aim of UDG in the Netherlands is to produce process heat for industry. Reservoir permeability decreases with increasing depth due to increasing weight and associated pressure of the overburden rock. When targeting UDG reservoirs it may be necessary to develop them as an EGS. EGS involves the use of reservoir stimulation methods in order to improve the permeability of an existing reservoir [McClure and Horne (2013)]. Stimulation methods include chemical stimulation, radial jetting, thermal stimulation and hydraulic stimulation. Except for chemical stimulation, reservoir stimulation is not applied in conventional geothermal projects in the Netherlands because the targeted geothermal reservoirs have sufficient permeability. Compared to conventional geothermal, UDG can be characterised as follows: (1) higher temperature, (2) higher pressure, (3) higher concentration of corrosive substances or radioactive elements in formation water, (4) higher salinity of formation water, (5) higher probability of unexpected presence of hydrocarbons, (6) higher volumes for drilling fluids, test fluids and additives, (7) longer period of drilling and testing and (8) possible requirement for stimulation of the reservoir (EGS).

2.2 UDG plays in the Netherlands

A geothermal play is a potential geothermal system based on the presence of water in a rock formation with similar geological characteristics and circumstances. Four UDG plays have been identified in the Netherlands: (1) Triassic, (2) Rotliegend, (3) Dinantian and (4) Devonian. The main characteristics of each play are described in Figure 1. All UDG plays target sedimentary rocks. The Dinantian play has the highest geothermal potential due to its wide distribution, significant thickness and multiple forms of permeability, i.e. karstification, natural fractures and matrix permeability. Both the Triassic and Rothliegend UDG plays are limited in lateral distribution and the reservoir quality diminishes with increasing depth. The distribution and thickness of the plays are illustrated in a cross-section of the Netherlands in Figure 2. The knowledge about the Devonian play is very limited and the play may only become relevant in the long term.

Play name	Age	Group	Formations	Lithology	Play potential
Triassic	Triassic	Lower Germanic Trias Group	Hardegsen Fm. Detfurth Fm. Volpriehausen Fm. Lower Buntsandstein Fm.	Sandstone	Local potential
Rotliegend	Permian	Upper Rotliegend Group	Slochteren Fm.	Sandstone (fluvial, aeolian)	Local potential
Dinantian	Carboniferous	Carboniferous Limestone Group	Zeeland Fm.	Limestone (carbonate platforms)	Highest potential
Devonian	Devonian	Banjaard Group	Bosscheveld Fm.	Sandstone (?)	Limited knowledge

Figure 1: Overview of the UDG plays in the Netherlands and their main characteristics. For reference see the lithostratigraphic nomenclature of the Netherlands in [Van Adrichem Boogaert and Kouwe (1993-1997].

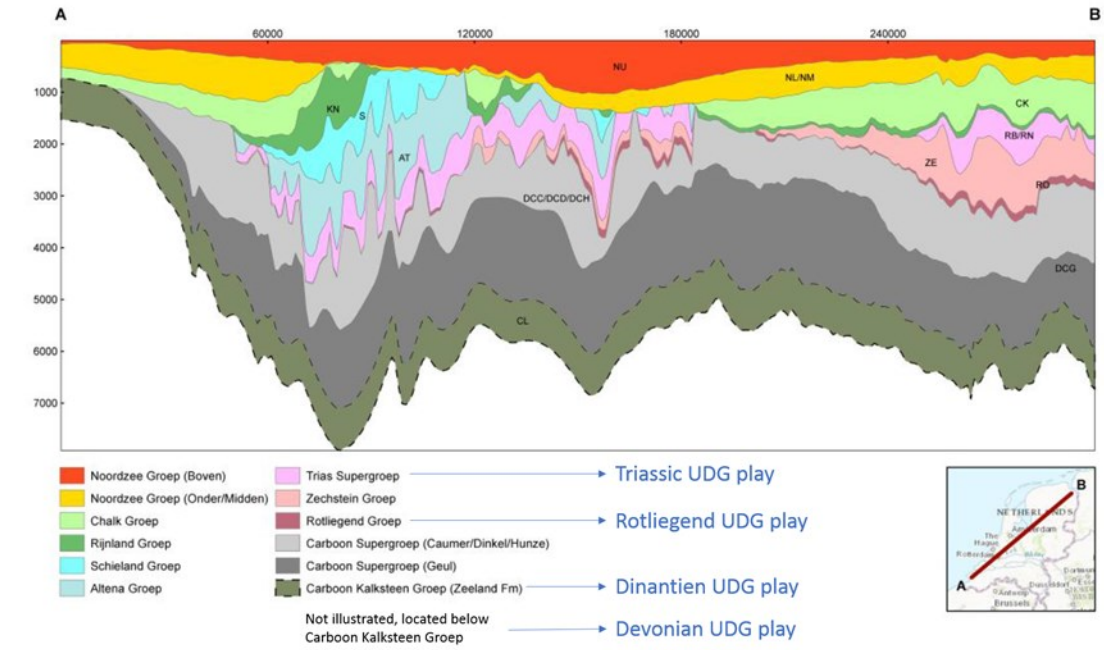

Figure 2: SW-NE cross-section of the subsurface of the Netherlands illustrating the depth, distribution and thicknesses of the Triassic, Rotliegend and Dinantian UDG plays. The thickness of the Zeeland Formation (Dinantian) is not well constrained and therefore indicated as dashed lines [Boxem, Veldkamp and van Wees (2016)].

2.4 Existing UDG and EGS projects

In the Netherlands, there is no UDG or EGS project experience yet. There is experience from UDG and EGS projects in countries such as Belgium, Germany, France, Italy and Iceland. Since all UDG plays in the Netherlands target sedimentary rocks, representative analogues are projects in sedimentary rocks rather than crystalline rocks. There are at least 2 geothermal wells of >4 km depth targeting sedimentary (carbonate) rocks in Bavaria (Sauerlach and Traunreut) and the abandoned St. Gallen project in Switzerland having reached carbonate rocks at 4.4 km depth. EGS in sedimentary rocks exist in Germany at depths between 3.3 and 3.8 km (Landau, Insheim, Horstberg). EGS projects in crystalline rocks at depths larger than 4 km exist in France (Soultz-sous-Forêts and Rittershoffen), Germany (Bad Urbach), Australia (Cooper Basin) and Korea (Pohang). The Balmatt geothermal site in Belgium, close to the Dutch border, produces at a temperature of 126-128 °C from Dinantian carbonates at approximately 3.8 km depth. The Balmatt geothermal installation operated by VITO is considered to be the best analogue for the UDG Dinantian play in the Netherlands.

2.5 Ultra deep subsurface data

The Dutch deep subsurface is well known due to extensive well and seismic data from oil and gas exploration, which are publicly available via the Dutch Oil and Gas Portal (NLOG). However, the number of onshore boreholes reaching depths greater than 4 km is limited. Existing geothermal wells in the Netherlands reach maximum depths up to 3 km, except for the recently drilled Trias Westland geothermal doublet which reached a depth of 4.1 km.

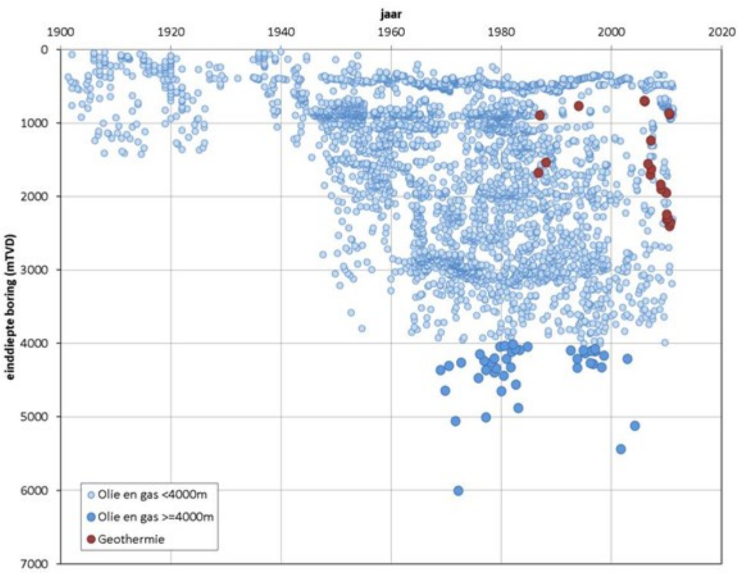

Figure 3: Overview total vertical depth (TVD) of wells drilled onshore in the Netherlands. Blue: oil and gas drilling, red: geothermal wells. 41 Wells are deeper than 4 km, 6 deeper than 5 ([Boxem, Veldkamp and van Wees (2016)].

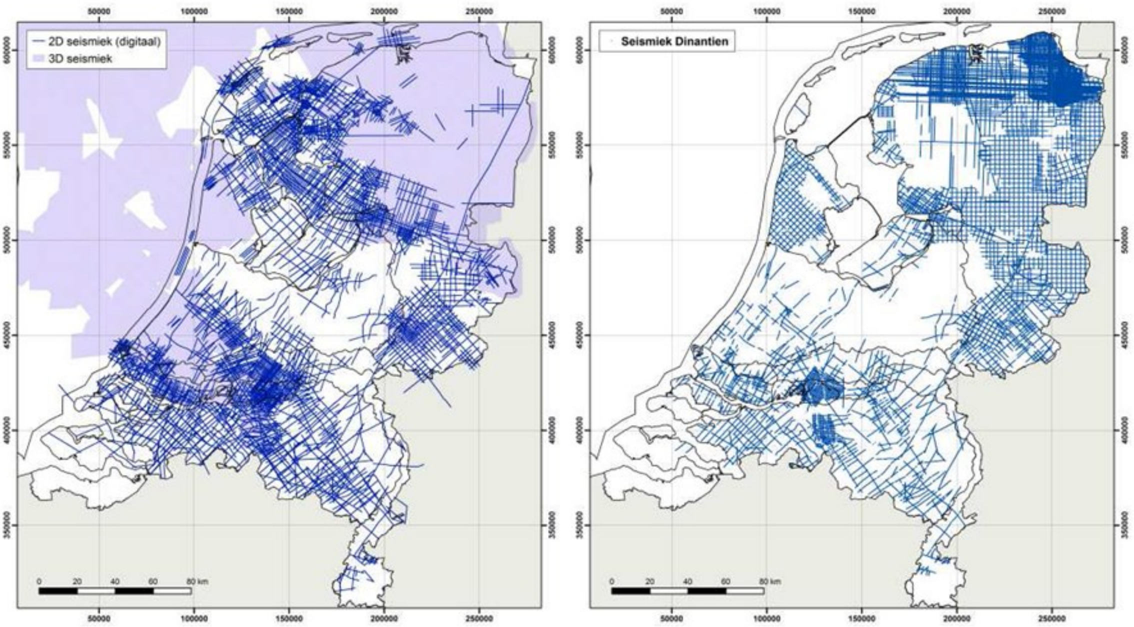

Figure 4: Overview total available seismic data (left) and overview available seismic data which images Dinantian Carbonates (right) [Boxem, Veldkamp and van Wees (2016)].

Existing seismic surveys are concentrated in conventional hydrocarbon regions, which do not necessarily overlap with potential regions for UDG exploration. Furthermore, existing seismic surveys were not designed and executed to provide good quality images at depths greater than 4 km. Therefore, there is limited geological information and few (reliable) geological models at depths greater than 4 km. In 2019, EBN started the SCAN Dinantian program to gain more knowledge on the deep subsurface. The SCAN program investigates the potential of the ultra-deep subsurface through seismic data acquisition and re-processing and interpretation of existing data and potentially exploration wells.

3. APPROACH

Since there is no experience with UDG and EGS in the Netherlands on the basis of which risks can be identified, an international team of experts on drilling, stimulation, testing, operation and seismicity from the Netherlands and abroad combined knowledge from literature and their own experience and translated this to the situation in the Netherlands. To identify all risks and develop a classification scheme the approach as illustrated schematically in Figure 4 was followed.

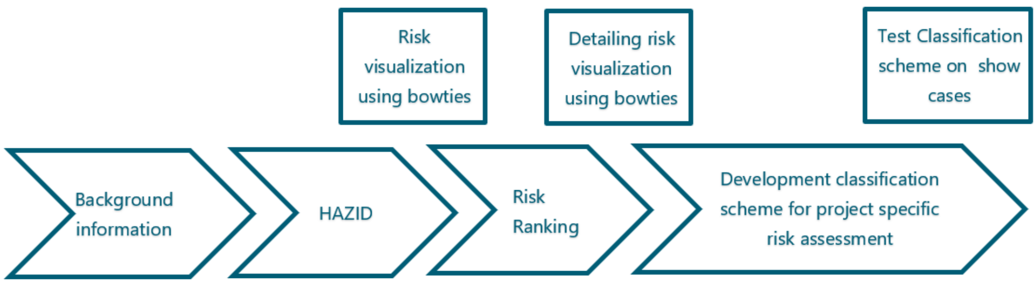

Figure 4: Overview of the approach.

Based on literature and HAZID (hazard identification) sessions an international team of experts from inside and outside the project team identified the top risks. These identified top events have been ranked and the ones with the highest impact on health, safety and environment were worked out in more detail as bowtie diagrams. Following the scope of this study, bowties have been developed at a sufficiently high level to identify and classify the main risks of a UDG or EGS project. The project-specific risk classification scheme is worked out in separate modules for non-seismic risks and seismic risks. The module for the non-seismic risks follows the bowtie structure. The purpose of this scheme is to identify the top risks of a specific project. This is done by linking project- and site-specific parameters to threats, adding relative contributing factors to the threats based on their importance and assigning impact and effectiveness to consequences and mitigation measures. This classification scheme uses an Excel-based relational-database structure and is filled with factors based on expert elicitation. It was tested on one analogue UDG site in Belgium (Balmatt) but allows for improvement when more UDG or EGS projects are implemented and more information becomes available. For the seismic risks the bowties are used as a visualisation tool of threats, events and consequences. Multiple factors may be responsible for the occurrence of induced seismicity, making it challenging to discriminate the exact threats as causes. The module in the classification scheme for seismic events uses the existing QuickScan [Baisch et al. (2016)] as a basis and has been extended including effectiveness of traffic light systems and potential damage levels.

4. OVERVIEW OF RISKS

Figure 5 presents the overview of risks for UDG and EGS in the Netherlands as identified and ranked qualitatively by the team of experts. Top events are ranked according to degree of impact and likelihood.

Rank	Top Event	Hazardous activity	Explanation risk	Argumentation Ranking
1	Loss of well control resulting in blow-out (internal or external)	UDG Drilling	Loss of well control due to sudden increase in pressure involving an uncontrolled release of fluids and/or steam from a well.	Very high impact, well control incident is likely. Can be mitigated well. Likelihood of blowout: low.
2	Integrity loss of well and surface facilities impacting environment/ people	Production of hazardous fluid/steam	Processes such as corrosion can cause integrity loss. Pressurized hazardous fluid (superheated water) rapidly expanding into steam might leak to the subsurface or migrate to and escape at surface. This can lead to groundwater contamination and injuries.	High impact, corrosion is very likely. Can be mitigated well. Likelihood of integrity loss is low.
3	Staff exposed to hazardous situation (impact internal facility)	UDG Drilling	UDG drilling operations involve a higher risk of injuries, intoxication or exposure to radiation to staff.	High impact, high likelihood. Can be mitigated well.
4	Leakage or spillage impacting surface and subsurface environment	UDG Drilling	Fluids such as stored additives, waste fluids and drilling mud could leak to the subsurface. This can lead to groundwater or surface water contamination.	Moderate impact, high likelihood. Can be mitigated well.
5	Moderate earthquake (DG2)	UDG and/or EGS near existing, critically stressed faults/weak zones	Earthquake occurrence due to injection of cold fluids or stress increase especially near faults, loss of strength of fault/weak zones.	High impact, likelihood considered low, but depends very much on (generally poorly known) initial stress state. Poorly mitigatable
6	Uncontrolled release of more hazardous produced fluid/steam	UDG well testing and disposal of fluid/steam	The well test will likely produce large volumes of superheated water rapidly expanding into steam which poses risk of injuries. During disposal of test fluid, fluids might leak. This can lead to groundwater or surface water contamination.	High impact, medium-high likelihood because of temporary pipework involved. Can be mitigated well.
7	Small earthquake (DG1)	UDG and/or EGS near existing, critically stressed faults/weak zones	Earthquake occurrence due to injection of (cold) fluids or stress increase, especially near faults.	High impact, likelihood considered medium, but depends very much on (generally poorly known) initial stress state. Poorly mitigatable
8	Radioactivity in system	Production of hazardous fluid/steam	Naturally occurring radioactive material (NORM) in formation fluids or cuttings, formation of scales.	Low impact, high likelihood. Can be mitigated well.
9	Felt earthquake, not causing damage	UDG and/or EGS near existing, critically stressed faults/weak zones	Earthquake occurrence due to injection of cold fluids or stress increase, especially near faults.	Low impact, likelihood considered high, but depends very much on (generally poorly known) initial stress state. Poorly mitigatable
10	Leakage / spillage impacting environment and staff on-site	Development of EGS through hydraulic stimulation	Stimulation fluids containing inhibitors or biocides might leak. This can lead to groundwater or surface water contamination. Temporary pipework and the high pressures applied enhance the risk of injuries as a result of a high-pressure incident.	Low impact, medium likelihood. Can be mitigated well.

11	Release of toxic, flammable, corrosive or radioactive gas outside system	Co-production of gas during testing	Toxic gases or large amounts of gases might be released unexpectedly (natural gas, H2S, CO2).	Low impact, high likelihood. Can be mitigated well.
12	Nuisance	UDG drilling / stimulation	Noise and light pollution due to drilling practices and traffic.	Low impact, high likelihood. Can be mitigated well.
13	Unwanted distribution of hot steam possibly combined with development of fog/icing during testing	Production of hot steam	Release of steam could cause nuisance for surroundings in the form of fog formation of icing on nearby roads.	Low impact, medium likelihood. Can be mitigated well.
14	Degassing	Production of hazardous fluid/steam	Dissolved gas in formation water is released when pressure decreases.	Low impact, low likelihood Can be mitigated well.
15	Thermal radiation from well	Production of hazardous fluid/steam	Temperature around the well might increase, leading to heating of groundwater.	Low impact, medium likelihood. Can be mitigated well.
16	Hot surfaces in surface facilities	Production of hazardous fluid/steam	Staff could get burned or injured.	Low impact, medium likelihood. Can be mitigated well.

Figure 5: Overview of identified top events for UDG and EGS. The ranking, based on degree of impact and likelihood, is generic, not project specific, and applies to the top event during the specifically indicated hazardous activity. Some risks can also occur during other hazardous activities.

In this study the top 11 events are described in more detail in terms of threats, consequences and mitigating measures, following the bowtie methodology (see an example in figure 6). The list of mitigating measures should not be considered exhaustive. Measures may vary in effectiveness and in cost and are subject to change due to the growing geothermal industry and new innovations. The effectiveness of mitigating and preventive measures is discussed in this study as well as the remaining risks. Whether a measure is cost-effective should for each project be assessed individually using the ALARP (as low as reasonably practicable) principle and taking into consideration of the acceptability of the remaining risks. The top 11 risks contain 3 risks related to induced seismicity. The 8 other risks are related to drilling, testing, stimulation and production. In the Netherlands the potential risk of seismicity is a sensitive discussion, yet critical for operators to obtain a 'social license-to-operate'. Whether and to what degree potential risk of damage is acceptable or not is up to the regulator and society to decide and needs to be carefully evaluated. Remaining risks (top events 12 up to 16) have not been worked out in bowtie diagrams because of the project scope limitations. It is recommended to work out the remaining risks with the bow-tie systematic and implement the result in the classification scheme.

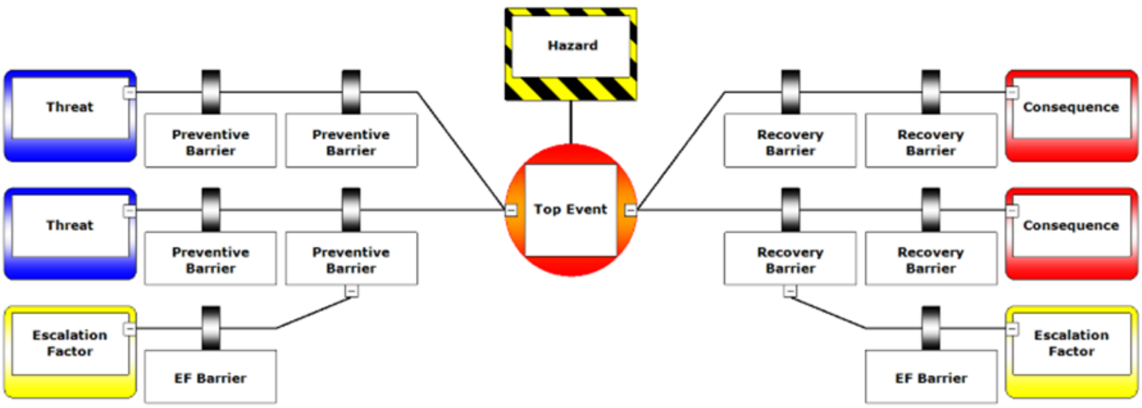

Figure 6: Example of a bowtie diagram.

5. RISK CLASSIFICATION SCHEME

The ranking of top 11 events (see Figure 5) is based on the generic impact on Health, Safety and Environment. Project specific characteristics, such as fluid chemistry, pressure and temperature may result in a different ranking. Also experience of the operator, project preparation time and availability of subsurface information are project-specific and affect the likelihood and impact of the events. The main purpose of the classification scheme is to rank the project-specific risks and to determine for what risks further detailed risk assessments are required. A classification schemes consisting of 2 modules has been developed: one for the non-seismic risks and one for the seismic risks.

5.1 Classification scheme for non-seismic risks

This classification scheme uses a database following the bowtie structure. The database links project- and site-specific parameters to define the likelihood of threats and assigns impact and effectiveness to consequences and mitigation measures. Figure 7 provides a schematic overview of the methodology to determine the naked, unmitigated, risk.

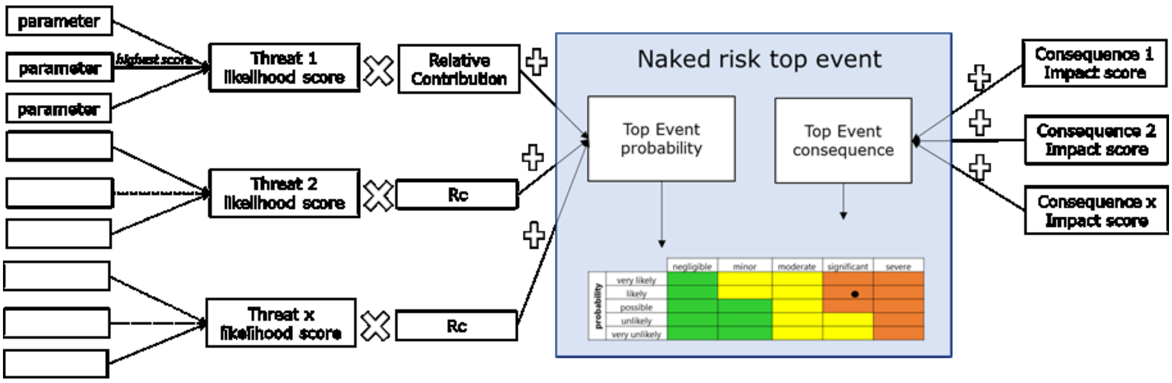

Figure 7: Schematic overview of methodology to determine the naked risk in the classification scheme

The likelihood assessment for drilling, testing, stimulation and production risks uses a set of parameters that characterise the UDG/EGS project. Each parameter is subdivided into a maximum of 5 classes: from very low to very high. The parameters and their ranges are provided in figure 8. In the classification scheme each threat is linked to one or more parameters to determine the likelihood score of a specific threat, following the same categorisation: a 'high' qualitative risk category for the parameter automatically leads to a 'high' score category. A threat that is linked to more than one parameter will receive the highest risk category of the linked parameters. So even if there are 5 parameters linked to a threat and 4 of the 5 parameters have a category 'low' and the 5th parameter a category 'high', then the threat would still receive the score 'high'.

Parameter	Unit	Qualitative risk categorisation				
		Very high	High	Medium	Low	Very low
Pressure	Bar	>1250	1000-1250	750-1000	500-750	<500
Temperature	°C	>180	150-180	120-150	90-120	<90
Chemistry	ppm	presence CO2 or H2S				no CO2 < # ppm and H2S < 7 ppm
NORM in brine	Bq/l	> 100	50 - 100	5 - 50	1 - 5	< 1
NORM in scales/fines	Bq/g	>100	50 - 100	0.5 - 50	0.1 - 0.5	<0.1
Hydrocarbons presence		presence of hydrocarbons				no hydrocarbons
Gas content brine	Nm^3/m^3	free gas	>5	2.5 - 5	1 - 2.5	< 1
Mud weight	Kg/m^3	>1/6		1.2 - 1.6		1 - 1.2
Offset wells	Nr. offset wells	<= 1	2 to t 3	3 to 4	4 to 5	>5
Experience	Nr. HPHT/Explo projects	<= 1	2 to t 3	3 to 4	4 to 5	>= 5
Preparation time	Months	<6		6 to 12		>12
Working pressure (hydraulic stimulation)	Bar	>680	590-680	500-590	500-410	<410
Population density	inhabitants/km^2	>2000	1000-2000	500-1000	250-500	<250

Figure 8: Parameters to characterise the UDG/EGS project. Note: the list of parameters in this table is not complete. Other parameters can be identified (such as H2S and resources like budget constraints) that influence UDG and EGS

threats. The user of the relational database can easily adjust the classification scheme and add parameters themselves.

The next step is to assign a 'relative contribution' (RC) to each threat. Not all threats are equally important to cause its top event. By assigning a RC value, the relative importance of each threat can be specified. Similar to the parameters, the RC is divided into five classes ranging from 'very low' to 'very high'. The RC is expressed as a percentage in relation to the other threats that can cause the top event. The RC is considered to be independent of the characteristics of the project. The sum of threat scores multiplied with each threat's RC gives the unmitigated likelihood of occurrence of the top event.

The consequences are provided with a qualitative impact value (severity factor), also ranging between 'very low' to 'very high'. The impact of a top event is determined by the sum of the impacts of the linked consequences.

The mitigated risk is the risk including the application of preventive and mitigation measures. Figure 9 provides a schematic overview of the methodology to determine the mitigated risk. The likelihood of threats can be reduced by implementing barriers. The impact of consequences can be reduced by implementing recovery barriers. The effectiveness of the barrier is determined with a reduction factor (RF). A barrier that is highly effective receives a low reduction factor (e.g. BM = 0.5) and a barrier that is not effective receives a reduction factor close to or equal to 1.

On the left side of the bowtie diagram, the barrier reduction factor is multiplied with the likelihood of the related threat. On the right side of the bowtie diagram the effectiveness of the recovery barriers is also provided with a reduction factor, the recovery reduction factor (RRF), similar to the preventive barriers. The summed consequences of each top event is re-calculated into a reduced impact of top event. For each threat and consequence, various barriers are defined. Not all barriers may be applicable or used in a project. In the relational database, the user must choose whether or not to employ certain barriers.

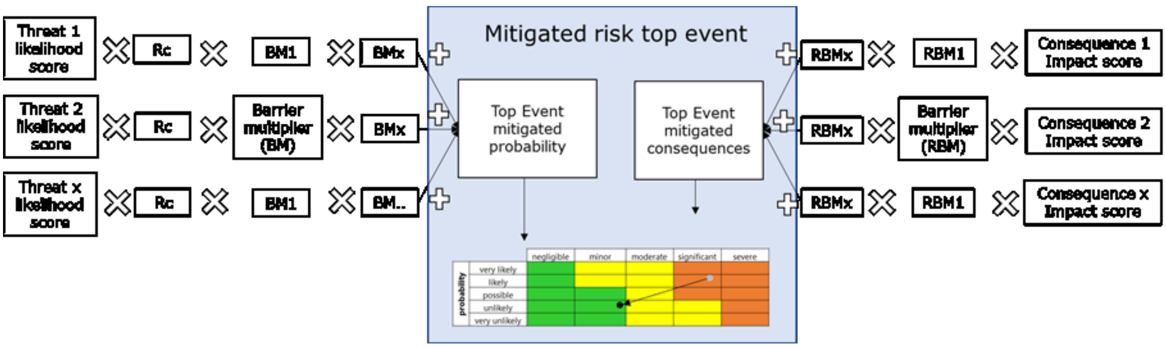

Figure 9: Schematic overview of methodology to determine the naked risk in the classification scheme

5.2 Classification scheme for seismic risks

The basis for the proposed classification scheme for induced seismicity is the QuickScan scoring scheme based on subsurface and operational parameters by [Baisch et al. (2016)]. Due to the larger test-database and since the scoring scheme has already been put in place in the Netherlands, the QuickScan scoring scheme by [Baisch et al. (2016)] is adapted for the current study. Of course, a scoring scheme is a living document where revisions will be necessary as more observational data and different interpretation become available. The QuickScan provides an empirical proxy for the induced seismicity potential of geothermal operations. The QuickScan score is converted into a proxy for probability per year per damage grade (DG) using the following relations: (1) Gutenberg-Richter statistics (b=1) indicating that the rate/probability of an earthquake of magnitude M+1 is 10 % of the rate/probability of an earthquake of magnitude M and (2) the local magnitude definition (Richter) where 1 magnitude unit corresponds to a factor of 10 in signal amplitude. In the classification scheme a quick scan to categorize the consequence is also included. The (semi-)quantitative manner is chosen to create internal consistency with the non-seismic module. Figure 10 provides a schematic overview on the methodology used to assess the seismic risk for a specific project.

The purpose of the classification is to quickly assess for a specific project whether seismicity is a risk that needs managing and further study is required. This classification does not replace a detailed probabilistic or deterministic analysis, it merely indicates the need for such an analysis. In the classification scheme we propose to limit the ranking to the Damage Grade 0 (DG 0), DG 1 and DG 2 level, since we assume that no geothermal project will be developed in the Netherlands which is exhibiting a considerable risk for causing DG>2 damage. Ranking the severity of earthquakes is both a technical and a societal decision. Projects that fall in DG 1 and DG 2 level will require project specific hazard and risk analysis e.g. a probabilistic seismic risk analysis.

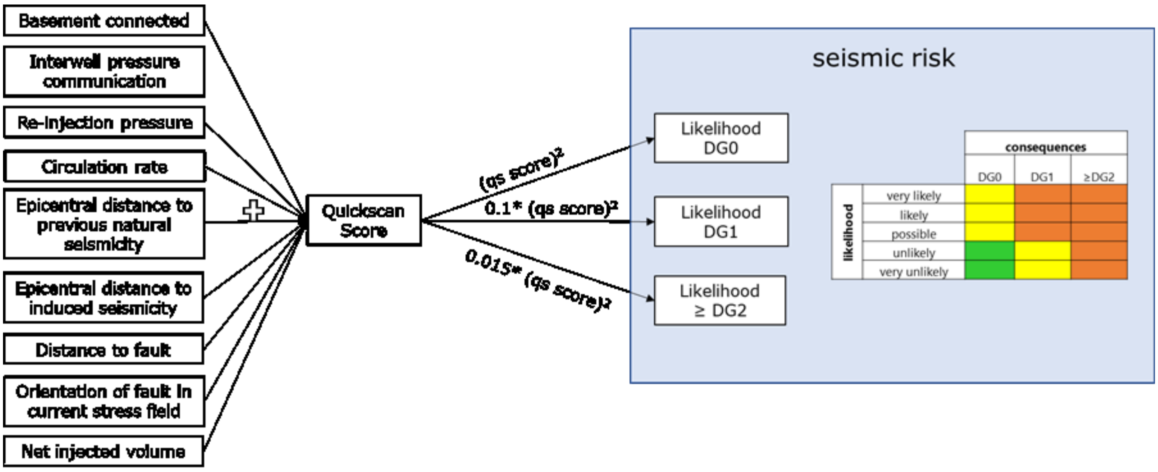

Figure 10: Overview of risks (top events) for UDG and EGS in the Netherlands. The ranking, based on degree of impact and likelihood, is generic, thus not project specific.

5. CONCLUSIONS AND RECOMMENDATIONS

This study presents a comprehensive overview of the HSE risks for UDG and EGS projects in The Netherlands and a pragmatic approach to rank the project-specific risks and to determine for what risks further detailed risk assessments are required. The risk overview and classification scheme can be used to develop strategies for risk management and mitigation by both regulators and geothermal operators in The Netherlands and abroad. While the proposed classification scheme is done in a (semi-)quantitative manner and thus may appear both precise and accurate, it needs to be emphasized that the presented methodology is non-standard, has not been operationalized or trialled in field settings, and thus may not be immediately suitable to be embedded in a regulatory framework.

The most important risks have been identified based on literature, experience abroad, experiences from the oil and gas industry and expert elicitation. No experience has been gained with UDG and EGS in the Netherlands yet. This implies that the identified risks, including defined threats, consequences and mitigation measures should be treated with care, and to be re-evaluated and updated once UDG projects have started. Because of the large uncertainties, the actual risks could turn out to be smaller than identified here, or larger. The identified risk and the classification scheme could be used by the UDG/EGS regulator and operators alike as a check or methodology for the risk management strategy of the project. However, it should be emphasized that the risk analysis provided in this study is likely not complete and possibly inaccurate. The UDG/EGS operator is thus still responsible to perform their own assessment and critically evaluate the proposed measures and threats. Where required and if appropriate, additions or modifications can be made to the classification scheme. In the classification scheme, the ranking of the risks and the effectiveness of the proposed measures is based on a qualitative approach. The classification scheme requires actual project data in order to make it more quantitative. Because of the absence of reliable project data in the Netherlands, it will require time in order to quantify the risks accurately. It is recommended to develop a database in which statistics can be collected to update and improve the classification scheme as presented.

A point of attention is that the proposed measures are associated with a cost. We follow common practice of operators and suggest that managing HSE is not a 'cost' but required to obtain a license-to-operate. Whether an operator decides to obtain a license-to-operate depends on a large number of factors, among them economic considerations. The latter reflect whether consumers are willing to pay the price for products where geothermal energy is a cost factor. Hence, in the risk assessment there is no consideration made as to the economic feasibility of the measures. Most measures exist and are standard practice in the oil and gas industry. However, in the oil and gas industry the economic rewards are usually larger than in geothermal projects, and certain measures could result in unfeasible business cases for some UDG projects. Research and development of more economic 'fit for purpose' measures for geothermal projects is recommended to reduce risks and costs.

For conventional geothermal projects, there is no similar classification scheme available. In order to provide a consistent advice to both conventional geothermal and UDG/EGS projects, it is recommended to extend the risk assessment and derived classification scheme to conventional geothermal projects, using the same approach that has been used in this study.

Because of the uncertainties in knowledge of the deeper subsurface and lack of experience with UDG/EGS, the actual risks can differ. Especially data acquisition on subsurface characteristics of initial stress state, transmissivity of target formations or structures, (over)pressure, temperature, formation water/gas chemistry and historical/baseline seismicity is required. Moreover further research is required on the following topics: (1) the impacts of pressure, temperature and chemistry changes on the stress conditions of faults, (2) the impact of pressure, temperature and chemistry changes on the integrity of the wells and surface production facilities, (3) the impact of leakage from the geothermal well to the environment (site specific, local conditions), (4) the impact of thermal radiation (site specific, local conditions), (5) NORM on radio activity levels of scales, filters and sludges (6) the development of measures and protocols for treatment of NORM-containing brines and gasses and (7) research and tests on the feasibility of Non-Condensable Gas reinjection working towards an improved protocol to define the bubble point.

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