GeoWell

Innovative materials and designs for long-life high-temperature geothermal wells

Deliverable D6.1

Well integrity risk assessment in geothermal wells – Status of today

Grant agreement no.	654497		
Duration	01.02.2016 – 31.01.2019		
Work package	WP6 – Risk assessment for geothermal wells		
Type	R - document, report		
Dissemination level	PU - Public		
Due date	30.11.2016		
Actual submission date	30.11.2016		
Lead author	-		
Contributors	Hans Petter Lohne, Eric P. Ford, Mohammad Mansouri Majoumerd and Erlend Randeberg		
Version	1.0		
Document status	Completed		
Change history	Version	Date	Changes

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 654497. The contents of this publication do not necessarily reflect the Commission's own position. The document reflects only the author's views and the European Union and its institutions are not liable for any use that may be made of the information contained here.

Executive summary

As part of activities in work package 6 of the GeoWell project, deliverable 6.1 aims to present the current status of risk assessment methods and well integrity for geothermal wells, in order to provide a starting point for listing future requirements for geothermal risk assessments.

In order to map the status of risk assessment methods/techniques and well integrity related to geothermal wells, a literature review and a risk assessment survey have been conducted. The survey has been sent to stakeholders in both geothermal and petroleum industries with the aim to map the status of risk assessments that are performed in these industries.

An overview of the publications that were reviewed, together with the risk assessment survey and its scope, methodology, criteria and preparatory requirements for conducting it, the collected (raw) data and the analysis of data are also presented in this report. The results from both the review and the survey should be interpreted as indicative, not conclusive evidence, due to a limited portion of publications reviewed and limited responses to the survey.

The main findings can be summarized as follows:

- Based on the papers reviewed, the mostly addressed risk type relates to project/financial risk, which differs significantly from our impression of focus in the petroleum industry. This is probably due to the fact that while there is an enormous financial upside when drilling petroleum exploration wells, this is not the case for geothermal wells. Furthermore, the financial margins during production of geothermal projects are typically far less than for oil and gas.
- Another important focus area in the papers is geological risk. However, this is often tightly related to project/financial risk; large uncertainties in the resources to be exploited will consequently result in large uncertainty in the project feasibility as well.
- Only 11% of the publications cover well integrity as a topic addressed.
- Only a few publications reviewed concern risk of loss of containment, or risks of failures in barriers. In fact, the term barrier is hardly mentioned, and even the papers dealing with well integrity do so to a large extent without considering the system as comprised of barriers with failure modes and reliabilities.
- In the literature review, monetary indices were the most used method, with either probabilistic methods or coarse risk ranking following.
- The survey finds brainstorming to be the most used risk identification method.
- The use of methods varies more between the areas of application for risk analysis. The most used methods were HAZOP, root cause analysis, scenario analysis and environmental risk and decision tree analysis, depending on the area.
- For risk evaluation, the situation was similar to risk analysis. This is not surprising, given that the risk evaluation is based on the risk analysis. Depending on the area, Monte Carlo simulation, root cause analysis, structured what-if technique analysis and environmental risk analysis were most frequently chosen methods.
- Regarding the use of risk assessment methods in terms of resource demands, nature of uncertainty and complexity, there is no evidence to suggest that there is an overweight of simplistic, low-complexity methods in use in the geothermal industry.

Contents

Tables

Figures

Abbreviations

API	American Petroleum Institute
BHA	Bottom hole assembly
$CaCO_3$	Calcium carbonate
CBA	Cost/benefit analysis
CaP	Calcium aluminate phosphate
CCS	Carbon capture and storage
Cl	Chloride
CO_2	Carbon dioxide
DF	Design factor
EGS	Enhanced geothermal system
EMV	Expected monetary value
ERA	Environmental risk assessment
ETA	Event tree analysis
EU	European Union
Fe	Iron
FEP	Features, events and processes
FMEA	Failure mode and effects analysis
FMECA	Failure mode, effects and criticality analysis
FTA	Fault tree analysis
GEA	Geothermal Energy Association
GRC	Geothermal Resource Council
HACCP	Hazard analysis and critical control points
HAZID	Hazard identification
HAZOP	Hazard and operability studies
HDR	Hot dry rock
HPHT	High pressure, high temperature
HRA	Human reliability analysis
H_2S	Hydrogen sulfide
IAEA	International Atomic Energy Agency
IEA GHG	International Energy Agency Greenhouse Gas R&D Programme
IGA	International Geothermal Association
IRR	Internal rate of return
ISO	International Organization for Standardization
LCF	Low cycle fatigue
LCM	Lost circulation material

LOPA	Layer of protection analysis
MCDA	Multi-criteria decision analysis
NCS	Norwegian Continental Shelf
NH_4	Ammonium
NJRISE	North Japan Research Institute for Sustainable Energy
NORSOK	the competitive standing of the Norwegian offshore sector ("Norsk sokkels konkurranseposisjon", standards that are developed by the Norwegian petroleum industry)
NPV	Net present value
N_2	Nitrogen
OSTI	Office of Scientific and Technical Information
PDC	Polycrystalline diamond compact
PHA	Preliminary hazard analysis
PRA	Probabilistic risk assessment
PSA	Petroleum Safety Authority
QRA	Quantitative risk assessment
RAMS	Reliability, availability, maintainability and safety
ROI	Return on investment
ROP	Rate of penetration
SF	Safety factor
Si	Silica
SSAS	Sodium silicate-activated slag
SWIFT	Structured what-if technique
UCS	Unconfined compressive strength
US DOE	United States Department of Energy
WP	Work package
WSD	Working stress design

1 Introduction

The geothermal industry is in steady growth. In 2015, geothermal energy systems produced 73.6 TWh of electricity in 24 countries [1] and 163 TWh of thermal energy [2]. In order to accelerate the development of geothermal resources for power generation in Europe and worldwide in a cost effective and environmentally friendly way, the European Union (EU) has awarded the GeoWell project funding [3]. This collaborative research project (2016-2019) aims at developing reliable, cost-effective and environmentally safe technologies for design, completion and monitoring of high-temperature geothermal wells.

As part of the GeoWell project, work package six (WP6) "risk assessment for geothermal wells" has the overall objective to develop risk and reliability analysis tools for assessment of both high enthalpy wells and extreme temperature wells in volcanic areas. This WP has the following secondary objectives:

- Raise the standard of risk analysis tools for geothermal wells to a standard that is comparable to that of oil and gas wells;
- Propose a risk management framework that can be used for any deep geothermal wells;
- Evaluate and manage risks related to the introduction of new materials and tools developed in other work packages within the GeoWell project.

In order to achieve all the WP6 objectives, existing experiences and the vast volume of knowledge and methodologies developed in the petroleum industry will be employed. Accordingly, the foundations for the development of new risk analysis tools and a framework for risk assessments in the geothermal industry, more specifically for the needs of geothermal wells, will be established.

Deliverable 6.1 is aimed at providing a state-of-the-art report covering different well integrity issues and risk assessment methods that are currently practiced in geothermal wells. For this purpose, a review of recently published articles and reports has been conducted. Moreover, the "GeoWell risk assessment survey" has been prepared and sent to stakeholders dealing with risk assessment in both the geothermal and petroleum industries. Deliverable 6.1 presents the findings of both the literature review and the risk assessment survey.

Parallel efforts have been devoted to provide a separate deliverable from WP6 covering practices of the petroleum industry with respect to well integrity and risk assessment methods (D6.2). Note that D6.1 and D6.2 are complementary to each other. These deliverables share some common topics including introduction to well integrity and risk assessment as well as the GeoWell risk assessment survey. The main purpose for presenting common topics with similar description in both deliverables is to enable both reports to stand independently and to provide necessary background information that readers might need to digest the main messages of each report.

1.1 Scope

The life cycle of a geothermal well is similar to that of an oil and gas well and can be divided into four main phases as shown in Figure 1-1.

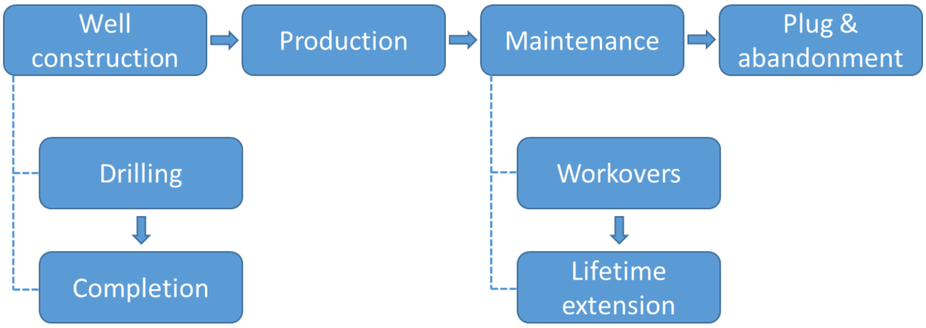


Figure 1-1. Different phases in the life cycle of a well.

Risk assessment is performed for both the initial execution of the job and the long-term consequences of the activity for every life cycle phase. However, this deliverable mainly focuses on methods for performing risk assessment during the well construction, production and maintenance phases.

One may distinguish between technical and non-technical risk assessments. WP6 of the GeoWell project addresses only technical risk assessment for geothermal wells. For completeness, financial/economic risks for development of geothermal projects and risks connected to personnel's health and safety are also partly covered in D6.1.

In this work, the focus is on geothermal systems in which wells are constructed to produce thermal power at a relatively high temperature (for electricity production). For the GeoWell project, high-temperature issues such as thermal strains on well tubulars, corrosion, casing/cement/formation bond are particularly relevant. As such, shallow geothermal systems at low temperatures (typically utilizing heat pumps) are not treated in any detail.

1.2 Methodology

To carry out the literature review covering different technical risk assessment methods, a number of articles have been reviewed. The main approach for finding relevant articles has been to search the online database of International Geothermal Association[1] (IGA) for geothermal-related publications, as well as including other publications from various sources, which were found to be relevant. The search words "risk" or "well integrity" have been used as a selection basis for those papers selected in this review. There might be a weakness in this approach as papers that primarily deal with risk methodologies, but are applied to geothermal cases, could be published in risk-related journals (such as Journal of Risk and Reliability). Nevertheless, there should still be a sufficient amount of papers within the geothermal publication realm focusing, to a lesser or larger degree, on risk assessment and well integrity. This is at least true in the petroleum industry, where numerous publications can be found when searching for these topics in OnePetro[2] (an online library of technical literature for the oil and gas exploration and production industry). The reviewed papers are classified based on different indicators such as 1) publication year; 2) the topics that are addressed e.g. uncertainty quantification and well integrity; 3) different types of risks that are assessed; and 4) tools that are used for assessing risks. It should be stressed that the classification of types of risks addressed and risk assessment methods used are interpretations of the authors and as such do not represent an "objective truth".

[1] https://www.geothermal-energy.org/publications_and_services/conference_paper_database.html
[2] https://www.onepetro.org/

The methodology for preparing the GeoWell risk assessment survey, covering the reasoning for the questions, potential hypothesis, making the recipient list and data analysis methodology, is elaborated in Section 4.

1.3 Outline of the report

Section 2 presents a brief introduction to well integrity and the main differences between geothermal and petroleum. Section 3 provides a short introduction to risk assessment, general risk assessment frameworks, regulations and guidelines influencing the risk assessment process and existing risk assessment methods and techniques.

Section 4 presents the objectives, methodology, criteria, preparatory requirements and post survey evaluations of the risk assessment survey. Section 5 provides results of both the literature review and the risk assessment survey and summarizes the analysis of findings from both the survey and the literature review. Section 6 provides the concluding remarks of this deliverable, while Section 7 presents dissemination and future activities within WP6. Appendices I and II provide the questions in the risk assessment survey and its assembled raw data, respectively, while Appendix III presents a list of the reviewed papers (i.e. Section 5.1).

2 Well integrity in geothermal and petroleum industries

This section primarily aims to provide a concise description of well integrity relevant for geothermal and petroleum industries. Fundamental differences between geothermal and petroleum wells are outlined, as these differences might influence both the approach undertaken, and the tools used, to assess risk in each of the two contexts, and consequently how well integrity is addressed.

2.1 Introduction to well integrity

Wells can be classified into two main categories; i) exploration wells, with the aim to characterize potential reservoirs for future development and production, and ii) production or injection wells that either extract the resources from the reservoir or inject water or gas for pressure support.

The term "well integrity" has different definitions. Two of the most commonly used and accepted definitions are found in standards NORSOK D-010 and ISO TS 16530-2:

NORSOK D-010: "Application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well" [4].

ISO TS 16530-2: "Containment and the prevention of the escape of fluids (i.e. liquids or gases) to subterranean formations or surface" [5].

NORSOK D-010 is developed by the Norwegian petroleum industry and has a focus on well barrier elements, and that the integrity of these shall be verified by pressure testing or by other specified methods. The standard requires at least one primary and one secondary barrier. It also requires the risk assessment of well integrity failure or well control incidents. Risk assessments of well integrity shall consider:

a) Cause of degradation;
b) Potential for escalation;
c) Reliability and failure modes of primary well barrier elements;
d) Availability and reliability of secondary well barrier elements;
e) Outline plan to restore or replace degraded well barriers.

As mentioned earlier in Section 1, the life cycle of the well is from the construction phase to final abandonment (i.e. including drilling and completion, production, workovers and lifetime extension, and plug and abandonment). NORSOK D-010 also specifies a well integrity management system, comprised of the following elements: organization, design, operational procedures, data system and analysis.

ISO TS 16530-2 applies to all wells that are utilized by the oil and gas industry, regardless of age, type or location. It considers only the operational phase (i.e. not well construction, workover/lifetime extension nor abandonment), and similarly requires addressing risk assessment aspects of well integrity management. While NORSOK is more barrier-focused, ISO TS 16530-2 lists considerations such as:

- Location;
- outflow potential;
- well effluent (i.e. fluid components);
- external environment, and
- redundant systems.

There are generally four ways in which a leakage may occur from the well to the environment; 1) through the downhole completion tubing, 2) through the downhole completion annulus, 3) through the cement between the annuli or 4) outside and around the well casing system.

Well integrity has been an important topic that has been investigated comprehensively for petroleum wells. However, there are not many papers covering this topic for geothermal wells as stated by [6].

The primary and long-term function of a geothermal well is to act as a conduit between the surface and the underground geothermal reservoir [7]. Similar to hydrocarbon wells, the integrity of wellbores throughout the life cycle of wells needs to be assured to provide good zonal isolation.

2.2 Petroleum vs. geothermal wells

The geothermal industry has elements unique to it and also risks and uncertainties that differ from those related to the petroleum industry. Some of the key features of geothermal prospects and the drilling of geothermal wells are presented in the following sub-sections.

2.2.1 Financial

While most of the time hydrocarbons may be produced and sold very soon after discovery and development, geothermal resources cannot generate a return on investment until a suitable power plant is constructed and connected to the electrical and/or district heating grid, and thus revenues are significantly delayed. In addition, in some cases, the need for casings that are more expensive and other equipment to withstand the high temperature and corrosive environment increase the costs of geothermal wells. For deep geothermal wells, the cost increases sharply due to both stimulation in order to achieve sufficient production rates, and completion of the well.

In addition, due to the less collaborative environment in the geothermal industry (unlike the internationally oriented petroleum sector), it might not have been developed into an open spirit community, and lessons learned and common technical standards are still today impossible to establish across the business community.

2.2.2 Formation characteristics

Reservoir fluids should be at least 120 °C and preferably 150 °C to generate electricity efficiently. However, there are systems for temperatures down to 90 °C, but the efficiency of energy conversion is significantly lower than the systems with higher temperature levels. For hot dry rock (HDR) geothermal systems, temperatures may range from 200 to 350 °C, while for magmatic systems temperatures range from 600 to 1400 °C [8].

In addition to having high temperatures, formations where geothermal energy is exploited are also characterized by being/having:

- Hard (> 240 MPa compressive strength)
- Abrasive (> 50% quartz content)
- Highly fractured (fracture apertures of centimeters)
- Under-pressured
- Corrosive fluids
- Very high solids content in the formation fluids in some cases

One of the most important differences between petroleum and geothermal wells is that the latter are exposed to high temperatures and high temperature variations (specifically in the case of deep wells or wells that are in high temperature areas). In the petroleum industry, high temperature is defined as temperatures greater than 150 °C for undisturbed bottom hole temperature at prospective reservoir depth or total depth [9].

2.2.3 Drilling

Some geothermal wells drill a “controlled blowout”, i.e. drilling into the production zone while the hole is producing dry steam, a conventional practice in The Geysers. In other cases, instead of dry steam, brine inflow occurs while drilling (often a clean-out workover). This requires special equipment and drilling tools such as high temperature wellhead/blowout preventer (BOP) or special BOP cooling processes, and implies making connections in a hot hole and sometimes running liners in a “live” well [8].

Geothermal wells, even within the same field, are more variable then oil and gas wells in a specific hydrocarbon field; the resulting learning curve for geothermal wells based on experience appears to be less useful. Development of enhanced geothermal systems often involves hard rock drilling that is more challenging and costly compared to oil and gas drilling [10]. The hardness of the rock is often defined as its capacity to withstand deforming loads. In oil and gas drilling industry, 30 kpsi (about 200 MPa) unconfined compressive strength (UCS) is by some considered as a limit to define hard rock. This criterion might be related to technological limits, as 200 MPa is close to the limit of performance of current polycrystalline diamond compact (PDC) drillbits in the oil and gas wells. Above this level of compressive strength, different drilling methods are used depending on the industry. In both deep geothermal and oil and gas industries, the typical response to hard sections is to use roller cone bits, or to grind through the rock with impregnated diamond bits. In addition to high drilling costs in hard rock formations, other challenges are:

- High equipment wear and failure, in particular regarding the bottom hole assembly (BHA) and the drill string, as the drill bit is exposed to strong forces during hard rock drilling;
- Low rates of penetration (ROP) and equipment lifetime;

There is also a higher risk of bit clogging or bit balling[1] (as hard rocks are broken in smaller cuttings sizes than softer rock) if cuttings removal (mud flow) is not efficient for a given bit and formation. Although in general, hole cleaning is not a challenge for hard rock drilling, as the ROP is low and the amount of cuttings to remove is somewhat moderate.

Different parameters affect the above-mentioned drilling challenges in hard rock formations including rock hardness, rock abrasiveness (e.g. when quartz is part of the rock composition) and formation heterogeneity (i.e. when formation consists of alternating layers of different rock types, more specifically when alternating layers of hard and soft rock are in close proximity to each other) [11]. Different evolutionary and revolutionary improvements in drilling operation that might result in significant costs reduction, enabling access to deeper and hotter geothermal resources are covered in [12].

With respect to drilling fluids, liquid-based drilling fluids are typically simple mixtures of fresh water and bentonite clay (possibly also with polymer additives to clean the hole and stabilize the wellbore) for geothermal wells, whereas oil- and saltwater-based liquids are also used for hydrocarbon wells. In geothermal wells with high temperature environment, it is essential to keep the drilling fluids cool to avoid alterations in mud properties. This also implies employing special electronic tools (e.g. downhole measurement systems), not used in hydrocarbon wells, to withstand the high temperatures. Aerated (i.e. gas-injected) mud is commonly used in low-pressure formations where lost circulation is a problem. Drilling with air is common in places where the reservoir produces dry steam [8], or in hot dry rock.

[1] It should be noted that in general hole cleaning is not a challenge for hard rock drilling, as the ROP is low and the amount of cuttings to remove is somewhat moderate.

2.2.4 Well design

In order to have an efficient downstream energy system connected to geothermal wells, the wells require large holes and casings, and in many cases require more casing strings than an onshore oil well of the same depth. High drill string and casing weights imply the need for large drilling rigs with sufficient hoisting capability. Large diameter casing and hole sizes require large amounts of cement and more complex placement methods to be applied.

Geothermal wells also require a complicated casing design, especially for wells located in tectonically active regions. The casing design and particularly the material of the casing, is also complicated by temperature cycling [8].

The high-temperature environment that is common in geothermal wells has detrimental effects on the production casing and wellhead [6]. The movement of the casing is restricted by the presence of a cement sheath. Temperature variations, therefore, induce thermal stresses in the casing string that may exceed the yield strength of the casing material [13]. This results in different considerations e.g. for design and analysis of casings and couplings in geothermal wells than in the petroleum wells [14]. As an example, changes need to be considered in case of using working stress design (WSD) methodology that is very common to design and analyze oil and gas wells. This method is used to analyze expected loads versus strength of the selected casing and tubing. This design methodology assumes minimum strength and maximum load assumptions with a safety factor (SF) to ensure a safe design. Minimum strength is based on minimum yield strength and minimum wall thickness. Maximum expected loads are assumed and compared to the strength to calculate the safety factor. The design check is to have the SF equal or larger than the design factor (DF). Due to the high temperatures of geothermal wells, the minimum yield strength is de-rated for elevated temperatures as part of the design check [15]. Moreover, yield strength needs to be de-rated in geothermal wells as the temperature during production is significantly above the room temperature where minimum casing and tubing yield strengths are measured and checked. A typical average derating factor for temperature is 5.4%/100 °C above 21 °C room temperature (as an example minimum yield strength of casing or coupling would be de-rated by 5.4% if the local temperature at depth is 121 °C under production condition) [15]. The combination of high temperature fluids and high flow rates (that is desirable to produce more electricity or heating/cooling) can induce additional stresses on the casing string in geothermal wells [16].

2.2.5 Production

Geothermal wells typically produce directly through the casing, instead of through a production tubing inside the casing, as for most hydrocarbon production wells. In addition, the flow rates are typically much higher in geothermal wells than in hydrocarbon wells. Geothermal wells may also be exposed to corrosive fluids and face problems related to scaling, a challenge also encountered in high pressure, high temperature (HPHT) and sour gas wells for oil and gas.

2.2.6 Cementing

Most geothermal wells have a complete cement sheath from bottom to surface, as opposed to oil and gas wells, where casings typically are only cemented at the bottom (with a fluid above). The reason is both for mechanical support during the intense temperature cycling and protecting the casing from stress corrosion cracking due to in-situ fluids in the case of geothermal wells [15]. Uncemented voids in casing annuli will result in casing failures; hence, one of the primary important factors of a geothermal well is a good cement job on all casing strings.

Geothermal cement is often lightweight (compared to conventional cement). Geothermal cements must also be resistant to acid and CO_2 attack. This has led to the use of e.g. calcium aluminate phosphate (CaP) cement, designed for use in mildly acidic CO_2-rich environments, and sodium silicate-activated slag (SSAS) cement, designed for use in hot, acidic environments with low levels of CO_2 [8].

Cementing can be challenging in lost circulation zones where cement can flow into the formation, preventing cementation to the surface [17].

2.3 Geothermal wells – Challenges, risks and well integrity issues

Failure in the integrity of geothermal wells can result in lost production and induce significant maintenance costs potentially comparable to well completion costs. Often in geothermal wells, failures are related to the casing and cement used in the wells. Improved design and proper selection of casing as well as performing a good cement job have been the most important approaches to minimize the risk of catastrophic well failures [7].

In high temperature geothermal wells, there are risks of failure due to the initial heating up the well, temperature variations during the operational life and formation environment (e.g. presence of corrosive fluids) [7, 13]. Different studies elaborate various casing and coupling failure modes and measures to mitigate the risk for such failures occurring [7, 13, 15, 16].

The study by Southon (2005) [7] is based on investigations of casing failures in geothermal wells in a number of countries within the Pacific – Southeast Asia region. Teodoriu and Falcone [13] evaluated the effects of thermal stresses induced by temperature variations (100-250 °C) and low cycle fatigue (LCF) resistance in the casing string (18 5/8” casing) of a geothermal well, both theoretically and experimentally. Hodson-Clarke et al. [15] focused on different factors for drilling and completion of successful enhanced geothermal system (EGS) wells in Cooper Basin, Australia. Similar to Hodson-Clarke et al., Kaldal and Thorbjörnsson [14] also highlight the failure modes that can occur in the couplings. Lentsch et al. [16] studied different casing failure modes and measures to avoid such failures based on drilling and construction of deep geothermal wells in the Molasse Basin in southern Germany. Such a study can be useful for other deep sedimentary basins.

The following list summarizes some challenges, risks and well integrity issues that may be encountered in geothermal wells [6-8, 16, 18]:

- Difficult drilling conditions: low rate of penetration (ROP) and low bit life (leading to more time spent tripping and idle).
- Higher risk of corrosion: the presence of hydrogen sulfide (H_2S), which also limits the type of drilling equipment materials and casing steels (these must be lower strength steel, as higher strength steel fails by sulfide stress cracking) particularly imposes higher risk of corrosion. External corrosion normally occurs in the presence of a shallow environment (containing corrosive gases) where the casing is attacked from the outside resulting in reduction in the casing wall thickness [7]. Some of the relevant corrosion mechanisms can be found in [6].
- Higher risk and greater severity of lost circulation: this is due to high productivity fractures combined with a low permeability and porosity matrix. Many geothermal wells have been abandoned because of the inability to pass a loss zone, and many more have required an unplanned string of casing to seal off a problem.
- Complex cement job: cement is often used to repair/plug fractures in the upper interval of wells, but is difficult to place accurately, and if the cementing is done after the casing is run, the cementation becomes even more complicated, see Shadravan et al. [6]. Cement casing de-bonding and cement sheath failures (such as formation of micro-annuli and channels) are also common failures, mainly because geothermal operations face high or extreme temperatures.

- Risk for loss of well control: drilling while the hole is producing dry steam, or especially while there is brine inflow, presents a particular risk for losing well control.
- Risk for lost circulation material (LCM): this often happens when the size of the fracture aperture exceeds that of the LCM particles.
- Scaling: brine chemistry may cause scaling, i.e. mineral deposits both inside and outside the casing and in the production interval, potentially resulting in reduced flow area.
- Stress: casings and connectors may be stressed beyond the yield point due to extreme and quick temperature cycling.
- Risk of casing collapse: if water is trapped between the cement and the casing, especially in the intervals where one casing is inside another, there is risk for casing collapse due to volume expansion. Over-pressured zones and tectonic stresses can also cause casing collapse [16]. This usually happens in the body of the casing and is commonly seen in big hole completions [7].
- Compression failure in casing or couplings: this failure mode is due to the loss of mechanical integrity of the couplings, during compression under hot conditions that would normally result in reduction in capacity of couplings to withstand tensile loading. This mode can occur in high temperature fields and high temperature productions conditions (with wellhead temperature exceeding 260 °C) [7].
- Under-pressured formations aggravate differential sticking.
- Aggravation of all the above issues due to high temperatures.
- There are also specific challenges, pertaining to geothermal fluid chemistry, such as:
    - Corrosion: chloride (Cl^-) in the steam entering the steam turbine could cause corrosion damage to internal turbine components.
    - Electronic tool damages and health risks: H_2S in the steam may degrade sensitive electronics and poses health risks to the local population and operating personnel.
    - Fouling: the presence of H_2S, NH_4^+ or N_2 in condensed steam may cause bio-fouling in condensers and cooling towers.
    - Precipitation: hyper-saline brines require either to keep dissolved solids in solution or to control mineral precipitation.
    - Scaling and erosion: silica (Si), calcium carbonate ($CaCO_3$) or iron (Fe) in geothermal brines creates a potential for both formation of mineral scales and erosion of the injection system, injection wells and heat exchangers.
    - Leakage: hydrocarbon-based working fluids used in binary geothermal plants, pose a risk of air pollution and fire, in the event of a leak.

Some of the challenges with respect to cementing is covered by WP3 of the GeoWell project, entitled “Improved cement, ductile surface layer and composite casing”. WP4, entitled “Flexible coupling and casing materials”, covers challenges associated with well tubulars, including connections and material properties suitable for a high-temperature well. Finally, WP5 “Well monitoring” deals with well integrity using downhole fiber optic sensing techniques.

3 Risk assessment

This section is aimed at presenting definitions of risk-related keywords that are often used throughout this document. Moreover, risk assessment and its underlying activities as part of generic risk management frameworks are described. This section also presents the available regulations and standards that govern risk assessments to be performed within geothermal and petroleum industries. Finally, different risk assessment methods/techniques that have been touched upon by the Geowell risk assessment survey are briefly introduced.

3.1 Important risk-related definitions

The following important key words/phrases are frequently used throughout this report, based on ISO 31000:2009 [19]:

- **Risk** – Effect of uncertainty on objectives. An effect is a deviation from the expected – positive and/or negative. Objectives can have different aspects including strategic, organization-wide, project, product and process. Risk is often characterized by reference to potential events and consequences, or a combination of these. Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of occurrence. Uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequence, or likelihood.
- **Risk assessment** – The overall process of risk identification, risk analysis and risk evaluation.
- **Risk identification** – Process of finding, recognizing and describing risks. Risk identification involves the identification of risk sources, events, their causes and their potential consequences. Risk identification can involve historical data, theoretical analysis, informed and expert opinions, and stakeholder's needs.
- **Risk analysis** – Process of comprehending the nature of risk and determining the level of risk. Risk analysis involves developing an understanding of the risk and provides an input to risk evaluation, to decisions on whether risks need to be treated, and on the most appropriate risk treatment strategies and methods. It also involves consideration of the causes and sources of risk together with their positive and negative consequences, and the likelihood that consequences can occur.
- **Risk evaluation** – Process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude or likelihood is acceptable or tolerable. Risk evaluation involves comparing the level of risk found during the analysis process with risk criteria established when the context of the risk assessment was considered. The aim here is to assist in making decisions about which risks need treatment and the priority for treatment implementation.

3.2 General risk frameworks

According to ISO 31000:2009 [19], risk management is "coordinated activities to direct and control an organization with regard to risk". Risk assessment is one part of a risk management process, and is in the same standard defined as "the overall process of risk identification, risk analysis and risk evaluation".

Typically, other parts of the risk management framework include establishing the context, risk treatment, communication and consulting, and monitoring and review, as shown in Figure 3-1.

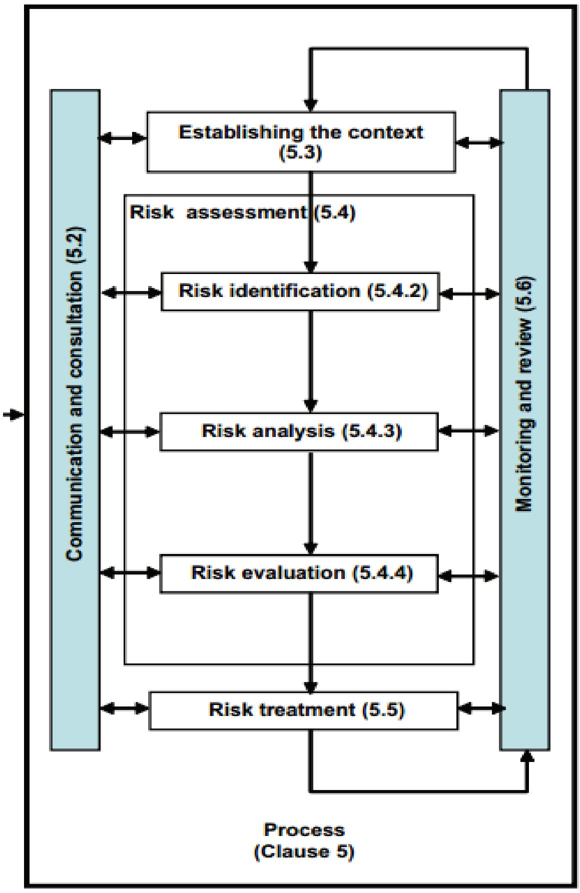


Figure 3-1. A general framework for risk management as presented in ISO 31000:2009.

The ISO framework for risk management and risk assessment is generic and high-level, and does not give detailed guidelines on specifically what tool or methods should be used to achieve the overall objectives. Naturally, the specific implementations of risk assessment frameworks will vary in accordance with the area of application. The nature of the risk and its associated uncertainty will be different when considering areas or industries such as petroleum, nuclear energy, space aviation, societal security or natural disasters. The actual implementation of the risk assessment framework will also vary with the types of risk that are the focus of the assessment. Such categories include project- and financial risks, geological risks, barrier risks, health and safety risks, environmental risks or pressure- and wellbore risks, and are quite different.

Examples of other high-level standards or guidelines for risk management and assessment include OCEG "Red Book" 3.0 GRC Capability Model[1], BS 31100:2011 Risk Management: Code of practice and guidance for the implementation of BS ISO 31000[2], COSO:2004 Enterprise Risk Management – Integrated Framework[3], FERMA:2002 A Risk Management Standard and Solvency II[4].

The petroleum industry has several standards for risk management and assessment. On the Norwegian Continental Shelf (NCS), the NORSOK Z-013 [20] standard is widely used, and

[1] http://www.oceg.org/resources/red-book-3
[2] http://shop.bsigroup.com/ProductDetail/?pid=000000000030228064
[3] http://www.coso.org/documents/coso_erm_executivesummary.pdf
[4] http://www.ferma.eu/app/uploads/2011/11/a-risk-management-standard-english-version.pdf

has been developed by the petroleum industry. This standard has a focus towards a quantitative risk assessment (QRA), as shown in Figure 3-2.

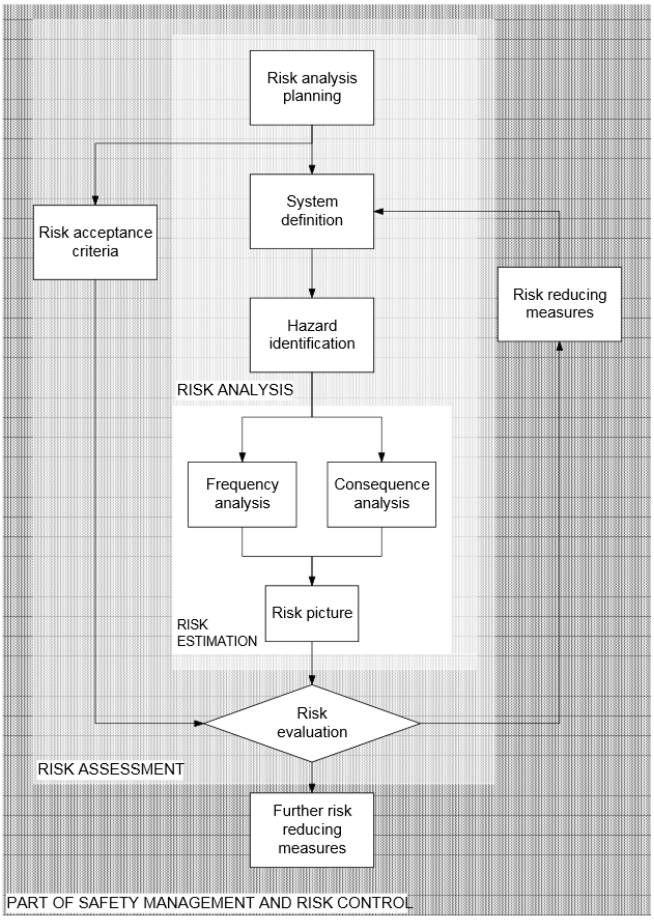


Figure 3-2. Risk assessment framework with a quantitative focus, as presented in NORSOK Z-013.

In quantitative risk assessments, the probability and consequence dimensions of risk are expressed in quantitative terms, using for example risk matrices, historical data or probability distributions, whereas in a qualitative assessment, a descriptive approach is used to express risk. The use of these two approaches may be by design, due to a lack of available data required to use quantitative models, or due to the complex nature of the risk or its inherent uncertainty.

Other examples of high-level risk assessment frameworks from the industry include those from International Atomic Energy Agency (IAEA) for the nuclear industry [21] and from the International Energy Agency Greenhouse Gas R&D Programme (IEA GHG) [22] for CO_2 storage projects, as shown in Figure 3-3.

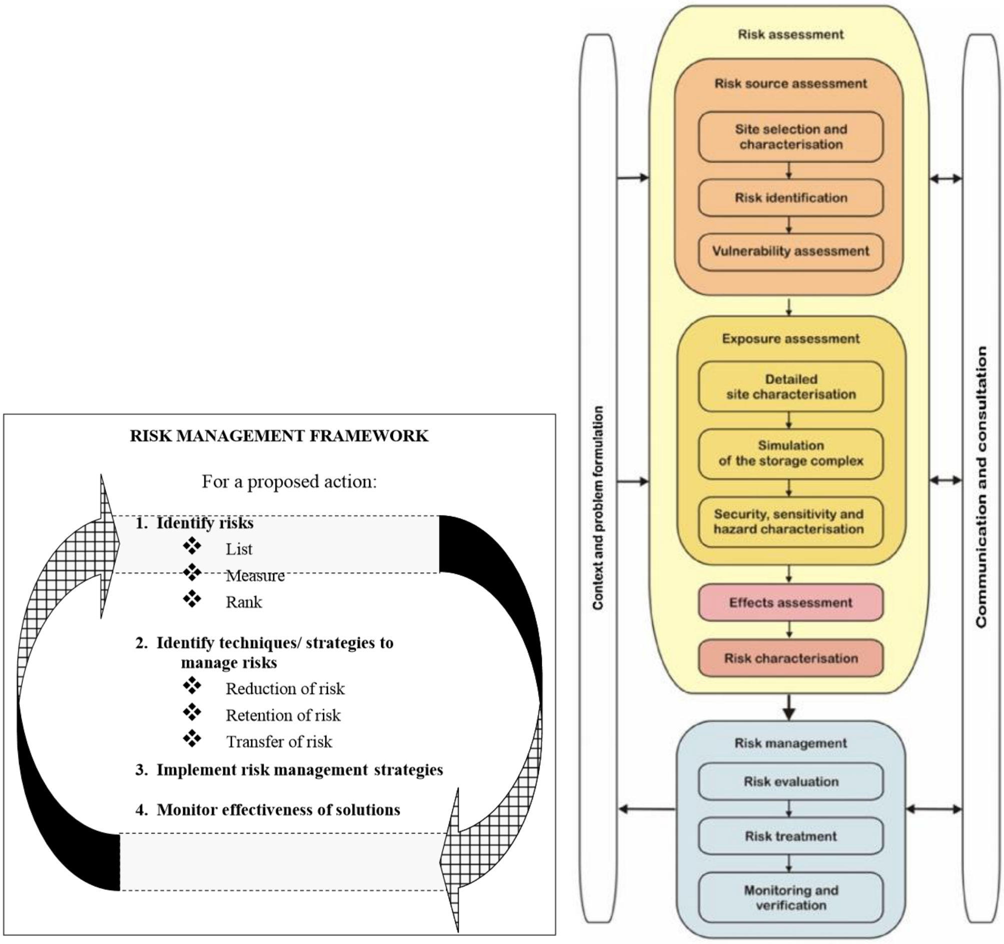


Figure 3-3. Risk assessment frameworks for nuclear industry (left, IAEA 2001) [21] and for CO_2 geological storage (right, IEA GHG 2009) [22].

There seem to be few published or widely-used publications suggesting recommendations, such as that of Heijnen et al. [23], but there are, to the best of our knowledge, no industry standards specifically governing risk assessment or providing risk frameworks for geothermal drilling.

3.3 Regulations

Generally, most industrial activities involve hazards/risks towards humans, safety or the environment, and thus there are laws and regulations requiring risk assessments to be performed. Distinction should be made between directives, standards and guidelines. In the EU, “a directive is a legislative act that sets out a goal that all EU countries must achieve. However, it is up to the individual countries own laws on how to reach these goals” [24]. A standard is a description of a set of activities, and constitutes a particular level in which compliance is met. A guideline is more advisory, for example in terms of how to reach compliance with a standard. Developments in regulations over the past decades has seen a gradual shift from prescriptive-based regulation to performance-based regulation, where the management is held responsible for ensuring appropriate safety systems are in place [25].

In Europe, EU directive 82/501/EEC[1] (often referred to as the Seveso Directive, and its amended post-Piper Alpha in 1996, Seveso II) concerns the control of major accident hazards

[1] http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:31996L0082

involving dangerous substances. In the United States, 29 CFR 1910.119[1] "Process safety management of highly hazardous chemicals" constitutes similar legislation. Other examples of wide-reaching legislative acts governing risk assessment include EU Directive 89/392/EEC[2], covering safety aspects for a wide range of machinery, for which the ISO standard ISO 12100:2010 [3]was also developed, the UK Health and Safety at Work Act of 1974[4], the UK Offshore Installations (Safety Case) Regulations of 1992[5], and the US Maritime Transportation Security Act of 2004[6].

There are various standards pertaining to different industries. The NORSOK Z-013 standard for Risk and Emergency Preparedness Analysis [20] is used for the petroleum industry. In the nuclear industry the guideline NUREG/CR-2300 concerns the risk assessments for nuclear power plants [26], while in the space industry NASA has developed guides for probabilistic risk assessment (PRA) procedures [27]. The standard EN50126[7] concerns "the specification and demonstration of reliability, availability, maintainability and safety (RAMS)" for railway applications.

On the NCS, the Petroleum Safety Authority (PSA) for example has requirements related specifically to well barriers in PSA's Facility Regulations, §48, and guidelines providing further details, which link to specific parts of the NORSOK D-010 standard, which is the standard covering well integrity in drilling and well operations. Other standard related to well integrity in the petroleum industry include ISO/DIS 16530-2:2014 – Petroleum and natural gas industries – Well integrity[8] and NOG 117 – Recommended guidelines for Well Integrity[9].

Many geothermal wells have been drilled to comply with the local petroleum regulations and standards such as those set by ISO, American Petroleum Institute (API) etc. The code of practice for deep geothermal wells (NZS 2403:2015) [28] is a standard commonly used as the basis for designing geothermal wells.

Hodson-Clarke et al. highlighted that in an enhanced geothermal system project, design and construction of the wells with a double barrier were performed in compliance with the South Australian Petroleum regulations [15]. According to the authors, selection of the casing and tubing materials as well as testing of materials for an enhanced geothermal system project in Australia has been done using common standards for the oil and gas industry, namely ISO 15156-2, 2003 [29] and ISO 13679:2002 [30], respectively.

Lentsch et al. [16] stated that the guideline of the German economic community of oil and gas production or "Wirtschaftsverband Erdöl- und Erdgasgewinnung e.V." (WEG) have been used for geothermal wells located in the Molasse Basin in the southern Germany. This standard is commonly used for casing design of oil and gas wells in Germany. However, they mention that because other guidelines such as NZS 2403:2015 [28] recommend different design factors, currently used design factors for the design of wells in the southern part of the Molasse Basin apply the stricter standard to reduce the risk of any failures.

---

[1] https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9760
[2] http://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:31989L0392&qid=1458901186986
[3] http://www.iso.org/iso/catalogue_detail?csnumber=51528
[4] http://www.legislation.gov.uk/ukpga/1974/37/contents
[5] http://www.legislation.gov.uk/uksi/1992/2885/contents/made
[6] https://www.gpo.gov/fdsys/pkg/PLAW-107publ295/html/PLAW-107publ295.htm
[7] http://standards.globalspec.com/std/1272146/cenelec-en-50126-1
[8] http://www.iso.org/iso/catalogue_detail.htm?csnumber=57056
[9] https://www.norskoljeoggass.no/Global/Retningslinjer/Boring/117%20Norwegian%20Oil%20and%20Gas%20%20recommended%20guidelines%20Well%20Integrity.pdf

Often, geothermal wells during drilling, construction, operation and plugging, are regulated by mining authorities, and must comply with the specific rules of that sector. Exploitation of geothermal resources may also fall under existing regulatory legislation and regulatory frameworks for natural resources, hydrocarbons, geology, groundwater and planning [31]. The cause of this is in part due to a lack of a unified terminology (in legal and regulatory acts) for the geothermal sector.

3.4 Risk assessment methods/techniques

There exist a wide range of available methods/tools/techniques for assessing risks, varying in degree of depth and detail, complexity and requirements in terms of resources, the type of focus (e.g. quantitative or qualitative), and the its place in the risk assessment process. This section will briefly outline an overview of what exists, and some of the main differences. The methods and classifications outlined are based on the ISO 31010:2009 standard as shown in Table 3-1, which was also used as a basis for the survey that was conducted.

Table 3-1. Different available methods and techniques for assessing risks [32]

Tools and techniques	Risk assessment process				
	Risk Identification	Risk analysis			Risk evaluation
		Consequence	Probability	Level of risk	
Brainstorming	SA[1)]	NA[2)]	NA	NA	NA
Structured or semi-structured interviews	SA	NA	NA	NA	NA
Delphi	SA	NA	NA	NA	NA
Check-lists	SA	NA	NA	NA	NA
Primary hazard analysis	SA	NA	NA	NA	NA
Hazard and operability studies (HAZOP)	SA	SA	A[3)]	A	A
Hazard Analysis and Critical Control Points (HACCP)	SA	SA	NA	NA	SA
Environmental risk assessment	SA	SA	SA	SA	SA
Structure « What if? » (SWIFT)	SA	SA	SA	SA	SA
Scenario analysis	SA	SA	A	A	A
Business impact analysis	A	SA	A	A	A
Root cause analysis	NA	SA	SA	SA	SA
Failure mode effect analysis	SA	SA	SA	SA	SA
Fault tree analysis	A	NA	SA	A	A
Event tree analysis	A	SA	A	A	NA
Cause and consequence analysis	A	SA	SA	A	A
Cause-and-effect analysis	SA	SA	NA	NA	NA
Layer protection analysis (LOPA)	A	SA	A	A	NA
Decision tree	NA	SA	SA	A	A
Human reliability analysis	SA	SA	SA	SA	A
Bow tie analysis	NA	A	SA	SA	A
Reliability centred maintenance	SA	SA	SA	SA	SA
Sneak circuit analysis	A	NA	NA	NA	NA
Markov analysis	A	SA	NA	NA	NA
Monte Carlo simulation	NA	NA	NA	NA	SA
Bayesian statistics and Bayes Nets	NA	SA	NA	NA	SA
FN curves	A	SA	SA	A	SA
Risk indices	A	SA	SA	A	SA
Consequence/probability matrix	SA	SA	SA	SA	A
Cost/benefit analysis	A	SA	A	A	A
Multi-criteria decision analysis (MCDA)	A	SA	A	SA	A

1) Strongly applicable.
2) Not applicable.
3) Applicable.

A preliminary hazard analysis (PHA) is an example of a simple method requiring limited knowledge of the process or activity in question. It can be viewed as high-level, with the objective of prioritizing risks based on coarse probability or consequence assessments. The requirement for conducting such an analysis is not considerable, and also in terms of execution time, the process can be performed quickly. A PHA can typically be useful in the risk identification phase, but has limited value in the later analysis phase, as it is neither comprehensive nor detailed. The failure mode and effects analysis (FMEA) is another method that can be used to identify risks, but is somewhat more comprehensive as it requires listing all relevant failure causes/modes/mechanisms by which a system component may fail. It requires more knowledge of the system in question than a PHA, and can become tedious if the number of assessed components is large. An example of an analysis that is more used in the risk analysis phase than the identification phase is the fault tree analysis (FTA). It uses logical gates, root causes or combinations of failures that could lead to a single, identified failure. This analysis is often used in engineered systems where the components have reliabilities, and thus has a quantitative focus. It is often an analysis that requires both time and a high level of expertise.

As previously mentioned, some tools are more common for some areas of application, and for assessing certain types of risks, than others. For example, in the petroleum industry on the NCS, well integrity is strongly related to barrier analysis. Such analyses often revolve around technical or physical barriers and the failure modes such components may encounter. Thus, the use of e.g. FMEA/FMECA (failure mode, effects and criticality analysis) and FTA are commonly used methods in this context. In other areas, such as the nuclear industry or the carbon capture and storage (CCS) industry, scenarios analyses and checklists are commonly used together with the features, events and processes (FEP) approach as stated in [33].

It is also important to emphasize that the method classification presented in ISO 31010:2009 does not represent an objective “true” classification. It is simply one way of representing an overview of different methods for risk identification, analysis and evaluation. That does not mean that methods not listed in the standard are inferior in any way, or that the classification between identification, analysis and evaluation is the correct one. Monte Carlo simulation is by many viewed as more logically belonging to analysis than evaluation, and there are also arguments for not having many structured methods for evaluation at all, as this phase mostly focuses on comparing analysis results with regulations, acceptance criteria, etc. It was chosen to use ISO 31010:2009 as a basis for the survey, but allowing for adding methods not listed to any of the three parts of the risk assessment, precisely because of the aforementioned challenges.

4 Risk assessment survey

4.1 Objectives

The main objective of the survey performed in the GeoWell project was to get an overview of how risk assessments are performed in the geothermal and petroleum industries and consequently to identify differences between the sectors.

4.2 Methodology

4.2.1 Hypothesis

The petroleum industry may be considered more mature than the geothermal industry, with significantly more wells drilled, and stricter regulations. Based on this, a hypothesis that the geothermal industry has less mature standards on risk assessments than the petroleum industry seems reasonable. The primary purpose of the survey is to map the current application of risk assessment methods in both geothermal and petroleum industries and to identify differences that may let the geothermal industry raise the standard to that of the petroleum industry.

Note that the differences in risk assessments might also be caused by:

- Difference in standards between onshore and offshore wells (offshore wells are more costly to drill and spills will spread in the water, causing harm over a larger area).
- Difference between legislation and region in the world (e.g. Norwegian regulations are considered strict compared to many other countries).
- Difference between sizes of companies (not all oil companies are staffed for costly and resource intensive assessments, or may lack personnel with expertise).

Many companies involved in the geothermal industry are also involved in petroleum. This is particularly true for the companies providing drilling services. It is likely these companies will apply the same methods for both the petroleum and geothermal wells they are involved in. However, there may be differences in how the assessments are performed with respect to the collaboration between the contractors, service providers and operators.

4.2.2 Reasoning for survey questions

The web based survey, attached in Appendix I, consists of 7 pages. The initial page is a simple welcome page, explaining the background for the survey, such as the purpose of the survey, who is performing the survey and in what context, and how the results will be used. This provides context for the receivers of the survey, giving them confidence in the seriousness of the survey as well as an idea of how they should respond if any of the questions are considered ambiguous.

The second page asks for information about the respondent. As respondents may not wish to supply personal information about themselves, the company they work for and the country they reside in are marked as optional. Most of the questions do not actually require a response; however, responses are expected. The reason for allowing many unanswered questions was to get as much as possible of the questionnaire answered, and the creation of unnecessary barriers.

The other questions on page 2 relate to the type of company and the respondent’s role in relation to risk assessments for wells. Common company types from the industry were used to identify their responsibilities related to wells.

Another question was posed to be able to separate the respondents working in geothermal from those in petroleum, as well as those working offshore with those working onshore.

Offshore geothermal was not considered a relevant alternative. The final question on the second page; whether the respondent performs risk assessments related to wells is a qualifying question, intended to filter out those who would not be in a position to provide relevant answers to the more risk specific questions. This question also served to identify who is involved in risk assessments related to wells. Answering “No” to this question takes the respondent to the end of the survey, where they can provide their email addresses (for future dissemination activities) and any feedback they may have.

The third page is used to identify in which area the respondents apply risk assessments. As a main purpose of the GeoWell project is related to well integrity, it was desirable to distinguish assessment of downhole conditions from assessments related to the work processes. Different areas, accompanied with a short description, are:

- Health and safety risk: assessment regarding the health and safety of personnel.
- Project/financial risk: risk assessment related to project execution such as delays, timing, reputation, capital, regulatory etc.
- Geological risk: assessment related to reservoir characterization uncertainty.
- Geological event risk: risk assessment related to seismic events, fracking, reopening of faults etc.
- Pressure/well control risk: assessment regarding wellbore pressure control related incidents such as lost circulation, kick, stuck pipe etc.
- Equipment reliability: assessment of failure of non-barrier equipment such as drilling tools.
- Barrier reliability: assessment of the condition of integrity related equipment such as casing and cement.
- Environmental risk: assessment of environmental impact of operations.
- Flow assurance: assessment related to production.

The fourth page requests the respondent to identify which methods are used in risk identification, risk analysis and risk evaluation. These are common terms in risk management, and definition can for example be found in ISO 31010:2009 [32]. The methods were subject to discussion, as many different names are used for similar methods. As there was a large number of methods, trying to group the methods by types was considered. However, introducing new naming conventions would easily make it more difficult for the respondents to recognize which type of methods they are using. In the end, the methods strongly applicable to each risk assessment activity as defined in ISO 31000:2009 were used. It was believed that most would understand which methods would apply to them. A direct use of the method as defined in the standard would not be assumed, but the answers would at least give an indication of the type of method. Each method was also given a tool-tip text in the survey, giving a brief description of the method for clarification.

The fifth page breaks down the use of methods in to the different life cycle phases considered (including drilling, completion, production and maintenance). To avoid unnecessary alternatives, only the methods selected on the previous page were shown, as the rest should be irrelevant.

The sixth page is similar to the fifth, breaking down which methods are applied to which areas of application (e.g. project/financial, geological and environmental risks). Similarly, only the previously selected methods and the previously selected areas were shown. The comprehensiveness of this question depends on how many methods were selected earlier.

The final page of the survey informs the respondent of how the results will be communicated, and asks whether they are interested in attending a webinar for the purpose of dissemination and communication of the findings of the survey. Comments are also requested, to get feedback on the survey and get additional information.

4.2.3 Selection of the recipients

As the survey was targeted to map the status of risk assessments performed in a well integrity context in the geothermal and petroleum industries, the survey is sent to experts active in each or both of industries.

While the list of contacts for the petroleum industry was based on an internal IRIS database, the contact list for the geothermal industry was based on:

- Contacts provided in Hirosaki University, Aomori Campus, North Japan Research Institute for Sustainable Energy (NJRISE) (http://njrise.cc.hirosaki-u.ac.jp/hiro/indexE.html);
- Office of Scientific and Technical Information (OSTI) Database, United States Department of Energy (US DOE), (http://www.osti.gov/geothermal/)
- Geothermal Energy Association (GEA) membership list (http://geo-energy.org/gea_members.aspx);
- Geothermal Resource Council (GRC) publication database (https://www.geothermal.org/publications.html);
- Search through the paper database of IGA (International Geothermal Association) and finding active authors in the field (https://www.geothermal-energy.org/publications_and_services/conference_paper_database.html); and
- Contacts provided by GeoWell partners.

4.3 Preparatory requirements

Prior to the risk assessment survey, different preparatory and quality assurance considerations were made, as listed in Table 4-1.

All of the considerations listed in Table 4-1 are obvious, but the most important ones are to create questions that serve the objectives, are simple to understand and unambiguous, and have alternatives that are exhaustive and mutually exclusive. In addition, the survey should be able to provide results that are of mutual interests to both recipient and the survey team.

Table 4-1. Different preparatory and quality assurance considerations for the survey.

Consideration	Remarks	Quality assurance checklist
Length of the survey	All questions were discussed to see if they could be excluded without losing needed information Reasonable and short (about 10 min estimated by survey provider)	Can any question be excluded? Is it too time consuming to complete it?
Simplicity	As simple as possible	Are all the questions simple? Are the questions understandable for the target audience?
Layout	Clear and consistent form with the GeoWell's logo	
Target group	Relevance to the recipients and precise definition of target group	Is the survey clear on who the recipients are, and are the questions suitable for them?
Type of questions	Clear and relevant	Are all the questions relevant? Are all the questions balanced? Are all the questions unambiguous? Will the questions provide the answers that are desired? Is there a combination of open and closed questions? Are the questions asked in a logical order? Do the questions match the alternatives?
Type of answers	Mainly multiple choices are provided. Alternatives based on literature sources, e.g. ISO standard.	Are the alternatives exhaustive? Are the alternatives mutually exclusive? Is similar type of scale used consistently throughout the survey?
Time for sending the survey	The survey sent at a time that the respondents have time to answer it (during summer time). Risk of being overlooked due to being in summer vacation.	
Results	Recipients have been informed about the use of results.	Is the purpose of the survey clear? Is it clear how the results will be used?
Reminder sending	One reminder was sent to those who had not left their e-mail in the questionnaire.	
Incentives use	Communication of the results through a planned webinar has been promised.	Why would the target audience complete the survey?
Teaser format	An e-mail invite is used as a teaser. Target audience incentivized by the e-mail invite.	How has the target group been informed about the survey?
Communication	An email account was specifically created for communication with recipients of the survey.	Is there any contact information provided for future communication between recipients and the GeoWell team?

4.4 Post survey evaluation

The survey status as of September 14, 2016, includes 46 finished responses and 18 partial responses (in total 64 response) as well as 31 in progress. Most of those who completed the survey spent less than 10 minutes (to the left in Figure 4-1). Of those that did not finish, most stopped at the company information page, (i.e. first page, see Appendix I and II for the questionnaire and its collected data, respectively) as seen to the right in the figure, and some did just not press the finish button. These results indicate that the last part of the questionnaire was not time consuming enough to make the respondents stop, which due to the matrix functionality of the question, was feared. Alternatively, one could argue that due to comprehensiveness, respondents rushed through just to get finished with the survey, giving random answers along the way. While this could of course be the case, we do not see any arbitrariness or contradictory survey results suggesting this.

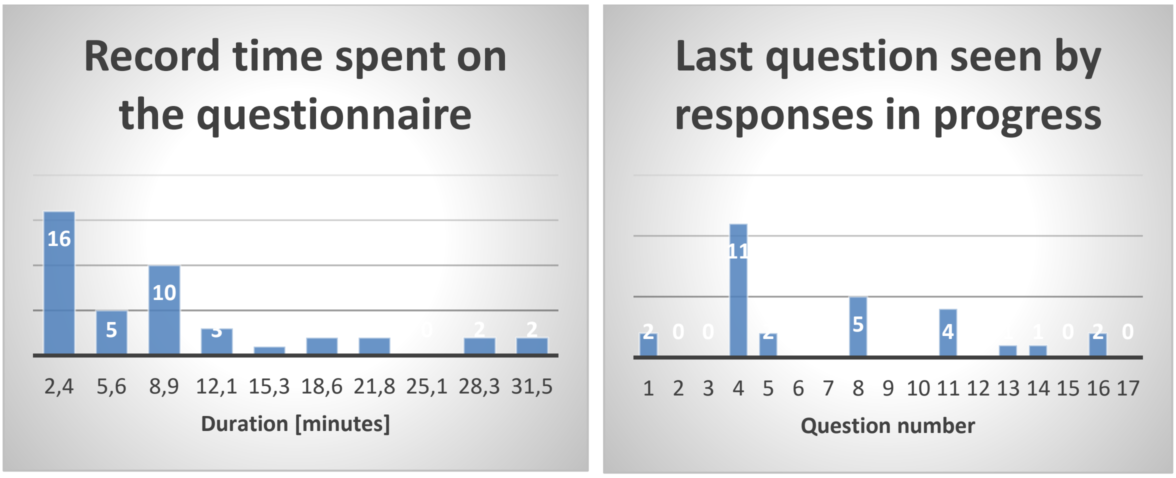


Figure 4-1. Registered time spent for respondents spending less than 2 hours (Left) and registered last question answered for the unfinished responses (Right).

Only two comments on the survey itself have been received through the comment functionality. One was particular to the mentioned matrix functionality between methods and application area, where many combinations had to be considered if the respondent used many methods and applied them to many areas. The respondent commented that many methods and applications overlap, which means many boxes had to be ticked off. Knowing that filling out parts of survey could take a lot of time in some cases makes the appreciation for their efforts even larger.

The other comment was that too many “risk-insider” terms were used in the questionnaire, and that this may lead to unclear results. Introducing custom categories for the methods was a concern, as this could possibly lead to different interpretations of the categories. To ensure consistency and traceability, the methods as mentioned in the ISO standard were used, with tool-tip text describing the methods. However, many might not have seen the tool-tip text, or been inclined to read it for every method. Thus, the actual methods chosen by the respondents should only be used as indications of the risk assessments performed, rather than the conclusive basis for use of the methods.

5 Results and discussion

5.1 Risk assessment status in the geothermal industry – Literature

Similar to many industries, the geothermal industry faces various kinds of risks including technical risk, geological risk, health and safety risk, project/financial risk, political risk, environmental risk etc. As mentioned earlier, in order to provide an overview of different technical risk assessment methods that are being used in the geothermal industry, many articles have been reviewed.

In the following, some of the main findings of the literature survey of geothermal publications relating to risk assessment and well integrity are presented. For each paper included in the selection, we have classified it in terms of publication year, whether the paper addresses uncertainty quantification, which types of risks are addressed, which tools are used for assessing risks and whether the paper addresses well integrity. We would like to stress that the classification of types of risks addressed and risk assessment methods used are interpretations of the authors, and, as such, do not represent an "objective truth".

The papers reviewed span the last 11 years as shown in Figure 5-1. Except a slight overweight of papers from 2015, the distribution over the years is generally fair. There is no particular reason for setting a cut-off year of 2005, but papers dating much further back would arguably not represent the current state-of-the-art. A total of 54 papers or publications were included in the review. Most of these papers were presented at various geothermal conferences world-wide and few of them were from peer-reviewed journals. A list of papers reviewed is given in Appendix III.

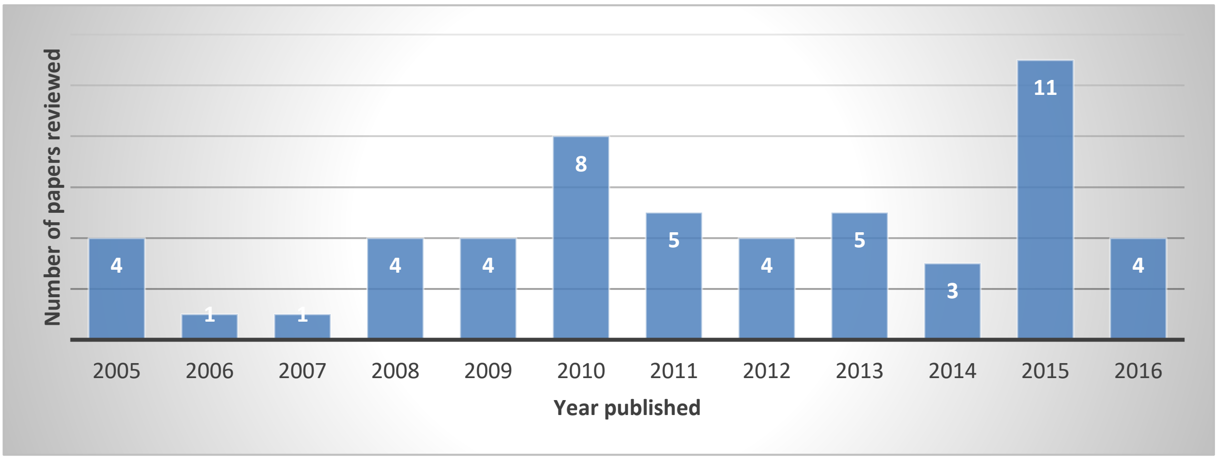


Figure 5-1. An overview of the reviewed papers by publication year.

The review also looked into which types of risks were addressed in each case (see Figure 5-2). There are many ways in which risks can be categorized; in this case different categories have been defined based on previous experience. The distribution of types of risks in the reviewed papers are shown below. Note that many of the papers address more than one type of risk, and the total does therefore not sum to 100%.

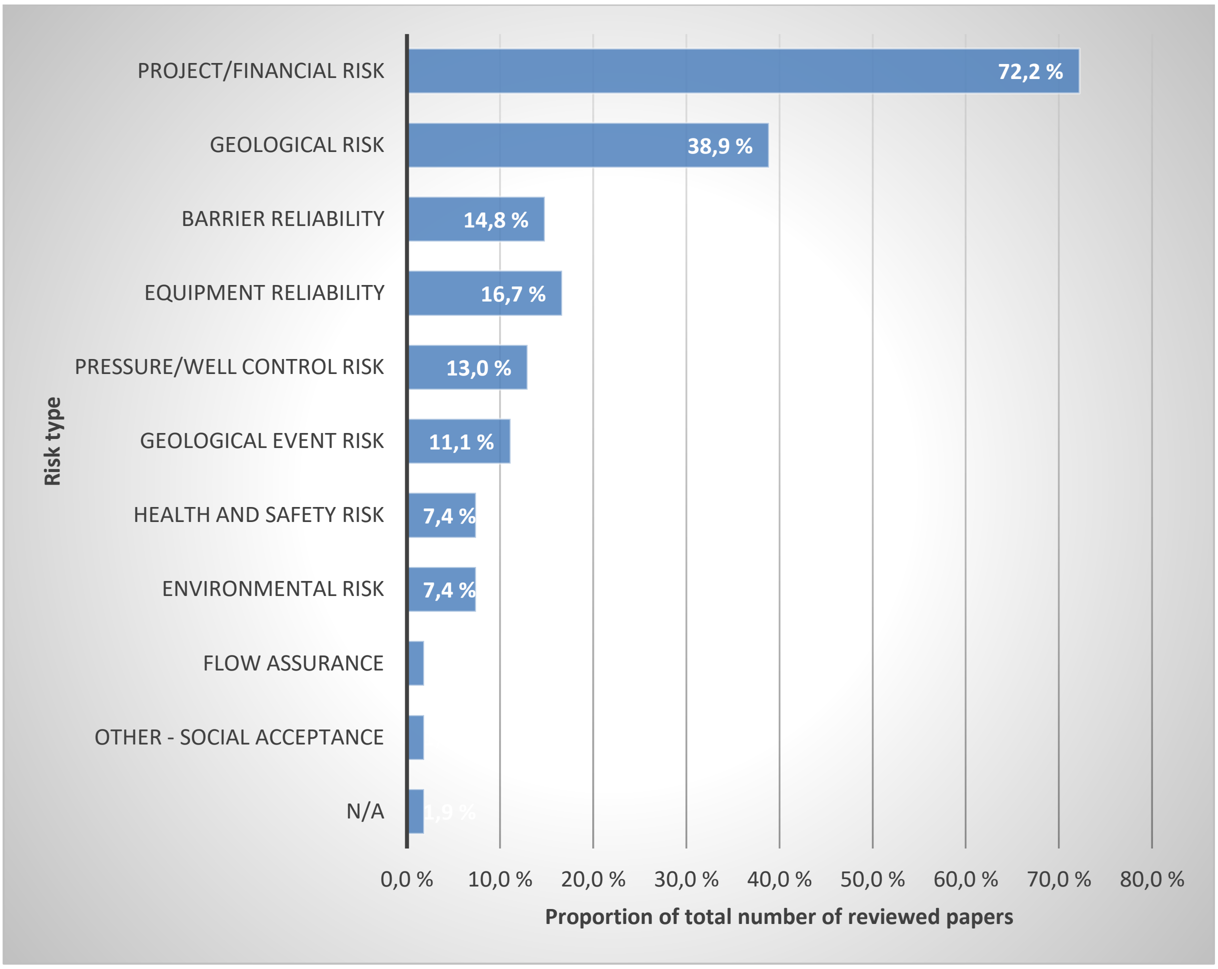


Figure 5-2. Different types of risks addressed in the reviewed papers.

Figure 5-2 interestingly shows that the by far most addressed risk type is related to project/financial risk, i.e. risk related to the project viability and feasibility. This differs significantly from our impression of the focus in the oil and gas industry. The finding is probably attributable to the fact that while there is an enormous financial upside when drilling petroleum exploration wells, this is not the case for geothermal wells. Furthermore, the financial margins during production are several magnitudes less than for oil and gas. In fact, when reviewing the geothermal publications, many papers did not even define risk properly; it was implicitly taken to be project/financial risk.

Geological risk is also a key focus area regarding risk (nearly 40% of the papers address this area). However, this is often tightly related to project/financial risk; large uncertainties in the resources to be exploited will consequently yield large uncertainty in the project feasibility as well. Barrier reliability and equipment reliability, which are those areas most closely related to well integrity, have been discussed in ca. 1/6 of the papers reviewed.

In terms of whether the papers address uncertainty quantification is also a question of interest. In many papers the definition of risk includes the consideration of uncertainty; however, the majority do not explicitly address how to quantify it, as shown in Figure 5-3.

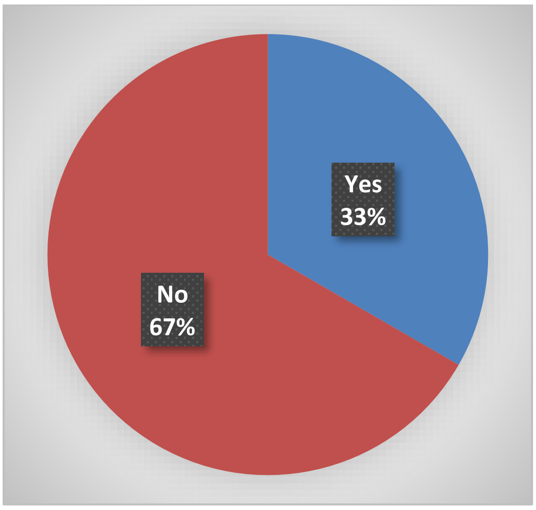


Figure 5-3. Distribution of the reviewed papers covering uncertainty quantification.

Furthermore, we investigated the risk assessment methods used (or described) in the reviewed papers. The basis for the types of risk assessment methods was that defined in ISO 31010: 2009; however, as that list is not exhaustive, we added method types to the list as needed. Throughout the 54 papers, 96 mention or describe risk assessment methods. Figure 5-4 lists method types as a proportion of these 96, as an indication of how frequently each type was used.

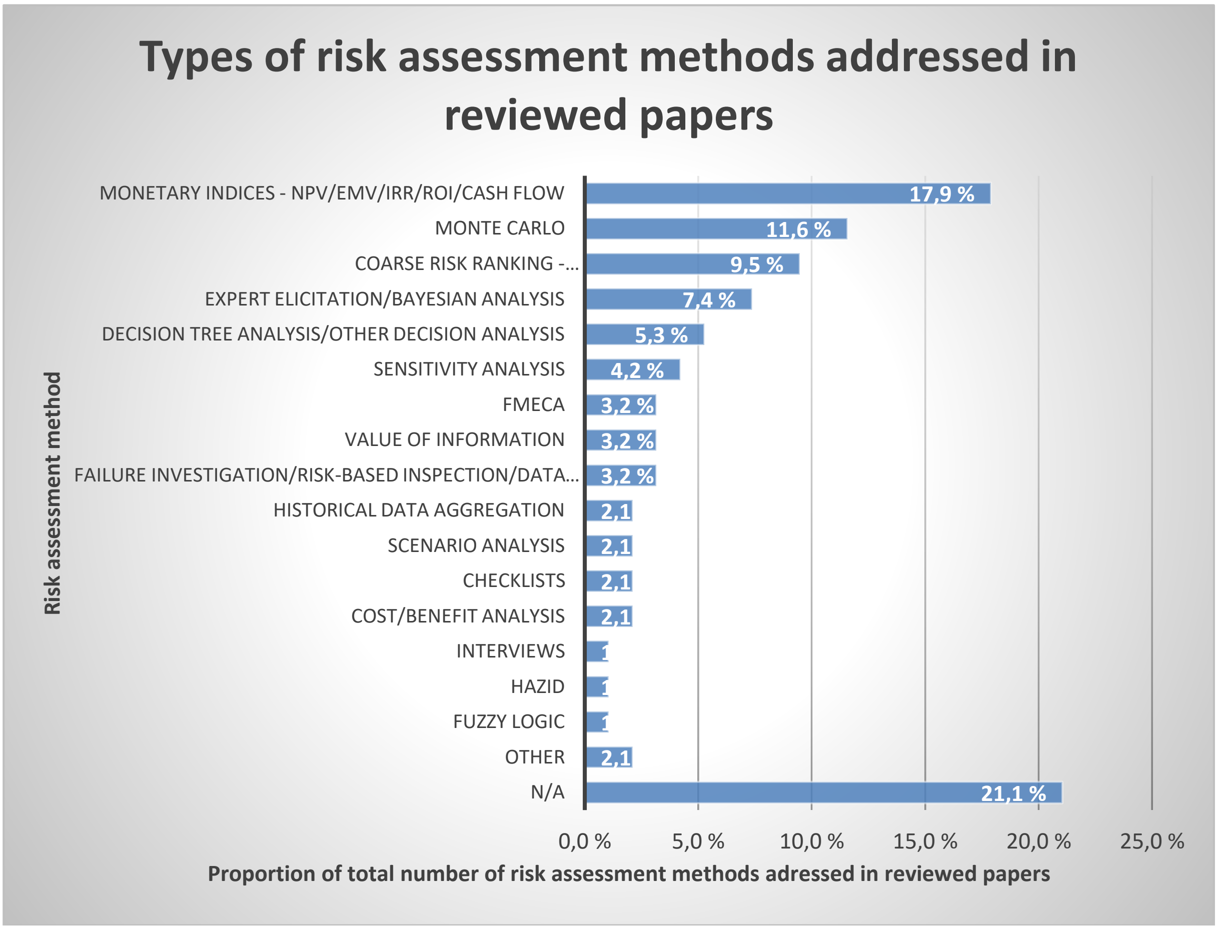


Figure 5-4. An overview of different types of risk assessment methods addressed in reviewed papers.

In line with the findings on risk types, the most used risk assessment methods relate to financial metrics such as net present value (NPV), expected monetary value (EMV), internal rate of return (IRR), return on investment (ROI) and cash flow. Monte Carlo, often in conjunction with expert elicitation and/or Bayesian analysis was also addressed in several papers. Coarse risk ranking, such as the use of simple risk indices, consequence/probability matrices, was also a commonly used tool. The remaining methods were rarely used. One observation was that many of the papers did not have risk in particular as the main focus. In many cases, geological/reservoir simulations were the focus, with some discussions of risk/uncertainty around the calculated values, missing the context of a particular method for risk analysis. The overall impression was that there was little consensus on common approaches to risk assessment methods and why they were chosen. That said, the topics covered in the reviewed papers spanned many and diverse topics.

The risk assessment methods were also grouped according to the ISO 31010: 2009 [32] in terms of resource demands, nature of uncertainty and complexity. Where either the method was not listed, or it was listed but not classified in ISO 31010: 2009, we applied our own interpretation. For papers where there was no mention of any specific risk assessment method, it was obviously not possible to perform any classification ("N/A").

The resource demands of a risk assessment method are related to experience and capability of the risk assessment team, organizational constraints on time and other resources, and available budget. The nature of the uncertainty is linked to the quality, quantity and integrity of information relating to the risk under consideration, and the availability of information about the risk and its sources, causes and consequences.

Regarding all three dimensions (resource demands, nature of uncertainty and complexity) there is no evidence to suggest that there is an overweight of simplistic, low-complexity methods in use, nor of sophisticated, highly demanding tools. Figure 5-5 shows an overview of the resource demands, nature of uncertainty and complexity in risk assessment methods that are addressed in the reviewed papers.

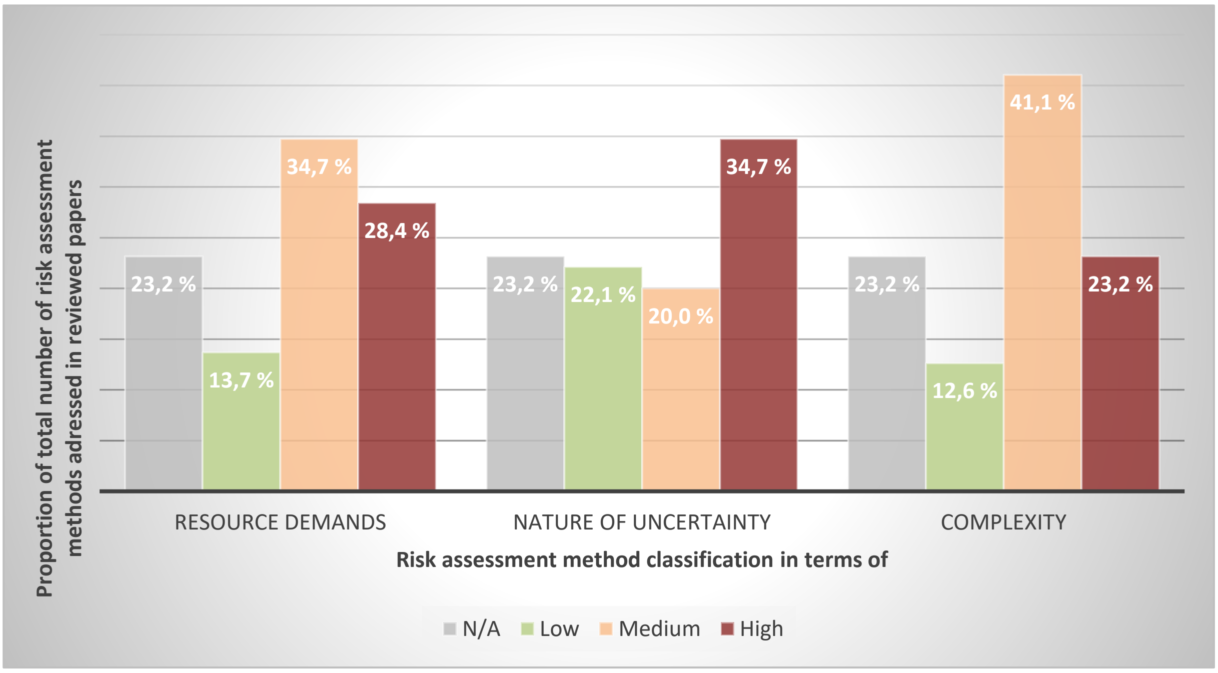


Figure 5-5. An overview of the resource demands, nature of uncertainty and complexity in risk assessment methods addressed in the reviewed papers, as classified in ISO 31010:2009. N/A are papers where no specific risk assessment method is mentioned/presented.

The reason that both resource demands and complexity are more weighted towards the medium/high group, is partly due to the fact that both Monte Carlo and monetary indices have a medium or high classification for these dimensions, and together account for a large proportion of the total number of methods. With this in mind, it appears that the geothermal publications concerning risk assessment methods cover a rather large span in types of methods, covering the low/medium/high range in terms of resource demands, nature of uncertainty and complexity.

Finally, with respect to well integrity, this topic is to a very small extent covered in the reviewed publications. As shown in Figure 5-6, only 11% of the publications cover, to some extent, well integrity as a topic addressed.

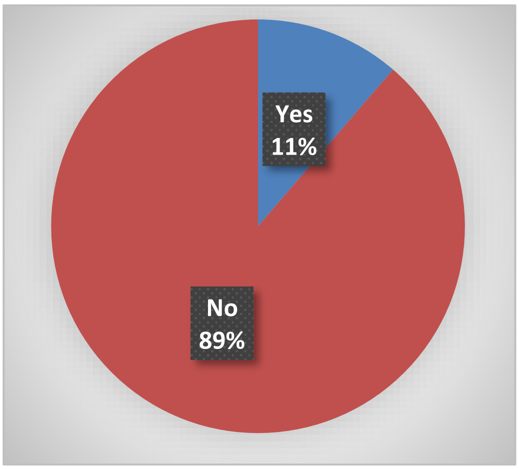


Figure 5-6. Distribution of the papers that address well integrity.

Very few publications we studied concern risk of loss of containment, nor risks of failures in barriers. In fact, the term barrier is hardly mentioned, and even the papers dealing with well integrity do so to a large extent without considering the system as comprised of barriers with failure modes and reliabilities.

5.2 Risk assessment status – Survey

In this sub-section, results from the risk assessment survey are presented using only the responses from those classifying themselves as working in geothermal, and do not have activity related to petroleum. Note that the analysis is limited to fully completed responses who have selected "yes" when asked whether they perform risk analysis for wells or not. This reduces the number of relevant respondents to 15. Although this number is too low to generate statistically significant results, the results will still give an indication on what is performed related to risk assessments. These results look into what methods are applied, to which activities, and by whom.

5.2.1 Respondent overview

In Section 4, a description of the recipients of the risk assessment survey is provided. Due to the encouragement to forward the survey to relevant contacts, there was no real control over the respondents. This sub-section provides information about the respondents of the survey.

Most of the responses came from the geothermal industry, probably due to the survey being posted on geothermal websites and being sent to more geothermal industry contacts. Many of the traditional petroleum companies also defined themselves as involved in geothermal, while few categorized themselves as pure petroleum companies. This is shown in Figure 5-7. In this report, the focus is on the 57% working only in the geothermal industry.

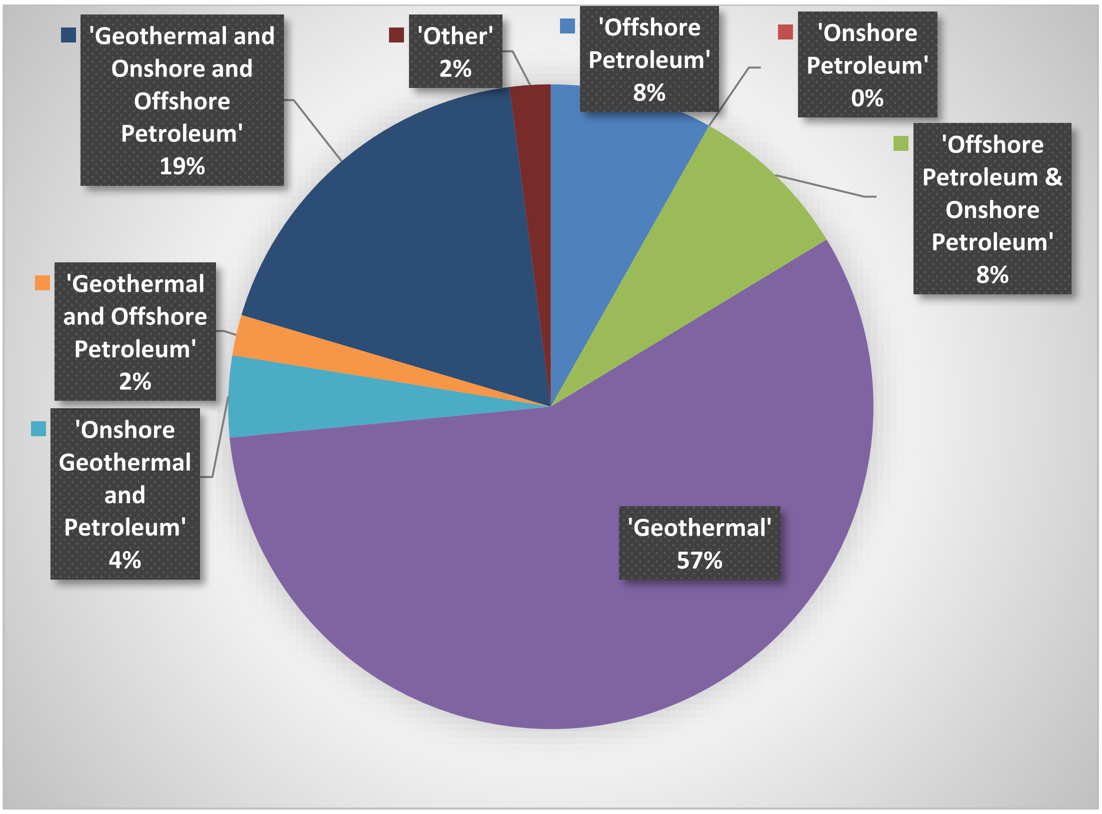


Figure 5-7. Industry as categorized by the respondents.

There is a possibility that there may be regional differences concerning how risk assessments are performed. Some countries have stricter regulations related to the risk assessment than others do, and different parts of the world may have different geological challenges. The distribution of the respondents among the continents is displayed in Figure 5-8. In both Figure 5-7 and Figure 5-8, responses where no information was available have been excluded, and those marked “other” have been interpreted and assigned to the most relevant response where possible.

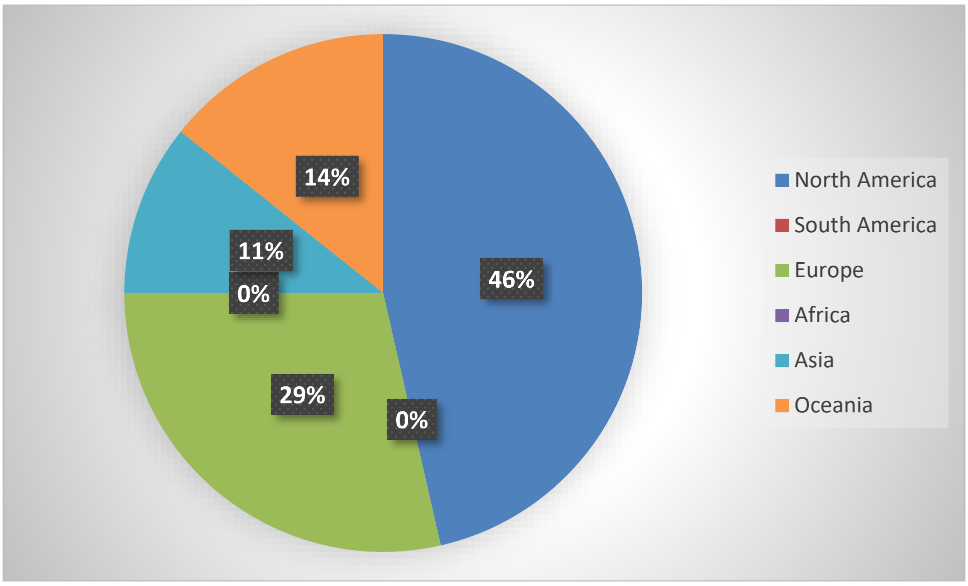


Figure 5-8. Registered continents of respondents from the geothermal industry.

Figure 5-8 shows participation from most continents. The bulk of respondents comes from North America and Europe, which is not surprising, as the survey was distributed mainly to these continents. Some responses were also received from Asia and Oceania, while none came from Africa or South America (although there were representatives from these regions in the survey mailing list).

As many of the respondents of the survey are not performing risk assessments related to wells, it could be interesting to see which types of companies perform risk assessments in geothermal industry. This is shown in Figure 5-9 that also shows which types of companies have responded to the survey.

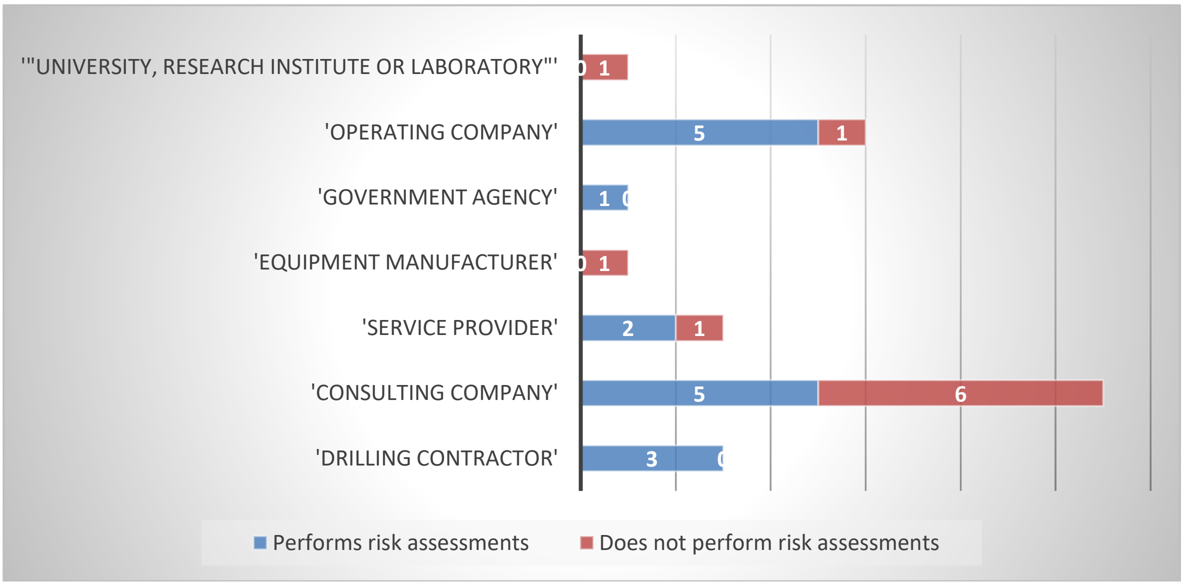


Figure 5-9. Breakdown of the respondents based on company type, and whether or not they perform risk assessments of wells.

5.2.2 Areas of application

Risk assessments are performed for different purposes. Figure 5-10 shows how many of the respondents perform risk assessment in different areas. This is based on the 15 respondents working only in the geothermal industry and perform risk assessments for wells.

As is reasonable, most companies are responsible for health and safety risk assessments. A majority of the respondents are also performing assessments related to project/financial risk, geological risk, pressure/well control and environmental risk. These are general areas that are related to the business case, safety of personnel, and for the purpose of meeting regulations. Just less than half the respondents work with risk related to barriers, geological events and flow assurance. These are more specific areas, which might not be relevant in all cases, or are long-term activities in the production phase.

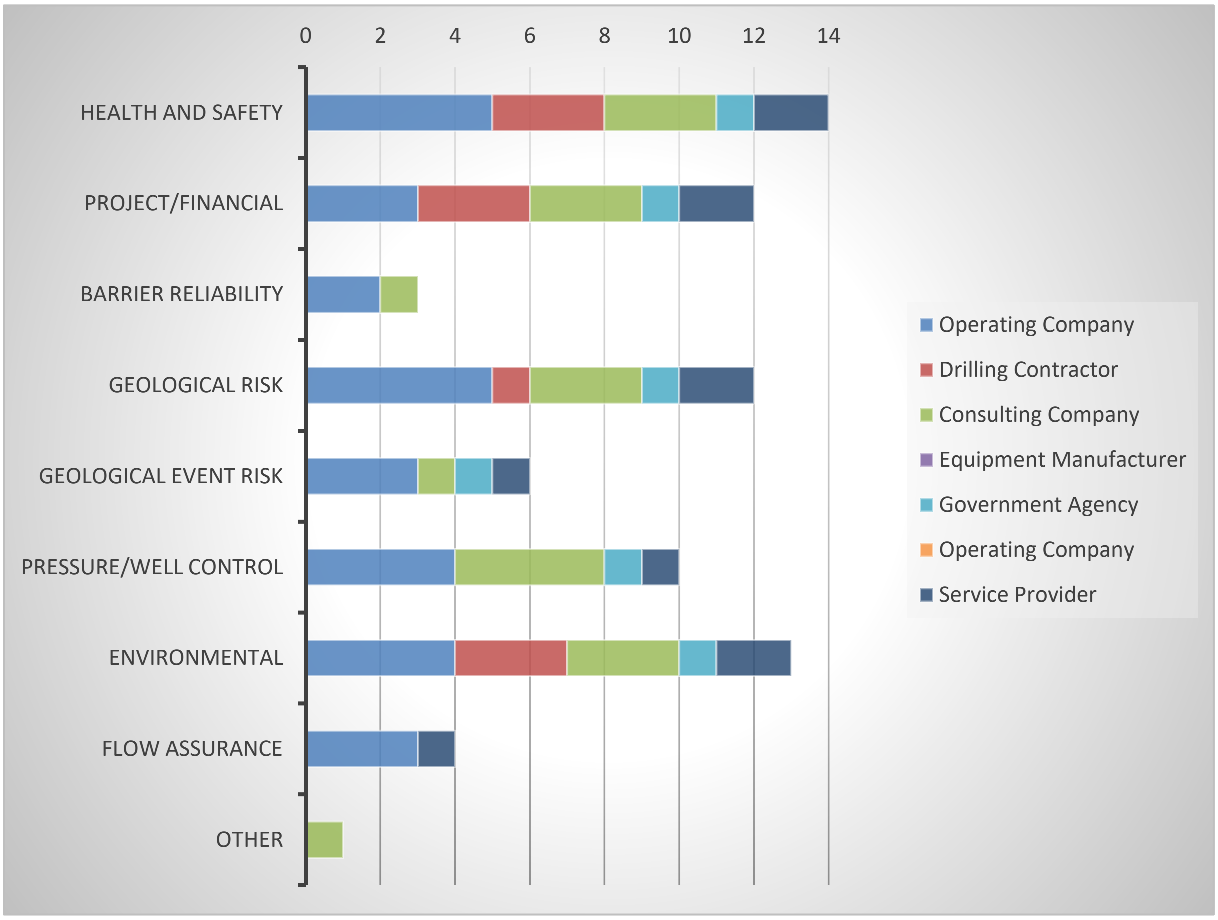


Figure 5-10. An overview of different areas for which companies perform risk assessments.

Each of these areas will be looked into more thoroughly to understand which methods are applied.

Financial risk

Twelve respondents fully completed the survey work on financial/project risk. As seen in Figure 5-11, the by far most popular method for risk identification is brainstorming, with scenario analysis coming second. Only seven out of the 15 listed methods were used. In Figure 5-12, the risk analysis methods applied to financial/project risk are primarily scenario analysis, business impact analysis and cost-benefit analysis. About half of the methods have been applied. For evaluation of financial/project risk, Monte Carlo simulation is the primary method used as shown in Figure 5-13.

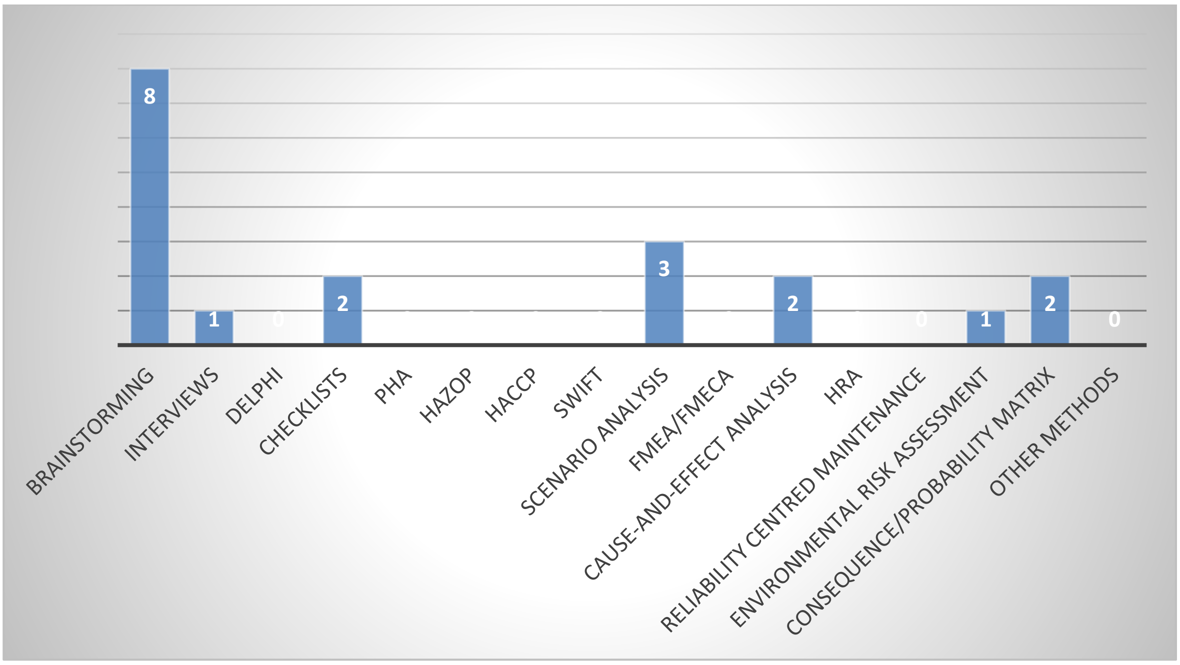


Figure 5-11. Distribution of methods used for financial/project risk identification.

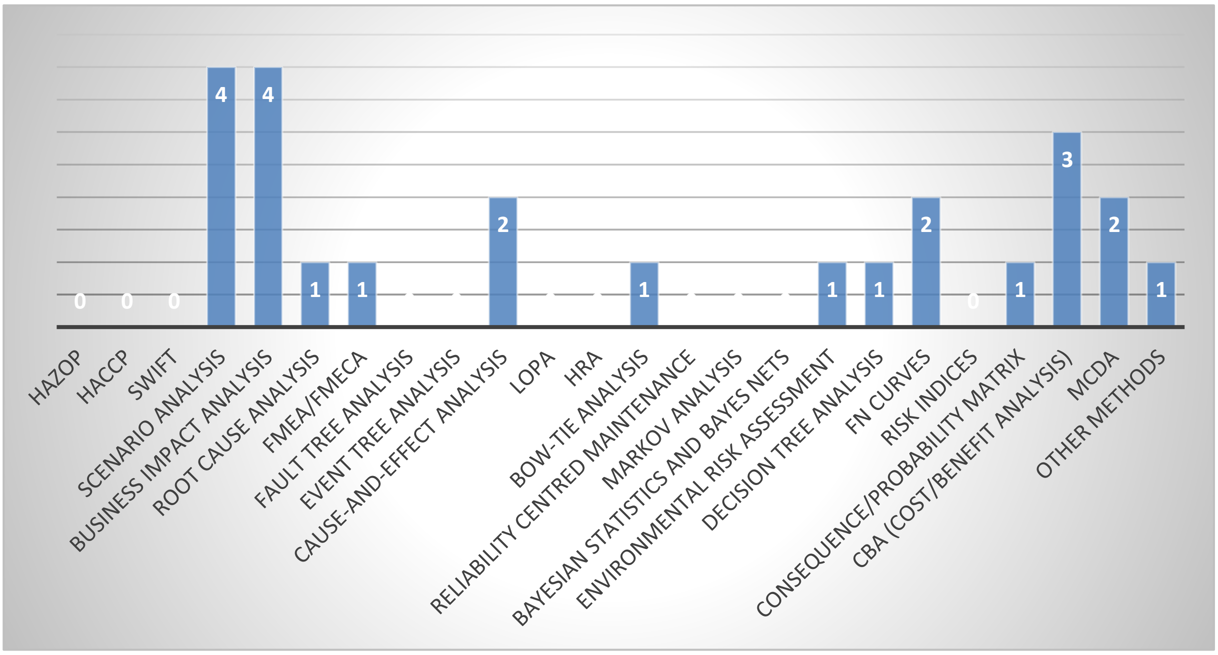


Figure 5-12. Distribution of methods used for financial/project risk analysis.

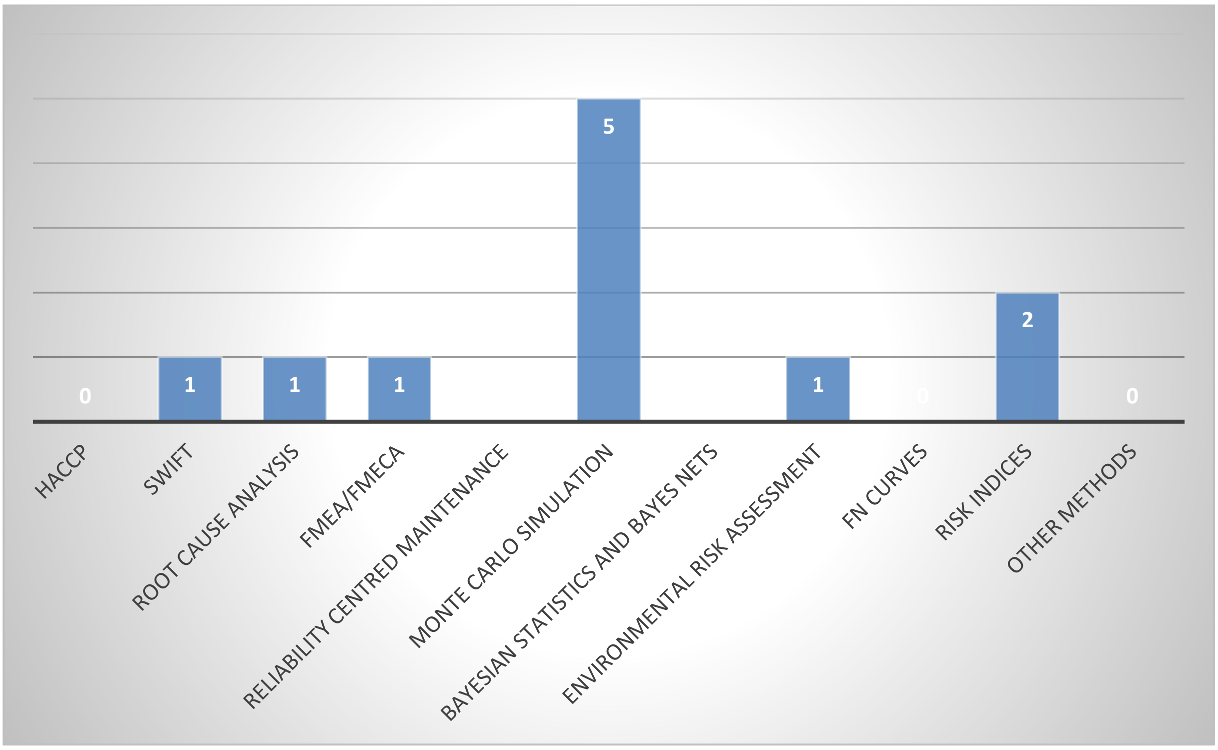


Figure 5-13. Distribution of methods used for financial/project risk evaluation.

Health and safety

Within health and safety, the primary method for risk identification is again brainstorming. Checklists and hazard and operability studies (HAZOP) follows as popular methods for this purpose, as seen in Figure 5-14. In general, more methods are used in this area than in financial/project risk. Figure 5-15 illustrates that for risk analysis there are four almost equally used methods. These are HAZOP, root cause analysis, environmental risk assessment (ERA) and decision trees. Figure 5-16 shows that for risk evaluations, root cause and environmental risk assessments are the most used, with no use of Monte Carlo simulations, Bayesian statistics and two others.

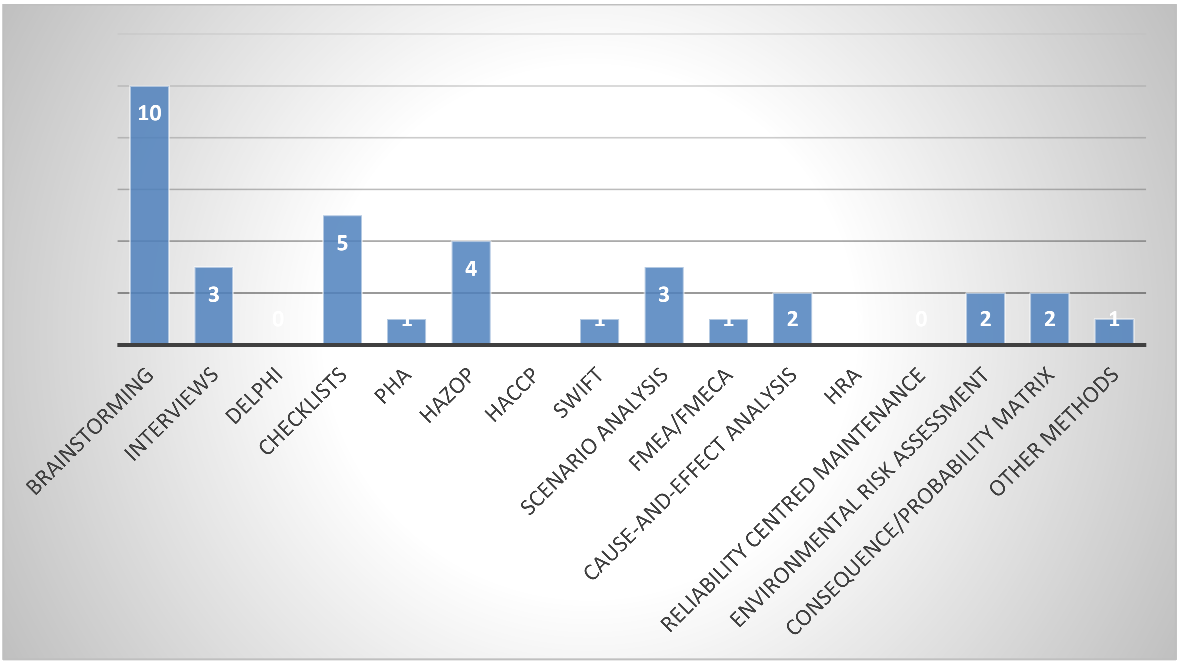


Figure 5-14. Distribution of methods used for health and safety risk identification.

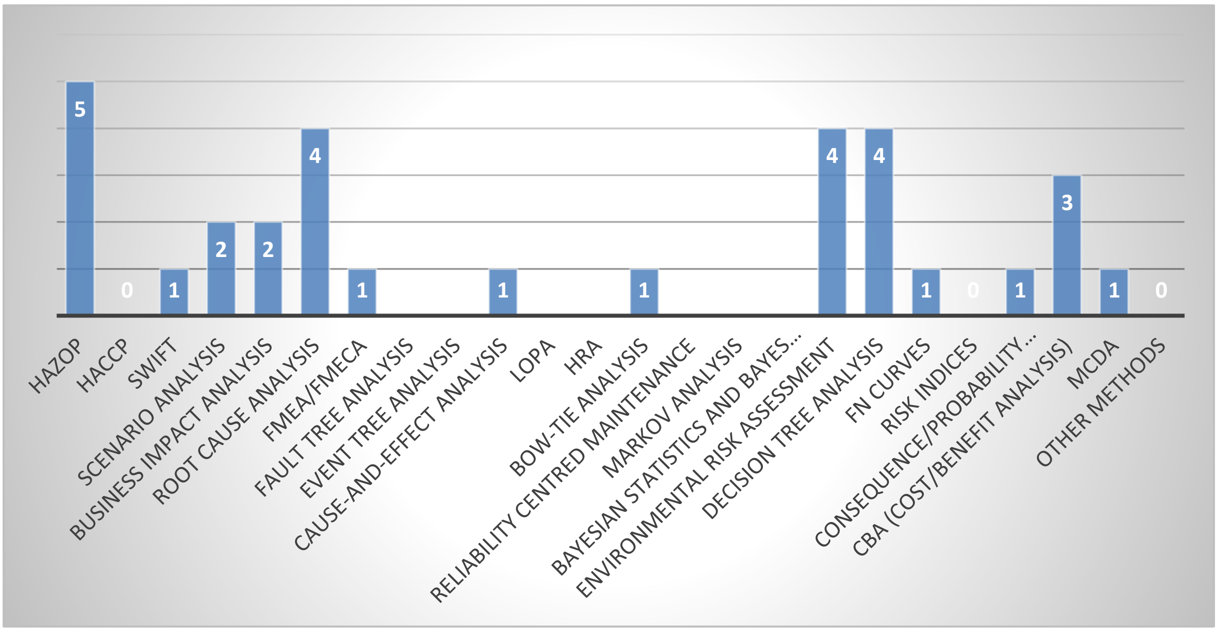


Figure 5-15. Distribution of methods used for health and safety risk analysis.

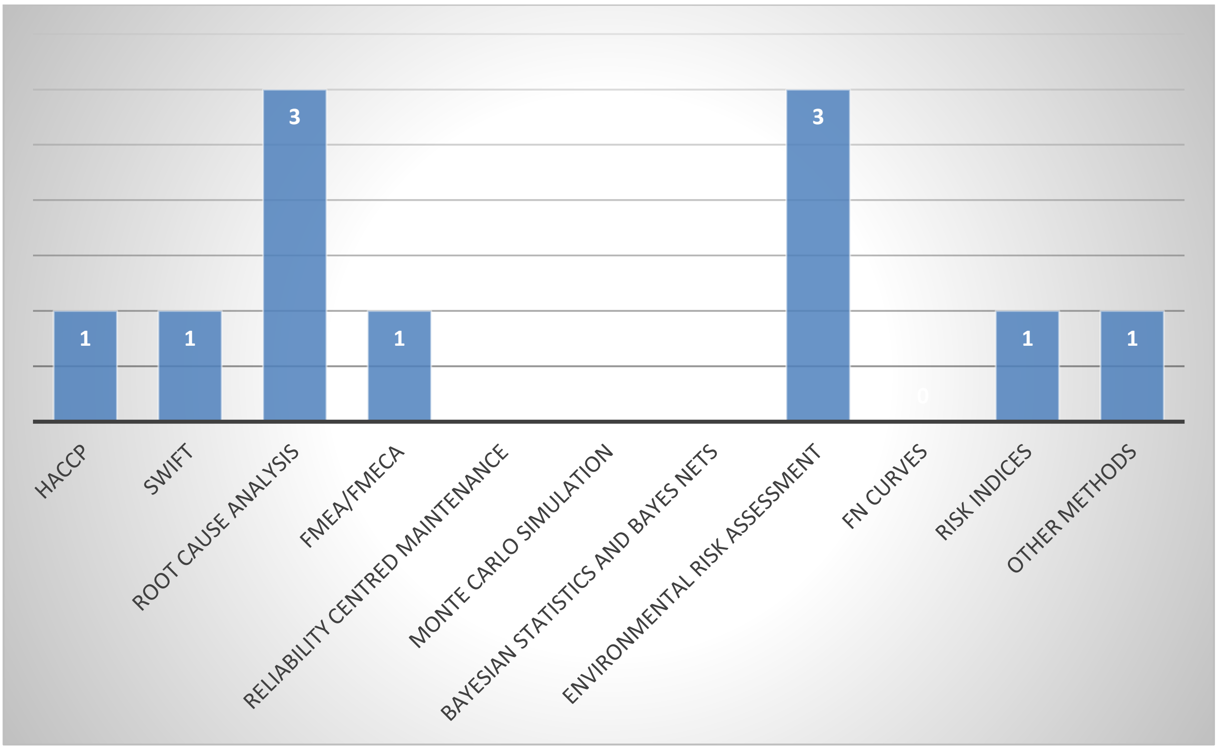


Figure 5-16. Distribution of methods used for health and safety risk evaluation.

Barrier risk

Figure 5-17, Figure 5-18 and Figure 5-19 present the distribution of methods used for barrier risk identification, analysis and evaluation, respectively. Only three respondents from the geothermal industry selected barrier reliability.

For barrier assessments, brainstorming remains the most used risk identification method, together with HAZOP and cause-and effect analysis. The only other method used is consequence/probability matrices. In risk analysis HAZOP are the most used, with some applications of root cause analysis, bow-tie analysis, cost-benefit analysis and multi-criteria decision analysis. For risk evaluation, only root cause analysis is reported used.

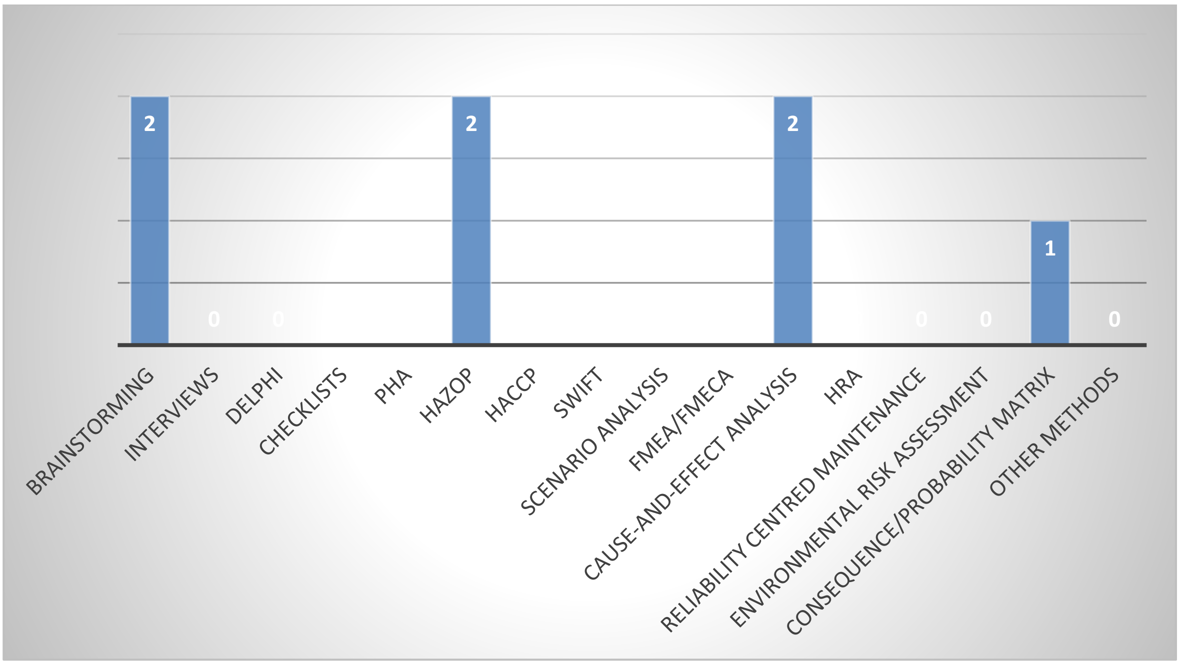


Figure 5-17. Distribution of methods used for barrier risk identification.

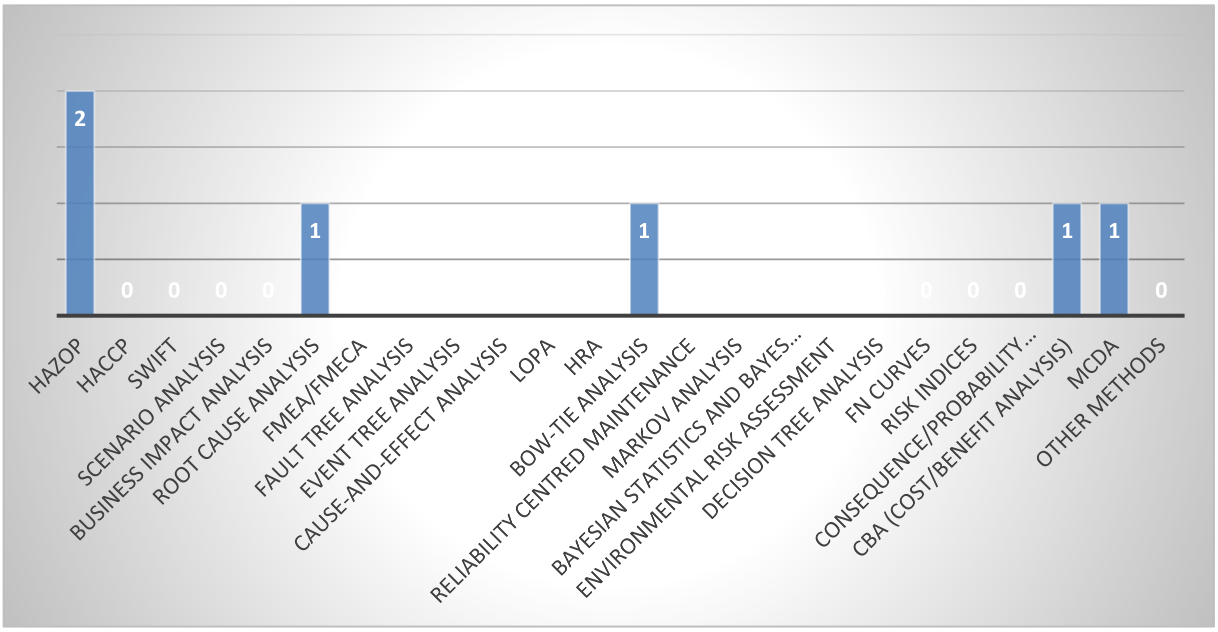


Figure 5-18. Distribution of methods used for barrier risk analysis.

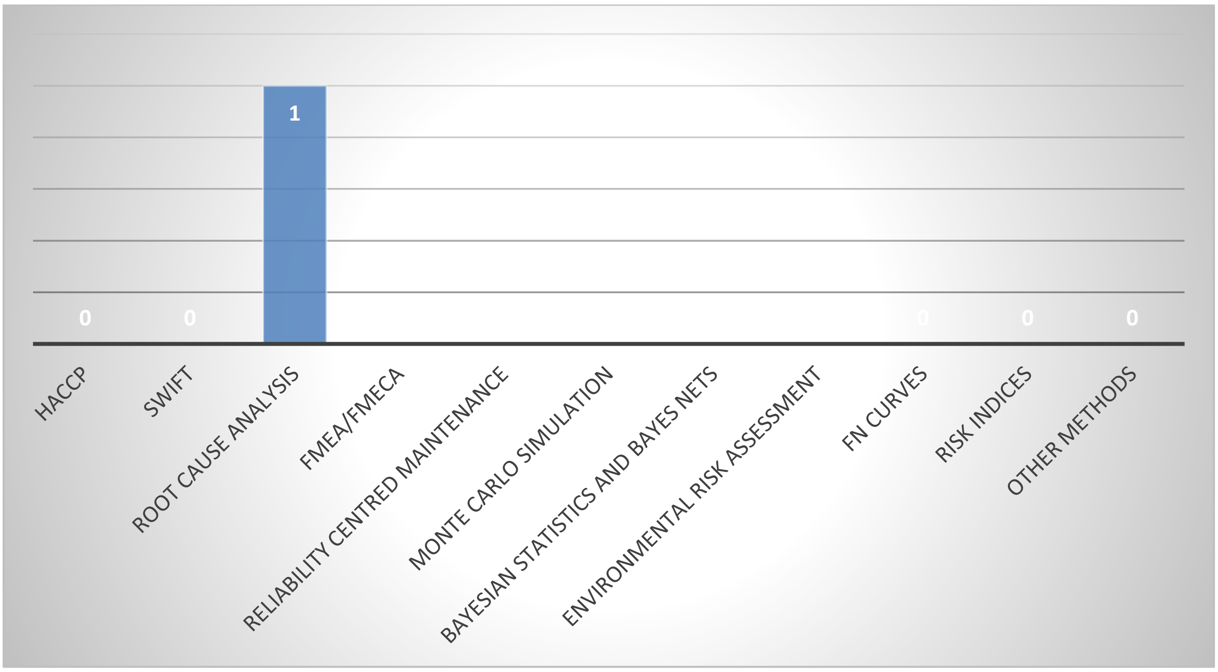


Figure 5-19. Distribution of methods used for barrier risk evaluation

Geological risk

For identification of geological risks, brainstorming and checklists are the most used methods as shown in Figure 5-20. Other methods are also used, but to a lesser extent. For risk analysis (Figure 5-21), the most used methods are scenario analysis and root cause analysis. There is less variety in the methods used compared to the previous applications with a similar number of respondents. For risk evaluation, Monte Carlo simulations and risk indices are the most used (see to Figure 5-22).

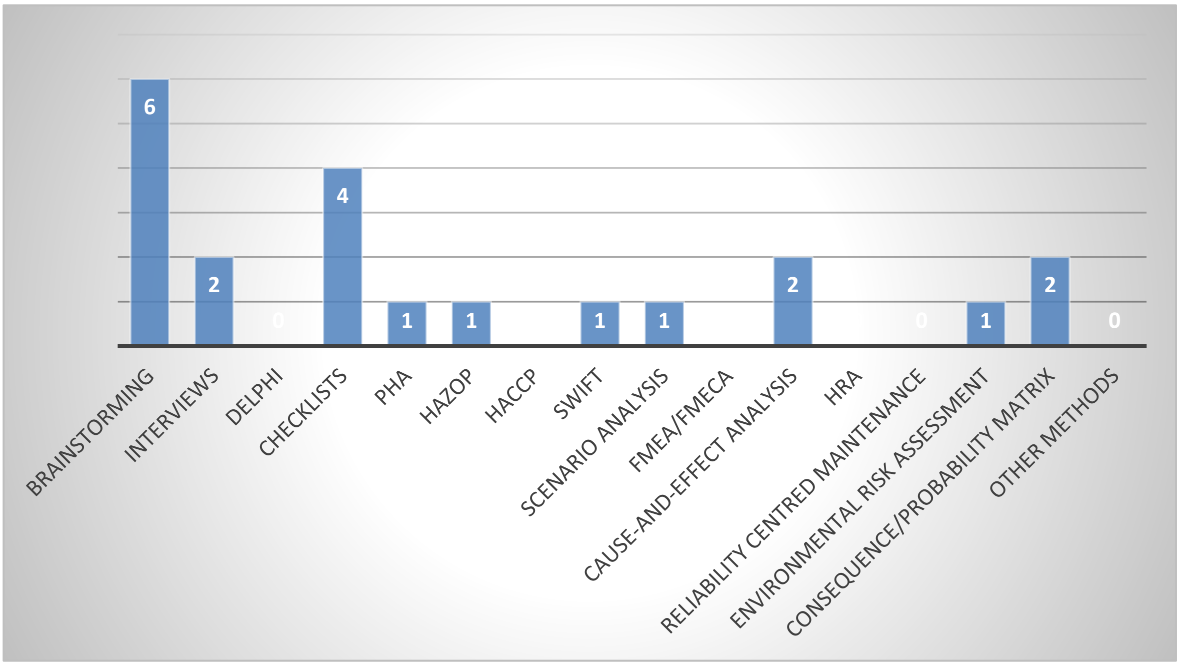


Figure 5-20. Distribution of methods used for geological risk identification.

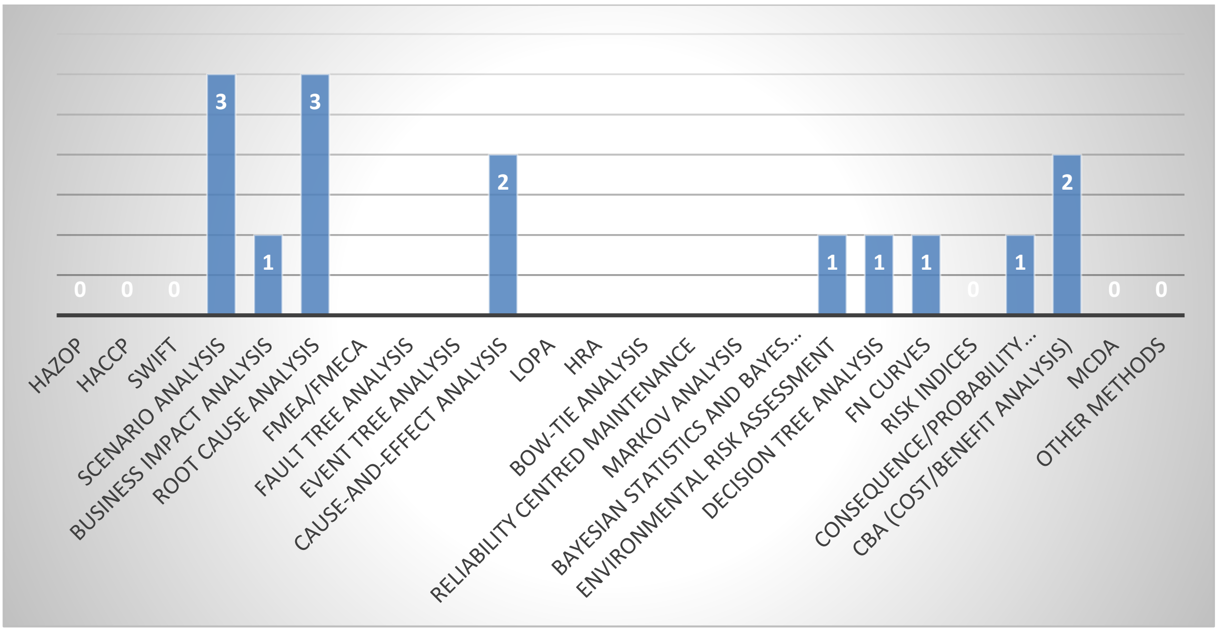


Figure 5-21. Distribution of methods used for geological risk analysis.

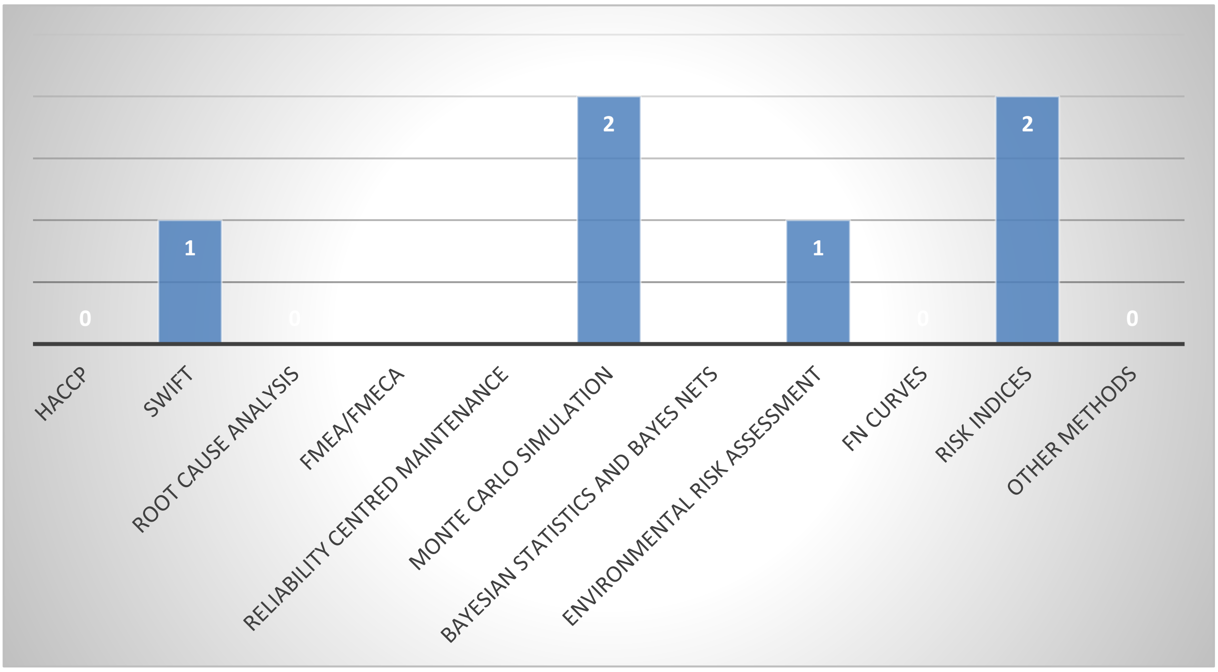


Figure 5-22. Distribution of methods used for geological risk evaluation.

Geological event risk

Geological event risk identification methods mainly are, as in the other applications, brainstorming and checklists. This can be seen in Figure 5-23. For risk analysis, root cause analysis and cause-and effect analysis is most used, as shown in Figure 5-24. Some other methods are also used, including decision tree and multi-criteria decision analysis (MCDA). For risk evaluation, what-if analyses are the most used according to Figure 5-25.

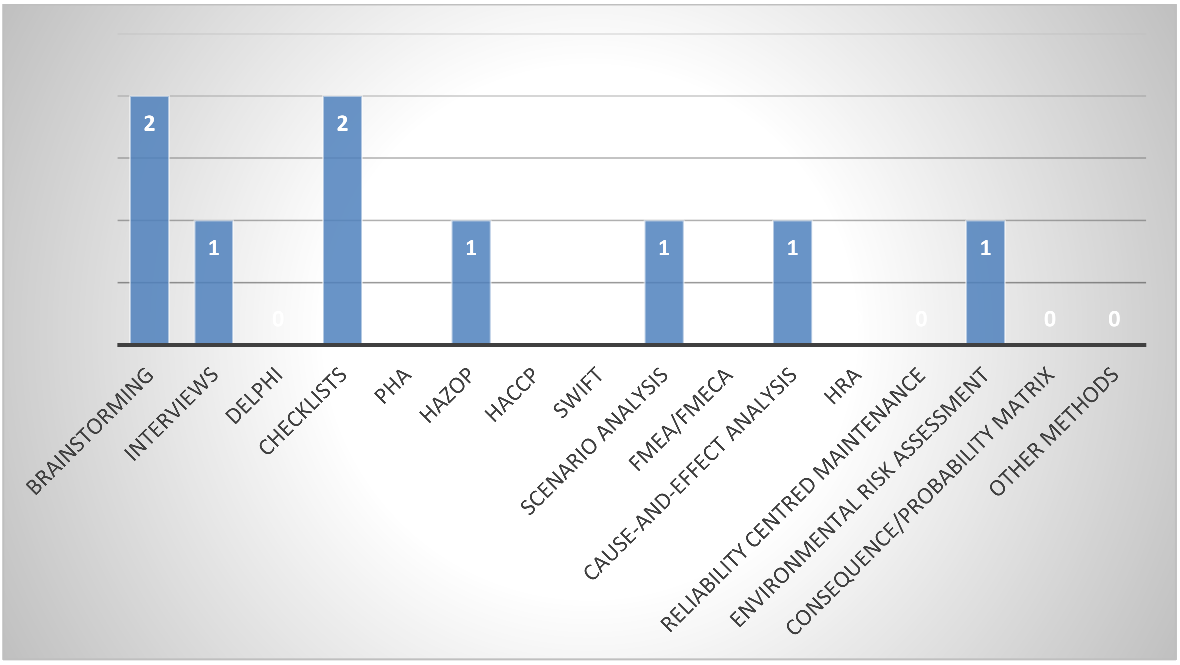


Figure 5-23. Distribution of methods used for geological event risk identification.

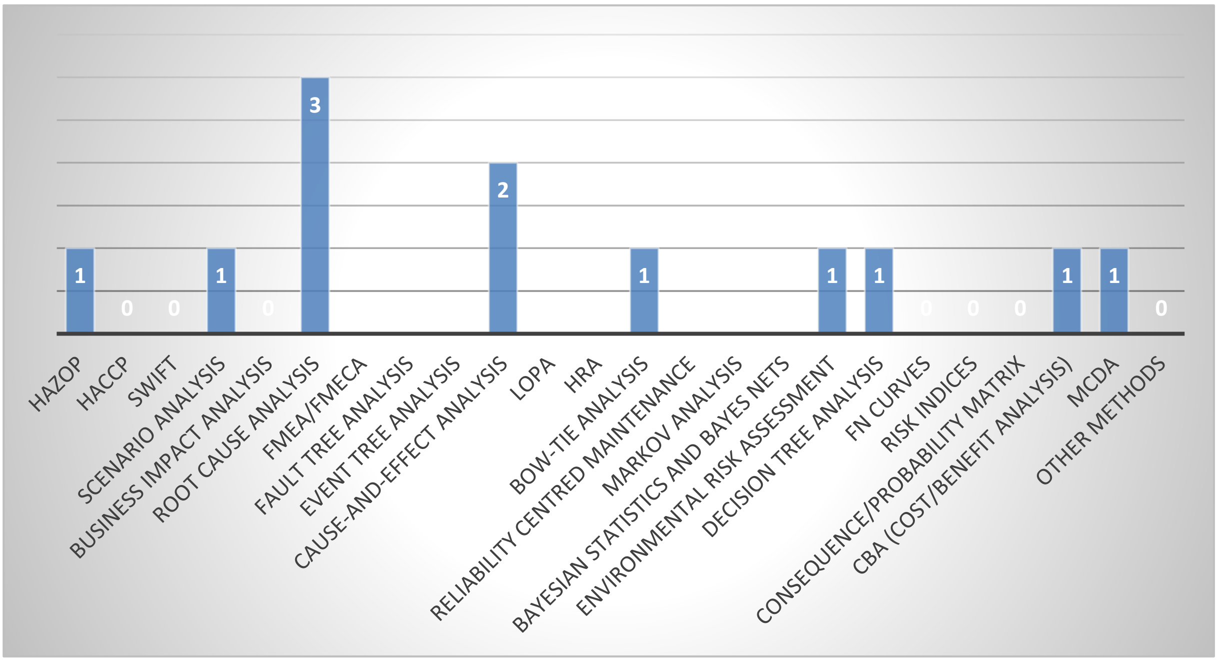


Figure 5-24. Distribution of methods used for geological event risk analysis.

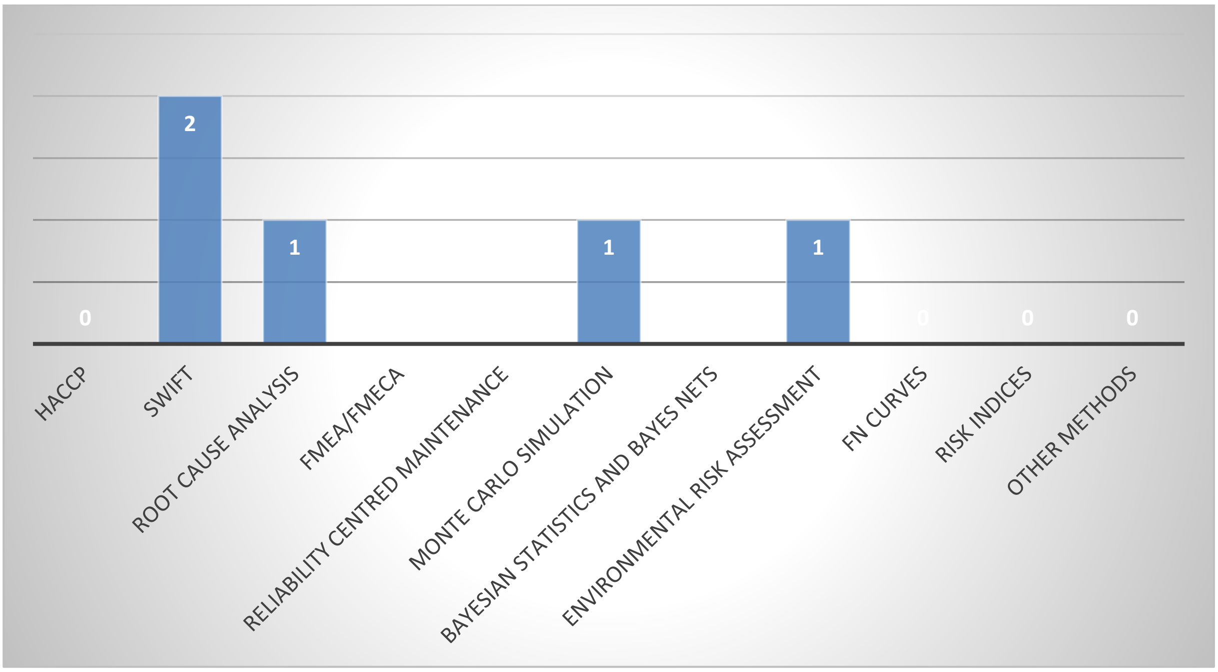


Figure 5-25. Distribution of methods used for geological event risk evaluation.

Pressure/well control risk

Within pressure/well control, the most used risk identification methods seems to be brainstorming, scenario analysis and cause and effect analysis (see Figure 5-26). Nine of the fifteen methods are used to some extent. There is not a wide variety of methods used in risk analysis, with root cause analysis being a preferred method according to Figure 5-27. For risk evaluation, root cause analysis remains the most used as shown in Figure 5-28. Though reliability centred maintenance, Monte Carlo simulations, environmental risk assessment and risk indices are also used.

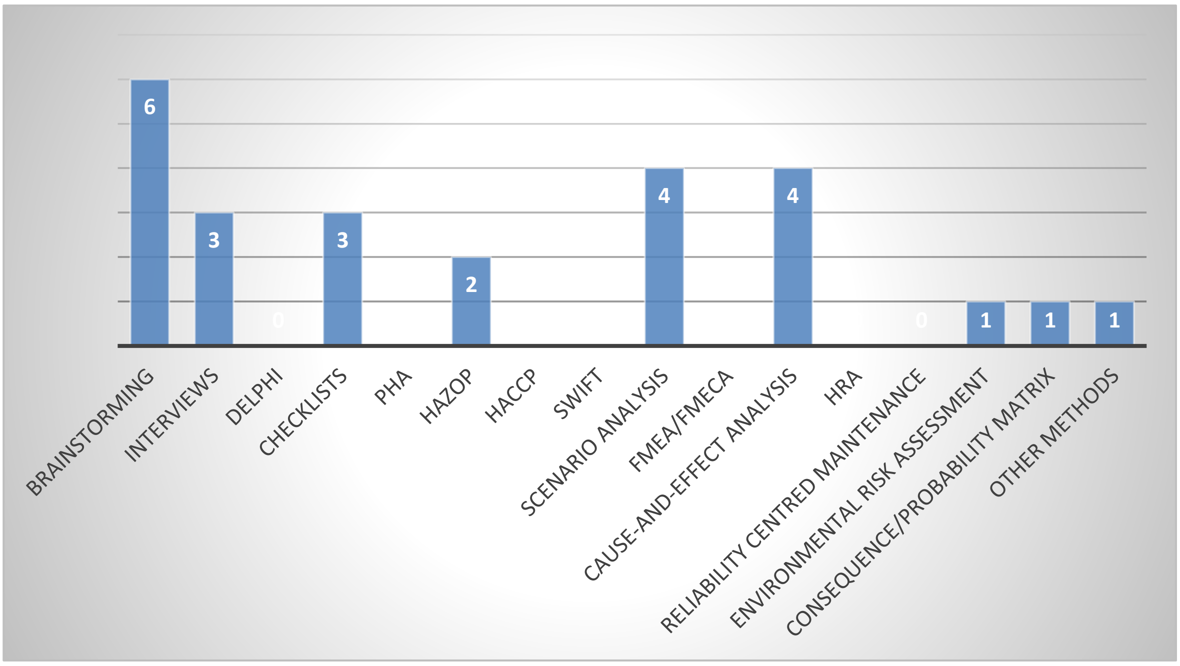


Figure 5-26. Distribution of methods used for pressure/well control risk identification.

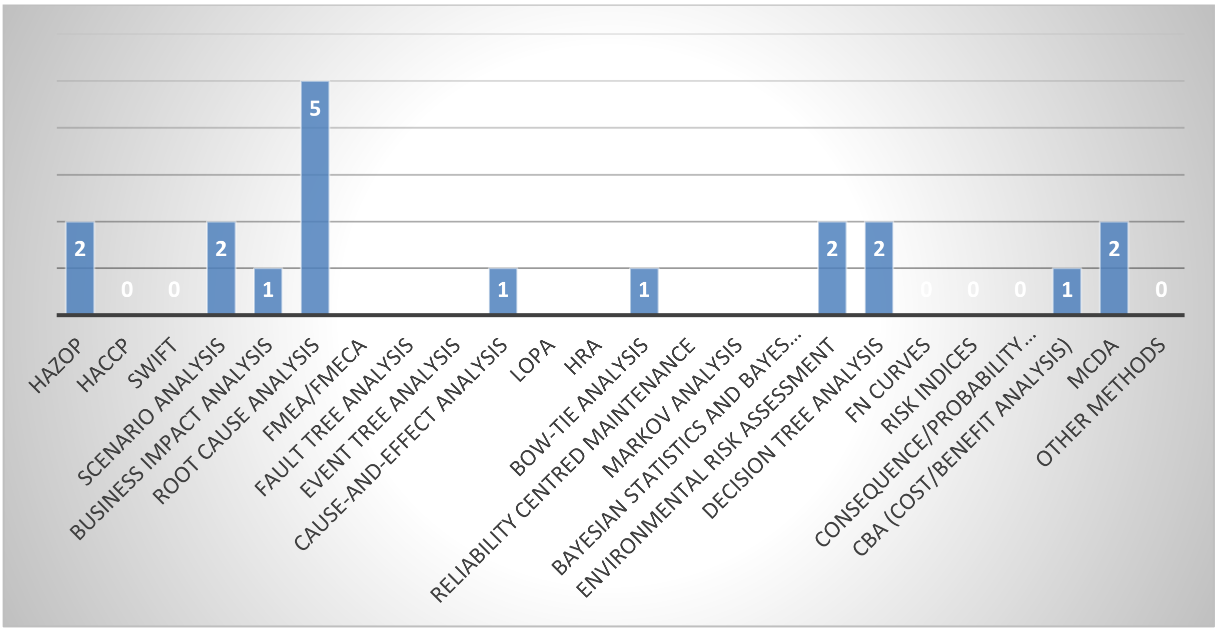


Figure 5-27. Distribution of methods used for pressure/well control risk analysis.

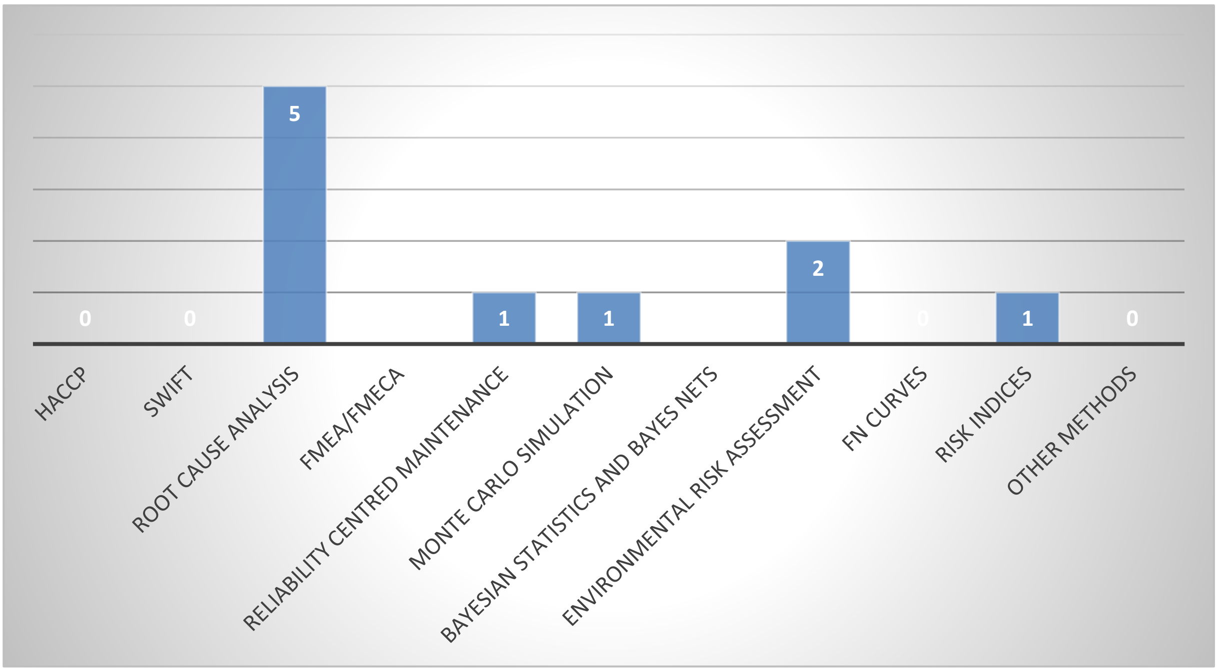


Figure 5-28. Distribution of methods used for pressure/well control risk evaluation.

Environmental risk

Methods used for environmental risk identification, analysis and evaluation are shown in Figure 5-29, Figure 5-30 and Figure 5-31, respectively. For environmental assessments, the most used methods for risk identification are brainstorming and, not surprisingly, environmental risk assessment (see Figure 5-29). Several of the other methods are also used. In risk analysis (Figure 5-30), environmental risk assessments and decision tree analysis are the most used, followed by cost-benefit analysis and root-cause analysis. For risk evaluation, which is shown in Figure 5-31, environmental risk assessments are the primary method, with root cause analysis coming second.

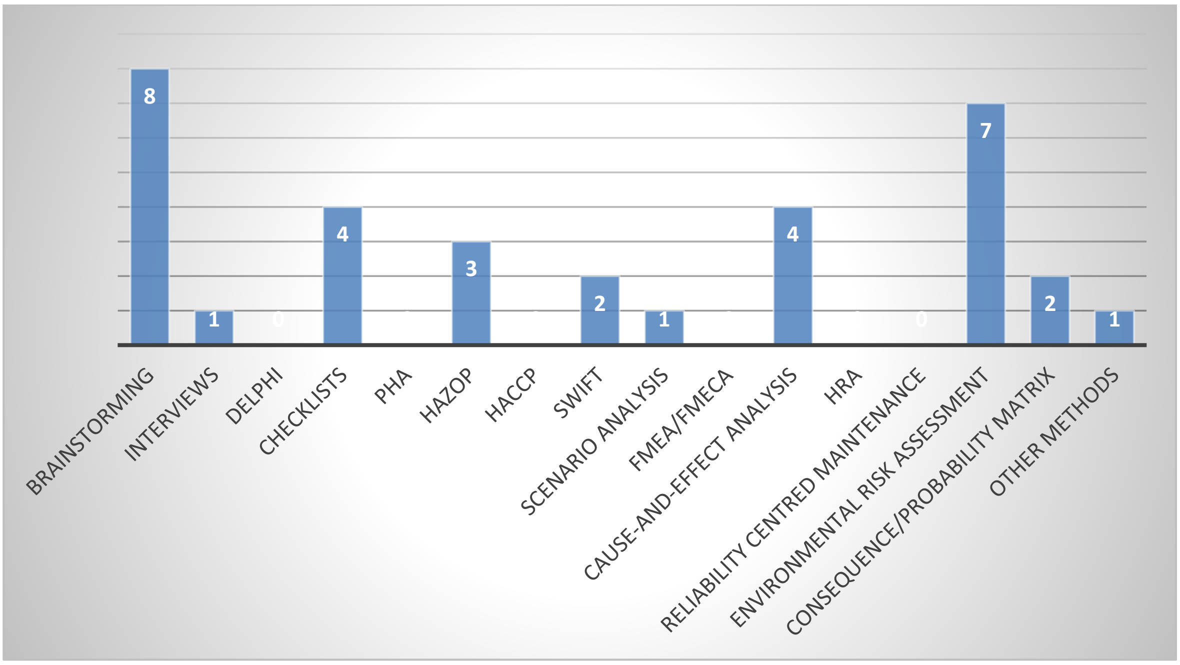


Figure 5-29. Distribution of methods used for environmental risk identification.

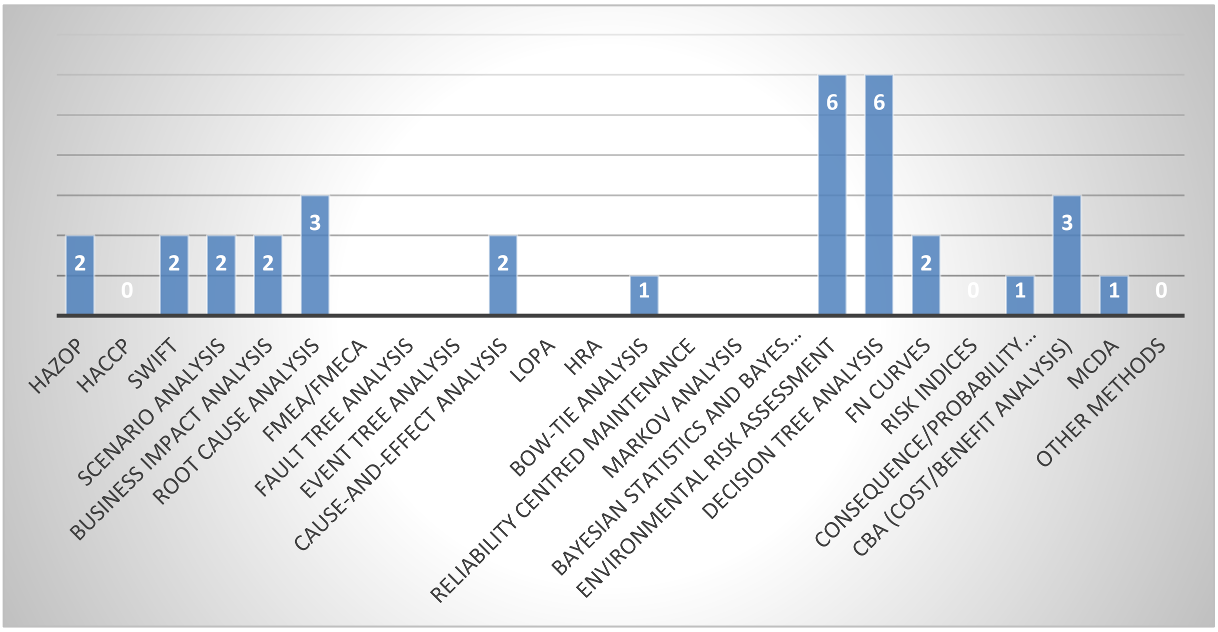


Figure 5-30. Distribution of methods used for environmental risk analysis.

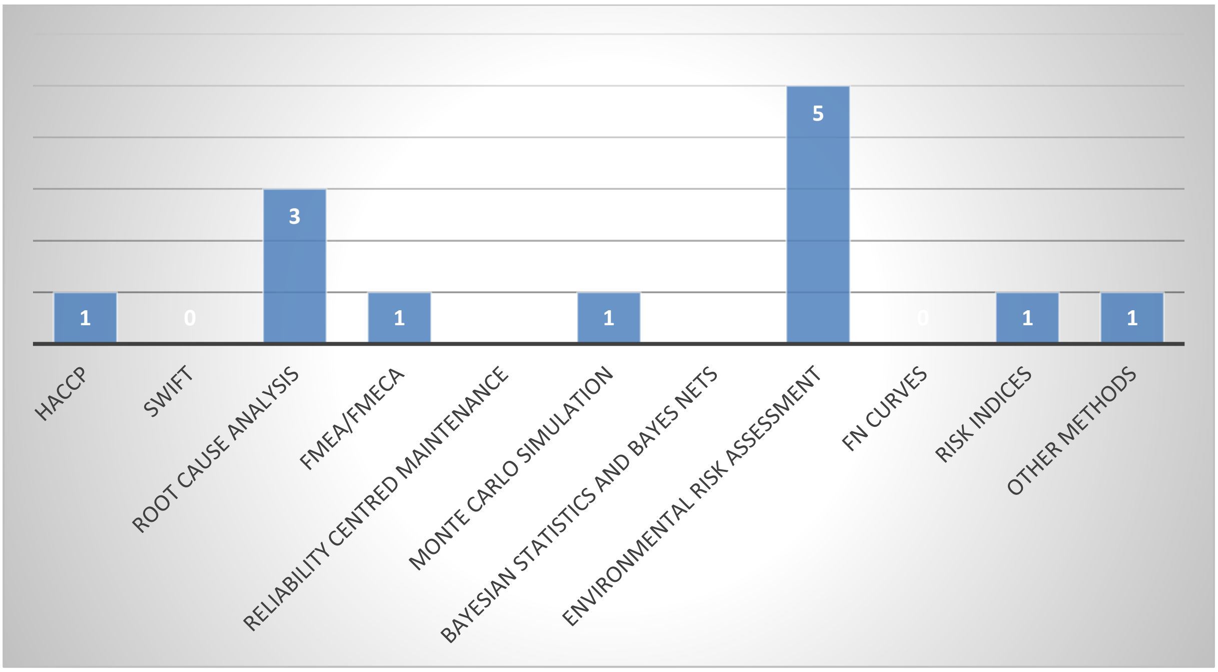


Figure 5-31. Distribution of methods used for environmental risk evaluation.

Flow assurance risk

For flow assurance, brainstorming is the most used risk identification method. This is not an area chosen by many respondents, and only four other methods have been chosen, as shown in Figure 5-32. No risk analysis method has full support, but many use business impact analysis. Six other methods are also applied, according to Figure 5-33. As seen in Figure 5-34, the risk evaluation methods reported used for this purpose is root-cause analysis, Monte Carlo simulations and risk indices.

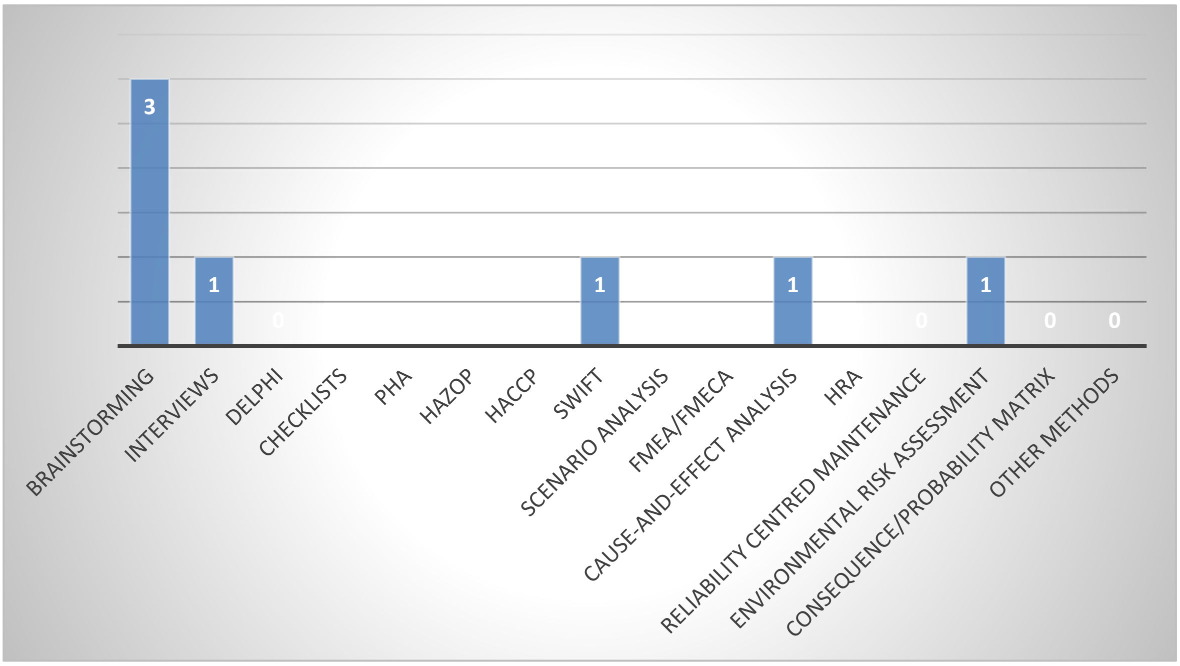


Figure 5-32. Distribution of methods used for flow assurance risk identification.

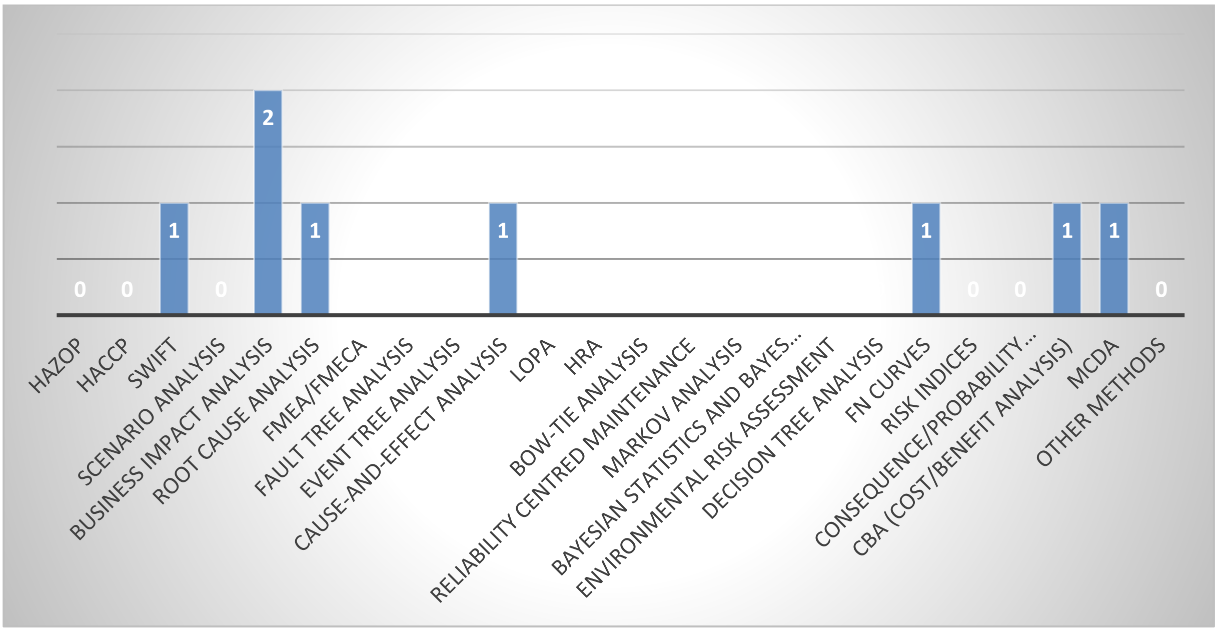


Figure 5-33. Distribution of methods used for flow assurance risk analysis.

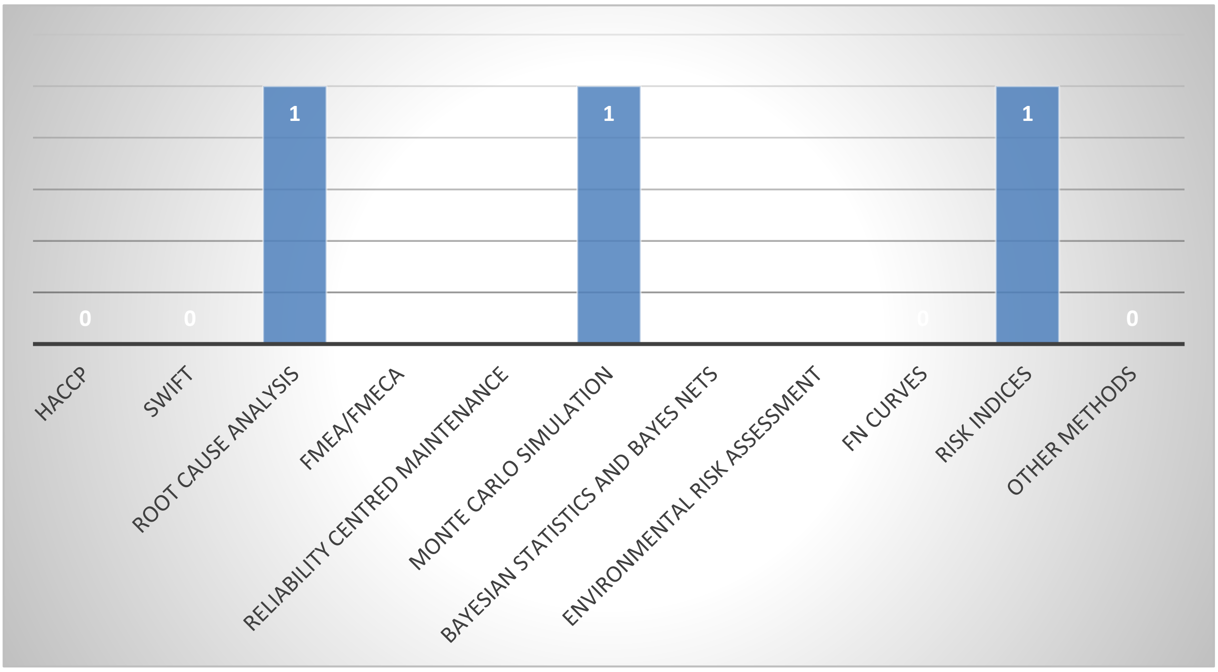


Figure 5-34. Distribution of methods used for flow assurance risk evaluation.

5.3 Summary of the analysis

As was seen in both the literature review and the survey, well integrity is less focused on in the geothermal industry than what is believed to be the case in the petroleum industry. A significant part of the findings may be related to the geothermal industry mainly being in the exploration stage, where the feasibility is the issue more than operational concerns.

An early question was if the geothermal operators were mostly power plant operators, outsourcing concerns related to wells to consulting companies. As seen in Figure 5-9, there is little indication of this, with at least some of the operating companies involved in all the areas mentioned in the survey.

In the literature review, monetary indices were found to be the most used method, with either probabilistic methods or coarse risk ranking following. The questionnaire finds brainstorming to be the most used risk identification method. Most of the identification methods are applied across the different areas, except Delphi, human reliability analysis (HRA) and reliability centred maintenance. The use of methods varies more between the areas of application for risk analysis. The most used methods were HAZOP, root cause analysis, scenario analysis and environmental risk and decision tree analysis, depending on the area of application. Several methods were not mentioned by anyone, such as Markov analysis, Bayesian statistics and Bayesian nets, fault tree analysis and event tree analysis (ETA). For risk evaluation, the situation was similar to risk analysis. Depending on the area, Monte Carlo simulation, root cause analysis, structured what-if technique (SWIFT) analysis and environmental risk analysis were the most frequently chosen methods.

6 Conclusions

The findings of the work presented here as part of GeoWell deliverable 6.1 are based on the literature review and analysis of responses to the GeoWell risk assessment survey. The conclusions can be summarized as follows:

- Based on the papers reviewed, the mostly addressed risk type relates to project/financial risk, which differs significantly from our impression of focus in the petroleum industry. This is probably due to the fact that while there is an enormous financial upside when drilling petroleum exploration wells, this is not the case for geothermal wells. Furthermore, the financial margins during production of geothermal projects are typically several magnitudes less than for oil and gas.
- Another important focus area in the papers is geological risk. However, this is often tightly related to project/financial risk; large uncertainties in the resources to be exploited will consequently result in large uncertainty in the project feasibility as well.
- Only 11% of the publications cover well integrity as a topic addressed.
- Only a few publications reviewed concern risk of loss of containment, or risks of failures in barriers. In fact, the term barrier is hardly mentioned, and even the papers dealing with well integrity do so to a large extent without considering the system as comprised of barriers with failure modes and reliabilities.
- In the literature review, monetary indices were the most used method, with either probabilistic methods or coarse risk ranking following.
- The survey finds brainstorming to be the most used risk identification method.
- The use of methods varies more between the areas of application for risk analysis. The most used methods were HAZOP, root cause analysis, scenario analysis and environmental risk and decision tree analysis, depending on the area.
- For risk evaluation, the situation was similar to risk analysis. This is not surprising, given that the risk evaluation is based on the risk analysis. Depending on the area, Monte Carlo simulation, root cause analysis, structured what-if technique analysis and environmental risk analysis were most frequently chosen methods.
- Regarding the use of risk assessment methods in terms of resource demands, nature of uncertainty and complexity, there is no evidence to suggest that there is an overweight of simplistic, low-complexity methods in use in the geothermal industry.

7 Dissemination and future activities

For the purpose of dissemination and communication of the findings of the GeoWell risk assessment survey in the work package 6, a webinar is planned. Respondents leaving their email addresses have been invited to join the webinar. In the planned event, a summary of key findings from the survey will be presented followed by a question and answer session.

In addition to the planned webinar, it is an aim to publish selected findings from this report at relevant conference(s). At the time of writing this report, details about this were not ready.

Thus far, the work in GeoWell WP6 has focused on establishing a foundation for the present state of risk assessment in the geothermal and petroleum industries. With this information, the work package will focus more on particular challenges associated with integrity of geothermal wells by including input from the other work packages of the project. The following tasks will build on the work performed in tasks 6.1 and 6.2 of GeoWell:

- Task 6.3 is entitled “Develop risk assessment methods for phenomena that are currently not covered for geothermal wells, particularly at elevated temperatures up to 450 °C”. The aim is to establish barrier definitions for geothermal wells and corresponding risk assessment tools for the relevant barriers. The results from this task will supply a framework for a quantitative approach to risk assessment for geothermal wells.
- Task 6.4 is entitled “Develop a European protocol for risk assessment in geothermal drilling in compliance with European and domestic regulations”. Here, the foundations for geothermal well integrity and risk assessment methodology will be established as a basis for a future European protocol. This can contribute to developing a basis for a common European standard for planning and execution of geothermal well construction.
- Task 6.5 is entitled “Reliability analysis of new developed materials and technology”. In this task, results from GeoWell work packages dealing with new materials (casing, cement and tubulars) and corresponding technology will be input. An evaluation will be made to answer to what degree the newly developed technologies can replace existing ones in terms of risk properties.

References

1. Bertani, R., Geothermal power generation in the world 2010-2014 update report, in Proceedings World Geothermal Congress, 2015. Melbourne, Australia: International Geothermal Association (IGA).
2. Lund, J.W., Boyd, T.L, Direct utilization of geothermal energy 2015 worldwide review, in Proceedings of World Geothermal Congress 2015. Melbourne, Australia: International Geothermal Association (IGA).
3. GeoWell. http://www.geowell-h2020.eu/. 2016 [03.10.2016].
4. NORSOK Standard D-010 - Well integrity in drilling and well operations, 2004, Standards Norway: Lysaker, Norway.
5. ISO, ISO/TS 16530-.2:2014– Well integrity -- Part 2: Well integrity for the operational phase, 2014, the International Organization for Standardization (ISO).
6. Shadravan, A., Ghasemi, M., Alfi, M., Zonal isolation in geothermal wells, in Fortieth Workshop on Geothermal Reservoir Engineering, 2015. Stanford University, Stanford, California, USA.
7. Southon, J.N.A., Geothermal well design, construction and failures, in Proceedings World Geothermal Congress 2005. Antalya, Turkey: International Geothermal Association (IGA).
8. Finger, J., Blankenship, D., Handbook of best practices for geothermal drilling, 2010, Sandia National Laboratories: Albuquerque, New Mexico, USA. p. 84.
9. Petrowiki. Glossary:HPHT (high pressure, high temperature). 2013 [11.10.2016]; Available from: http://petrowiki.org/Glossary%3AHPHT.
10. Randeberg, E., Fordi, E., Nygaard, G., Erikssoni, M, Gressgård, L.J., Hansen, K, Potentials for cost reduction for geothermal well construction in view of various drilling technologies and automation opportunities, in Proceedings, Thirty-Sixth Workshop on Geothermal Reservoir Engineering, 2012. Stanford University, Stanford, California, USA.
11. Polsky, Y., Capuano, L., Finger, J., Huh, M., Knudsen, S., Mansure, A.J.C., Raymond, D., Swanson, R, Enhanced geothermal systems (EGS) well construction technology evaluation report, 2008, Sandia National Laboratories: USA. p. 108.
12. Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., Drake, E.M., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., Petty, S., Toksöz, M.N., Veatch, R.W, The future of geothermal energy - Impact of enhanced geothermal systems (EGS) on the United States in the 21st century, 2006, Massachusetts Institute of Technology.
13. Teodoriu, C., Falcone, G., Comparing completion design in hydrocarbon and geothermal wells: The need to evaluate the integrity of casing connections subject to thermal stresses. Geothermics, 2009. **38**: p. 238-246.
14. Kaldal, G.S., Thorbjörnsson, I.Ö, Thermal expansion of casings in geothermal wells and possible mitigation of resultant axial strain, in European Geothermal Congress2016, European Geothermal Congress (EGC): Strasbourg, France.
15. Hodson-Clarke, A., Rudolf, R., Bour, D., Russell, P., Key factors to successful drilling and completion of EGS well in Cooper Basin, in 41st Workshop on Geothermal Reservoir Engineering, 2016. Stanford University, Stanford, California, USA: Stanford University.

16. Lentsch, D., Dorsch, K., Sonnleitner, N., Schubert, A., Prevention of casing failures in ultra-deep geothermal wells (Germany), in World Geothermal Congress, 2015. Melbourne, Australia: International Geothermal Association (IGA).
17. Goodman, M.A., Lost circulation experience in geothermal Wells, in International Geothermal Drilling and Completions Technology Conference1981, Office of Scientific and Technical Information (OSTI), US DOE: Albuquerque, NM, USA.
18. Matek, B., The manageable risks of conventional hydrothermal geothermal power systems: A factbook on geothermal power's risks and methods to mitigate them, 2014, Geothermal Energy Association (GEA).
19. ISO, ISO 31000-2009 Risk management – Principles and guidelines, 2009, the International Organization for Standardization (ISO).
20. NTC, NORSOK Z-013 Rev. 2 - Risk and emergency preparedness analysis, 2001, Norwegian Technology Centre (NTC): Oslo, Norway.
21. De Castro, S., Gasper, J.A., Gasper, J.K., Gessler, A., Gomez-Cobo, A., Labroille, S., Langlois, L., Lawrence, G., Mazour, T., Nettleship, D., Pakan, M., Na, J.H., Surendar, Ch., Risk management: A tool for improving nuclear power plant performance, 2001, International Atomic Energy Agency (IAEA): Vienna, Austria.
22. Korre, A., Durucan, S, A review of the international state of the art in risk assessment guidelines and proposed terminology for use in CO_2 geological storage, 2009, Report Number 2009-TR7, International Energy Agency Greenhouse Gas R&D Programme (IEA GHG): Cheltenham, United Kingdom.
23. Heijnen, L., Rijkers, R., Ohmann, R.G, Management of geological and drilling risks of geothermal projects in the Netherlands, in Proceedings of World Geothermal Congress 2015. Melbourne, Australia: International Geothermal Association (IGA).
24. EU. EU law. 2016 [10.10.2016]; Available from: https://europa.eu/european-union/law/legal-acts_en.
25. Rausand, M., Risk assessment: Theory, methods, and applications, 2013, Hoboken, New Jersey, USA: John Wiley & Sons, Inc.
26. USNRC, PRA procedures guide: A guide to the performance of probabilistic risk assessments for nuclear power plants (NUREG/CR-2300), 1983, Washington, D.C., USA: Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission (USNRC).
27. Stamatelatos, M., Dezfuli, H, Probabilistic risk assessment procedures guide for NASA managers and practitioners, 2011, NASA: Washington, D.C., USA.
28. NZS, NZS 2403:2015 -- Code of practice for deep geothermal wells (Superseding NZS 2403:1991) 2015, Standards New Zealand.
29. ISO, ISO 15156-2:2003 Petroleum and natural gas industries – Materials for use in H_2S-containing environments in oil and gas production -- Part 2: Cracking-resistant carbon and low alloy steels, and the use of cast irons, 2003, the International Organization for Standardization (ISO).
30. ISO, ISO 13679:2002 Petroleum and natural gas industries – Procedures for testing casing and tubing connections, 2002, the International Organization for Standardization (ISO).
31. GTR-H. The GeoThermal Regulation-Heat (GTR-H) project: Geothermal regulation framework. 2009 [10.10.2016]; Available from: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/gtr-h_final_gtr_h_framework.pdf.

32. ISO, IEC/ISO 31010 Risk management – Risk assessment techniques, 2009, the International Organization for Standardization (ISO).

33. Savage, D., Maul, P.R., Benbow, S., Walke, R.C, A generic FEP database for the assessment of of long-term performance and safety of the geologic storage of CO_2, 2004, Quintessa Report QRS-1060A-1. p. 73.

Appendices

Appendix I: The GeoWell risk assessment survey

EU-GeoWell Risk Assessment Survey

GeoWell

Welcome to the GeoWell Risk Assessment Survey

The International Research Institute of Stavanger (IRIS), Norway, conducts a short survey within the framework of the GeoWell project. The project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement no. 654497. The purpose of this survey is to collect and analyze information that can help to map the currently used methods for risk assessment in the geothermal and petroleum industries and more specifically during the drilling and completion, production and maintenance phases. The findings will be communicated to the participants via a planned webinar in Fall 2016. Please take your time to answer this survey that should take no more than 10 minutes to complete. Answers to most of the questions are given by selecting the alternative which best describes your company and its practice. Please direct any questions or comments to the GeoWell team at IRIS. Email: GeoWell@iris.no

1 Company Information

- Company Name (Optional) (1)
- Country (Optional) (2)

2 How would you define your company/organization type?

- ❑ Operating Company (1)
- ❑ Drilling Contractor (2)
- ❑ Service Provider (3)
- ❑ Consulting Company (4)
- ❑ Equipment Manufacturer (5)
- ❑ Government Agency (6)
- ❑ University, Research Institute or Laboratory (7)
- ❑ Other (Please Specify) (8) ____________________

3 In which of the following areas is your company/organization active?

- ❑ Onshore Geothermal (1)
- ❑ Offshore Petroleum (2)
- ❑ Onshore Petroleum (3)
- ❑ Other (Please Specify) (4) ____________________

4 Is your company responsible for performing risk assessments in the context of well operations?

- ❍ Yes (1)
- ❍ No (2)

5 Which types of risk assessments do you perform?

- ❑ Health and Safety Risk (1)
- ❑ Project/Financial Risk (2)
- ❑ Geological Risk (3)
- ❑ Geological Event Risk (4)
- ❑ Pressure/Well Control Risk (5)
- ❑ Equipment Reliability (6)
- ❑ Barrier Reliability (7)
- ❑ Environmental Risk (8)
- ❑ Flow Assurance (9)
- ❑ Other (Please Specify) (10) ____________________

Note: According to IEC/ISO 31010, a risk assessment process is accomplished in three different steps including: i) Risk identification - Risk identification is activities related to the identification of sources of risks, areas of impacts, events and their causes and their potential consequences. ii) Risk analysis - Risk analysis is the consideration of the causes and sources of risk, their positive and negative consequences, and the likelihood that those consequences can occur. iii) Risk evaluation - Risk evaluation involves the comparison of the level of risk found in the risk analysis with risk criteria established, taking into account tolerance to risk.

6 Which of the following methods are used for risk identification at your company?

- ❑ Brainstorming (1)
- ❑ Interviews (Structured or Semi-structured) (2)
- ❑ Delphi (3)
- ❑ Checklists (4)
- ❑ PHA (Preliminary Hazard Analysis) (5)
- ❑ HAZOP (HAZard and Operability studies) (6)
- ❑ HACCP (Hazard Analysis and Critical Control Points) (7)
- ❑ SWIFT (Structured What-If Technique) (8)
- ❑ Scenario Analysis (9)
- ❑ FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis) (10)
- ❑ Cause-and-Effect Analysis (11)
- ❑ HRA (Human Reliability Analysis) (12)
- ❑ Reliability Centred Maintenance (13)
- ❑ Environmental Risk Assessment (14)
- ❑ Consequence/Probability Matrix (15)
- ❑ Other Methods (Please Specify) (16) ____________________

7 Which of the following methods are used for risk analysis at your company?

- ❑ HAZOP (HAZard and Operability studies) (1)
- ❑ HACCP (Hazard Analysis and Critical Control Points) (2)
- ❑ SWIFT (Structured What-If Technique) (3)
- ❑ Scenario Analysis (4)
- ❑ Business Impact Analysis (5)
- ❑ Root Cause Analysis (6)
- ❑ FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis) (7)
- ❑ Fault Tree Analysis (8)
- ❑ Event Tree Analysis (9)
- ❑ Cause-and-Effect Analysis (10)
- ❑ LOPA (Layer of Protection Analysis) (11)
- ❑ HRA (Human Reliability Analysis) (12)
- ❑ Bow-Tie Analysis (13)
- ❑ Reliability Centred Maintenance (14)
- ❑ Markov Analysis (15)
- ❑ Bayesian Statistics and Bayes Nets (16)
- ❑ Environmental Risk Assessment (17)
- ❑ Decision Tree Analysis (18)
- ❑ FN Curves (19)
- ❑ Risk Indices (20)

- ❑ Consequence/Probability Matrix (21)
- ❑ CBA (Cost/Benefit Analysis) (22)
- ❑ MCDA (Multi-Criteria Decision Analysis) (23)
- ❑ Other Methods (Please Specify) (24) ____________________

8 Which of the following methods are used for risk evaluation at your company?

- ❑ HACCP (Hazard Analysis and Critical Control Points) (1)
- ❑ SWIFT (Structured What-If Technique) (2)
- ❑ Root Cause Analysis (3)
- ❑ FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis) (4)
- ❑ Reliability Centred Maintenance (5)
- ❑ Monte Carlo Simulation (6)
- ❑ Bayesian Statistics and Bayes Nets (7)
- ❑ Environmental Risk Assessment (8)
- ❑ FN Curves (9)
- ❑ Risk Indices (10)
- ❑ Other Methods (Please Specify) (11) ____________________

Please specify the phases you perform risk management methods. Note that every phases also include pre-planning prior to execution.

9 Please check the corresponding phases you perform risk identification methods:

	Drilling	Completion	Production	Maintenace
Risks that are selected in Q.6	O	O	O	O

10 Please check the corresponding phases you perform risk analysis methods:

	Drilling	Completion	Production	Maintenace
Risks that are selected in Q.7	O	O	O	O

11 Please check the corresponding phases you perform risk evaluation methods:

	Drilling	Completion	Production	Maintenace
Risks that are selected in Q.8	O	O	O	O

12 Please check the corresponding risks you apply the risk identification methods:

	Risks that are selected in Q.5	risks that are selected in Q.5
Methods that are selected in Q.6	O	O

13 Please check the corresponding risks you apply the risk analysis methods:

	Risks that are selected in Q.5	risks that are selected in Q.5
Methods that are selected in Q.7	O	O

14 Please check the corresponding risks you apply the risk evaluation methods

	Risks that are selected in Q.5	risks that are selected in Q.5
Methods that are selected in Q.8	O	O

15 Please provide your email address here if you are interested in participating in a webinar presenting the findings of this survey.

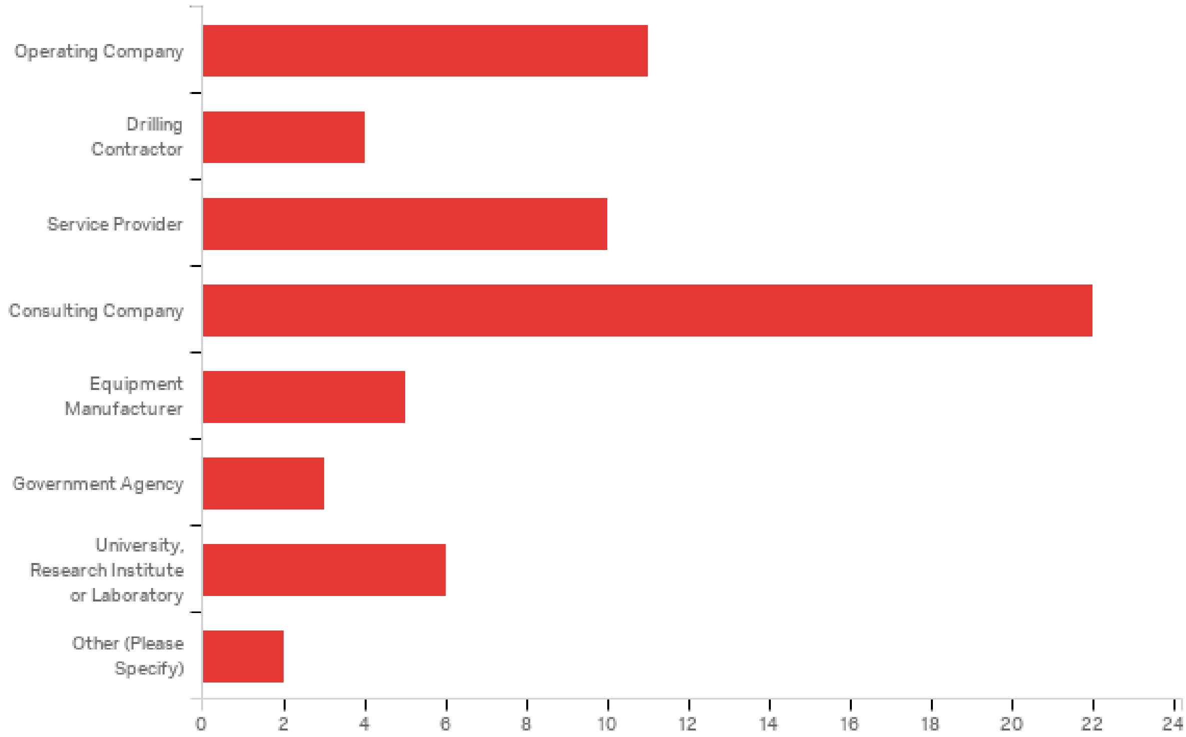
16 Do you have any other comments, questions or concerns?

Appendix II: Responses to the survey

1 - Company Information

Please note that because of confidentiality issues, these information are excluded from the report.

2 - How would you define your company/organization type?

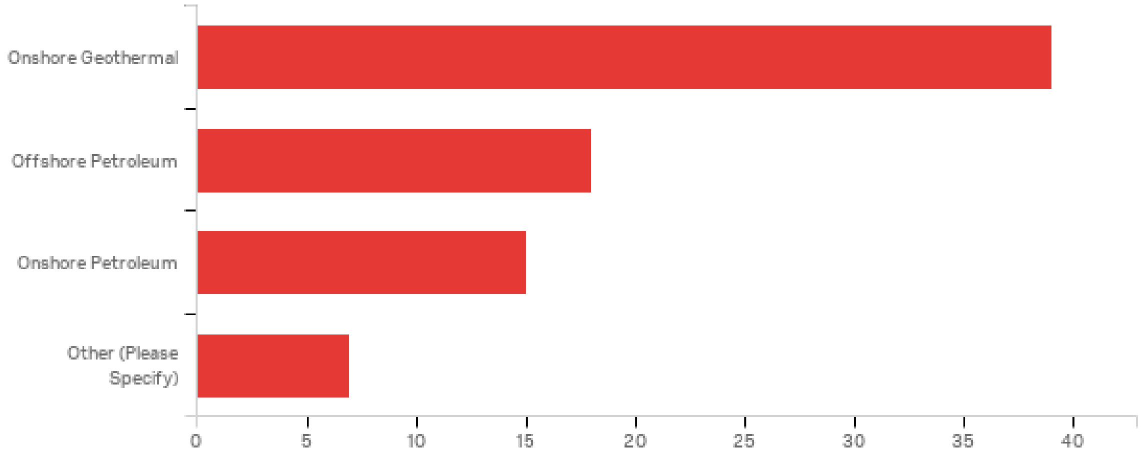


Answer	%	Count
Operating Company	22.45%	11
Drilling Contractor	8.16%	4
Service Provider	20.41%	10
Consulting Company	44.90%	22
Equipment Manufacturer	10.20%	5
Government Agency	6.12%	3
University, Research Institute or Laboratory	12.24%	6
Other (Please Specify)	4.08%	2
Total	100%	49

Other (Please Specify)

Other (Please Specify)
Pilot plant of CLEAG Geothermal energy
Contract drilling supervision

3 - In which of the following areas is your company/organization active?

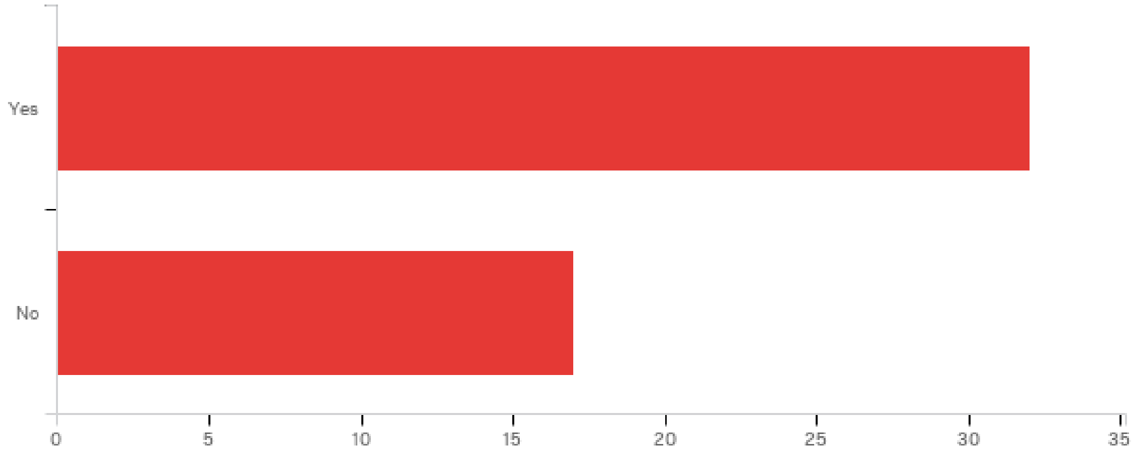


Answer	%	Count
Onshore Geothermal	79.59%	39
Offshore Petroleum	36.73%	18
Onshore Petroleum	30.61%	15
Other (Please Specify)	14.29%	7
Total	100%	49

Other (Please Specify)

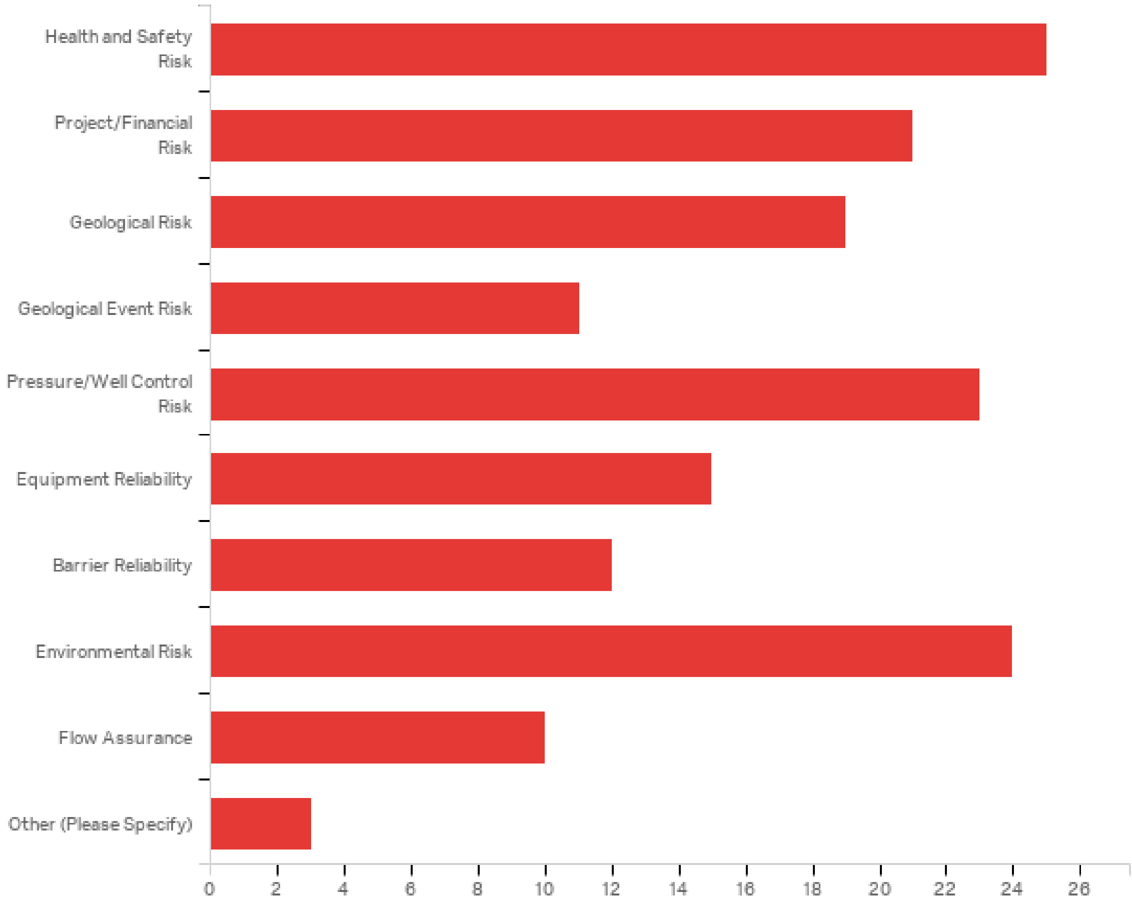
Other (Please Specify)
Mineral prospecting
CLEAG CloZEd Loop Energy
Offshore wind
mapping
Geothermal
Pipeline Failure Analysis
Mining, Geotechnical

4 - Is your company responsible for performing risk assessments in the context of well operations?



Answer	%	Count
Yes	65.31%	32
No	34.69%	17
Total	100%	49

5 - Which types of risk assessments do you perform?

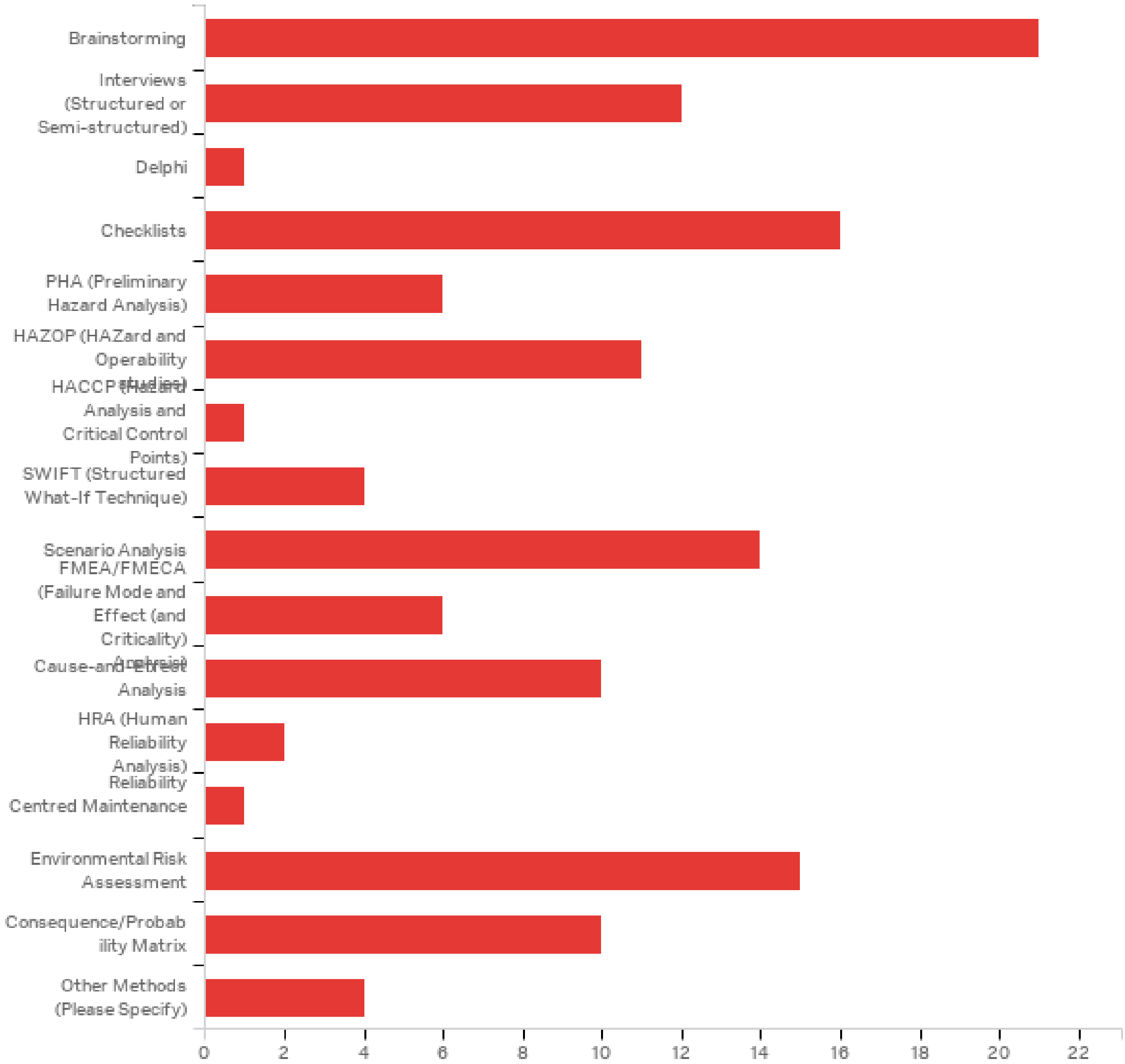


Answer	%	Count
Health and Safety Risk	80.65%	25
Project/Financial Risk	67.74%	21
Geological Risk	61.29%	19
Geological Event Risk	35.48%	11
Pressure/Well Control Risk	74.19%	23
Equipment Reliability	48.39%	15
Barrier Reliability	38.71%	12
Environmental Risk	77.42%	24
Flow Assurance	32.26%	10
Other (Please Specify)	9.68%	3
Total	100%	31

Other (Please Specify)

Other (Please Specify)
Integrity
Drilling Problem Risk
Well integrity risk (may be pressure, but not well control)

6 - Which of the following methods are used for risk identification at your company?

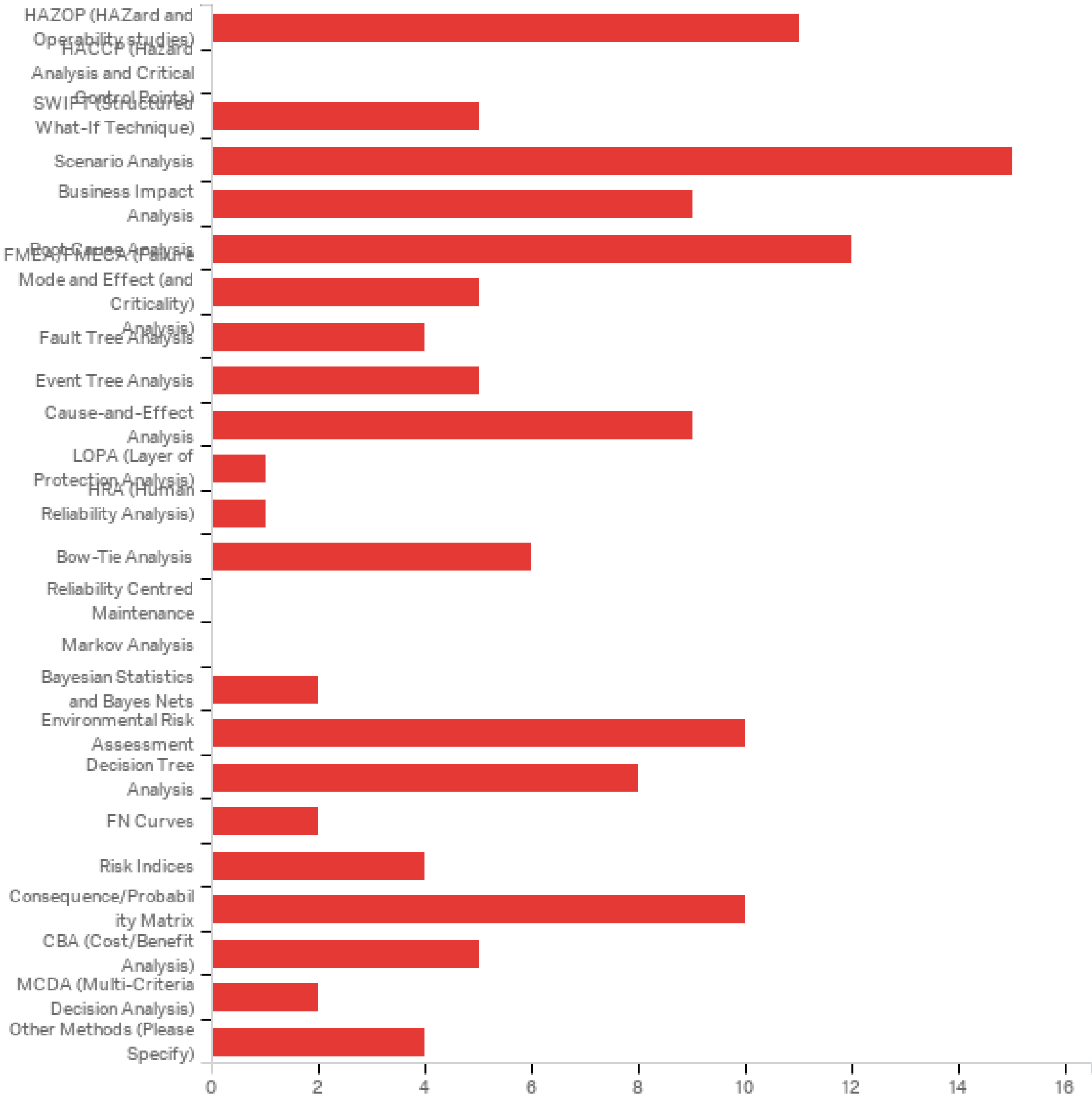


Answer	%	Count
Brainstorming	80.77%	21
Interviews (Structured or Semi-structured)	46.15%	12
Delphi	3.85%	1
Checklists	61.54%	16
PHA (Preliminary Hazard Analysis)	23.08%	6
HAZOP (HAZard and Operability studies)	42.31%	11
HACCP (Hazard Analysis and Critical Control Points)	3.85%	1
SWIFT (Structured What-If Technique)	15.38%	4
Scenario Analysis	53.85%	14
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	23.08%	6
Cause-and-Effect Analysis	38.46%	10
HRA (Human Reliability Analysis)	7.69%	2
Reliability Centred Maintenance	3.85%	1
Environmental Risk Assessment	57.69%	15
Consequence/Probability Matrix	38.46%	10
Other Methods (Please Specify)	15.38%	4
Total	100%	26

Other Methods (Please Specify)

Other Methods (Please Specify)
Top-Set
Hazard Identification Risk Assessment and Controls (HIRAC)
Contractor & Service Prespud Operations Review
DWOP (Drill Well on Paper), CWOP (Complete Well on Paper)

7 - Which of the following methods are used for risk analysis at your company?

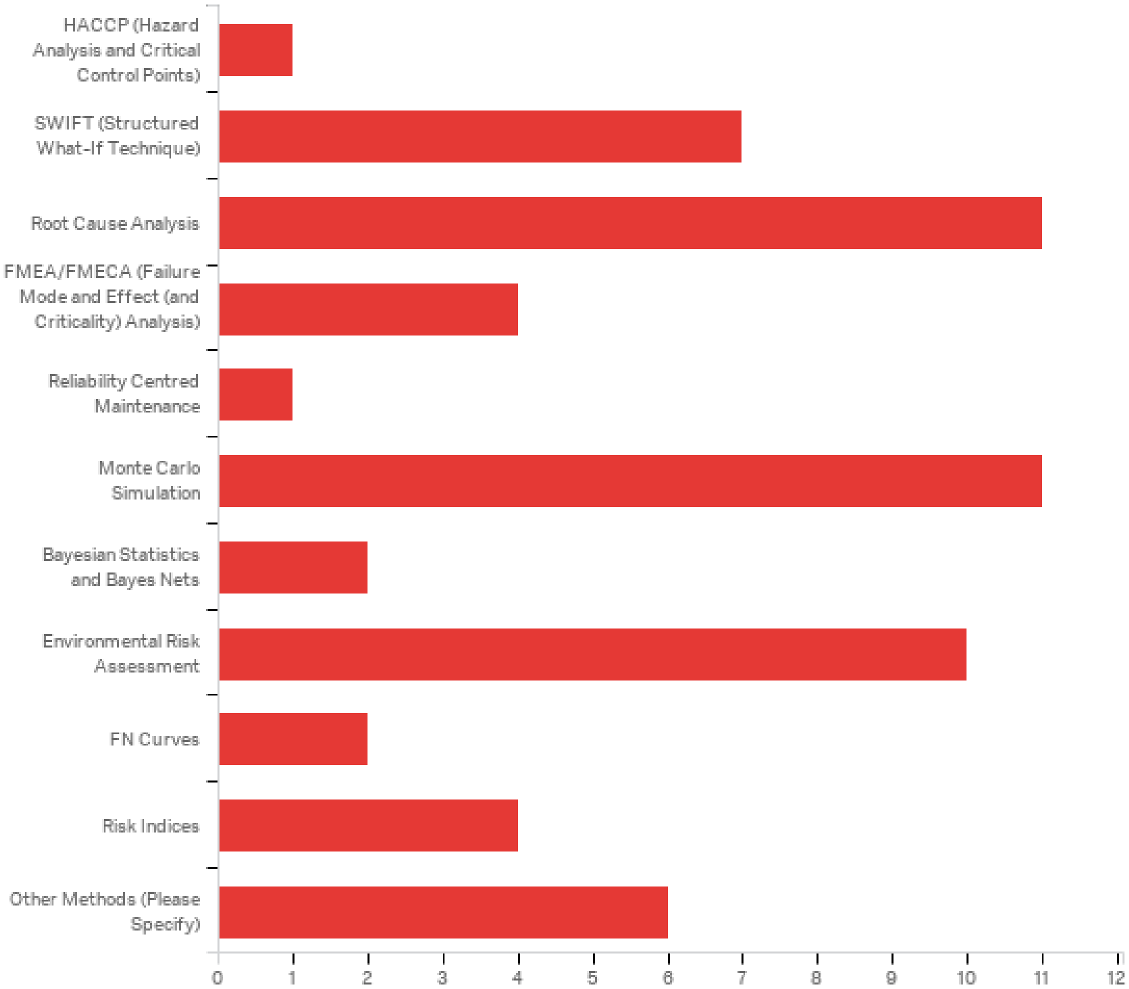


Answer	%	Count
HAZOP (HAZard and Operability studies)	42.31%	11
HACCP (Hazard Analysis and Critical Control Points)	0.00%	0
SWIFT (Structured What-If Technique)	19.23%	5
Scenario Analysis	57.69%	15
Business Impact Analysis	34.62%	9
Root Cause Analysis	46.15%	12
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	19.23%	5
Fault Tree Analysis	15.38%	4
Event Tree Analysis	19.23%	5
Cause-and-Effect Analysis	34.62%	9
LOPA (Layer of Protection Analysis)	3.85%	1
HRA (Human Reliability Analysis)	3.85%	1
Bow-Tie Analysis	23.08%	6
Reliability Centred Maintenance	0.00%	0
Markov Analysis	0.00%	0
Bayesian Statistics and Bayes Nets	7.69%	2
Environmental Risk Assessment	38.46%	10
Decision Tree Analysis	30.77%	8
FN Curves	7.69%	2
Risk Indices	15.38%	4
Consequence/Probability Matrix	38.46%	10
CBA (Cost/Benefit Analysis)	19.23%	5
MCDA (Multi-Criteria Decision Analysis)	7.69%	2
Other Methods (Please Specify)	15.38%	4
Total	100%	26

Other Methods (Please Specify)

Other Methods (Please Specify)
Top-Set
qras, Monte carlo simulations
Hazard Identification Risk Assessment and Controls (HIRAC)
Formal quantitative risk analysis

8 - Which of the following methods are used for risk evaluation at your company?

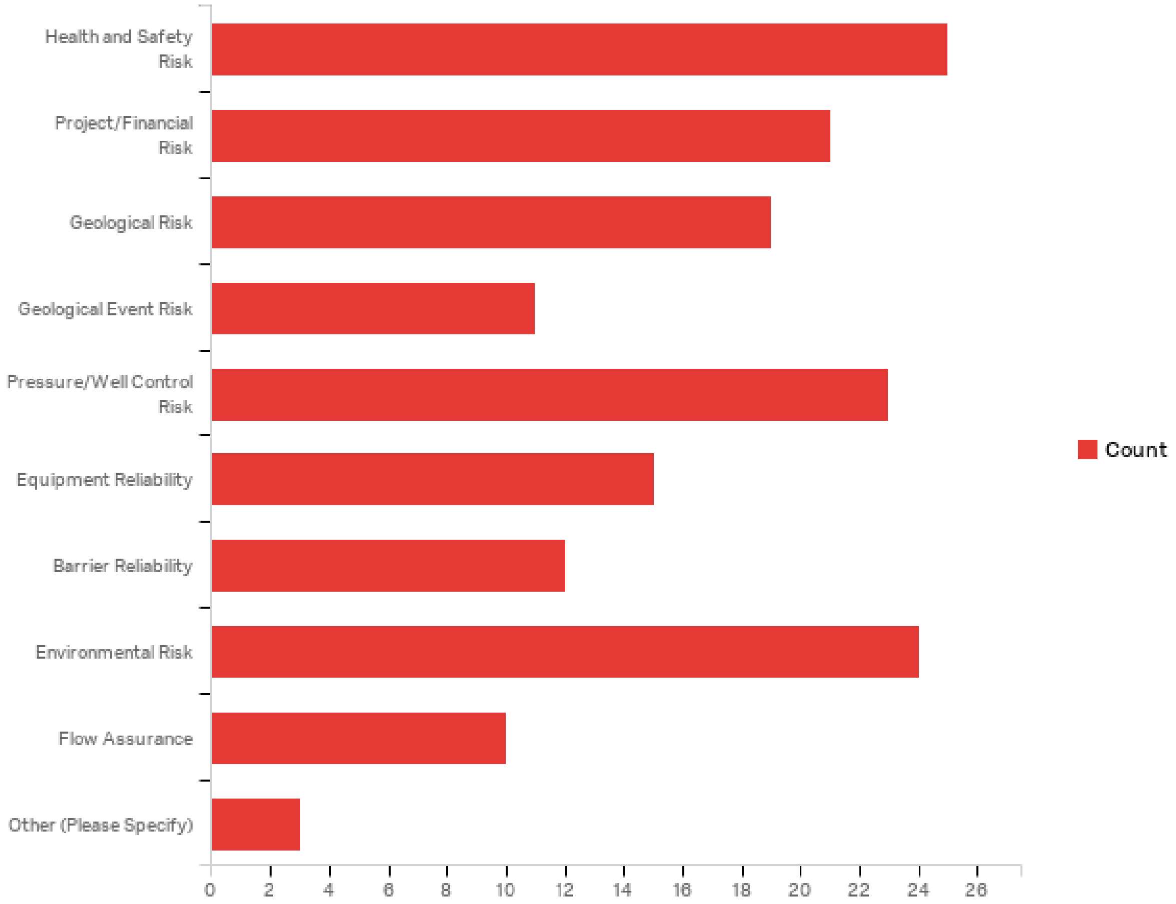


Answer	%	Count
HACCP (Hazard Analysis and Critical Control Points)	4.17%	1
SWIFT (Structured What-If Technique)	29.17%	7
Root Cause Analysis	45.83%	11
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	16.67%	4
Reliability Centred Maintenance	4.17%	1
Monte Carlo Simulation	45.83%	11
Bayesian Statistics and Bayes Nets	8.33%	2
Environmental Risk Assessment	41.67%	10
FN Curves	8.33%	2
Risk Indices	16.67%	4
Other Methods (Please Specify)	25.00%	6
Total	100%	24

Other Methods (Please Specify)

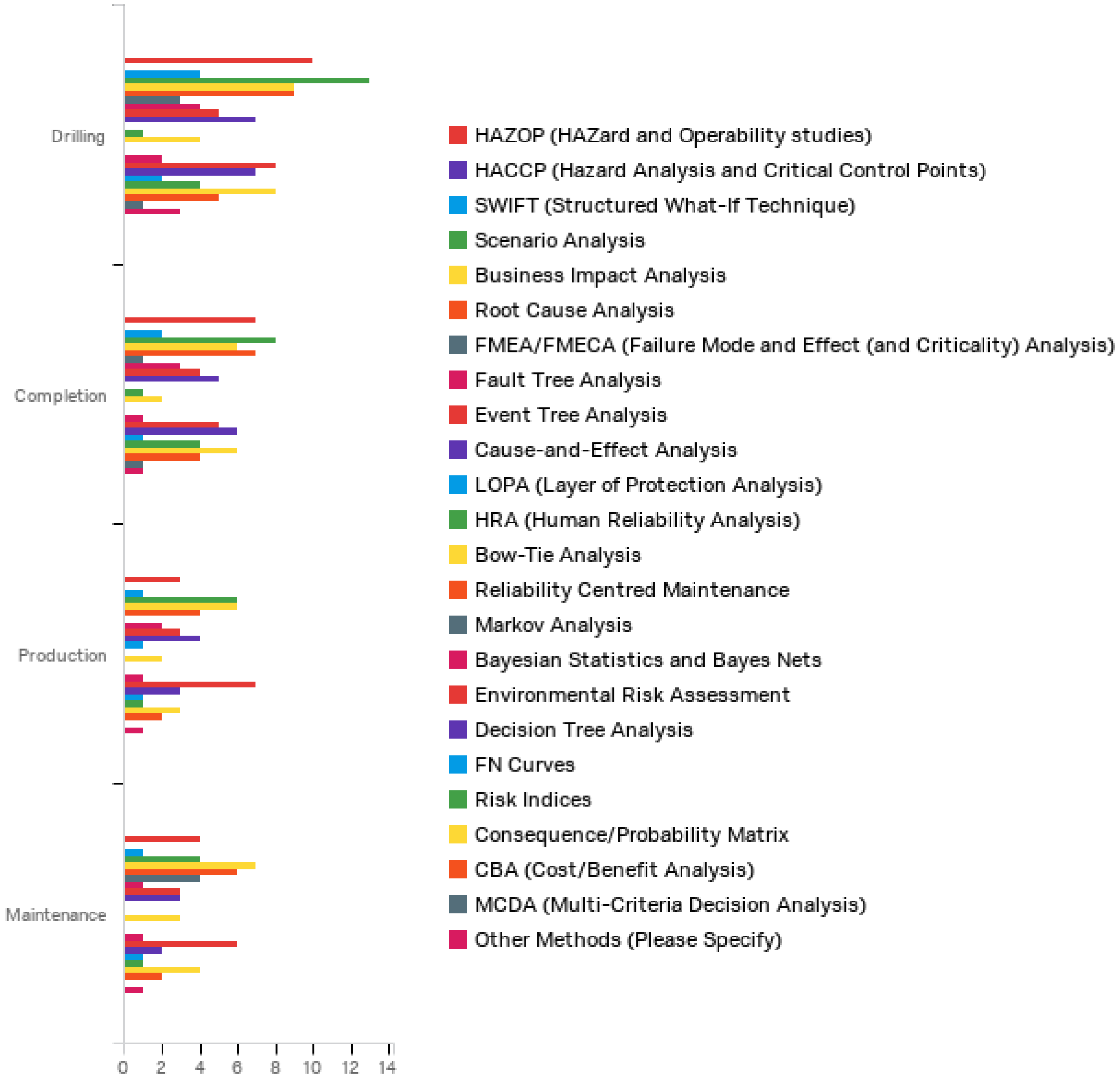
Other Methods (Please Specify)
Top-Set
Risk matrices, risk tolerance criteria
Risk Register
Hazard Identification Risk Assessment and Controls (HIRAC)
Extreme Event Statistics
Formal quantitative risk analysis

9 - Please check the corresponding phases you perform risk identification methods:



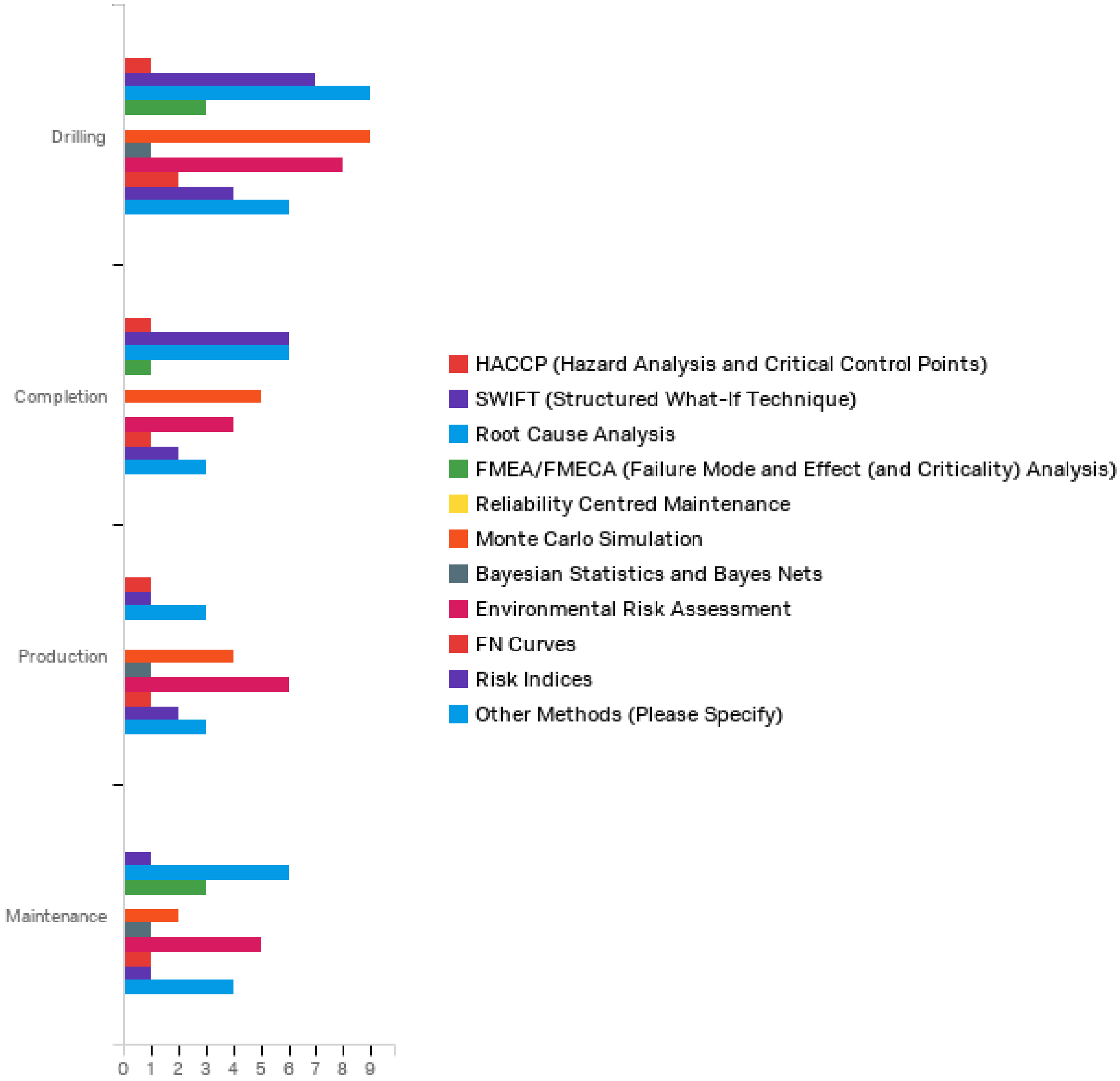
Question	Drilling	Completion	Production	Maintenance	Total
Brainstorming	100.00%	65.00%	50.00%	55.00%	20
Interviews (Structured or Semi-structured)	100.00%	45.45%	45.45%	63.64%	11
Delphi	100.00%	100.00%	0.00%	0.00%	1
Checklists	100.00%	64.29%	50.00%	64.29%	14
PHA (Preliminary Hazard Analysis)	100.00%	66.67%	50.00%	50.00%	6
HAZOP (HAZard and Operability studies)	90.91%	63.64%	27.27%	36.36%	11
HACCP (Hazard Analysis and Critical Control Points)	100.00%	0.00%	100.00%	100.00%	1
SWIFT (Structured What-If Technique)	100.00%	100.00%	66.67%	33.33%	3
Scenario Analysis	90.91%	63.64%	54.55%	54.55%	11
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	80.00%	40.00%	0.00%	80.00%	5
Cause-and-Effect Analysis	100.00%	100.00%	37.50%	37.50%	8
HRA (Human Reliability Analysis)	100.00%	100.00%	0.00%	0.00%	1
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	0
Environmental Risk Assessment	100.00%	58.33%	75.00%	75.00%	12
Consequence/Probability Matrix	100.00%	71.43%	28.57%	14.29%	7
Other Methods (Please Specify)	100.00%	50.00%	0.00%	25.00%	4

10 - Please check the corresponding phases you perform risk analysis methods:



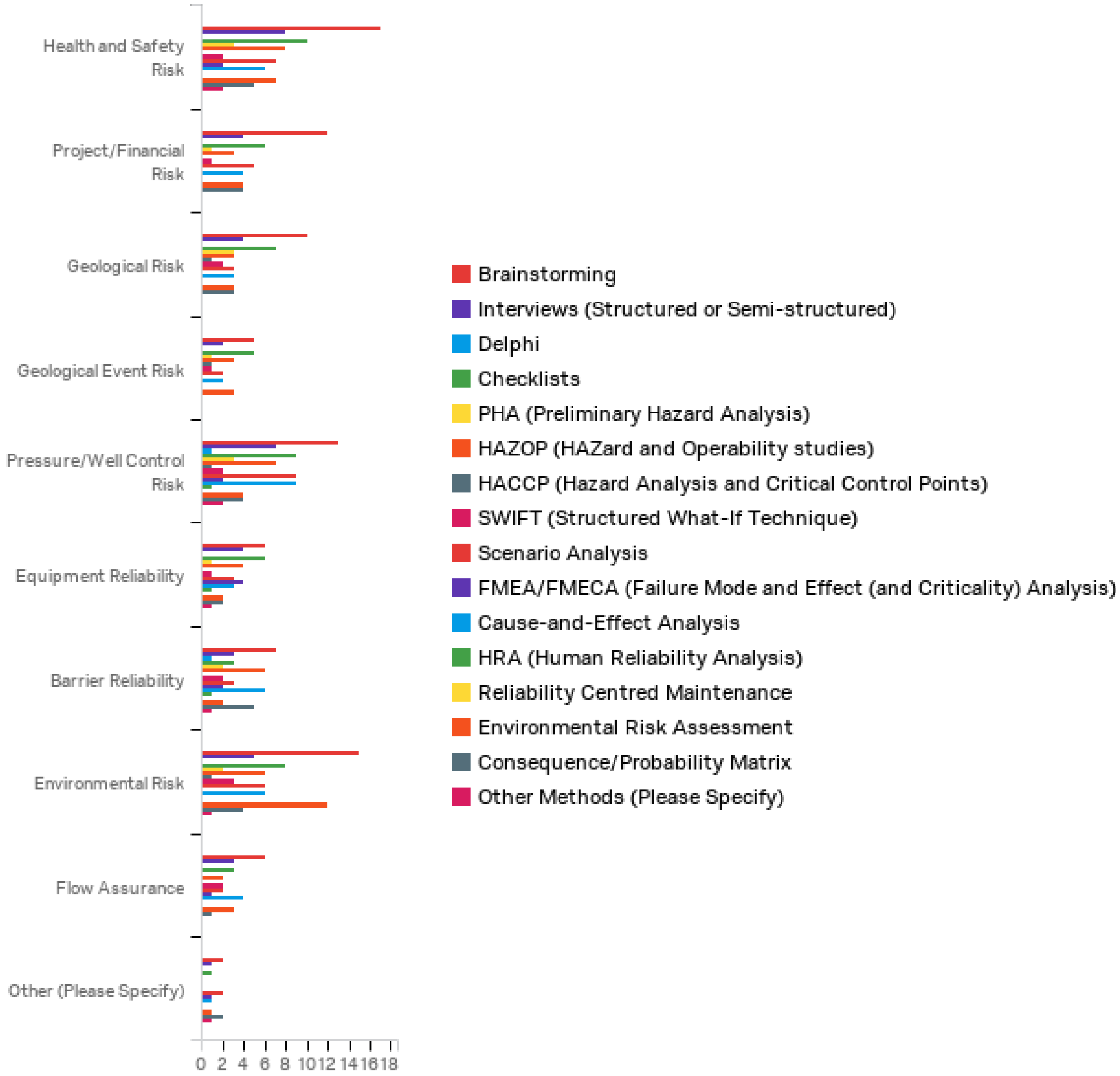
Question	Drilling	Completion	Production	Maintenance	Total
HAZOP (HAZard and Operability studies)	100.00%	70.00%	30.00%	40.00%	10
HACCP (Hazard Analysis and Critical Control Points)	0.00%	0.00%	0.00%	0.00%	0
SWIFT (Structured What-If Technique)	100.00%	50.00%	25.00%	25.00%	4
Scenario Analysis	100.00%	61.54%	46.15%	30.77%	13
Business Impact Analysis	100.00%	66.67%	66.67%	77.78%	9
Root Cause Analysis	90.00%	70.00%	40.00%	60.00%	10
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	75.00%	25.00%	0.00%	100.00%	4
Fault Tree Analysis	100.00%	75.00%	50.00%	25.00%	4
Event Tree Analysis	100.00%	80.00%	60.00%	60.00%	5
Cause-and-Effect Analysis	87.50%	62.50%	50.00%	37.50%	8
LOPA (Layer of Protection Analysis)	0.00%	0.00%	100.00%	0.00%	1
HRA (Human Reliability Analysis)	100.00%	100.00%	0.00%	0.00%	1
Bow-Tie Analysis	80.00%	40.00%	40.00%	60.00%	5
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	0
Markov Analysis	0.00%	0.00%	0.00%	0.00%	0
Bayesian Statistics and Bayes Nets	100.00%	50.00%	50.00%	50.00%	2
Environmental Risk Assessment	88.89%	55.56%	77.78%	66.67%	9
Decision Tree Analysis	100.00%	85.71%	42.86%	28.57%	7
FN Curves	100.00%	50.00%	50.00%	50.00%	2
Risk Indices	100.00%	100.00%	25.00%	25.00%	4
Consequence/Probability Matrix	100.00%	75.00%	37.50%	50.00%	8
CBA (Cost/Benefit Analysis)	100.00%	80.00%	40.00%	40.00%	5
MCDA (Multi-Criteria Decision Analysis)	100.00%	100.00%	0.00%	0.00%	1
Other Methods (Please Specify)	100.00%	33.33%	33.33%	33.33%	3

11 - Please check the corresponding phases you perform risk evaluation methods:



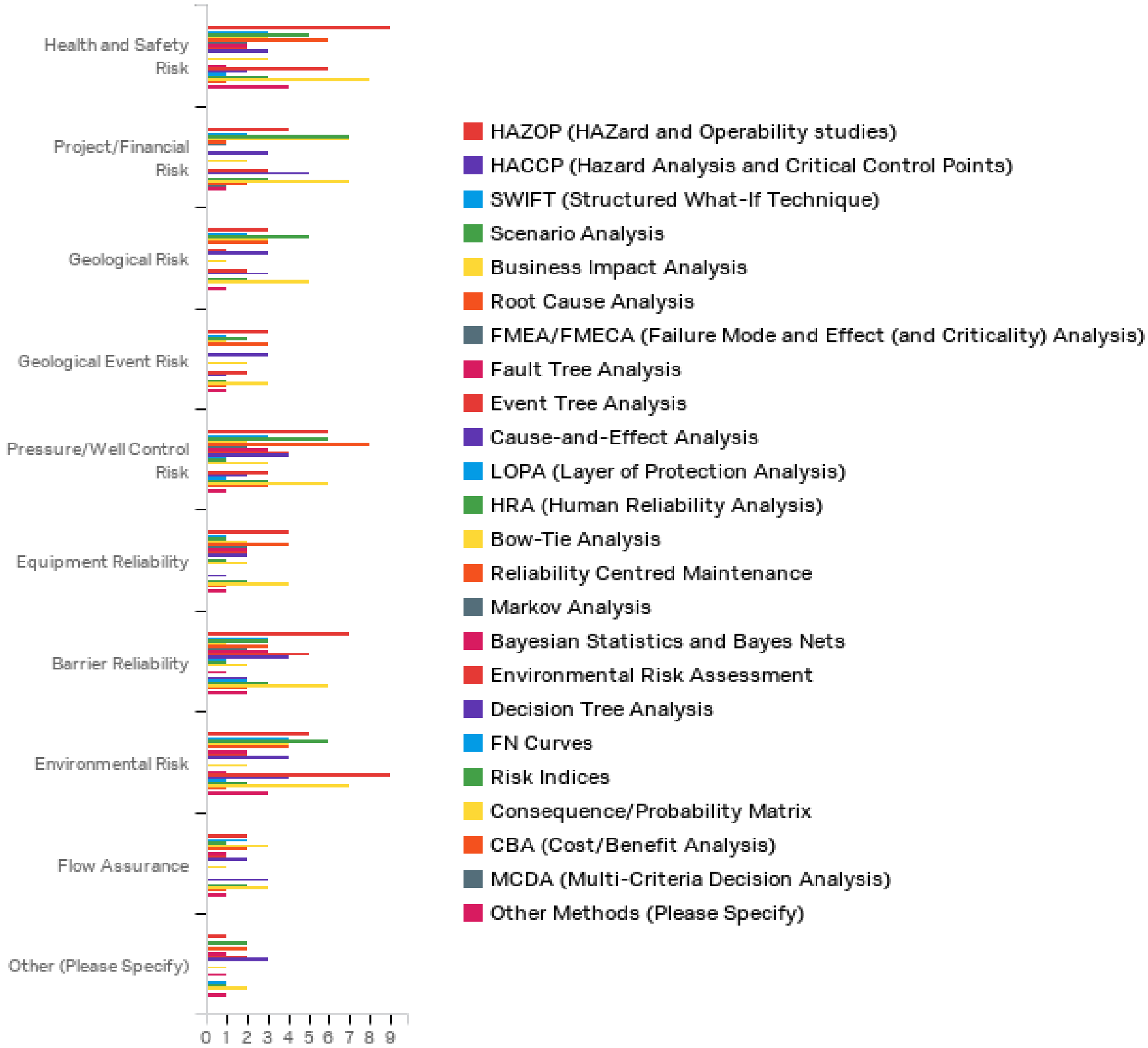
Question	Drilling	Completion	Production	Maintenance	Total
HACCP (Hazard Analysis and Critical Control Points)	100.00%	100.00%	100.00%	0.00%	1
SWIFT (Structured What-If Technique)	100.00%	85.71%	14.29%	14.29%	7
Root Cause Analysis	81.82%	54.55%	27.27%	54.55%	11
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	75.00%	25.00%	0.00%	75.00%	4
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	0
Monte Carlo Simulation	90.00%	50.00%	40.00%	20.00%	10
Bayesian Statistics and Bayes Nets	100.00%	0.00%	100.00%	100.00%	1
Environmental Risk Assessment	88.89%	44.44%	66.67%	55.56%	9
FN Curves	100.00%	50.00%	50.00%	50.00%	2
Risk Indices	100.00%	50.00%	50.00%	25.00%	4
Other Methods (Please Specify)	100.00%	50.00%	50.00%	66.67%	6

12 - Please check the corresponding risks you apply the risk identification methods:



Question	Health and Safety Risk	Project/Financial Risk	Geological Risk	Geological Event Risk	Pressure/Well Control Risk	Equipment Reliability	Barrier Reliability	Environmental Risk	Flow Assurance	Other (Please Specify)	Total
Brainstorming	89.47%	63.16%	52.63%	26.32%	68.42%	31.58%	36.84%	78.95%	31.58%	10.53%	19
Interviews (Structured or Semi-structured)	72.73%	36.36%	36.36%	18.18%	63.64%	36.36%	27.27%	45.45%	27.27%	9.09%	11
Delphi	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	1
Checklists	76.92%	46.15%	53.85%	38.46%	69.23%	46.15%	23.08%	61.54%	23.08%	7.69%	13
PHA (Preliminary Hazard Analysis)	50.00%	16.67%	50.00%	16.67%	50.00%	16.67%	33.33%	33.33%	0.00%	0.00%	6
HAZOP (HAZard and Operability studies)	72.73%	27.27%	27.27%	27.27%	63.64%	36.36%	54.55%	54.55%	18.18%	0.00%	11
HACCP (Hazard Analysis and Critical Control Points)	0.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	1
SWIFT (Structured What-If Technique)	50.00%	25.00%	50.00%	25.00%	50.00%	25.00%	50.00%	75.00%	50.00%	0.00%	4
Scenario Analysis	63.64%	45.45%	27.27%	18.18%	81.82%	27.27%	27.27%	54.55%	18.18%	18.18%	11
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	33.33%	0.00%	0.00%	0.00%	33.33%	66.67%	33.33%	0.00%	16.67%	16.67%	6
Cause-and-Effect Analysis	60.00%	40.00%	30.00%	20.00%	90.00%	30.00%	60.00%	60.00%	40.00%	10.00%	10
HRA (Human Reliability Analysis)	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	1
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0
Environmental Risk Assessment	58.33%	33.33%	25.00%	25.00%	33.33%	16.67%	16.67%	100.00%	25.00%	8.33%	12
Consequence/Probability Matrix	83.33%	66.67%	50.00%	0.00%	66.67%	33.33%	83.33%	66.67%	16.67%	33.33%	6
Other Methods (Please Specify)	50.00%	0.00%	0.00%	0.00%	50.00%	25.00%	25.00%	25.00%	0.00%	25.00%	4

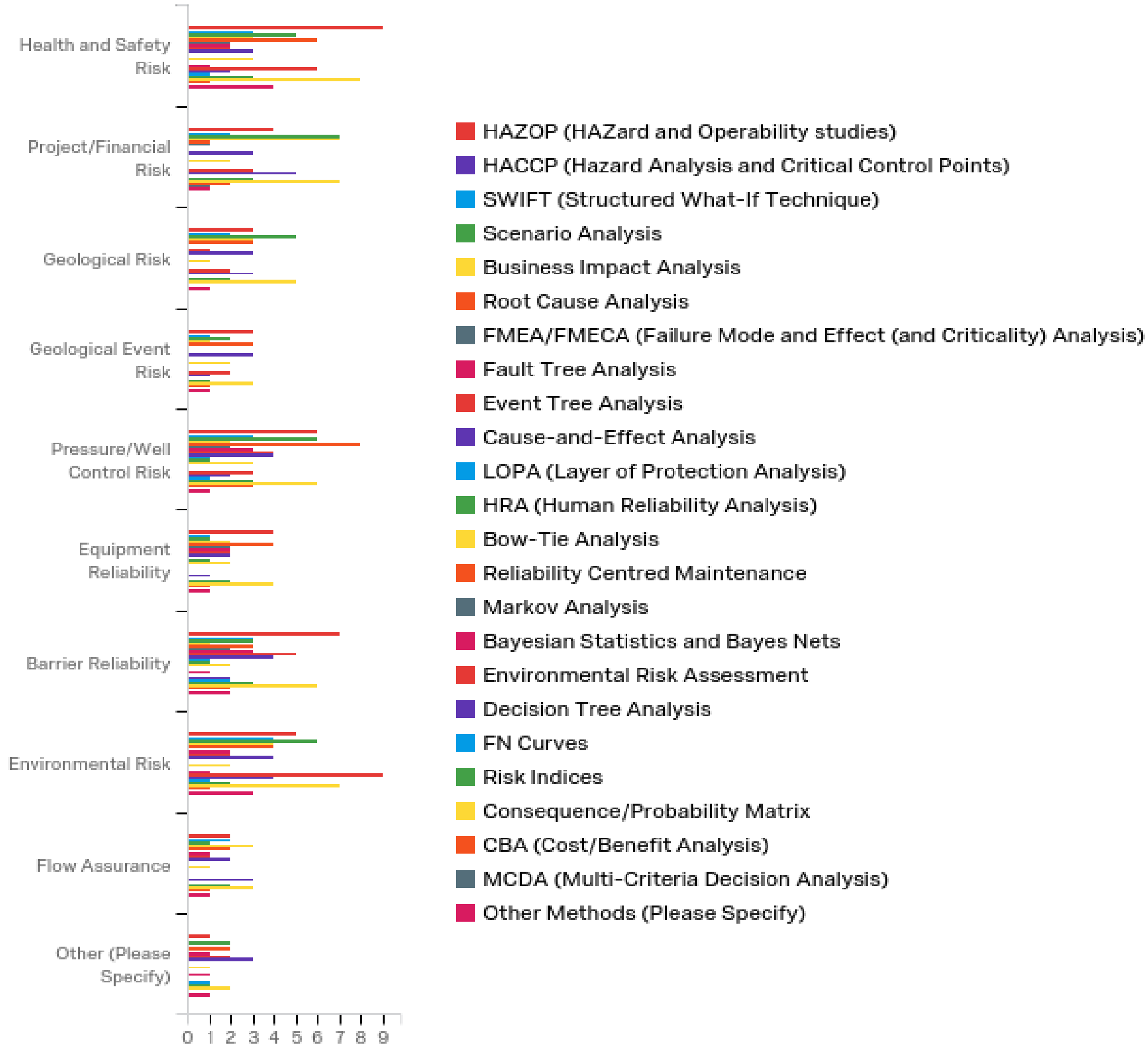
13 - Please check the corresponding risks you apply the risk analysis methods:



Question	Health and Safety Risk	Project/Financial Risk	Geological Risk	Geological Event Risk	Pressure/Well Control Risk	Equipment Reliability	Barrier Reliability	Environmental Risk	Flow Assurance	Other (Please Specify)	Total
HAZOP (HAZard and Operability studies)	81.82%	36.36%	27.27%	27.27%	54.55%	36.36%	63.64%	45.45%	18.18%	9.09%	11
HACCP (Hazard Analysis and Critical Control Points)	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0
SWIFT (Structured What-If Technique)	60.00%	40.00%	40.00%	20.00%	60.00%	20.00%	60.00%	80.00%	40.00%	0.00%	5
Scenario Analysis	41.67%	58.33%	41.67%	16.67%	50.00%	8.33%	25.00%	50.00%	8.33%	16.67%	12
Business Impact Analysis	37.50%	87.50%	37.50%	12.50%	25.00%	25.00%	12.50%	50.00%	37.50%	0.00%	8
Root Cause Analysis	54.55%	9.09%	27.27%	27.27%	72.73%	36.36%	27.27%	36.36%	18.18%	18.18%	11
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	40.00%	20.00%	0.00%	0.00%	40.00%	40.00%	40.00%	0.00%	0.00%	0.00%	5
Fault Tree Analysis	50.00%	0.00%	0.00%	0.00%	75.00%	50.00%	75.00%	50.00%	25.00%	25.00%	4
Event Tree Analysis	40.00%	0.00%	20.00%	0.00%	80.00%	40.00%	100.00%	40.00%	20.00%	40.00%	5
Cause-and-Effect Analysis	33.33%	33.33%	33.33%	33.33%	44.44%	22.22%	44.44%	44.44%	22.22%	33.33%	9
LOPA (Layer of Protection Analysis)	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	1
HRA (Human Reliability Analysis)	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	1
Bow-Tie Analysis	60.00%	40.00%	20.00%	40.00%	60.00%	40.00%	40.00%	40.00%	20.00%	20.00%	5
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0
Markov Analysis	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0
Bayesian Statistics and Bayes Nets	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	0.00%	100.00%	1
Environmental Risk Assessment	66.67%	33.33%	22.22%	22.22%	33.33%	0.00%	0.00%	100.00%	0.00%	0.00%	9
Decision Tree Analysis	28.57%	71.43%	42.86%	14.29%	28.57%	14.29%	28.57%	57.14%	42.86%	0.00%	7
FN Curves	50.00%	0.00%	0.00%	0.00%	50.00%	0.00%	100.00%	50.00%	0.00%	50.00%	2

Risk Indices	75.00%	75.00%	50.00%	25.00%	75.00%	50.00%	75.00%	50.00%	50.00%	25.00%	4
Consequence/Probability Matrix	88.89%	77.78%	55.56%	33.33%	66.67%	44.44%	66.67%	77.78%	33.33%	22.22%	9
CBA (Cost/Benefit Analysis)	25.00%	50.00%	0.00%	25.00%	75.00%	25.00%	50.00%	25.00%	25.00%	0.00%	4
MCDA (Multi-Criteria Decision Analysis)	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1
Other Methods (Please Specify)	100.00 %	25.00%	25.00%	25.00%	25.00%	25.00%	50.00%	75.00%	25.00%	25.00%	4

14 - Please check the corresponding risks you apply the risk evaluation methods



Question	Health and Safety Risk	Project/Financial Risk	Geological Risk	Geological Event Risk	Pressure/Well Control Risk	Equipment Reliability	Barrier Reliability	Environmental Risk	Flow Assurance	Other (Please Specify)	Total
HACCP (Hazard Analysis and Critical Control Points)	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	1
SWIFT (Structured What-If Technique)	42.86%	57.14%	42.86%	42.86%	42.86%	14.29%	42.86%	28.57%	14.29%	0.00%	7
Root Cause Analysis	50.00%	10.00%	0.00%	10.00%	60.00%	20.00%	20.00%	30.00%	10.00%	10.00%	10
FMEA/FMECA (Failure Mode and Effect (and Criticality) Analysis)	50.00%	25.00%	0.00%	0.00%	25.00%	50.00%	25.00%	25.00%	0.00%	0.00%	4
Reliability Centred Maintenance	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	1
Monte Carlo Simulation	11.11%	77.78%	33.33%	11.11%	33.33%	11.11%	33.33%	22.22%	22.22%	22.22%	9
Bayesian Statistics and Bayes Nets	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	100.00%	0.00%	100.00%	1
Environmental Risk Assessment	62.50%	25.00%	25.00%	25.00%	37.50%	0.00%	0.00%	100.00%	0.00%	0.00%	8
FN Curves	50.00%	0.00%	0.00%	0.00%	50.00%	0.00%	100.00%	50.00%	0.00%	50.00%	2
Risk Indices	50.00%	75.00%	75.00%	25.00%	75.00%	0.00%	25.00%	50.00%	25.00%	0.00%	4
Other Methods (Please Specify)	83.33%	33.33%	33.33%	33.33%	50.00%	33.33%	66.67%	66.67%	33.33%	16.67%	6

15 - Please provide your email address here if you are interested in participating in a webinar presenting the findings of this survey:

Please note that because of confidentiality issues, these information are excluded from the report.

16 - Do you have any other comments, questions or concerns?

Please note that because of confidentiality issues, these information are excluded from the report.

Appendix III: List of papers reviewed for Section 5.2.1

#	Paper title	Authors	Year	Type of risks assessed/covered	Uncertainty quantification	Type of Method	Well integrity covered
1	Integrated risk assessment for geothermal energy development and evaluation	Lowry, T.S., Kalinina, E., Hadgu, T., McKenna, S.A., Cutler, L.	2012	Project/financial risk	Yes	Monte Carlo	No
2	ROI - oriented project realization and risk management	Schönwiesner-Bozkurt, C., Imolauer, K., Richter, B.	2005	Project/financial risk	No	Return on investment (ROI)	No
3	Risk mitigation systems in comparison	Imolauer, K., Ueltzen, M.	2015	Project/financial risk	No	N/A	No
4	Geothermal play fairway analysis: Phase i summary	Garchar, L., Badgett, A., Nieto, A., Young, K., Hass, E., Weathers, M.	2016	Project/financial risk Geological risk	Yes	Value of information Bayesian analysis Fuzzy Logic Multi-Criteria Decision Making Expert Elicitation	No
5	Risk of seismicity from potential direct-use operations in the appalachian basin geothermal play fairway project	Horowitz, F.G, and Appalachian Basin GPFA Team	2016	Geological event risk	Yes	Other - Coarse risk categorization based on seismic evaluations	No
6	Slim hole reservoir characterization for risk reduction	Nielson, D.L., Garg, S.K.	2016	Project/financial risk	No	Cost/benefit analysis	No
7	A procedure for appraisal of drilling success	Ari Ingimundarson and Helga Tulinius	2015	Project/financial risk	No	N/A	No
8	Assessment of new approaches in geothermal exploration decision making	Akar, S., Young, K.R.	2015	Project/financial risk	No	Value of information Internal rate of return (IRR)	No
9	Reducing geothermal resource risk and project schedule prior to exploration drilling	Ussher, G., Hochwimme, Ar	2015	Project/financial risk	No	N/A	No

#	Paper title	Authors	Year	Type of risks assessed/covered	Uncertainty quantification	Type of Method	Well integrity covered
10	Geologic risks assessment and quantification in geothermal exploration case studies in green field and developed prospects	Suryantini, Wibowo, H.	2015	Geological risk	No	Checklists Probability assessments	No
11	An evaluation of risk mitigation approaches for geothermal development	Robertson-Tait, A., Jayawardena, M., Sanyal, S., Berman, L., Huttrer, G.	2015	Project/financial risk	No	N/A	No
12	Management of geological and drilling risks of geothermal projects in the Netherlands	Heijnen, L., Rijkers, R., Ohmann, R.G.	2015	Project/financial risk Geological risk Pressure/well control risk	Yes	Checklists Consequence/probability matrix Decision Tree Analysis	No
13	Cooperation in geothermal development at Great Rift Valley in Africa	Hayashi, M., Kuge, K., Sato, H., Tanaka, H.	2015	Project/financial risk	Yes	Internal rate of return (IRR) Monte Carlo	No
14	Geothermal Risk Mitigation Schemes in Germany	Horst Kreuter1 and Christina Schrage	2010	Project/financial risk	No	N/A	No
15	Innovative Approach for risk Assessment in Green Field Geothermal Project	Fausto batini1 and Jan-Diederik van Wees	2010	Geological risk Project/financial risk Environmental risk	Yes	Risk indices Cost/benefit analysis Monte Carlo Decision Tree Analysis Expert Elicitation	No
16	Managing geothermal resource risk - Experience from the United States	Robertson-Tait, A., Henneberger, R., Sanya, S.I	2008	Project/financial risk Geological risk	No	N/A	No
17	Private and state risk mitigation programs for geothermal exploration risk	Kreuter, H., Schrage, C.	2009	Project/financial risk	No	N/A	No

#	Paper title	Authors	Year	Type of risks assessed/covered	Uncertainty quantification	Type of Method	Well integrity covered
18	SW-CPDEP, project management process for the right decision in geothermal field drilling and completion	Dumrongthai, P., Putra, W.M.	2015	Project/financial risk Health and Safety risk Environmental risk Geological event risk	Yes	N/A	Only implicitly - the paper presents a general decision making framework
19	RISK based approach to geothermal project valuation	Barnett, P.	2013	Project/financial risk	No	Return on investment (ROI) Cash flow EMV	No
20	Risk control for disaster at the geothermal field	Adachi, M.	2011	N/A	No	N/A	No
21	Risk management and contingency planning for the first icelandic deep drilling project well in Krafla, Iceland	Homuth, S., Palsson, B., Holmgeirsson, S., Sass, I.	2010	Geological risk Geological event risk Pressure/well control risk Equipment reliability Barrier reliability	No	Historical data to set probabilities Scenario analysis Expert Elicitation Consequence/probability matrix	Yes
22	Risk mitigation in deep geothermal projects – experience in Germany	Kreuter, H.	2008	Project/financial risk Geological risk	No	N/A	No
23	The AUC/KFW geothermal risk mitigation facility (GRMF) — A aatalyst for East African geothermal development	Bloomquist, G., Niyongabo, P., El-Halabi, R., Löschau, M.	2012	Project/financial risk	No	N/A	No
24	The French geothermal risk guarantee system	Bézèlgues-Courtade, S., Jaudin, F.	2008	Project/financial risk	No	N/A	No
25	When smaller is better — Cost/size/risk analysis of geothermal projects	Elíasson, L., Smith, C.	2011	Project/financial risk	No	Internal rate of return (IRR) NPV	No

#	Paper title	Authors	Year	Type of risks assessed/covered	Uncertainty quantification	Type of Method	Well integrity covered
26	Modeling the risk of geothermal energy production using GT-Mod	Lowry, T.S., Kalinina, E., Hadgu, T., McKenna S.A.	2011	Project/financial risk Geological risk	Yes	NPV Sensitivity analysis	No
27	Risk management for recoverable thermal energy using a probabilistic decision analysis approach	Black, P., Fitzgerald, M., Sully, M., Klingel, E.	2012	Project/financial risk	Yes	Probabilistic decision analysis Value of information Monte Carlo	No
28	Geothermal well design, construction and failures	Southon, J.N.A.	2005	Equipment reliability Barrier reliability	No	FMECA Historical failure frequencies	Yes
29	Key factors to successful drilling and completion of EGS well in Cooper Basin	Hodson-Clarke, A., Rudolf, R., Bour, D., Russell, P.	2016	Equipment reliability Barrier reliability Pressure/well control risk	No	Failure investigation	Yes
30	Prevention of casing failures in ultra-deep geothermal wells (Germany)	Lentsch, D., Dorsch, K., Sonnleitner, N., Schubert, A.	2015	Geological risk Pressure/well control risk Equipment reliability Barrier reliability	No	FMECA	Yes
31	Zonal isolation in geothermal wells	Shadravan, A., Ghasemi, M., Alfi, M.	2015	Pressure/well control risk Equipment reliability Barrier reliability	No	Scenario analysis FMECA	Yes
32	Comparing completion design in hydrocarbon and geothermal wells: The need to evaluate the integrity of casing connections subject to thermal stresses	Teodoriu, C., Falcone, G.	2009	Equipment reliability Barrier reliability	No	FEM for casing fatigue	Yes

#	Paper title	Authors	Year	Type of risks assessed/covered	Uncertainty quantification	Type of Method	Well integrity covered
33	Enhanced geothermal systems (egs) well construction technology evaluation report	Polsky, y., Capuano, L., Finger, J., Huh, M., Knudsen, S., Chip Mansure, A.J., Raymond, D., Swanson, R.	2008	Project/financial risk	No	Cost analysis of operations	No
34	Handbook of best practices for geothermal drilling	Finger, J., Blankenship, D.	2010	Project/financial risk Pressure/well control risk Equipment reliability Barrier reliability	No	N/A	No
35	Application of risk based inspection methodology to aging geothermal fluid collection and disposal system in Tongonan, Philippines	Salonga, N.D., Lichti, K.A.	2005	Equipment reliability Health and Safety risk Environmental risk	No	Risk-based inspection Consequence/probability matrix	No
36	Best practices for geothermal power - Risk reduction workshop follow-up manual	US Department of State, GEA	2014	Project/financial risk Geological risk	No	N/A	No
37	Preliminary technical risk analysis for the geothermal technologies program	McVeigh, J., Cohen, J., Vorum, M., Porro, G., Nix, G.	2007	Project/financial risk	Yes	Expert Elicitation Consequence/probability matrix	No
38	Geothermal energy utilization in low-enthalpy sedimentary environments	Norden, B. (Ed.)	2006	Project/financial risk Geological risk Geological event risk	No	NPV Monte Carlo Sensitivity analysis Decision Tree Analysis Portfolio analysis	No

#	Paper title	Authors	Year	Type of risks assessed/covered	Uncertainty quantification	Type of Method	Well integrity covered
39	Quantifying risk in geothermal development—high-enthalpy and low-enthalpy cases	Antics, M., Ungemach, P.	2010	Project/financial risk Geological risk Barrier reliability Equipment reliability Environmental risk Other - Social acceptance	Yes	NPV Consequence/probability matrix Success/Failure criteria	No
40	Report on the U.S. DOE geothermal technologies program's - 2009 risk analysis	Young, K.R., Augustine, C., Anderson, A.	2010	Project/financial risk	Yes	Monte Carlo Expert Elicitation	No
41	Risk assessment for geothermal wells — A probabilistic approach to time and cost estimation	Lentsch, D., Schubert, A.	2013	Project/financial risk	Yes	Monte Carlo Expert Elicitation Sensitivity analysis	No
42	Risk management for geothermal projects	Sarmiento, Z.F.	2011	Project/financial risk Geological risk	No	N/A	No
43	Software for geothermal corrosion and risk based assessment	Lichti, K.A., White, S.P., McGavin, P.	2005	Geological event risk	No	N/A	No
44	The manageable risks of conventional hydrothermal geothermal power systems: A factbook on geothermal power's risks and methods to mitigate them	GEA	2014	Project/financial risk Geological risk Health and Safety risk	No	N/A	No
45	EGS Probabilistic Seismic Hazard Assessment with 3-D Discrete Fracture Modeling	Karvounis D., Gischig V. and Wiemer S.	2014	Geological event risk	No	N/A	No
46	Enhanced Geothermal System in the Lower Carboniferous in the Netherlands – a geological risk and modelling study	Rijkers, R., van der Hoorn, K., van Gijtenbeek, K. Ohmann, R.G., Nitters, G., Rombout, B., Spiers, C., de Zwart. ,B.	2013	Flow assurance Geological risk Project/financial risk	Yes	Monte Carlo Internal Rate of Return (IRR)	No

#	Paper title	Authors	Year	Type of risks assessed/covered	Uncertainty quantification	Type of Method	Well integrity covered
47	Geothermal resource risk in indonesia – a statistical inquiry	Sanyal, S.K., Morrow, J.W., Jayawardena, M.S., Berrah, N., Li, S.F., Suryadarma	2011	Project/financial risk	No	Data review	No
48	Geothermal systems assessment — Identification and mitigation of egs exploration risk	Beardsmore, G.R., Cooper, G.T.	2009	Geological risk Project/financial risk	No	N/A	No
49	MeProRisk-II - A joint research project for optimization strategies and risk analysis for deep geothermal reservoirs	Marquart, G., Clauser, C. and the MeProRisk Research Consortium	2013	Geological risk Pressure/well control risk	Yes	Monte Carlo	No
50	Modeling contribution to risk assessment of thermal production power for geothermal reservoirs	Vogt, C., Iwanowski-Strahser, K., Marquart, G., Arnold, J., Mottaghy, D., Pechnig, R., Gnjezda, D., Clauser, C.	2013	Geological risk	Yes	Monte Carlo	No
51	Quantifcation of geothermal resource risk — A practical perspective	Sanyal, S.K., Morrow, J.W.	2010	Geological risk Project/financial risk	Yes	Sensitivity analysis Internal Rate of Return (IRR) Monte Carlo	No
52	Resource risk assessment in geothermal greenfield development; An economic implications	Hadi, J., Quinlivan, P., Ussher, G., Alamsyah, O., Pramono, B., Masri, A.	2010	Project/financial risk Geological risk	No	N/A	No
53	What target to drill? geothermal pre-drill play evaluation (PDPE): Understanding the nexus between project risk and value	Cooper, G.T., Beardsmore, G.R., Mortimer, L.	2009	Project/financial risk Geological risk	Yes	NPV EMV	No
54	Occupational risk assessment for hydrogen sulfide concentrations from a geothermal power plant	Daniel, C., Guadalupe, G., Nayeli, M.	2012	Health and Safety risk	No	HAZID Interviews Consequence/probability matrix	No