GeoWell

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

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Foundations for well integrity and risk assessment

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Foundations for well integrity and risk assessment

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Executive summary

The aim of the GeoWell project is to develop reliable, cost effective and environmentally safe technologies for improved productivity and lifetime of high-temperature geothermal wells. As part of this, a framework that can be applied to risk assessment and management is developed and described in this report. The document constitutes a basis for discussions relating to regulations, guidelines/standards and industry best practice, thus providing a foundation for a common approach to geothermal risk assessment and well integrity.

Current European Union (EU) legislation related to geothermal wells and geothermal energy is reviewed. Even though geothermal energy is defined in EC (European Commission) Directives, the specific implementation and legislation vary greatly between different regions across Europe. It has been suggested by others that the legislative and regulatory framework should be harmonized and that this can be led by the EU. A step towards such harmonization could be through the development of a geothermal well protocol, providing guidance on how risk assessment with a focus on well integrity should be conducted for different types of geothermal wells for the well life-cycle. The summary of relevant legislation/standards to the geothermal industry offers a basis for understanding the main concerns that need to be addressed by risk assessment and/or management activities, such as gas emissions, operational and occupational safety, and environmental hazards.

In the development of a framework for assessment and management of geothermal well risks, certain requirements should be fulfilled. This document outlines the general characteristics of such a framework, reviews what data is necessary and which well integrity considerations are relevant throughout the life-cycle of a geothermal well, and provides the necessary phases and activities in a risk management process. It is suggested that a future protocol should result in a comprehensive, transparent and verifiable risk assessment and management practice during all phases of the (high-temperature) geothermal well life.

The overall approach to risk assessment and management for geothermal wells is not fundamentally different from other comparable industries. However, the assessment context, influenced in part by prevailing legislation determining issues of concern and mandating requirements differs between countries, depending on how geothermal energy is defined and hence how it is regulated. A shift towards a common definition and regulation for geothermal wells across the EU could also represent a first step towards a more cohesive approach to risk assessment. The establishment of a common definition for well barriers and associated well barrier elements, would in the same way improve geothermal well integrity management.

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Vocabulary

ALARA/ALARP	As low as reasonably achievable/As low as reasonably practicable
Hazard	Potential source of risk
HAZID	Hazard identification
Measure	Plan or course of action to reduce risk (physical or organisational)
Monitoring	Continuous or time-lapse measurement of risk indicator
Protocol	Procedure for carrying out risk assessment and management of (HT) geothermal wells
Risk	Effect of uncertainty on outcomes [1]; consequences of the activities, with associated uncertainty [2]
Risk assessment	Investigation into the effects that uncertainty has on the consequences of potential fluid leakage. The intention of a quantitative risk assessment is to support decision-making by providing numbers on how much effect uncertainty has on the consequences.
Root cause	The basis cause of a hazard or risk

1 Introduction

1.1 Background

Description of the project,

New concepts for high-temperature geothermal wells are developed in the GeoWell project addressing the lifetime of the wells, to improve the economic viability and environmental friendliness of geothermal projects. The project objective is to develop reliable, cost effective and environmentally safe well completion and monitoring technologies; such as optimized well designs involving corrosion resistant materials, optimized cementing procedures, and compensation for thermal strains between casing and the well. The project also targets the development of methods and tools to assess the main life stages of the well, and manage the associated risks.

Risk assessment in the petroleum industry is described in several standards. The practices described in these standards is considered to be at the highest quality level, in particular those for offshore petroleum exploitation in Europe. Thus, it is considered to be desirable to bring relevant practices in the petroleum industry to the geothermal industry. The New Zealand Code of Practice for deep geothermal wells [3] is commonly referred to as the most advanced standard within geothermal wells. For example, it was used as the basis for The African Union Code of Practice for Geothermal Drilling [4], adapting it to the conditions of the geothermal industry in Africa. The geothermal industry relies to a degree on the practices in the petroleum industry, primarily onshore practices and standards provided by the American Petroleum Institute (API). It is of interest to also consider the place of petroleum approaches to risk management in a geothermal context.

In [5], [6] and [7], have gone through the common uses of risk assessment methods and in particular quantitative risk assessments.

The applicability of the framework described in [7] needs to be put in context with existing regulations; and exemplified further for practical use. This document, i.e. “Foundations for well integrity and risk management”, attempts to create a foundation for the development of a European protocol for Risk assessment and Well integrity in geothermal wells, which means it is a recommendation in compliance with European and domestic regulations.

1.2 Objectives

The objective of the document is to provide building blocks for a protocol for risk assessment and management of geothermal wells. To this end an elaborated assessment and management framework has been provided which can be applied in a “recipe”-based manner to deep high temperature (HT) geothermal wells (i.e. wells reaching temperatures required for electricity production and requiring multiple casing strings) within the EU member states. The presented building blocks are meant to be a basis for possible future regulation on risk assessment and management of HT geothermal wells. While the presented risk assessment and management framework is generally applicable also to oil & gas wells, the specific relation to geothermal wells is presented in the form of addressing legislation specific to this industry, which is an integral part of the assessment context. The generality of the foundations presented here does not permit covering all aspects unique to HT geothermal wells, but does provide some relevant examples throughout. Issues that concern geothermal wells in general, may also apply to HT geothermal wells.

1.3 What is a geothermal well protocol?

Many member states of EU have different geothermal legislations, different current practices and regulations. A geothermal well protocol should provide guidance on how risk assessment with a particular focus on well integrity should be conducted for different types of geothermal wells through the well life-cycle.

There are no clear definitions of what a protocol should be, though it is often understood as a formal or official document documenting a sequence of agreed elements. A geothermal well protocol could be considered in terms of regulation, a specification of the regulations as a guideline as to how to satisfy the regulations, or in terms of industry agreed practice describing how to perform operations. An industry agreed practice needs to be created by the joint industry, in order to incorporate all experiences and find an agreed common practice amongst the many opinions. As a specification of legislation, the regulators need to be involved and go through a hearing process for opinions for and against elements of the specification to be voiced. The intention of this document is to provide a foundation for such a process, from which further work could be based.

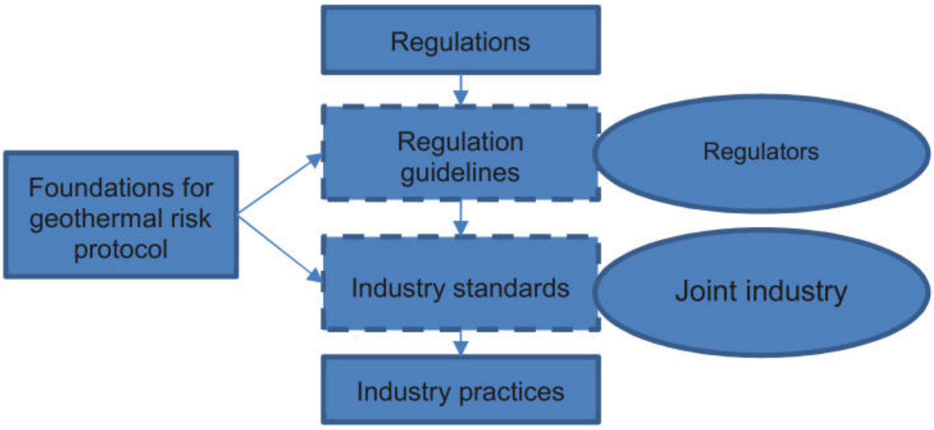

Figure 1 The role of this document related to regulations and industry practices.

This document aims to prepare a foundation for geothermal well integrity risk assessment, that could help facilitate conformity in the way risk assessments are performed, what they are based on and what they could provide in terms of input to a decision-making context. The contents of the protocol presented rely heavily on the foundations set forth in ISO 31000 [1] and ISO/TS 16530-2 [8], that describe overall guidelines for risk management and well integrity, respectively.

The protocol should be interpreted as suggestive rather than prescriptive. It does not in any way set forth requirements of any kind, nor does it lay claim to providing an answer to every aspect of well integrity risk assessment. The protocol aims to compile and give general advice as to how a well integrity risk assessment could be performed, from a risk analyst perspective, taking into account as far as possible, existing risk assessment techniques available, factors to consider for the analysis context, possible sources of information relevant for the assessment, barrier elements of a geothermal well and possible failure modes that can occur and possible measures for monitoring and reviewing well integrity.

The protocol is however not exhaustive, and while it outlines the required steps of the risk management process, the focus is on the risk assessment steps, i.e. identification, analysis and evaluation of risk, and relating specifically to well integrity, thus delimiting the scope to only include elements of the well that are considered to be well barrier elements, i.e. elements that have a function of isolating formation fluids. While all life-cycle phases are covered, a stronger emphasis is placed on the production phase. Finally, the main group of wells this protocol is intended for, are high temperature geothermal wells.

Previous studies in the GeoWell project have highlighted the lack of any widely used guidelines for how to perform risk assessments for geothermal wells. It is the aim of this document to provide a first step towards a more uniform approach towards geothermal risk assessment and well integrity.

2 Concepts and principles

2.1 Definition of well integrity

Well integrity is in general terms related to the functionality of a well to prevent loss of containment or its ability to perform its intended functions. However, there are various definitions that differ in both scope and focus area, that are briefly outlined in this section.

The NORSOK D-010 standard [9] governs well integrity on the Norwegian Continental Shelf (NCS), and is here defined as “application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well”. The standard focuses on establishing well barriers by use of Well Barrier Elements (WBE), their acceptance criteria, their use and monitoring of integrity during their life cycle. The risk element is the uncontrolled release of formation fluids, while the integrity aspect covers technical, operational and organizational solutions that will either lower the probability of the risk occurring, or reduce the consequences, should it occur.

Another common standard from the oil & gas industry, is the API RP 17N [10]. In this standard, integrity is defined as the ability of a system of components to perform its required function while preventing or mitigating incidents that could pose a significant threat to life, health and the environment over its operating life. This is a broader definition, as the risk aspect is not limited to loss of containment, but rather any potentially harmful event, while there are also no specific dimensions (such as technical or organizational) to the integrity aspect. The term integrity management is also included and is defined as “the systematic implementation of the activities necessary to ensure that critical systems are properly designed and installed in accordance with specifications, and remain fit for purpose until they are retired”.

NOGEPA Industry Standard No. 90 [11] is a Dutch oil and gas standard that defines asset integrity. The definition of well integrity is expressed as “the ability of the well(s) to perform its required function effectively and efficiently whilst protecting Health, Safety and the Environment (HSE)”. Well Integrity Management (WIM) is the means to ensure that the people, systems, processes and resources which deliver integrity are in place, in use and will perform when required over the whole lifecycle of the well(s). The definition is similar in scope and focus to API 17 RP 17 N.

ISO/TS 16530-2:2014 [8] is a standard explicitly addressing well integrity, covering the operational phase of oil & gas wells. Here, well integrity is defined as “containment and the prevention of the escape of fluids (i.e. liquids or gases) to subterranean formations and surface”, while well integrity management is “a combination of technical, operational and organizational processes to ensure a well’s integrity during the operating life cycle”. Similarly to NORSOK D-010, the risk element is limited to the escape of formation fluids, while the integrity aspect covers processes aimed to prevent loss of containment.

There are no similar standards that explicitly define well integrity for geothermal wells, but there are standards that cover design and best practices, that also cover well integrity. One of the most common reference documents in the geothermal industry, is the New Zealand NZS 2403:2015 Code of practice for deep geothermal well drilling, used by the geothermal industry and regulators worldwide [3]. This document covers all life-cycle phases of the well, and provides guidance on managing the well site, drilling equipment, tools and materials, drilling techniques and well integrity management.

2.2 Risk management principles

The approach to risk management is usually to follow some suitable principles that can be applied to different situations. The suitability of the principles depends to a large degree on the potential consequences and if third-parties will be affected.

2.2.1 The precautionary principle

The application of the precautionary principle is a EU principle, as described in [12]. It is at the extreme risk averse end of the scale, usually backed on a pillar of social responsibility to protect the public from exposure to harm. The principle states that a more risk averse approach should be taken where there is insufficient scientific data to permit a complete evaluation of the risk. This puts the burden of proof on the proponent of an activity to show that there is sufficient understanding of the activity such that harm will be avoided. However, it is also often stated that lack of scientific certainty should not be used as a reason to postpone implementation of cost-effective measures that can reduce risk.

The precautionary principle is included in the EU Directives to enable a rapid response to threats to human health and the environment.

2.2.2 ALARP

This principle, usually called ALARP (As Low as Reasonably Practicable or Possible) or ALARA (As Low as Reasonably Applicable), introduces a more gradual decision-making argumentation. The principle states that risks should be reduced as much as possible, within reason, even when it is already at an acceptable level. This principle opens for less strict acceptance criteria, as any actors will have to reduce the risk even when these criteria have been satisfied, unless it can be shown that no identified measures are reasonable to implement.

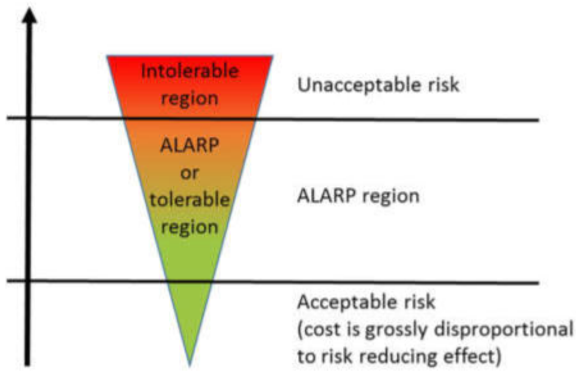

Figure 2. ALARP principle adapted from NORSOK Z-013 [60]

The reasonability argument is not pre-determined, and a grossly disproportionate argument is typically made, i.e. that the cost is at a completely different scale from the benefit. Introducing cost to the principle is important to prevent suboptimality (the cost of risk reduction would be more efficient elsewhere in reducing total risk to society) and not strangle industries.

2.2.3 Cost-benefit

The cost-benefit principle is a fairly risk neutral principle, which states that measures should be implemented if the benefits they provide outweigh the costs. This is a typical principle used by economists to ensure optimal utilization. It is most relevant where the consequences are limited to economic factors taken by a single party.

The choice of risk management principles will to a large degree shape the focus and direction of the risk assessment, from which information is considered to be relevant, which risks are considered, what analyses are performed, the acceptability of risk to measures and procedures to act on the risk.

2.3 Definitions of geothermal energy in legislation

In a European context, geothermal resources have been listed as one of the renewable energy sources in the Article 2 of the Directive 2001/77/EC of the European Parliament and of the Council on the promotion of electricity produced from renewable energy sources in the internal electricity market [13]. However, there was not any clear legal definition of geothermal energy until that expressed in Directive 2009/28/EC on the promotion of the use of energy from renewable sources. According to Article 2 of the Directive 2009/28/EC, “geothermal energy means energy stored in the form of heat beneath the surface of solid earth” [14].

On an individual country level, definition of geothermal energy and its implementation in the legislations vary from mature to non-mature regions across Europe. Pasquali states [15] that geothermal energy is defined in legislation in the mature regions such as France, Germany, the Netherlands and Italy. The classifications are often different in these countries, e.g. based on system installed capacity, depth of drilling, end-use, etc. Nevertheless, lack of consistent considerations for depth of geothermal resources, installed capacity and system size, as well as temperature and utilization of water or resources are apparent in the legal definitions of geothermal energy.

3 Review of legislation

To understand what is needed to comply with EU requirements, it is useful to review legislation and standards relevant to the geothermal industry. This chapter aims to provide a summary of legislation/standards that are relevant to the context of the GeoWell project, i.e. improving well integrity at high temperatures. The goal is to understand the main concerns of the legislations/standards that need to be addressed by risk assessment activities. Note that the intention is not to list all the international, national and regional legislation that might be relevant to the geothermal industry.

3.1 Different European Union legislative terms

Prior to reviewing different relevant regulations, it is important to understand differences between various legal terms that are typically used in the European Union. This will be of assistance when it comes to searching different databases for finding relevant regulations. The sources of European Union law include [16]:

i) Primary law: founding Treaties that establish the EU and determine the legal framework within which the EU institutions implement European policies.

ii) Secondary law: legal instruments based on the Treaties that include unilateral secondary law (regulations, directives, decisions, opinions and recommendations, and "atypical" acts e.g. communications and recommendations, and white and green papers), and conventions and agreements.

iii) Supplementary law: elements of law not provided for by the Treaties such as Court of Justice case-law, international law and general principles of law.

Based on the description of different EU law sources, secondary law seems to have most relevance to the scope of this report. Table 1 presents different types of secondary law [17] that are listed in Article 288 of the Treaty on the Functioning of the EU [18].

Table 1. Description of different types of unilateral acts of EU secondary law

Term	Description

Regulations	Binding legislative acts that must be applied in their entirety across the EU.
Directives	Binding legislative acts that set out different goals that all EU countries must achieve. It is up to the individual countries to devise their own laws on how to reach these goals.
Decisions	Binding legislative acts on those to whom it is addressed (e.g. an EU country or an individual company).
Recommendations	Recommendations are not binding and do not impose any legal obligation on those to whom they are addressed.
Opinions	Instruments that allow the institutions to make a statement in a non-binding fashion, i.e. without imposing any legal obligation on those to whom it is addressed. It can be issued by the main EU institutions (Commission, Council, Parliament), the Committee of the Regions and the European Economic and Social Committee. While laws are being made, the committees give opinions from their viewpoint.

Based on the information provided in Table 1, regulations, directives and decisions have been selected as relevant legislation for further search to identify the important concerns that should be addressed by a European protocol on geothermal well risk assessment.

3.2 Review of relevant geothermal legislation

Different publications have compiled various lists of national regulations relevant to the geothermal industry across Europe [19, 15, 20]. Although there might be some changes in the national regulations since publication of these references, the intention here is not to update those lists. As mentioned earlier, we try to keep the review of legislation at a European level, with emphasis on relevant EU directives. However, as a reference to documents related to high temperature geothermal wells, a recent national Italian guideline for medium-high enthalpy geothermal wells has been discussed in Appendix B.

Based on a report from European Geothermal Energy Council (EGEC), there are great differences in existing legislation between European countries (both EU Member States and non-EU countries) [20]. These differences do not necessarily influence requirements of a risk assessment and are rather related to simplifications of application and licensing procedures. Nevertheless, it has been highlighted that the legislative and regulatory framework for geothermal energy should be harmonized and this can be led by the EU.

There are several EU directives that may influence geothermal installations. Key legislation relevant to the geothermal industry, more specifically to drilling and operation of wells, include:

- Water Framework Directive (WFD) or Directive 2000/60/EC [21] that establishes a framework in the field of water policy.
- Groundwater Directive or Directive 2006/118/EC [22] that aims to protect groundwater against pollution and deterioration.

- Environmental Quality Standards Directive (EQSD) also known as the Priority Substances Directive or Directive 2008/105/EC [23] that establishes environmental quality standards in the field of water policy.
- Natura 2000 based on Birds Directive (Directive 79/409/EEC) [24] and Habitats Directive (Directive 92/43/EEC) [25] that ensures the long-term survival of Europe's most valuable and threatened species and habitats.
- Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment [26] updating the original Environmental Impact Assessment (EIA) Directive (Directive 85/337/EEC) [27] that aims to ensure the environmental implications of projects are considered before decisions are made, i.e. in the projects preparation phase.
- Environmental Liability Directive (ELD) or Directive 2004/35/EC [28] that establishes a framework of environmental liability based on the “polluter-pays” principle, to prevent and remedy environmental damage.
- Directive 2006/21/EC on the management of waste from extractive industries [29] that lays down minimum requirements to prevent or reduce as far as possible any adverse effects on the environment (in particular water, air, soil, fauna and flora and landscape), or on human health brought about as a result of the management of waste from the extractive industries.
- Directive 92/104/EEC [30] and Directive 92/104/EEC [30] that lay down minimum requirements for safety and health protection of workers in the mineral- extracting industries.
- Industrial emissions Directive (IED) or Directive 2010/75/EU [31] that aims to achieve a high level of protection of human health and the environment by reducing harmful industrial emissions across the EU, through better application of best available techniques (BAT). Note that geothermal power plants do not need to necessarily comply with this Directive as they are not listed within the industrial activities listed in the Annex I of this Directive. However, measures and limits provided in IED can be useful for performing environmental assessments of geothermal projects.
- Environmental Noise Directive (END) or Directive 2002/49/EC [32] that aims to determine exposure to environmental noise, to ensure that information on environmental noise and its effects is made available to the public, and to prevent and reduce environmental noise where necessary and preserve environmental noise quality where it is good [33].

The directives usually do not explicitly recommend that an individual best practice or standard be used as a guiding principle. However, some of them such as Directive 2006/21/EC or Directive 2010/75/EU require that the measures to be taken are, among other things, based on best available techniques. Appendix D presents a non-exhaustive list of the relevant directives together with a short summary and relevance of them to the geothermal industry.

For a better understanding of the topics that should be kept in mind while laying down the foundations for geothermal well risk assessment, the main concerns that are covered in the legislation are listed in Table 2.

Table 2. Summary of the main concerns of legislation

Main concern	Description (relevant regulations)	Legislation

Protection of water (including groundwater)	Any risk to aquatic ecosystem/environment shall be avoided.	WFD [21]
	Hazardous substances shall be identified through risk assessment focusing on aquatic ecotoxicity and on human toxicity via the aquatic environment.	WFD [21]
	Concentration limits shall not be exceeded for priority substances and priority hazardous substances in case of surface waters.	EQSD [23]
	Waste from extractive industries needs to be subject to certain requirements to protect surface water and/or groundwater. The stability of such waste should be secured, and appropriate monitoring should be done.	Directive 2006/21/EC [29]
Discharge or re-injection of water	Member States may authorize the reinjection into the same aquifer of water used for geothermal purposes. Therefore, it is within the competence of the national governments to decide whether reinjection of the geothermal fluids is required. However, such discharges shall not compromise the achievement of the environmental objectives established for that body of groundwater.	WFD [21]
Protection and long-term survival of valuable and threatened species and habitats	Appropriate steps shall be taken to avoid pollution or deterioration of habitats or any disturbances affecting the birds in the areas covered by Natura 2000. As an example, necessary steps shall be taken where the maintenance or improvement of the status of water is an important factor for protection of birds and habitats.	WFD [21], Directive 2009/147/EC [34], and Directive 92/43/EEC [25]
	Even outside these protection areas, Member States shall strive to avoid pollution or deterioration of habitats.	Directive 2009/147/EC [34], and Directive 92/43/EEC) [25]
Well repair, well stimulation, well drilling and testing phase	Operators shall take all necessary measures to prevent or reduce as far as possible any negative effects, actual or potential, on the environment or on human health because of the management of waste from the extractive industries. Operators need to prepare appropriate waste management plans for the prevention or minimization, treatment, recovery and disposal of extractive waste.	Directive 2006/21/EC [29]
Heat emission /heat transfer	Discharge of heat (because of human activity) into the air, water or land is considered as pollution. This may be harmful to human health or the quality of aquatic ecosystems or terrestrial ecosystems	WFD [21]

	directly depending on aquatic ecosystems, which result in damage to material property, or which impair or interfere with amenities and other legitimate use of the environment. This shall be avoided if it results in change of temperature outside the range in which the bodies of water have good status.	
Gas emission	Regarding pollution prevention and control, a combined approach is followed using control of pollution at source through the setting of "emission limit values" and of "environmental quality standards". Pollution through the discharge, emission or loss of "priority hazardous substances" must cease or be phased out.	WFD [21]
	A high level of protection of human health and the environment shall be achieved by reducing harmful industrial emissions across the EU, in particular through better application of best available techniques (BAT). Note that geothermal power plants are not listed in Annex I of the IED. But, such a directive seems to be relevant for emission control and prevention. Geothermal power plants often meet the most stringent clean air standards because of their low emissions [19].	Directive 2010/75/EU [31]
Noise pollution	Noise limits may be of relevance during well construction and the hydraulic test work [19]. The necessary measures shall be taken particularly in built-up areas, in public parks or other quiet areas in an agglomeration, in quiet areas in open country, near noise-sensitive buildings (e.g. schools, hospitals).	Directive 2002/49/EC [32]
Occupational and operational safety (HSE-related)	The employer shall take the necessary measures to safeguard the safety and health of the workers including design of workplace, identification and assessment of worker risks, protection from fire explosions and health-endangering environments, warning and alarm systems, health surveillance etc.	Directive 92/104/EEC [30]

In addition to the concerns listed in the table above, issues such as monitoring and leak prevention as well as risk mitigation are of importance for laying down the foundations for a European protocol on the geothermal well risk assessment. Furthermore, relevant directives have been reviewed to see whether there is an explicit requirement for performing risk assessment.

In this regard, WFD explicitly requires that a list of priority substances shall be identified considering the precautionary principle, relying in particular on the determination of any potentially adverse effects of the product to humans and the environment and on a scientific assessment of the risk. Accordingly, a risk assessment should be performed under Council Regulation (EEC) No. 793/93 [35], Council Directive 91/414/EEC [36] and Directive 98/8/EC of the European Parliament and of the Council [37], or a targeted risk-based assessment (following the methodology of Council Regulation (EEC) No. 793/93) should be performed focusing solely on aquatic ecotoxicity and on human toxicity via the aquatic environment. The ultimate goal is to achieve concentrations in the marine environment near background values for naturally occurring substances and close to zero for man-made synthetic substances.

Also from WFD (and Environmental quality standards Directive), to set a maximum annual average concentration for setting chemical quality standards, Member States shall set appropriate safety factors consistent with the nature and quality of the available data and the guidance given in technical guidance document in support of Commission Directive 93/67/EEC on risk assessment for new notified substances [38] and Commission Regulation (EC) No 1488/94 on risk assessment for existing substances [39] and the safety factors set out in the water framework Directive.

In order to protect the environment as a whole, and human health in particular, detrimental concentrations of harmful pollutants in groundwater must be avoided, prevented or reduced. Similar to water framework Directive, risk assessment procedures required by 91/414/EEC or 98/8/EC.

In order to ensure a high-level protection of the environment, precautionary actions need to be taken for certain projects because of their vulnerability to major accidents, and/or natural disasters (e.g. flooding or earthquakes). According to EIA Directive [40], a description of the vulnerability of such projects to risks of major accidents or disasters and their adverse effects on human health, cultural heritage or the environment needs to be provided. To meet the requirements of this Directive, relevant information available and obtained through risk assessments pursuant to EU/national legislation may be used. Where appropriate, this description should include measures envisaged to prevent or mitigate the significant adverse effects of such events on the environment.

For assessing damages of the projects to land as defined in ELD, it is desirable to use risk assessment procedures to determine to what extent human health is likely to be adversely affected [28].

According to wastes management from extractive industries Directive, a waste facility shall be classified, among other conditions, under category A (i.e. waste facilities with stricter environmental regulations), if a failure or incorrect operation could give rise to a major accident, based on a risk assessment considering factors such as the location and the environmental impact of the waste facility [29].

4 Requirements for Risk Assessment and Management

4.1 Risk Assessment characteristics

It is useful to perform risk assessments in different contexts; such as a tool for decision support from engineering and financial points of view, or as a means to identify, control and document HSE risks typically required by laws as seen in section 3.2. The reviewed legislation did not provide any recommendation on how to perform the risk assessments they refer to, only when they are required (e.g. on potential water pollution).

In general, the purpose of a risk assessment is to execute a process that gathers and assesses information about what may happen and why, how measures (changes or already implemented) can influence what may happen, and what is acceptable. Based on previous sections and the framework presented in D6.3, a geothermal well risk assessment should possess the following characteristics:

- Be risk-based, i.e. consider both the probability of an event occurring and the impact of such an occurrence.
- Cover all phases of a traditional risk management process (including monitoring and risk treatment).
- Be reasonable and proportionate for the threats profile (e.g. according to ALARP principle).
- Use readily available data.
- Address data, information and model uncertainty.

The focus in this document is on well integrity, thus related to this, a risk assessment should cover:

- Assessment of the well integrity (technical, operational and organizational) during its life cycle.
- Both production and injection wells (doublet).
- The source, pathway and receptor components.

The most relevant consequences to consider are:

- Serious damage to human health, safety and the environment (ecosystem), and in particular related to substances mentioned in the legislation (see section 3.2).
- Impact on equipment/system performance.
- Communication and reputation.
- Financial.
- Whether the Geothermal well contains either hazardous waste or dangerous substances.

4.2 Data requirements

Site-specific data are needed to properly support the activities related to risk assessment and risk management. The actual collection may already start during the exploration phase, well before the development of the geothermal project starts and will continue during the project development. The outcome of the risk assessment may require additional data acquisition to reduce remaining uncertainty. Monitoring data will be gathered during the operation of the geothermal (HT) well (see also 4.4.5).

Data needs relate to:

- Overall well design and well barrier concept
- Detailed description of the well casing, cement and completion
- Well barrier properties
- Near-well rocks and sediments (cores, log data, seismic data)
- THMC (Thermal-Hydraulic-Mechanical-Chemical) properties of rocks and sediments
- Potential pathways to receptors of the fluids
- Production forecasts
- Composition of production fluids with physico-chemical properties
- Temperature and pressure

- Receptors of leaking fluids: population distribution, protected species, buildings, proximity of other resources, nearby activities (e.g. production of potable water)

The uncertainty associated with the above data, such as representativeness, accuracy, precision and underlying assumptions, must also be gathered.

In addition to site specific data, general purpose data are also useful for the risk assessment. Learnings from past activities are important. For example, the risk identification can make use of databases, checklists or detailed operating procedures as a basis.

As it may be difficult to identify all risks and assess them properly in the initial assessment, it is useful to have reporting systems and updates of the risk assessment over time to cover new information gather from events and detected incidents.

Much of the relevant documentation for well integrity is often stored in a well integrity management system (WIMS), with information such as history of the well, well design, operational data, maintenance data, testing data, logs, etc.

4.3 Well integrity considerations for the life-cycle of a well

The focus of well integrity issues of importance varies with the different life-cycle phases. During the **well design phase**, less data is available describing the formation and reservoir properties, and what is available is subject to potentially large uncertainty. Reliability in information relating to subsurface pressures (pore and fracture pressures), borehole stability, geothermal temperature, lithology and fluid characteristics all possess a degree of uncertainty, ultimately impacting the design of the well.

During the **well construction phase**, the main KPI (Key Performance Indicator) is often the time vs. depth curve, and to a lesser extent well integrity KPIs. However, from a well integrity perspective it is essential that control mechanisms exist, both prior to cementing and after as well as during the completion stage, to verify the validity of the planned design in light of measurements and data obtained during well construction.

Casing design is a crucial component of the integrity of any well, and there are a number of considerations in this respect. According to NORSOK D-010 (2013), these include maximum allowable setting depth with regards to kick margin, pore pressure development and formation strength, drilling fluid and cement program, induced loads, H_2S potential, circulation density, isolation of weak formations, potential loss zones and geo-tectonic forces. For high temperature wells particular considerations must be made for thermal expansion of steel and trapped fluids, weakening of the casing through temperature cycling, and presence of corrosive well fluids [7].

The integrity of the casing as a barrier element may be degraded during the drilling phase. The use of abrasive coating materials on drill pipe tool joints may wear the casing. Wear of casing also arises from the longer contact time between the casing and drill pipe tool joint due to low rate of penetration (ROP) and high revolution per minute (RPM).

The **drilling** of geothermal wells often poses many geological risks that affect the well integrity. In particular the challenge of lost circulation due to highly fractured formations poses a risk to the cement integrity. When cementing the casing in such cases, the cement may fail to reach surface, making it challenging to calculate the cement requirements for the well. This might also lead to trapping drilling mud or water between the casing and the cement, which in turn ultimately could lead to casing collapse due to fluid expansion. Another threat to cement integrity is high temperature, which may degrade the quality of the cement and cause problems later in the well life-cycle [41]. In CO2-rich environments, the use of traditional Portland cement is known to be thermodynamically unstable, and could cause cement degradation and casing corrosion. Furthermore, the cement placement is also essential to cement integrity, where proper hole-cleaning and casing centralization are important considerations.

In the **production phase**, the risk of corrosion is one of the main concerns due to a greater exposure to formation fluids. Another important aspect is that until the production commences, the well is the responsibility of the drilling department. The change in responsibility when moving into another life-cycle phase, implies the importance of a proper handover, to ensure that all important well-specific concerns, including those relating to well integrity, are transferred to the production department. This pertains not only to data transfer, but also to training and re-evaluation of the risk assessments conducted during the previous life-cycle phases, involving personnel from the production department.

The challenges in the **abandonment phase** can often relate to the fact that data on the well has been handed over multiple times, and gaps in data and/or inadequate handover may lead to poor decisions being made relating to risk management and well integrity. Issues, such as sustained casing pressure, that have been circumvented through dispensations in the production phase, may cause problems in the abandonment phase when attempting to verify barrier integrity, as restoration of e.g. annulus barriers is difficult [42]. An updated well evaluation, including cement bond logs etc., and abandoning the well in accordance with local regulations, as is industry practice, can help overcome such challenges.

4.4 Recommendations for a geothermal well risk assessment and management protocol

Background

The interest in exploiting high-enthalpy heat is growing at a rapid pace and will put extra demands on the quality of the well materials and their barrier functions. A common protocol to assess and manage the integrity of these barriers and the associated risks is strongly required by regulators at the national and European level. Such a protocol would make it easier for regulators to form legal rules around it, and make the review process of the operators activities more efficient. The recommendations are meant in particular for national and European bodies developing regulations.

Need for common procedures in geothermal legislation have already been highlighted in [20]. They highlight, among others, a need for formalized processes for environmental impact assessments (EIA) in order to reduce the time to perform such assessments, as well as a reference document of technical solutions to satisfy geothermal requirements. Such industry standard documents were created for and by the Norwegian petroleum industry to harmonize solutions and legislation, to ensure adequate safety, added value and cost effectiveness of operations [43].

Chapter 3 listed several concerns in the EU Directives. These concerns are mainly related to protecting the health and well-being of the public, workers and the environment. They are in the legislation given specific tolerance limits, require either risk identification or a full risk assessment, or monitoring requirements. There are no specific methods for risk assessment mentioned, except mentioning principles such as the precautionary principle or use of best available techniques (BAT).

Although the primary focus of risk assessment is to avoid surprises through a documented process gathering information about the effects of uncertainties (what is not known with certainty), there can be other uses of the results of a risk assessment. Frequently, risk assessments are associated with bureaucracy and being cost drivers due to e.g. HSE requirements from legislation, even though that is not the intention [44]. However, it can also be used for decision support for example in a design phase to balance different considerations. Even though one usually focuses on reducing the probability and/or consequences of negative outcomes in a risk assessment, there are also situations where reducing the probability of negative outcomes will also reduce the probability of favourable outcomes which might be valued higher. In such situations one might want to maintain the risk, even if the measure has no direct cost associated with it. Such a focus would be included in the ISO-definition of risk, although it would be more commonly referred to as decision and risk analysis. Considering the precautionary principle, a balanced view of the effect of uncertainty should only be taken when it is accepted by all parties, such as if all negative consequences are suffered by the company.

The risk assessment process proposed here is not intended to give a complete solution for a protocol, but to describe how to arrive at solutions which are consistent with a risk-based approach. Such an approach must include necessary elements given by the national and European regulations, such as directives related to water pollution, mining laws, other environmental laws and power-, work-, operational- and environmental permits (see chapter 3).

Objective

The purpose of the present proposal is to provide recommendations for a future European protocol on the risk assessment and management of high-temperature geothermal wells. The objective of the protocol is to ascertain that fluids cannot unintendedly escape from the well bore and adversely impact the environment, human beings, utilities and resources. The future protocol should result in a comprehensive, transparent and verifiable risk assessment and management during all phases of the (HT) geothermal well life.

Scope

The risk assessment and management protocol is primarily directed to the function of the well including completion, wellhead, safety valves and rocks and sediments which are directly exposed to the wellbore. Information on rocks and sediments in a wider region around the well are necessary if fluids may escape from the well in the subsurface and on the conditions at the surface including population density, land use etc.

The proposed protocol deals with the whole chain of events which could result in unintended leakage of fluids from the well bore and its consequences for the environment, human beings, utilities and resources. The emphasis in GeoWell however is on the integrity of the well and less on the possible consequences of an unintended release of fluids.

The recommendations will suggest guidelines for risk assessment of geothermal wells, their monitoring and measures to reduce risk. The proposed protocol will thus address the risk management next to the risk assessment.

The proposal will try to establish a practical level of detail of the protocol but without becoming overly prescriptive.

The proposed protocol will in principle deal with all phases of the geothermal project life but most emphasis will be placed on the construction and production phases of the geothermal well life-cycle (see Figure 3).

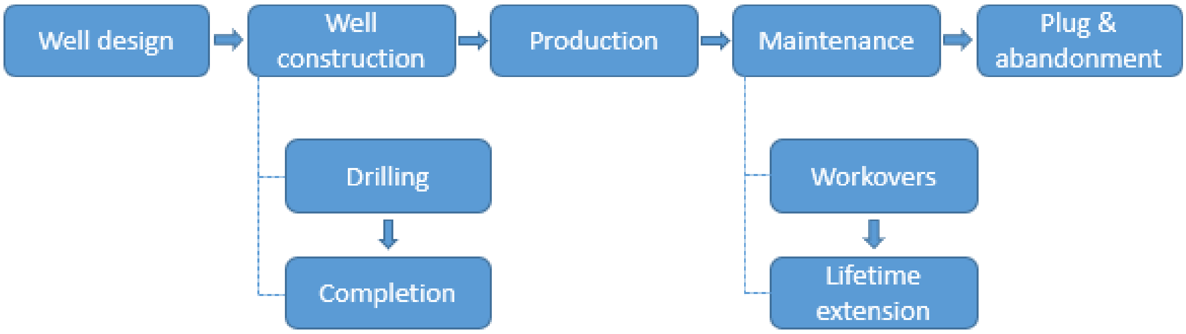

Figure 3. Different phases in the life-cycle of a well (modified after **[6]**)

The details of a risk assessment depend on the objectives. Early in a well planning stage the main focus would be on whether there are any showstoppers related to drilling, construction and operation of the well. At such a stage where information is limited to considerations related to the area in general (geographical or regional concerns) and general subsurface conditions (related to well integrity and well control), a company-specific checklist is a resource effective method to focus on feasibility and safety. Similarly, when different well concepts (alternatives for how the well will be constructed) have been identified, a more detailed checklist covering issues related to pressures, well barriers, hydraulics, friction etc. can be performed.

For a chosen well concept, a more complete risk assessment can be made. In the petroleum industry it is common to use risk matrices where issues are identified and evaluated in coarse scales in both probability and consequence dimensions. The consequences can be divided into different dimensions, such as HSE (e.g. health, safety, environment and reputation), cost (and/or time), and well performance objectives. This assessment can be used to give an overall score to the concept, identify the main risk drivers related to the concept and in general be used in the decision-making process. Detailed assessments are made when well design is almost finished (e.g. 80% finished). Then particular challenges can more appropriately be investigated with a more in-depth risk analysis using quantitative methods.

In the GeoWell report D6.3 a framework for risk assessment has been proposed [7] which will be included in the current proposed protocol. The framework for risk assessment of geothermal wells uses ISO 31000 [1] as a point of departure (Figure 4) and consists of the following main steps:

- Establishment of the context;
- Risk assessment sub-divided into risk identification, analysis and evaluation;
- Monitoring and risk reduction;
- Continuous communication with stakeholders and risk review.

In performing risk assessment and management activities of (HT) geothermal wells GeoWell recommends following the individual steps of the proposed framework. A rudimentary example is provided in the Appendix A.

4.4.1 Assessment context

The first step in the risk assessment and management process is to define the context of the risk assessment and management which is specific to the geothermal wells to be developed, operated, plugged and abandoned. The context deals with the specific objectives of the risk assessment and management, the acceptance criteria to be evaluated, the well barrier concept with system boundaries, the site-specific geological and geographical setting and resources needed.

Objectives describe what the risk assessment and management is aiming at in securing the integrity of the well barriers and minimizing damage from fluids leaking from the well. It should include any company policies relevant to the risk context, regulations or requirements as to how the risk assessment is conducted or what it must contain as a minimum.

Related to geothermal well integrity, there are several activities related to designing and maintaining well integrity. In the petroleum standard NORSOK D-010, [9], a list of documented activities that should be performed to ensure well integrity is provided, which includes design of well, assessment of the risk related to well integrity or well control, activity programs and procedures. The objective of the geothermal well integrity risk assessment will typically relate to one of these activities.

A thorough well design is important to make sure all components can withstand loads and stresses covering all the life cycle phases of the well. For well integrity this will focus on well barriers. This should be performed for new wells, wells that change purpose (e.g. from exploration to production), or other changes to the original scope of the design. The New Zealand code of practice [3] provides recommendations for well design in a geothermal context.

A good understanding of the **well barrier concept** is essential for the execution of the risk assessment and management protocol, in particular for the identification of possible failure modes. Defining the well barriers for the activities under consideration is important to specify the scope of analyses related to well integrity. This involves selecting sets of well elements that together can form an envelope which should be sufficient for its purposes, i.e. prevent leakage. It is useful to prepare it in the form of a well barrier schematic (WBS) to easily reference, communicate and identify operations or failures which may threaten the well integrity. Through the risk assessment, the well barrier elements should be described together with their function in the barrier, acceptance criteria and verification/monitoring method.

In addition to risk assessment of the well barriers, [9] recommends an analysis such as safe job analysis should be performed for new or non-standard operations, operations using new or modified equipment, or operations that are considered hazardous or could have increased risk compared to when the activity has been performed previously.

In addition to the performance of activities such as drilling and intervention, the well integrity must also consider wear from production or other states where no equipment is in the well. To preserve the integrity a maintenance program for the well barrier elements should be made. Some elements will have continuous monitoring, where indications of failures can be quickly identified. Other elements should have a prescriptive maintenance program. Periodic inspection (or test) intervals (how often they are performed) can be based on reliability data and field conditions that may influence reliability over time.

Acceptance criteria are to be defined which indicate the level of acceptable risk resulting from leakage of fluids from the well. They can either be quantitative or qualitative, relate to the possible damage resulting from leakage or can be indicators of increasing leakage risk (e.g. pressure, temperature, corrosion etc.). The acceptance criteria must often be defined by the company, as few are given in the legislation (see Chapter 3).

The **system boundaries** will define which elements of the well zone and which phases of the well life-cycle are included or excluded in the risk assessment.

The **setting** of the well is very important in terms of the subsurface rocks and sediments penetrated by the well, nearby subsurface activities and the surface conditions including population, protected water resources natural reserves and built-up areas.

Another important factor that will impact the subsequent steps is the availability of **resources** to successfully execute the risk assessment and management. This includes budget and personnel resources, competence and skills, and data and information concerning the well in question, as well as any resources that could be used to infer failure statistics, either in-house or external databases.

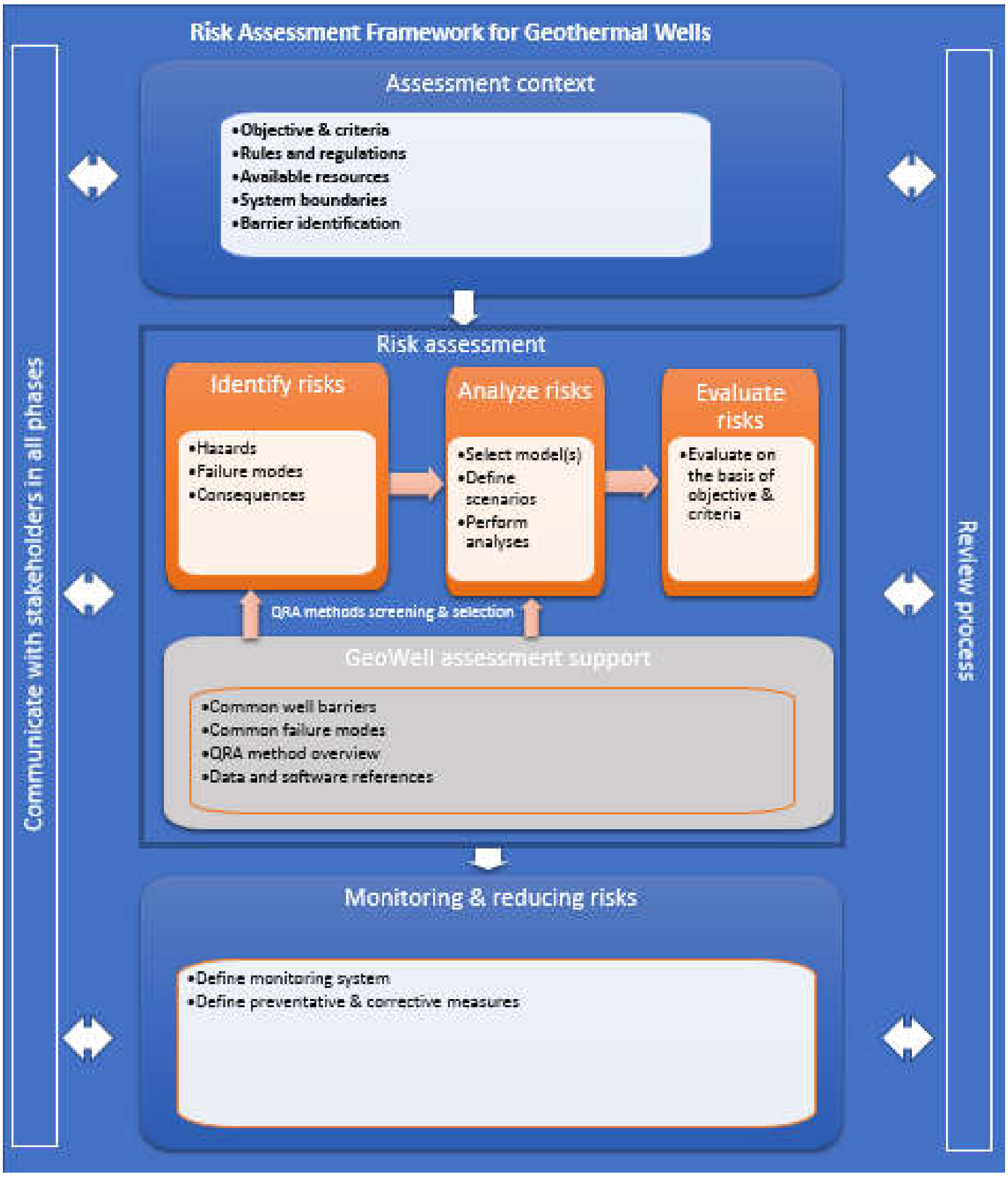

Figure 4 The proposed framework for risk assessment and management of geothermal wells **[7]**

4.4.2 Risk identification and quick screening

After the context of the risk assessment has been defined a comprehensive overview of risk factors will be assembled. Such an exercise may start with the identification of possible well barrier failure modes and their causes. This is also named hazard identification (HAZID) and depending on the assessment objectives the identification could be limited to this part or extended to the identification of consequences of unintended loss of fluids from the well, in particular those that lead to damage to the environment, human beings, built-up areas and subsurface or surface resources. This complete set of activities is referred to as risk identification. Special attention is to be directed to the occurrence of cascading events resulting in adverse consequences.

The identified risks are qualitatively or semi-quantitatively characterized in terms of probability and severity of the impact. This offers the possibility for ranking and screening the various risks. A first evaluation of possible risk treatment and its expected reducing effect on the risk level is to be included.

An appropriate method for risk identification and screening is to be selected or is prescribed by inhouse company risk management procedures. Various methods based on expert judgment and supporting databases are available, which are categorized on the basis of several characteristics (Figure 5). These categories are qualitative/quantitative, resource requirements, complexity, and degree of uncertainty. The result is a method selection basis for risk identification techniques.

As it is important to communicate the risk efficiently, representing the risk picture through visual means is recommended. Thus, using simple visual methods such as risk matrices and/or bow-tie diagrams are useful, even if other methods are used.

The identification should consider the ability of the elements defined in the context to perform their defined function considering information such as best practice documents, company procedures, historical data or lessons from previous wells, expert knowledge, and consequences expressed in regional, national and EU legislation (e.g. those mentioned in section 3.2 and Appendix B). For high temperature wells it is of particular importance to consider temperature related mechanisms that may lead to new failure modes or consequences that are less common or not relevant for low temperature wells. This could be new components in the produced fluid, plastic behaviour of the casing or severe blowouts.

Keeping track of identified risks and their treatment from the start of the life of the well is important.

4.4.3 Risk analysis

On the basis of the criticality of the identified hazards and risks, quantitative analysis is to be performed in a staged manner from simple to complex models. The level of detail of the analysis very much depends on the nature of the risks to be quantified. In some instances, a ‘back-of-the-envelope’ quantitative analysis is sufficient; in other situations one may need to use sophisticated coupled THMC-models. Choices are to be made whether deterministic or probabilistic approaches are required.

Depending on the objective the hazards are to be quantified in terms of resulting fluid leakage (hazard analysis). In other type of analyses fluid migration paths need to be quantified leading to the exposure to geothermal fluids (exposure analysis). Finally, the effects of exposure to various receptors (e.g. environment, potable water, human beings) can be quantified (effects analysis). The temporal and spatial scales of the impact of the hazards on the release of fluids, exposure to fluids and effects to receptors are to be characterized. Some consequences may be local and sudden whereas others are more diffusive over a larger area.

A lot of site-specific information including the characterization of uncertainties is required to execute a quantitative analysis (see Section 4.2). Before addressing uncertainties, one may perform sensitivity analysis to identify the most relevant parameters in the quantitative risk analysis. The representativeness of the information must also be considered. For example, the risk in extreme temperature wells may be poorly estimated if relying on data and models from lower temperature wells.

Appropriate risk analysis methods need to be selected which fit the requirements of the assessment context, which includes the specific objective of the risk analysis and the availability of adequate expertise. Also, the availability of relevant data and the complexity of the problem are of importance in selecting the appropriate methodology (Figure 5). At times regulations and company rules demand for specific risk analysis methodologies.

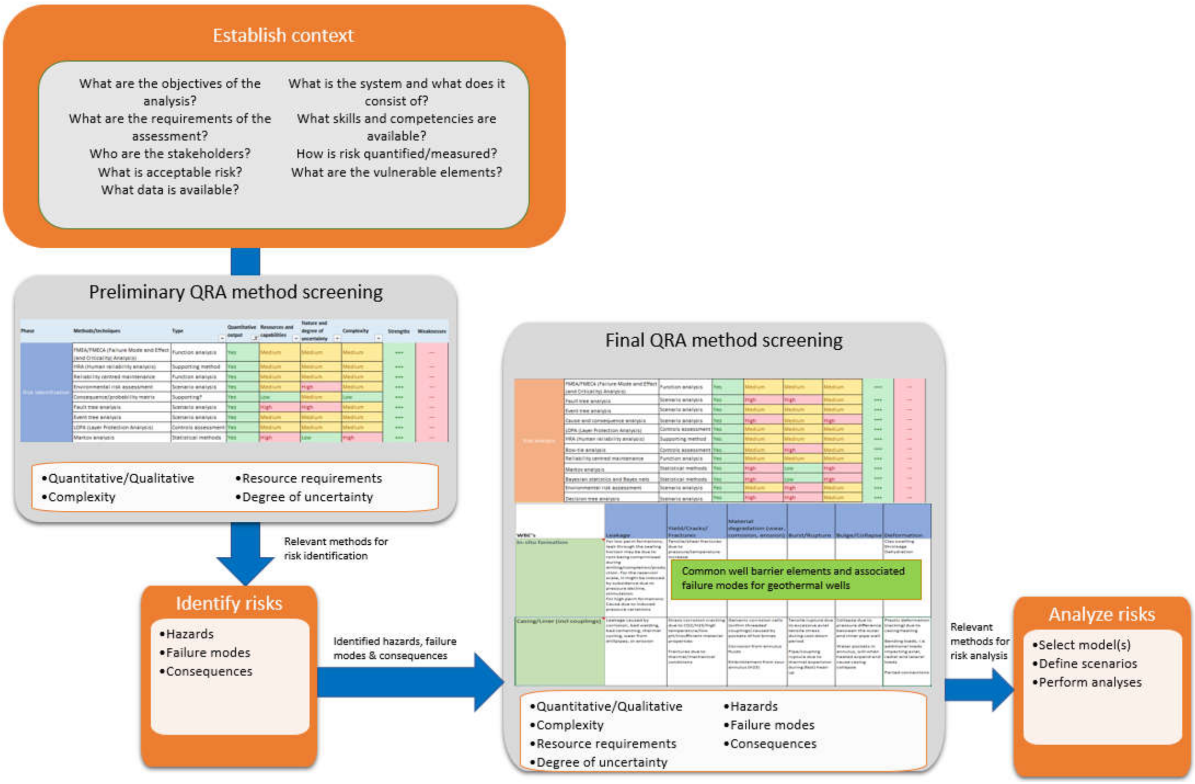

Figure 5. Screening and selection of methods in the risk assessment framework

4.4.4 Risk evaluation

The preparation work for the risk evaluation or risk assessment is covered by the risk identification and analysis described in the previous two sections. In the risk evaluation the integrated results of the analysis will be compared to the criteria and indicators for risk acceptance and a conclusion on compliance will be drawn.

Any critical uncertainties for the outcome of the evaluation will be identified and follow-up work may be defined to reduce these uncertainties (see also section 4.4.6).

4.4.5 Monitoring

Monitoring provides evidence for the integrity of the well and the absence of unacceptable damage to protected goods. A well monitoring plan is to be established with monitoring parameters which are adjusted to the performance and risk criteria, and associated indicators. Suitable monitoring technologies with monitoring locations, durations and sampling frequencies are part of the plan. Monitoring parameters may include the quality of the well barriers, fluid production and injection rates, fluid composition, pressure, temperature, leakage detection and impact of fluid leakage, which can be measured continuously or in a time-lapse mode.

The well monitoring plan is established before operations start. Some parts of the monitoring plan might start already before the start of operations in the case where baseline data are needed.

The output from monitoring is regularly verified for conformance with the expected performance of the well. In case the observed behaviour is deviating from the expected behaviour, follow-up actions may be necessary. Depending on the nature of the anomaly, this needs to be communicated with the state authorities and actions to mitigate or remediate adverse consequences may need to be started. Contingency monitoring may be necessary and the monitoring plan is to be updated. If the deviating behaviour has been resolved, the contingency monitoring may be ended.

4.4.6 Risk reduction

To reduce and keep the risks at ALARA levels risk reduction measures may be emplaced. Developing these measures already starts in the phase of risk identification. Once risks have been identified (see section 4.4.2), potential reduction measures can be assigned to individual risks.

Preference is given to **preventive measures**, which in most cases are implemented before the start of operations. A large part of the measures can be adopted in the design of the well. Additional preventive measures may be implemented during operations for example because new rules for material usage or preventive maintenance apply.

In case monitoring results point to deviating behaviour, one may deploy additional **corrective measures**, to mitigate the risks. In case damage by leaking fluids would occur remedial measures may need to be implemented to restore the damage.

In petroleum there is a high focus on blowouts, and a blowout contingency plan is required [9]. Blowouts also occur in geothermal wells if the conditions are sufficient (i.e. high pressure formations and/or high temperatures). High consequence events should be addressed (almost irrespective of probability per the precautionary principle), with regards to e.g. layout, well design, stopping method (kill strategy) and emergency response responsibilities. Simulations of the rate and requirements to stop the blowout for the most difficult scenarios should be performed to ensure the well can be controlled.

As part of mitigating measures, it is important to have the ability to employ them to desired effect, such as sufficient fluids available to quench a well, sufficient area to contain any leakage or waste and identification of soil areas which should be treated. This may create a larger footprint on the area around the well, and must as such be evaluated against other environmental concerns. Measures should also include organizational aspects for rapid response and minimizing worker exposure (such as responsibilities, evacuation plans, fire fighting plans, personal protective equipment etc.).

4.4.7 Communication with stakeholders

Continual communication with and engagement of stakeholders is an integral part of risk assessment and management from the development of the geothermal project and onwards to operations and abandonment. Confidence in the safety of the well-related activities is key to making decisions during the realisation of the project. Different groups of stakeholders can be identified with different interests, i.e. geothermal energy company (business case), regulator and inspector (compliance with safety and environment riles), local public (safety and environment), local authorities (socio-economic wellbeing) and local companies (interference with their business). Proper communication and engagement requires a strategy and implementation plan.

The geothermal project owner will have to report on the outcome of the risk assessment and the actions on monitoring and risk management to the state authorities. Regular updates on the safe performance of geothermal well activities including outcomes of monitoring, events occurring during operations and follow-up actions, maintenance activities etc.

4.4.8 Continuous risk review

The presented workflow for risk assessment and management of (HT) geothermal wells is not a one-time exercise but is continually being reviewed and updated during all stages of the HT geothermal project life.

Thus, new data, rules or criteria, or monitoring results may require updating all or part of the risk assessment and management work. The cyclic nature of risk assessment and management is illustrated in Figure 6.

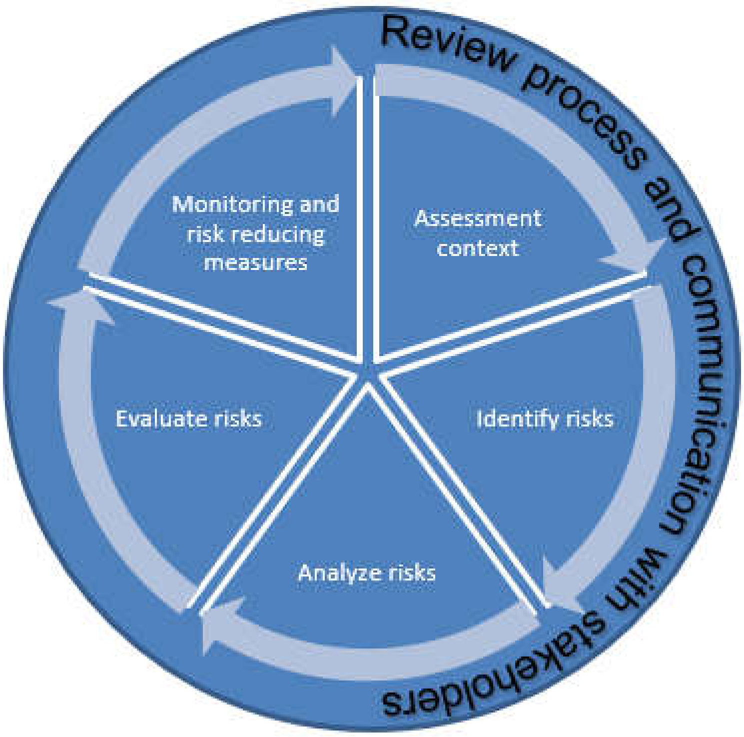

Figure 6. Risk management process, adapted from DESTRESS [45]

Plans for updating must be made, whether initiated at periodic intervals or triggered by events. An example is predetermined shut-down criteria which determine when normal activities should cease, such as when a well barrier is weakened or has failed, or the risk has increased beyond that which was planned for (e.g. operating limits of critical equipment will be exceeded or high content of hazardous gasses). In such cases the risk should be reassessed, and attempts made to normalize the situation, such as restoring degraded barriers.

A program describing the activities to be performed and procedures to be followed should typically be developed in cooperation with the main contractors, to ensure that the activities performed are consistent (e.g. in accordance with the assessments performed for the specific well and previously for similar activities). Significant deviations should be documented, approved and distributed to the users. Similarly, a management of change (MOC) procedure on how to deal with technical, operational or organizational changes to the approved information is important. Changes may introduce new risks that must be assessed, but often overlooked are consequences where implicit assumptions originally were made. Thus, the holistic overview gained in the planning stage should be used to describe how changes are dealt with.

5 Bibliography

[1] ISO, “ISO 31000:2009 Risk management - Principles and guidelines,” International Organization for Standardization (ISO), 2009.

[2] PSA, “New definition of the risk concept,” 2016. [Online]. Available: http://www.psa.no/risk-and-risk-management/new-definition-of-the-risk-concept-article11908-897.html..

[3] Standards New Zealand, “NZS 2403:2015: Code of Practice for deep geothermal wells,” Standards New Zealand, Wellington, 2015.

[4] African Union, “The African Union Code of Practice for Geothermal Drilling,” African Union's Regional Geothermal Coodrination Unit, 2016.

[5] H. P. Lohne, E. P. Ford, M. Mansouri Majoumerd and E. Randeberg, “Well integrity risk assessment in geothermal wells - Status of today,” GeoWell, Stavanger, 2016.

[6] H. P. Lohne, E. P. Ford, M. Mansouri Majoumerd and E. Randeberg, “A roadmap for transferring well integrity risk assessment from oil and gas to geothermal,” GeoWell, Stavanger, 2016.

[7] H. P. Lohne, E. P. Ford, M. Mansouri Majoumerd, E. Randeberg, S. Aldaz, T. Reinsch, T. Wildenborg and L. G. Brunner, “Barrier definitions and risk assessment tools for geothermal wells,” GeoWell, Stavanger, 2017.

[8] ISO, “ISO/TS 16530-2:2014 - Well integrity -- Part 2: Well integrity for the operational phase,” International Organization for Standardization (ISO), Geneva, 2014.

[9] Norwegian petroleum industry, “NORSOK Standard D-010: Well integrity in drilling and well operations, Rev. 4,” Standards Norway, Lysaker, 2013.

[10] American petroleum institute, “API recommended practice 17N, Second edition,” API Publishing Services, Washington, 2017.

[11] NOGEPA, “Industry standard no. 90: Asset Integrity,” Netherlands oil and gas exploration and production association, 2016.

[12] European Union, “http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM%3Al32042,” [Online].

[13] European Union, “Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market,” 2001. [Online]. Available: http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32001L0077. [Accessed 5 March 2018].

[14] European Union, “Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and

2003/30/EC," 2009. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0028. [Accessed 5 March 2018].

[15] R. Pasquali, "ReGeoCities - Best Practices related to regulation of shallow geothermal energy," 2013. [Online]. Available: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/report_of_the_best_practices_related_to_regulation_of_sge_systems.pdf. [Accessed 8 November 2018].

[16] European Union, "Sources of European Union law," 2017. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:l14534. [Accessed 5 March 2018].

[17] European Union, "Regulations, Directives and other acts," 2018. [Online]. Available: https://europa.eu/european-union/eu-law/legal-acts_en. [Accessed 1 March 2018].

[18] European Union, "Consolidated versionsConsolidated versions of the Treaty on European Union and the Treaty on the functioning of the European Union," 2010. [Online]. Available: , http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.C_.2010.083.01.0001.01.ENG&toc=OJ:C:2010:083:TOC. [Accessed 5 March 2018].

[19] P. Dumas, M. Serdjuk, R. Kutschick, S. Fraser, S. Reith and T. Koelbel, "Deliverable 4.1 of GEOELEC: Proposals for improving the regulatory framework for geothermal electricity," GEOELEC project, 2013.

[20] K4RES-H, "K4RES-H Key Issues for Renewable Heat in Europe - Key issue 3: Regulations for geothermal energy," 2006. [Online]. Available: http://geodh.eu/wp-content/uploads/2012/11/K4RES-H_Geothermal_Regulations.pdf. [Accessed 8 November 2018].

[21] European Union, "Directive 2000/60/EC Of The European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy," 2000. [Online]. Available: https://ec.europa.eu/health/sites/health/files/endocrine_disruptors/docs/wfd_200060ec_directive_en.pdf. [Accessed 5 March 2018].

[22] European Union, "Directive 2006/118/EC of the European Parliament and of the Council of 12 december 2006 on the protection of groundwater against pollution and deterioration," 2006. [Online]. Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:372:0019:0031:EN:PDF. [Accessed 5 March 2018].

[23] European Union, "Directive 2008/105/EC of the European Parliament and of the Council of 16 December 2008 on environmental quality standards in the field of water policy," 2008. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0105. [Accessed 6 March 2018].

[24] European Union, "Council Directive 79/409/EEC of 2 April 1979 on the conservation of wild birds," 1979. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A31979L0409. [Accessed 6 March 2018].

[25] European Union, "Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora," 1992. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31992L0043. [Accessed 6 March 2018].

[26] European Union, "Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment," 2011. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011L0092#ntr3-L_2012026EN.01000101-E0003. [Accessed 6 March 2018].

[27] European Union, "Council Directive of 27 june 1985 on the assessment of the effects of certain public and private projects on the environment (85/337/EEC)," 1985. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L:1985:175:FULL&from=EN. [Accessed 6 March 2018].

[28] European Union, "Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage," 2004. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02004L0035-20130718. [Accessed 7 March 2018].

[29] European Union, "Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC," 2006. [Online]. Available: http://eur-lex.europa.eu/resource.html?uri=cellar:c370006a-063e-4dc7-9b05-52c37720740c.0005.02/DOC_1&format=PDF. [Accessed 7 March 2018].

[30] European Union, "Council Directive 92/104/EEC of 3 December 1992 on the minimum requirements for improving the safety and health protection of workers in surface and underground mineral-extracting industries," 1992. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:01992L0104-20070627. [Accessed 8 March 2018].

[31] European Union, "Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control)," 2010. [Online]. Available: https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32010L0075. [Accessed 8 March 2018].

[32] European Union, "Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise," 2002. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32002L0049. [Accessed 8 March 2018].

[33] European Commission, "Environmental noise Directive," 2016. [Online]. Available: http://ec.europa.eu/environment/noise/directive_en.htm. [Accessed 8 March 2018].

[34] European Union, "Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds (codified version)," 2009. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0147. [Accessed 6 March 2018].

[35] European Union, "Council Regulation (EEC) No 793/93 of 23 March 1993 on the evaluation and control of the risks of existing substances," 1993. [Online]. Available:

http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31993R0793:EN:HTML. [Accessed 6 March 2018].

[36] European Union, "Council Directive 91/414/EEC of 15 July 1991 concerning the placing of plant protection products on the market," 1991. [Online]. Available: http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:31991L0414. [Accessed 6 March 2018].

[37] European Union, "Directive 98/8/EC of the European Parliament and of the Council of 16 February 1998 concerning the placing of biocidal products on the market," 1998. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31998L0008. [Accessed 6 March 2018].

[38] European Union, "Commission Directive 93/67/EEC of 20 July 1993 laying down the principles for assessment of risks to man and the environment of subtances notified in accordance with Council Directive 67/548/EEC," 1993. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31993L0067. [Accessed 6 March 2018].

[39] European Union, "Commission Regulation (EC) No 1488/94 of 28 June 1994 laying down the principles for the assessment of risks to man and the environment of existing substances in accordance with Council Regulation (EEC) No 793/93," 1994. [Online]. Available: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31994R1488:EN:HTML. [Accessed 6 March 2018].

[40] European Union, "Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment," 2014. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014L0052. [Accessed 6 March 2018].

[41] L. Okwiri, "Risk Assessment and Risk Modelling in Geothermal Drilling," Iceland School of Energy, Reykjavik, 2017.

[42] D. Etetim, "Well integrity behind casing during well operation. Alternative sealing materials to cement.," NTNU Department of Petroleum Engineering and Applied Geophysics, Trondheim, 2013.

[43] Standard Norge, "NORSOK standards," 14 3 2018. [Online]. Available: http://www.standard.no/en/sectors/energi-og-klima/petroleum/norsok-standards/.

[44] Health and Safety Executive, "Controlling the risks in the workplace," [Online]. Available: http://www.hse.gov.uk/risk/controlling-risks.htm. [Accessed 20 3 2018].

[45] DESTRESS project, "Risk assessment as part of risk management," [Online]. Available: http://www.destress-h2020.eu/en/Best-Practices/Risk-assessment/. [Accessed 9 March 2018].

[46] A. Manzella, R. Bonciani, A. Allansdottir, S. Botteghi, A. Donato, S. Giamberini, A. P. M. Lenzi, A. Pellizzone and D. Scrocca, "Environmental and social aspects of geothermal energy in Italy," *Geothermics,* vol. 72, pp. 232-248, 2018.

[47] MISE-MATTM, "Italian Ministry of Economic Development and Ministry of the Environment and Protection of Land and Sea," 2016. [Online]. Available: http://unmig.sviluppoeconomico.gov.it/unmig/agenda/upload/174_375.pdf. [Accessed 9 March 2018].

[48] A. Baldacci, M. Mannari and F. Sansone, "Greening of geothermal power: An inovative technology for abatement of hydrogen sulphide and mercury emissions," in *Proceedings of World Geothermal Congress*, Antalya, Turkey, 2005.

[49] Italian Parliament, "Decreto Legislativo 3 aprile 2006, n. 152 - Rules on the environment," 2006. [Online]. Available: http://www.camera.it/parlam/leggi/deleghe/06152dl2.htm. [Accessed 9 March 2018].

[50] T. Narasimhan and K. Goyal, "Subsidence due to geothermal fluid withdrawal," 1982. [Online]. Available: https://escholarship.org/uc/item/8zz4q56x. [Accessed 9 March 2018].

[51] US National Research Council, "Induced seismicity potential in energy technologies," The National Academies Press, Washington, D.C., 2013.

[52] CIRM Working Group, "Guidelines for monitoring seismicity, ground deformation and pore pressure in subsurface industrial activities," 2014. [Online]. Available: http://unmig.sviluppoeconomico.gov.it/unmig/agenda/upload/151_238.pdf. [Accessed 9 March 2018].

[53] European Commission, "Water framework Directive," 2010. [Online]. Available: http://ec.europa.eu/environment/pubs/pdf/factsheets/water-framework-directive.pdf. [Accessed 5 March 2018].

[54] European Commission, "Priority substances under the water framework Directive," 2016. [Online]. Available: http://ec.europa.eu/environment/water/water-dangersub/pri_substances.htm#intro. [Accessed 6 March 2018].

[55] European Commission, "Natura 2000," 2017. [Online]. Available: http://ec.europa.eu/environment/nature/natura2000/index_en.htm. [Accessed 6 March 2018].

[56] European Union, "Council Directive 97/11/EC of 3 March 1997 amending Directive 85/337/EEC on the assessment of the effects of certain public and private projects on the environment," 1997. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31997L0011. [Accessed 6 March 2018].

[57] European Union, "Directive 2003/35/EC of the European Parliament and of the Council of 26 May 2003 providing for public participation in respect of the drawing up of certain plans and programmes relating to the environment and amending with regard to public participation," 2003. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32003L0035. [Accessed 6 March 2018].

[58] European Union, "Directive 2009/31/EC of the European Parliament and of The Council of 23 April 2009 on the geological storage of carbon dioxide," 2009. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0031. [Accessed 6 March 2018].

[59] D. G. Lawrence, “Environmental liability Directive: A short overview,” 2006. [Online]. Available: http://ec.europa.eu/environment/legal/liability/pdf/Summary%20ELD.pdf. [Accessed 7 March 2018].

[60] European Union, “Directive 2013/30/EU of the European Parliament and of the Council of 12 June 2013 on safety of offshore oil and gas operations and amending Directive 2004/35/EC,” 2013. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013L0030&from=EN. [Accessed 7 March 2018].

[61] European Union, “Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment,” 2001. [Online]. Available: http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX:32001L0042. [Accessed 8 March 2018].

[62] Office of Energy Efficiency and Renewable Energy, “Geothermal power plants – minimizing solid waste and recovering minerals,” 2010. [Online]. Available: https://www.energy.gov/eere/geothermal/geothermal-power-plants-minimizing-solid-waste-and-recovering-minerals. [Accessed 7 March 2018].

[63] European Union, “Council Directive 92/91/EEC of 3 November 1992 concerning the minimum requirements for improving the safety and health protection of workers in the mineral- extracting industries through drilling,” 1992. [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:31992L0091. [Accessed 8 March 2018].

[64] NTC, “NORSOK Z-013 Rev. 2 - Risk and emergency preparedness analysis,” Norwegian Technology Centre (NTC), Oslo, 2001.

[65] ISO, “IEC/ISO 31010 Risk management - Risk assessment techniques,” International Organization for Standardization, 2009.

Appendix A Casing design

A.1 Introduction

Well design is an important step to make sure the well is designed to withstand the forces, stresses and environment it will be subjected to during its life. One aspect of well design is the casing design, which is described for petroleum wells in [9]. Due to the very high temperature of some geothermal wells, the geothermal industry has adapted to more relevant methods described in [3]. The method followed is a comparison of the load case against the casing design, where maximum load cases are defined according to a conservative common practice for different operations. Even though conservative assumptions are made, quality assurance through a risk assessment should be performed to ensure that all relevant effects will not give undesirable outcomes, and which measures can be taken to reduce the effect or likelihood of such from any effects. In a quality assurance context, a risk assessment will typically be qualitative in general, but include quantitative elements. A fully quantitative approach could alternatively be performed, to give further insight into optimizing the casing design.

A.2 Establishing context

In the assessment context, the objectives and criteria should be defined. The objective sets the scope of which elements to include in a risk assessment, such as which decisions the assessment should support and what company or regulatory requirements must be considered. This will frequently be related to the resources (time, competence and data) available to the assessment. Although acceptance criteria are recommended set by regulators, it is customary that the companies themselves also create their own criteria which are in line with the regulations. From a well integrity point of view, zero leakage is the criteria in the petroleum industry. In geothermal, at least in [3], there is often some acceptance for minor gas leakages due to the difficulty in maintaining gas tight connections under large temperature variations. Also, practical criteria based on the design, such as room for linear expansion should be described.

The casings are part of the barrier system, at least during parts of the well life. During which operations it will have the function of a barrier element will determine what loads and conditions must be considered. Setting the system boundary for what will be considered in the assessment will typically decide how the consequences will be modelled. In addition, the design life and other limitations for when, if exceeded, a revised assessment must be performed. It may be necessary to add further limitations based on the risk analysis; for example a significant potential threat may be better resolved when more information is available if its existence can be identified before escalating into a failure.

As mentioned, the context will narrow down which types of risk analysis methods are useful to satisfy the objectives and available resources. As different methods have different requirements, it is already at this point useful to screen relevant methods as the method selected will influence the risk identification process.

An example of a summary table from the context establishment phase, showing brief example values for illustrational purposes is provided below.

Establish context - summary	
Analysis system boundary	Casings
Well life-cycle phases	Well construction only
Decisons to support	Casing material choice, connection technology
Regulatory requirements/reference documents	Company specifications for casing design; NZS 2403:2015; ISO 31000:2018, EU Directives (e.g. WFD)
Time constraints	3 Man-Months allocated for risk assessment
Competence requirements	Risk assessment, geology/reservoir, fluid chemistry, flow modelling, HSE, drilling, well design, cementing
Data requirements	Well schematics, formation pressure gradients, PVT, rheology, reservoir model, temperature profile, casing failure and incident records from field
Risk acceptance criteria (measureable)	No risks relating to leakage shall be classified above Category I (per company risk matrix), after consideration of risk mitigating measures
Barrier objective	Prevent uncontrolled flow of formation fluid or injection fluid between wellbore and casing annulus
Scope - items to be addressed	Trajectory and bending stresses
	Max allowable setting depth
	Estimated pore pressure and formation integrity development
	Estimated temperature gradient and effects
	Drilling fluids and cement program
	Induced loads
	Estimated casing wear
	H2S/CO2 potential
	Metallurgic considerations
	ECD
	Geo-tectonic forces
	Relief well feasability
	Experience from previous wells

Figure 7: Summary of factors to consider for establishment of context

A.3 Risk identification

The risk identification process will typically start by identifying the failure modes of the assessed element. This is to create an overview over which failed or degraded states can result. For casings this can for example be collapsed casing or ruptured casing. The process of identifying such failure modes can be based on available in-house experience and data records of previous failures, or from external sources such as published literature and company shared data. An example of failure mode listing for a casing (including couplings), based on previous work in the GeoWell project is shown below.

WBE's	Burst/Rupture (body or connections)	Tearing	Bulge/Collapse	Deformation	Breakdown (e.g. due to stress, fatigue)	Spurious displacement	Plugged/ choked (e.g. scaling)	Parted connections
Casing/Liner (incl couplings)	x	x	x	x	x	x	x	x

Figure 8: Example of failure modes for a casing

These failure modes will be related to a failure event, which is the occurrence of the failure itself, i.e. when the assessed element transitions from working as intended to not working as intended. This is modelled as a limit-state, such as when the actual load on the casing exceeds the actual strength of the casing (as opposed to the estimated strength and loads).

The next step is to identify possible transitions from a working state to a failed or degraded state. These are the processes occurring over time describing how it can transition to a failed state. For casings these processes can be e.g. corrosion or temperature cycling/plastic deformation. In quantitative assessments the processes are often modelled using mechanical and chemical mathematical models, however, also logic-based models can be used for non-physical processes.

The identification can also be considered from initiating factors for the processes leading to the failure modes. For casings, a these can be the existence of a particular corrosive element in the reservoir fluids, or long-term temperature changes. For the latter, an example of a transition process to a failed state is shown.

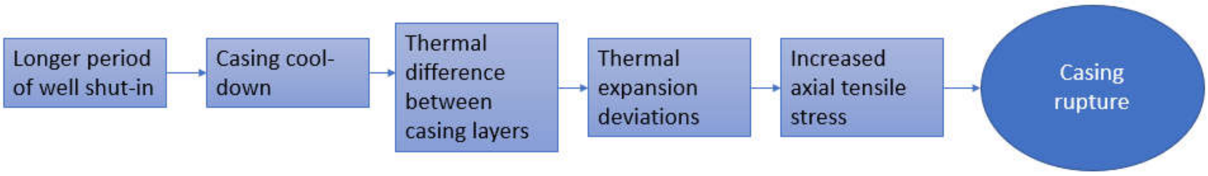

Figure 9: Transition from a normal to a failed state (casing rupture) for the casing

Depending on the complexity of the phenomena (cause) leading to the failed state, various techniques may be applied. Fault-tree analysis can be useful when the transition to a failed state is conditioned on a wide range of factors, or where the system being analysed is complex in nature. The purpose of this process is not only to identify the causes, but also to help highlight the particular system parameters (such as casing layer material and temperature, and thermal expansion) that need to be accounted and designed for.

No matter how many definitions are used to describe concepts in risk management, there is some freedom in what are considered causes, processes and failure modes depending on the view and level of the analysis. The important part is to ensure consistency in their treatment and that all relevant occurrences are included in the analysis that follows. This is one reason why the selection of methods to be used in the analysis is relevant to be screened in advance.

Typically initiated from a table, database and/or brainstorming, further risk identification will depend on the assessment context. For assessments related to specific operations, it is useful to go through the planned procedures, as well as any relevant contingency procedures, to identify factors that may influence the barrier elements, such as the casing. Examples would typically be factors influencing temperature changes, maximum temperature and pressures.

Although prevention of failures is preferred, and thus the focus is often on the probability of failure, the context will often define acceptance criteria in terms of consequences given a failure. The relevant regulations (some of which are listed in Appendix D) could for example impose requirements for the types of consequences to be considered, or require that specific types of risk analyses be applied, such as an environmental risk assessment. Consequences can often be divided into well objective, cost and health, safety, environment and reputation. While many of the vulnerable elements to consider are given by the assessment context, the possible paths from failed barrier element to impact on the vulnerable element as well as the escalation of failures must be identified. An example of this could be the location of nearby groundwater and possible pathways from the well, if a concern is leakage to this groundwater resource. HSE risks are always part of the considered consequences. There are a number of risks that could impair the health, safety and environment throughout the life-cycle of a well. The leakage of toxic gases, such as H_2S and CO_2 (large exposure) is one such risk to health. Noise, operations involving exposure to falling objects, massive moving parts, terrain and ground conditions, weather conditions, chemical substances, etc. are other examples. Brine ponds, disposed cuttings and air pollution from drilling equipment are examples of environmental risks [41].

In the risk identification stage, coarse judgments are used to screen and select the most important risks to be further analysed in the subsequent assessment steps. As such, the causes and failure modes are often used as a basis for listing risk elements in a risk matrix, where probability of occurrence and consequences for different dimensions are divided into categories. An example is provided in Figure 10.

		Well objective (profit/flow or information)	D&W cost (cost, time & resources)	HSE & reputation	Increasing probability				
					< 1%	1 - 5%	5 - 25%	25 - 50%	> 50%
					P1	P2	P3	P4	P5
Increasing impact	I5	> 50 M$ Production loss Future well intervention	> 50 M$ Lost well	Major injury/fatality/leak Loss of both well barrier					
	I4	10- 50 M$ Production loss Future well intervention	10- 50 M$ Sidetrack/delays	Moderate injury/leak Loss of one well barrier					
	I3	1-10 M$ Reduced production	1-10 M$ Delays/equipment failure	Minor injury/leak Unkown well barrier status					
	I2	< 1 M$	< 1 M$	Neglible injury/leak					
	I1	No impact	No impact	No impact					

Figure 10: Example of a risk matrix

The combination of probability and impact (consequence) yields a risk classification, here shown as red, yellow or green. This classification is normally established based on company policies but should be made case-specific if necessary. Essentially, the risk classification will represent acceptable (green) and unacceptable (red) risk levels, with an intermediate (yellow) level where further analysis is required. These levels must be aligned with the established context, implying that e.g. relevant regulations are taken into consideration as previously stated.

The judgment process (often called a HAZID) is typically based on a workshop facilitated by a risk analyst, where personnel from relevant disciplines are brought together to elaborate, review and assess the suggested risks. This process may well highlight new risks that were not initially considered. The risk analyst will process and formalize an initial draft, which will be QA'ed by the participants before a final version is submitted.

While much of the assessment context, in particular the acceptance criteria, should not be modified during the process, other parts such as limitations may need to be revised based on the risk identification.

The most suitable risk analysis method will depend on whether a qualitative assessment is sufficient, the existence of complex relationships and the level of detail these relationships would need to be investigated, what resources are available (especially what data is available) and the degree of uncertainty.

A.4 Risk analysis

The analysis itself will depend on the methods selected. For example, when using scenario-based methods one would typically find relevant models for the various failure mechanisms and define a range of plausible scenarios that incorporate these models. For casing design, scenarios could for example be certain temperature ranges and their development over time, while models for the related stress and deformation in the casing describe part of a potential path to failure. The failure itself would then occur when the deformation exceeds a criterion, which may also be the result of a model, which would over the scenarios generate failure probability as a function of time.

Consequences are more commonly estimated using scenario modelling than failure probabilities are, as useful historical data are more often available for the failure events. The analysis of the consequences would typically be performed by defining scenarios for the consequences given a failure mode, with a model to quantify the following escalation or end impact in the various scenarios. For a casing design, the failure of the casing may not give immediate problems, as fluid might still have to pass cement or other obstacles before reaching the surface or pollute underground resources. Models for the flow of these fluids will be able to estimate how much will be able to reach the areas of interest as well as how long it will take. Consequences are generally more difficult to quantify than probability of occurrence, because they are not restricted to one dimension; considering impact on human health, the environment or monetary loss essentially implies at least three different models of prediction.

Economic loss for the case of a ruptured casing could be assessed by identifying possible remedial steps required, for different severity levels. These would typically be found in contingency plans, operational procedures and other planning documents. In such cases, it is likely that the company has experience with similar, or comparable operations, and has records of the duration of these. By making assumptions on the required personnel, the estimated time to perform operations, and allocating costs to both, the main remaining challenge would be quantifying the uncertainty of each. In the simplest instance, one could use high/medium/low scenarios, and use e.g. a triangular distribution for each uncertain quantity. A simple model connecting the quantities could then be realized using a Monte Carlo framework to make tentative estimates. While similar approaches could be used for other types of consequences, such as impact on human health, this would be more challenging, as the range of different types of outcomes is not purely measured on one scale, and there would need to be a wide range of assumptions related to each. For example, a ruptured casing would likely not in itself cause impaired human health, but if considering that this leads to a surface leak, the assessment of what the severity would be would be conditioned on factors such as what is the leakage rate, what control mechanisms, including warning system would be breached and to what degree, as well as the number of persons subjected to exposure and at what proximity. That being said, the analysis should however focus on scenarios that are plausible and conceivable, and “likely” relative to one another. Data on human tolerance to exposure of substances such as H2S and CO2 are widely available, so consequence assessments could start by identifying the non-acceptable exposure levels, and then evaluate whether such levels could be reached, and under what conditions.

As a part of the analysis, it is also important to consider the assumptions made, and what uncertainties have not been accounted for. For example, the models and data used should be analysed in terms of the understanding of the valid domain, representativeness, simplifications and the implications of assumed independence of events. These aspects can quickly be forgotten when an engineering model has become close to an industry standard, but are taken into use in new settings.

A.5 Risk evaluation

When the analysis has described the risks in terms of probability of occurrence, associated range of consequences given occurrence, and a general description of the strength of knowledge they are based on, it is time to evaluate the risks. The evaluation is primarily a comparison of these numbers with the acceptance or decision criteria established in the assessment context. Typically, this would also include a ranking of how the different risks performed, such as is commonly displayed in a risk matrix. In addition, some analysis methods are also suitable to provide a sensitivity or uncertainty analysis of the impact and importance of risks, scenarios and/or parameters. This type of information is valuable when defining monitoring systems and risk reducing measures.

A.6 Risk monitoring and treatment

To control and manage the risk, the implementation of monitoring systems and other risk reducing measures should be considered. Such measures should be identified to the extent possible, but their implementation needs to consider the change in risk each would cause versus their implementation cost. For casing design, such measures can for example be continuous monitoring for fluid losses or pressure increases behind the casing, periodical monitoring with visual inspections utilizing a downhole camera, or limiting the number of temperature cycles before the design life is exceeded and any extension would have to go through a new assessment. As mentioned, the risk reducing effect of implementing these measures should be quantified, or at least estimated. For some measures that do not introduce any new risks this can be done fairly quickly based on the already performed risk assessment. However, for other measures such as new technologies or cladding of the casing, the process should be repeated to identify and estimate the change in risk.

Appendix B Italian high-temperature geothermal guideline

Different activities during construction and operation of geothermal power plants including drilling, repairs, and testing of wells can impact the environment. In high temperature applications, management of geothermal fluids that are used in power plants require certain level of safety procedures because of their chemical composition, temperature and pressure.

Like other EU countries, environmental aspects in Italy are regulated by EU, national and regional legislation. For geothermal power application regional legislation of Tuscany is of importance for construction and operation of geothermal power plants, as large power plants such as Larderello and Mount Amiata plants are located in the Tuscany area. Even for plants in other regions in Italy, Tuscany represents an important reference [46].

Recently, the first national guidelines on the use of geothermal energy at medium-high enthalpy resources were released in 2016. The best practices that need to be followed in phases of a geothermal project from such resources are described in these guidelines [47].

Some of the most important concerns that have been addressed by the relevant Italian national/regional legislation and standard practices (e.g. national guidelines for use of geothermal energy at medium-high enthalpy resources and regulations in the Tuscany area) are discussed in this section. These concerns mainly include important environmental impacts of geothermal power plants on air, water and ground.

B.1 Air quality

High temperature geothermal fluids usually contain a few percent (usually less than 10wt%) of non-condensable gases (NCG) that require treatment. NCG is composed of CO_2, H_2S, H_2, CH_4 and other trace elements, such as Hg, As, B, Rn, Sb and NH_3.

In Italy, partial reinjection of fluids, excluding NCG, and the adoption of abatement systems for NCG (such as AMIS technology for abatement of H_2S and mercury [48]) are common practice. Gas recirculation has not been adopted in Italy in contrast to Iceland. This is because of high safety and environmental risks due to potential gas breakthrough phenomena occurring if the reinjected gas is not properly mineralized and to the need for high pressure pipelines and equipment necessary for gas reinjection. In contrast to Iceland, where gases are partially injected in highly reactive basaltic rocks rich in calcium, magnesium and iron, composition of Italian reservoir rocks does not guarantee the rapid formation of carbonate minerals [46].

With respect to emissions form geothermal plants, EU and Italian legislation establish air quality standards defining emission limit values only for mercury and arsenic. Emissions from geothermal plants in Italy are fully compliant with these limits [46]. For other contaminants not covered in the EU or Italian legislation, reference values established by international organizations such as World Health Organization (WHO) can be used as good practices by regional authorities. In Tuscany, the regional government has taken different measures to reduce the release of pollutants into the atmosphere including: i) establishment of reference emission thresholds in accordance to technological advancements; ii) introduction and improvement of new/existing on-line emission monitoring systems for air quality; iii) financial support of R&D on new abatement technologies for other pollutants.

B.2 Noise

Noise can be produced during different phases of construction and operation of geothermal power plants. Noise relevant to the context of this report are those arising from production and reinjection wells where noise is produced during the initial setup and construction of drilling site, and noise produced by drilling operations and testing wells after drilling.

Noise production is classified as a form of pollution by Italian law that defines the maximum allowed noise levels, how to handle pollution, etc. By law, each municipality must perform an acoustic mapping and ranking of its local area. The level of noise allowed is regulated according to the local area (including six classes of land use ranging from hospitals to industrial areas) and its usage, and different levels are set for night-time and day-time.

Authorizations for temporary activities (such as drilling wells) that might exceed the noise limits can be requested to local municipalities. After plant construction, all the technologies adopted in geothermal power plants in Italy hold the noise level below the most restrictive standards of Class I (i.e. areas with special protection such as hospitals, schools, etc). Emission level, intake level and quality standard values for this class of land use are 45(day)/35(night) dB(A), 50(day)/40(night) dB(A), and 47(day)/37(night) dB(A), respectively [46].

B.3 Surface water and groundwater

Geothermal fluid contains a wide range of dissolved ions in its liquid phase, such as Na, K, Ca, B, Li, As, F, Mg, Si, chlorides and sulfates that can cause water contamination. Geothermal operation may cause surface and groundwater contamination through different ways, such as accidents during well drilling, continuous small spills of geothermal fluid due to failures in the casing, and accidental spills of mud and geothermal fluid temporarily stored in tanks prior to reinjection.

The reference law for the protection of water in Italy is Part Three, Section II (Environmental regulations on soil protection and combating desertification, protection of water from pollution and management of water resources) of Decreto Legislativo (D. Lgs.) 152/2006 and subsequent amendments [49]. D. Lgs.152/2006 transposes European Directive 2000/60/EC or WFD [21].

Water and groundwater contamination can be avoided through following and performing proper procedures for drilling, operating and maintaining the facilities [46]. Different applicable procedures such as blowout prevention, cementing procedures, waste disposal and material (mud, cement, casing) to be used to avoid pollution to the soil and underground water are described in the recent national guidelines for use of geothermal energy at middle-high enthalpy resources [47]. These guidelines also include further instructions related to monitoring techniques, suitable locations for monitoring stations, and the frequency of inspection.

B.4 Land subsidence

Land subsidence is commonly defined as vertical downward movement of the ground surface that may result from natural processes, or human activities. Geothermal power production is often accompanied by some subsidence [50].

Mitigation of land subsidence phenomena is initially stated in Italian law 183/1989. The main reference is the D. Lgs.152/2006 and subsequent amendments to Part Three. The 2016 guidelines for use of geothermal energy at middle-high enthalpy resources describe procedures and protocols for monitoring and analyzing the spatial-temporal evolution of seismicity, surface deformation and pore pressure [47]. They also require the use of synthetic aperture radar (SAR) interferometry or InSAR techniques complemented by GPS surveys during geothermal operations.

B.5 Induced seismicity

Geothermal fluid extraction and reinjection may generate stress field alteration in the subsurface, resulting in seismicity. This seismicity is however relatively rare and usually of a small magnitude [51].

During recent years, a couple of practices such as performing detailed geological and seismotectonic studies, use of technologies that maintain a balance between produced and reinjected fluid and minimize pore pressure changes at depth, and use of local micro seismic monitoring networks have been established as best practices. These practices help to assess, manage, and mitigate the potential seismic risk posed by some industrial activities, including geothermal [46]. Implementation of these practices has been described in “Guidelines for monitoring seismicity, ground deformation and pore pressure in subsurface industrial activities”, developed by a working group established at the Italian Ministry of Economic Development (MiSE) within the Commission on Hydrocarbon and Mining Resources [52]. The 2016 national guidelines have further detailed the monitoring and operational procedures to be applied for geothermal activities [47].

B.6 Visual impact

One of the other important public concerns is the visual impact of geothermal power plants. This has been raised in [46] focusing on the plants in Italy, more specifically in Larderello that has also historical buildings. It is mentioned that mitigation of visual impact has become increasingly important, and all the new plants are designed in harmony with the natural landscape.

B.7 Waste

Geothermal power plants produce both liquid and solid waste, resulting from different activities such as well construction, operation and maintenance of the plant etc. During well construction, fluid and solid wastes are produced, such as mud, other fluid additives, cement slurry, diesel and lubricant, cleaning fluid, geothermal brine, cuttings, excavated earth and rocks, and industrial waste of different types.

Waste is classified into urban, or industrial waste in the Italian law. Industrial waste is classified into non-hazardous, which is treated similarly to urban waste, or hazardous. Hazardous and non-hazardous waste cannot be mixed. Temporary storage of waste is allowed in an area within the production site, before disposal or recovery, and does not require any authorization. However, the waste must be disposed or recovered at least quarterly, regardless of the volume, or whenever a volume of 20 m^3 of non-hazardous waste, or 10 m^3 of hazardous waste, is reached. In any case, waste cannot be stored for more than one year. Excavated earth and rocks from drilling and construction can be reused or disposed.

Appendix C Industry feedback summary

Some information regarding what the industry partners of GeoWell would like from a risk assessment framework was gathered, along with some relevant regulations.

Compiled summary		
Category	**Topic**	**Summary of replies**
Risk assessment framework	Framework scope	Framework should cover monitoring and risk treatment (measures)
	Risk assessment methods	Examples of suggested risk assessment methods include risk matrix and bow-tie.
	Prescriptive?	General preferance towards a less prescriptive framework where risk assessment methods can be suggested, not not recommended
	Include consequences?	Necessary to also include consequences as part of the framework
	Consequence dimensions	Consequences should cover all of the following: Human safety and health, equipment/system performance, environment, society, financial, other (though perhaps less focus on society and financial)
	Consequence scale/classificatio	Coarse scales can be used for consequence classification, but can use detailed analysis (combined with use of design specs/test data, expert judgments, databases) as an underlying basis
	Qualitative vs quantitative?	Both quantitatively and qualitatively expressing both uncertainty and consequences is suggested
	Information sources	Sources of information for the assessment include well construction plans or schematics, casing material, formation temperature, estimated WHP, change in casing ID for older wells, databases, historical data, maintenance statistics, HSE statistics, operation KPI's, NPI and economical impact.
	Acceptable risk level	No common anwsers regarding what determines acceptable risk levels, some say it may be operator-specific, some say ALARP or using metrics such as time, HSE, financial measures or KPI's, while some say that the law defines measureable risk, while non-measureable risk is defined by risk matrix such as MoVaRisCh.
	Monitoring techniques	Monitoring systems or techniques used include "Traffic Light System" for seismic activity, with automatic notification for predetermined steps, inspections and supervisions, trend analysis based on recorded data and periodic maintenance.
	Risk communication	Risk communication includes internal and external e-mailing, embedding risk assessments as part of all work processes, special planning meetings for risk evaluations, periodical safety review, chains-of-command protocols for information flow and documentation procedures.
Regulations	Legislative documents	Power permits, work permits, National law for mining industry (D. lgs. 624/96, D. lgs. 81/2008). Enviromental law (D.lgs. 152/2006, L. R. 10/2010), operational and environmental permits,
	Risk assessment regulations	Some say there are regulations, others claim there are no regulations for risk assessments
	Monitoring regulations	Generally not, although there are sometimes technical norms, such as for non-destructive controls. Some countries require specific top of cement levels, mandatory pressure gauges and wellhead sensors combined with SCADA monitoring
	Testing regulations	Generally not, but could be technical norms, such as well control procedures. Could also be requirements such using water-based (not oil-based) testing fluids due to environmental regulations,
	Regulations governing loss of containment	Generally not. On Iceland, casing design has to comply with the NZ standard for pressure sealing. Could also be environmental policies that concern this topic.
	Regulations governing specific hazards/consequences	Environmental laws could require an environmental impact assessment. Could also govern other consequence types.
	Risk-reducing measures	Mixed replies. Some say partly for injection and in other cases through ETA and required permitting.
Test case		Corrosion and material changes in HT wellhead plugs, H2S incident during drilling, steam kick/blowout, collapsed casing due to poor cement job, rapid corrosion of liner/casing for a multizone wellbore, kick during workover, BOP failure, failure of casing or cement during production

Appendix D Legislation overview

Following Table 3 presents a non-exhaustive list of relevant directives together with a short summary and relevance of them.

Table 3. Relevant EU directives for geothermal industry

Name	Description	Relevance/remark
Water framework Directive (WFD) or Directive 2000/60/EC [21]	The water framework Directive, adopted in 2000, introduces a new legislative approach to managing and protecting water, based on natural geographical and hydrological formations, i.e. river basins, and not on national or political boundaries. This Directive sets out a precise timetable, with 2015 as the deadline for getting all European waters into good condition [53]. The main objective is to establish a framework to protect inland surface waters, transitional waters, coastal waters and groundwater [21].	A review of the status of water sources shall be performed and any steps shall be taken to prevent or limit input of pollutants into the body of water and to prevent the deterioration of the status of all bodies of water. Essentially precautionary approach shall be taken. Pollution through the discharge, emission or loss of priority hazardous substances must cease or be phased out. Anthropogenic induced pollution shall be reversed and monitored for through systems to detect or give warning.
Groundwater Directive or Directive 2006/118/EC [22]	This Directive complements the water framework Directive by setting up specific measures to prevent pollution or limit the inputs of pollutants into groundwater, criteria for the assessment of good groundwater chemical status and criteria for the identification and reversal of significant and sustained upward trends and for the definition of starting points for trend reversal.	Specific measures are established to prevent and control groundwater pollution.
Environmental quality standards Directive (EQSD) also known as the priority substances Directive or Directive 2008/105/EC [23]	This Directive also complements the WFD. According to Article 16 of the WFD, the first step to set out strategies against pollution of water, was to establish a list of priority substances to become Annex X of the WFD. This first list was replaced by Annex II of the EQSD, which sets environmental quality standards (EQS) for the substances in surface waters (river, lake, transitional and coastal). A subset of particular concern was designated as priority or priority hazardous substances [54].	EQSD put limits on concentration of 33 priority substances and 8 other pollutants. Good chemical status (refer to WFD for definition) is reached for a water body when it complies with the EQS for all the priority substances and other pollutants listed in Annex I of the EQSD [54]. Some of the substances are relevant for geothermal industry including mercury and benzene.

Name	Description	Relevance/remark
Natura 2000 based on birds Directive (Directive 79/409/EEC) [24] amended in 2009 by Directive 2009/147/EC [34], and habitats Directive (Directive 92/43/EEC) [25]	Natura 2000 is a network of core breeding and resting sites for rare and threatened species, and some rare natural habitat types that are protected based on the birds and habitats Directives. It covers 18% of EU's land area and 6% of its marine territory. The aim of the network is to ensure the long-term survival of Europe's most valuable and threatened species and habitats [55]	Stronger prevention measures must be utilized near areas covered by Natura 2000.
Directive 2011/92/EU on the assessment of the effects of certain public and private projects* on the environment	This Directive is the updated version of the environmental impact assessment (EIA) Directive or Directive 85/337/EEC [27]. It provides a high-level protection of the environment by integrating environmental considerations in the preparation of projects. The Directive requires that EIA is performed for a project subjects to Annex I (mandatory) or Annex II (discretion of Member States). Effects of the project is assessed on different factors including human beings, fauna and flora, soil, water, air, climate and the landscape, the inter-action between the factors mentioned before, and material assets and the cultural heritage.	Deep geothermal drilling and surface facility for production of electricity/steam/hot water are included in Annex II of Directive meaning that national authorities decide whether an EIA is needed [26] for a project or not. The EID Directive has been amended three times in 1997 by Directive 97/11/EC [56], 2003 by Directive 2003/35/EC [57], and 2009 by Directive 2009/31/EC [58]. The original Directive of 1985 and its three amendments have been codified by Directive 2011/92/EU [26] that has been amended in 2014 by Directive 2014/52/EU [40].
Environmental liability Directive (ELD) or Directive 2004/35/EC [28]	ELD establishes a framework of environmental liability based on the "polluter-pays" principle, to prevent and remedy environmental damages. It aims at ensuring that the financial consequences of certain types of harm caused to the environment will be borne by the economic operator who caused this harm. Operator is defined as any natural or legal, private/public person who operates or controls the damaging occupational activity or, where this is provided for in national legislation, to whom decisive economic power over the technical functioning of such an activity has been delegated [59].	This Directive requires that the operator takes immediate preventive or remedial actions in case of damage to the environment (including damage to protected species and natural habitat, water damage, and land damage). The ELD was amended three times through Directive 2006/21/EC on the management of waste from extractive industries [29], through CCS Directive [58], and through Directive 2013/30/EU on safety of offshore oil and gas operations and amending Directive 2004/35/EC [60].

*In case of relevance of public plans and programs, the environmental assessments shall be based on Directive 2001/42/EC on the assessment of the effects of certain plans and programmes on the environment [61].

Name	Description	Relevance/remark
Directive 2006/21/EC on the management of waste from extractive industries [29]	This Directive broadened the scope of ELD by adding the management of extractive waste. The goal is to lay down minimum requirements to prevent or reduce as far as possible any adverse effects on the environment (in particular water, air, soil, fauna and flora and landscape), or on human health brought about as a result of the management of waste from the extractive industries.	The Directive should cover the management of waste (e.g. minerals) arising from the prospecting, extraction (including the pre-production development stage) of land-based extractive industries. It does not apply to injection of water or reinjection pumped groundwater. National authorities should ensure that operators take all necessary measures to prevent or reduce as far as possible any negative effects, actual or potential, on the environment or on human health because of the management of waste from the extractive industries. The mineralized geothermal brine sometimes contains enough corrosive salts and heavy metals (mercury, silica, H_2S etc.) requiring special recovery and disposal units [62].
Directive 92/91/EEC [63] and Directive 92/104/EEC [30] on safety and health of workers, in mineral-extracting industries	These Directives lay down minimum requirements for improving the safety and health protection of workers in surface and underground mineral-extracting industries (Directive 92/104/EEC) and in mineral-extracting industries through drilling (Directive 92/91/EEC).	Employers must ensure that a safety and health document is drawn up and kept up to date. This document must be drawn up before work starts, and demonstrate in particular that risks to which workers are exposed have been determined and assessed; adequate measures will be taken to attain the aims of these Directives; and the design, use and maintenance of the workplace and equipment are safe.
Industrial emissions Directive (IED) or Directive 2010/75/EU [31]	The IED aims to achieve a high level of protection of human health and the environment by reducing harmful industrial emissions across the EU, in particular through better application of best available techniques (BAT).	Geothermal power plants are not listed in Annex I of the IED. However, this Directive seems to be the most relevant for emissions from such plants and industry.
Environmental noise Directive (END) or Directive 2002/49/EC [32]	This directive aims to determine exposure to environmental noise, ensure that information on environmental noise and its effects is made available to the public, and prevent and reduce environmental noise where necessary and preserve environmental noise quality where it is good [33].	The Directive applies to noise to which humans are exposed, particularly in built-up areas, in public parks or other quiet areas in an agglomeration, in quiet areas in open country, near noise-sensitive buildings (e.g. schools, hospitals). It does not apply to noise that is caused by the exposed person himself, noise from domestic activities or created by neighbours, or at work places or inside means of transport [33].