Project acronym and title:

SECURe – Subsurface Evaluation of Carbon capture and storage and Unconventional risks

# SUMMARY OF RECOMMENDATIONS FOR ENVIRONMENTAL MONITORING FOR GEOENERGY OPERATIONS IN EUROPE

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*Partly based on numerous contributions and finding from SECURe partners as described in the different work packages (see references section for key reports)*

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## Public introduction

Subsurface Evaluation of CCS and Unconventional Risks (SECURe) is gathering unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to underpin subsurface geoenergy development. The main outputs of SECURe comprise recommendations for good practice for unconventional hydrocarbon production and geological $CO_2$ storage. The project is funded from June 2018–May 2021.

The project is developing monitoring and mitigation strategies for the full geoenergy project lifecycle; by assessing plausible hazards and monitoring associated environmental risks. This is achieved through a program of experimental research and advanced technology development that includes demonstration at commercial and research facilities to formulate good practices. We will meet stakeholder needs; from the design of monitoring and mitigation strategies relevant to operators and regulators, to developing communication strategies to provide a greater level of understanding of the potential impacts.

The SECURe partnership comprises major research and commercial organisations from countries that host shale gas and CCS industries at different stages of operation (from permitted to closed). We are forming a durable international partnership with non-European groups; providing international access to study sites, creating links between projects and increasing our collective capability through exchange of scientific staff.

## Executive report summary


*Decarbonization of the energy sector plays an important role in achieving the European Commission's EU Climate Target Plan 2030 to cut net greenhouse gas emissions by at least 55% by 2030. A transition of the energy system is required to decarbonize the energy system, (likely) involving: (1) an increasing contribution of more sustainable energy sources such as wind, solar and geothermal energy, (2) a transition of the type of fossil fuel required during transformation of the energy system from coal to gas, (3) lowering $CO_2$ emissions to air by an acceleration of subsurface storage of $CO_2$ as part of wider industrial decarbonisation by CCS, and (4) including hydrogen as an energy carrier to buffer intermittent demand and supply of sustainable energy. Focussing on risks and environmental monitoring associated with these geoenergy applications, this summary mainly considers:*

- *Primary energy sources, including conventional and unconventional hydrocarbons and geothermal energy*
- *Subsurface storage of $CO_2$*
- *Energy buffering systems, including seasonal storage of natural gas and energy buffering by hydrogen storage in porous reservoirs such as depleted gas fields*

*SECURe mainly focussed on four main domains that are of prime importance for risks associated with CCS and UHE:*

- *Well integrity and leakage*
- *Subsurface integrity and fluid or gas migration*
- *Induced seismicity*
- *Stakeholder engagement & participatory monitoring*

*This report (1) discusses the risks studied for the four domains within a larger context of risks associated with CCS and UHE, (2) provides some crossover lessons learned and general implications for geoenergy operations performed for CCS, UHE as well as for some other subsurface activities in the energy domain, and (3) outlines a summary of general, overarching recommendations for environmental monitoring that can assess and mitigate these risks.*

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# 1 Introduction

## 1.1 DELIVERABLE CONTEXT

Research performed within the SECURe project gathered unbiased, impartial scientific evidence for risk mitigation and monitoring for environmental protection to underpin subsurface geoenergy development. The project mostly addressed risks associated with unconventional gas extraction [UHE][1] and carbon capture and storage [CCS], although other types of geoenergy operations were also studied in individual research tasks (e.g., geothermal energy, acid gas storage and seasonal storage of natural gas).

Research mainly focussed on four main domains that are of prime importance for risks associated with CCS and UHE:

- Well integrity and leakage
- Subsurface integrity and fluid or gas migration
- Induced seismicity
- Stakeholder engagement & participatory monitoring

The main overarching outputs of SECURe comprise recommendations for good practice for unconventional hydrocarbon production and geological $CO_2$ storage. These recommendations are reflected in a series of factsheets (BGS, 2021a, b) that follow a risk assessment framework developed in WP2 of the project (see Ter Heege et al., 2021 for a summary and references to specific studies).

This report aims to (1) discuss the risks studied for the four domains within a larger context of risks associated with CCS and UHE, (2) provide some crossover lessons learned and general implications for geoenergy operations performed for CCS, UHE as well as for some other subsurface activities in the energy domain, and (3) outline a summary of general, overarching recommendations for environmental monitoring that can assess and mitigate these risks. It should be regarded as a concise summary of recommendations and larger implications of research performed in the SECURe project. To avoid repetition, it does not provide a comprehensive review of environmental monitoring, list of references or findings of research performed in the SECURe project. These items already have been reported in detail elsewhere in the SECURe project deliverables (note that relevant references and deliverables can be found at the SECURe project website[2]).

## 1.2 BACKGROUND

The European Commission's EU Climate Target Plan 2030 outlines the ambition to cut net greenhouse gas emissions by at least 55% by 2030[3]. Decarbonization of the energy sector plays an important role in achieving this ambition. A transition of the energy system is required to decarbonize the energy system, (likely) involving: (1) an increasing contribution of more sustainable energy sources such as wind, solar and geothermal energy, (2) a transition of the type of fossil fuel required during transformation of the energy system from coal to gas, (3) lowering $CO_2$ emissions to air by an acceleration of subsurface storage of $CO_2$ as part of wider industrial decarbonisation by CCS, and (4) including hydrogen as an energy carrier to buffer intermittent demand and supply of sustainable energy and efficiently transport energy from source to demand, for example through pipelines (see also Ter Heege et al., 2021 and references therein).

Focussing on risks and environmental monitoring associated with geoenergy operations in naturally-occurring subsurface reservoirs, this summary mainly considers:

- Primary energy sources, including conventional and unconventional hydrocarbons and geothermal energy
- Subsurface storage of $CO_2$

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[1] Note that unconventional hydrocarbon extraction [UHE] rather than unconventional gas production [UGP] is used in this report as hydrocarbons other than dry natural gas (such as condensates or oil) are increasingly produced by projects in North America, and risks associated with UHE covered in the SECURe project involve a wider range of operations (e.g. waste water disposal) than production alone.

[2] https://securegeoenergy.eu/

[3] https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1599 (accessed January 2021).

- Energy buffering systems, including seasonal storage of natural gas and energy buffering by hydrogen storage in porous reservoirs such as depleted gas fields

Other prominent energy sources such as coal mining or nuclear energy, or energy buffering systems such as compressed air or hydrogen storage in salt caverns do not involve naturally-occurring subsurface reservoirs are not considered here.

**Conventional hydrocarbon extraction [CHE]** has a long track record in many countries worldwide. It plays an important role in ensuring the energy security of countries. Because of a lower carbon footprint compared to coal mining, some EU Member States consider a transition of coal- to gas-dominated energy mix an important (first) step in reducing the carbon footprint of national energy systems. Other EU Member States are (also) looking to reduce the contribution of conventional hydrocarbons in their energy mix as part of energy transition policies that aim to replace fossil fuels with sustainable energy sources, such as wind, solar or geothermal energy. Besides being primary energy sources, oil & gas are also used for strategic long term energy buffers or buffering seasonal fluctuation in energy supply and demand. Risks and environmental monitoring associated with CHE were not explicitly studied in the SECURe project, but some studies investigated effects of methane leakage without specifically distinguishing CHE from UHE or induced seismicity and ground motions associated with seasonal storage of natural gas.

Interest in **unconventional hydrocarbon extraction [UHE]** has been motivated by the rapid global increase in hydrocarbon production from unconventional resources over the last 20 years. However, the vast majority of production takes place in North America. Unconventional hydrocarbons can be produced in the form of gas, condensate or oil, depending on variations in maturity within plays (Ter Heege et al., 2021). Although generally considered to have a higher carbon footprint than CHE, UHE has been considered to reduce the carbon footprint by replacing coal in the energy mix. UHE was still on the agenda in some EU Member States at the start of the SECURe project, but is now on hold or suspended in most, if not all, Member States, due to (1) priorities on developing other energy resources (e.g. sustainable energy resources or conventional gas), (2) concerns with environmental impacts, (3) difficulties with obtaining economically viable production (e.g. in Poland) and (4) issues with induced seismicity (e.g. in England). Research in the SECURe project on risks and environmental monitoring associated with UHE focus on well integrity, subsurface integrity and gas migration, and induced seismicity associated with large scale injection of waste water from unconventional hydrocarbon operations in the U.S.A.

Worldwide, the number of projects aiming at **geothermal energy extraction [GEE]** is increasing as technology improves, and due to incentives to accelerate development of sustainable energy sources to lower the carbon footprint of energy systems. Geothermal energy can be used for the generation of electricity or direct heat that can be used for industrial processes or supplied to greenhouses or district heating networks. Worldwide, the installed geothermal electric capacity increased from 7000 MWe in 1995 to over 20,000 MWe in 2015, and for direct use (heating) the installed capacity increased from 10,000 MWt in 1995 to 70,000 MWt in 2015 (Buijze et al., 2019 and reference therein). In many EU Member States, geothermal energy is developed as part of ambitions to develop a more sustainable energy mix. Within the SECURe project, geothermal energy projects were considered in research on stakeholder engagement and participatory monitoring.

$CO_2$ emissions and concentrations in the atmosphere can be significantly reduced by **subsurface storage of $CO_2$ [CCS]** in relatively deep (typically > 1 km) subsurface rock formations. Initially, $CO_2$ was primarily used for enhanced oil recovery, but currently projects that permanently store $CO_2$ in depleted gas fields or aquifers are also being developed. If $CO_2$ from an emission source is captured, transported and stored in the subsurface, it directly reduces greenhouse gas emissions of fossil fuel based energy systems and helps mitigating associated global climate change. The Global CCS Institute states that there are currently 65 commercial CCS facilities worldwide, of which 26 are operational, 3 are under construction, 13 are in advanced development and 21 are in early development. CCS facilities that are currently in operation can capture and permanently store around 40 Mt of $CO_2$ every year. The USA is leading with 38 large-scale CCS facilities in operation and development with a total capture capacity of over 30 Mt/year. In Europe, 13 commercial facilities are in operation or development, followed by 10 facilities in Asia pacific, and 3 in the Middle East. In particular, long term injection and containment, and the unique physicochemical characteristics of $CO_2$ affecting reactive fluid flow are key issues for CCS risk management. Risks and environmental monitoring associated with CCS well integrity and subsurface integrity and gas migration are prominent research topics in the SECURe project.

**Underground hydrogen storage [UHS]** was not studied within the SECURe project, but is included in this summary as a relative new technology that gains momentum as an energy buffering system for intermittent solar and wind energy. Currently, storage projects targeting naturally-occurring subsurface reservoirs are mainly in relatively shallow (<1 km) aquifers (e.g., Beynes in France and Lobodice in Czech Republic) or depleted gas fields (e.g., Hychico in Argentina and Sun Storage in Austria), and involves co-mixing hydrogen with natural gas in different amounts (10-50%). Some interesting links (e.g., cyclic injection/extraction) as well as new aspects (subsurface hydrogen reactivity) exist between UHS and, for example, **underground storage of natural gas [UGS]** or CCS.

Much can be learned by looking at **crossovers between geoenergy activities**. The long track record of risk assessment for conventional gas operations provides important lessons learned that can be applied to other geoenergy operations. Focussing on common grounds as well as on differences helps focussing further research and risk assessment for subsurface operations in geoenergy activities with more limited track records. Availability of data is also an issue. For example, industry in North America has over a decade of experience with unconventional hydrocarbon extraction, and many thousands of wells have been drilled for UHE. Therefore important lessons can be learned for other subsurface activities, in particular in relation to efficiency (and thereby safety) of drilling and well operations, and experience with (remediation of) well integrity. Some good practices[4] from the oil and gas industry might, with modifications to account for differences in operations and fluid properties, be applicable to $CO_2$ storage. Long term processes and containment after decommissioning and abandonment[5] are particularly important for CCS projects, but large scale CCS has not yet reached the stage of permanent abandonment of storage sites. At least, not to the scale where these long term effects can be systematically evaluated. Therefore, lessons learned from decommissioning oil & gas infrastructure could be valuable for future stages in CCS projects. Effects of temperature changes in the reservoir and surrounding (cap)rock are particular important for CCS, and also well-studied for geothermal energy extraction, for example in the context of induced seismicity. Some risk aspects associated with cyclic injection and extraction cycles for underground hydrogen storage are also relevant for cyclic and extraction of natural gas with more projects and experience worldwide. On the other hand, UHS is unique in that large volumes of hydrogen are not present in subsurface reservoir, contrary to natural gas or $CO_2$. That introduces additional aspects in risk assessment of UHS, such as microbial activity that can alter rock or well materials and affect the composition of the hydrogen stream (Heinemann et al., 2021).

[4] As good practices may vary between regions and projects, the term "best practices" is avoided in this report. Instead, "good practices" or "recommended practices" are used to indicate practices that may be more widely or generally applied to improve current practices.
[5] See Ter Heege et al. (2021) for details on terminology related to the decommissioning of wells after permanent suspension of operations.

# 2 Risks associated with geoenergy operations

## 2.1 RISK BOW-TIES DEVELOPED IN THE SECURE PROJECT

Risk assessment approaches generally describe risks in terms of (1) hazards, events or incidents, (2) causes or threats of events, (3) impacts, effects or consequences of events, and (4) mitigation measures or barriers that can focus on prevention or on control or remediation (Ter Heege et al., 2021, and references therein). For risk assessment frameworks, the definitions of hazards is critical and depending on the level of detail that is considered feasible for distinguishing risks. If many hazards are specified, causes leading to the hazard and potential impacts can be analysed in detail, and closely linked to specific laboratory, modelling or field studies. However, lack of available data from field cases may hamper proper (statistically meaningful) assessment of risks. If few hazards are specified, risk management may be more easily implemented in operational protocols, and most important risk mitigation measures can be more readily prioritized. However, if too many hazards are lumped together it may be more difficult to establish causal relations between operations and risks, and implementation of suitable mitigation measures may be hampered. Besides distinction of relevant hazards and risks, it is also important to define the impact area or receptor of risks. For example, impacts can be defined in terms of specific processes or elements in operations, efficiency of operations in general, or human health, safety and environment.

Within the SECURe project, a qualitative bow-tie approach coupled with a semi-quantitative risk assessment tool is developed that is based on (1) expert opinion and user input on fact-based, (2) non-subjective questions regarding the relevance of threats and receptors, (3) the effectiveness of barriers, and (4) the uncertainty surrounding the assessment of barrier effectiveness. Nine bow-ties were developed which were taken to distinguish hazards associated with UHE and CCS operations (Figure 2-1):

- **Unconventional hydrocarbon extraction:**
  - Release of natural gas from wells during exploration, production and after decommissioning and abandonment (SBT01[6])
  - Release of natural gas from the shale production zone (SBT02)
  - Release of hydraulic fracturing fluid or flowback waters under pressure from wells during, between and following hydraulic fracturing stages (SBT03)
  - Release of hydraulic fracturing, flowback or formation fluids from the shale production zone (SBT04)
  - Induced/triggered seismicity and ground motions associated with hydraulic fracturing (SBT05)
- **Underground $CO_2$ injection:**
  - Release of $CO_2$ at pressure from a well during the injection phase (SBT06)
  - Release of $CO_2$ or formation waters from the storage complex through wells (SBT07)
  - Release of $CO_2$ or formation waters from primary storage reservoirs through geological formations or discontinuities (SBT08)
  - Induced/triggered seismicity and ground motions associated with $CO_2$ injection (SBT09)

These bow-ties basically focus on loss of containment in the subsurface (i.e. leakage along wells, geological structures) and induced seismicity. They form the basis for “Good practice summary factsheets” compiled by BGS (2021a, b).

## 2.2 COMPARISON OF RISKS AND OVERARCHING CONCEPTS FOR DIFFERENT GEOENERGY APPLICATIONS

Numerous risk assessment protocols, industry standards and recommendations for good practices for UHE and CCS have been compiled in previous studies (see for example Ter Heege et al., 2021 and references therein). Focus of the SECURe project was on UHE and CCS, but other geoenergy applications such as seasonal storage of natural gas and acid gas storage were addressed in some studies as well. In a previous project, a review of risks associated with unconventional hydrocarbon extraction in the U.S.A. and Canada

[6] SBT-SECURe bow-tie with number for reference (cf. Figure 2-1).

was compiled (Ter Heege, 2017). This review focussed on describing the most important risks and their potential impacts on human health, safety and environment (HSE). Due to the massive scale of operations associated with unconventional hydrocarbon extraction in the U.S.A. and Canada, vast amount of data and experience is available which allows a ranking of the relative importance of risks. Below, risks and overarching concepts are discussed for the four domains that the SECURe project focussed on: (1) Well integrity and leakage, (2) subsurface integrity and fluid or gas migration, (3) induced seismicity, and (4) stakeholder engagement and participatory monitoring. The risks are briefly described, and some important factors, mitigation measures and relative importance for different geoenergy applications are discussed (see Figure 2-1 for graphical reference of labels **R1-R9** and **SBT01-SBT09**, and Ter Heege et al. 2021 for list of references). It should be emphasized that the relative importance of risks is different for different geoenergy applications. Accordingly, the risks listed below should not be regarded as equally important in all applications, and risks should be independently assessed for each geoenergy application (i.e. some risks may be prominent in one application, but negligible in another).

### Release of fluids or gases through wells

The SECURe project addressed risks related to release of fluids of gases through wells in 2 bow-ties for UHE (**SBT01, SBT03**) and 2 bow-ties for CCS (**SBT06, SBT07**, cf. section 2.1), distinguishing between operational phases and type of fluid or gas that is potentially released. If impacts on HSE are considered, the risk can be defined as contamination due to loss of well integrity and leakage associated with drilling, construction, completion, operation, decommissioning or abandonment of wells (**R1**). Wells are usually designed with well barriers that ensure zonal isolation of different well sections, i.e. exchange of fluids or gases between different sections or formations is prevented (Figure 2-1). If zonal isolation is absent or jeopardized during well operations, fluids or gases may migrate upwards from reservoir or overburden formations, and, in extreme cases of full loss of well integrity, may reach shallow aquifers or surface environment and lead to contamination.

The following main factors for different phases of well placement may lead to issues with well integrity or zonal isolation:

- <u>Design</u>: Improper well design with too few or improper well barriers (e.g., large open hole well sections or single cemented casings at shallow depths)
- <u>Drilling</u>: Borehole instability during drilling that may lead to damaged or unstable borehole walls (e.g., improper mud weights for encountered formation pressure)
- <u>Completion</u>: Improper cementation of wells that may lead to (partially) uncemented well sections and lack of zonal isolation (e.g., unstable or irregular borehole walls or washouts in case of drilling through salt formations that hamper proper cementation)
- <u>Operation</u>: Pressure and temperature variations during well operations (e.g., production-**SBT01**, hydraulic fracturing-**SBT03** or $CO_2$ injection-**SBT06**) that may lead to critical stress state for failure of well materials
- <u>Drilling/operation/abandonment</u>: Interaction of formations with well systems that may lead to critical stress state for failure of well materials (e.g., salt creep, formation damage or sanding)
- <u>Decommissioning</u>: Improper plugging of wells during decommissioning that may lead to long term upward migration of fluids or gases over the plug or well (**SBT01, SBT07**; Figure 2-1)

### Fluid or gas migration due to loss of subsurface integrity and containment

The SECURe project addressed risks related to release of fluids of gases out of targeted production or storage reservoirs through geological seals in 2 bow-ties for UHE, distinguishing between operational phases and type of fluid or gas that is potentially released (**SBT02, SBT04**) , and 1 bow-ties for CCS (**SBT08**, cf. section 2.1). If impacts on HSE are considered, the risk can be defined as contamination due to the loss of geological containment and migration of hazardous substances through geological seals such as caprocks or faults (**R5**). Subsurface reservoirs used in geoenergy applications generally rely on top seals such as impermeable caprock formations, and, in some cases, on lateral seals such as fault seals that hamper exchange of fluids or gases between the reservoir and other formations (note that this is a simplified representation of all possible seals and trapping mechanisms). If operation-induced pressure and temperature variations change the properties of these seals, loss of subsurface integrity may occur, potentially leading to upward migration of fluids or gases. If operations are at relatively shallow depth or migration pathways extend over large distances or fluids or gases may reach shallow aquifers or surface environment and lead to contamination.

The following main factors for different operations may lead to issues with subsurface integrity and containment:

- Seal integrity: Operation-induced pressure, temperature and stress changes that may lead to development of permeable fractures in caprocks or fault reactivation and permeability increase of fault seals (e.g., caprock fracturing leading to loss of $CO_2$ or $CH_4$ from storage reservoirs-**SBT08**)
- Hydraulic fracturing: Extensive hydraulic fracturing that may lead to a fracture disturbed zone (stimulated reservoir volume) that enables upward migration of fluids or gases (e.g., hydraulic fractures reaching shallow aquifers-**SBT02**, **SBT04**)
- Rock properties: Operation-induced changes in rock or fault properties that alter the response of reservoirs and seals (e.g., chemical reactions between injected $CO_2$ or $H_2$ and rock materials)

**Induced seismicity and ground motions**

The SECURe project addressed induced seismicity risks in 1 bow-tie for hydraulic fracturing associated with UHE (**SBT05**) and 1 bow-tie for $CO_2$ injection associated with CCS (**SBT09**, cf. section 2.1). If impacts on HSE are considered, the risk can be defined as structural damage due to induced seismicity associated with fluid injection (**R8**). Induced seismicity is associated with movement along discontinuities such as faults or bedding planes that results in the release of energy in the form of earthquakes (i.e. seismic fault slip or rupture). Stress changes at faults can lead to seismic fault slip and seismic events with magnitudes that can be felt at surface or cause damage to surface infrastructure. It is important to note that movement along faults does not always lead to induced seismicity, i.e. aseismic fault slip may also occur. Therefore, analysis of fault reactivation by considering stress changes alone is not sufficient to address the likelihood of occurrence. It is important to consider seismic magnitudes (*M*) in addressing induced seismicity risks as seismic events: (1) seismic events with relatively low magnitudes (also sometimes referred to as micro-seismicity, roughly $M < 2$), (2) seismic events with magnitudes that can be felt at surface (roughly $M > 2$), and (3) seismic events with magnitudes that can cause damage to surface infrastructure (roughly $M > 3$ to 4). Note that the magnitude thresholds critically depend on site-specific conditions, such as properties of overburden and soils (in terms of seismic wave propagation) and surface environments (e.g., population density), and should not be regarded as generally applicable. Micro-seismicity is generally not considered to lead to significant risks, and is often used to monitor the spatial extent of fractures or fracture disturbed zone, mainly in UHE. Felt seismicity is mainly a concern because of its effect on public perceptions of geoenergy applications. Damaging seismicity is a major concern that may lead to suspension of operations, particularly in CGE (e.g., gas production in the Groningen gas field in the Netherlands), UHE (e.g., waste water injection around Oklahoma in the U.S.A. and shale gas fracturing in the U.K.), GEE (e.g., geothermal projects in Basel, Switzerland and near Pohang in South Korea). The magnitude threshold for damaging seismicity can vary considerably between regions. Part of the reason is that damage of surface infrastructure is more directly linked to ground motions (as measured, for example, by peak ground velocity or peak ground acceleration) than to seismic magnitude (where hypocentre depth and overburden properties affect the relation between magnitudes and ground motions).

The following main operations and factors that may lead to issues with induced seismicity and ground motions:

- Reservoir stimulation: Short term fluid injection for stimulation of reservoir permeability that may lead to induced seismicity mainly due to local increase in pressure (e.g., hydraulic fracturing for UHE-**SBT05** or GEE).
- Long term fluid injection: Disposal of fluids or gases that may lead to induced seismicity by combined effects of pressure and temperature changes (e.g., $CO_2$ injection-**SBT09** or wastewater injection associated with UHE in the U.S.A.).
- Hydrocarbon extraction: Production of hydrocarbons from subsurface reservoirs that may lead to induced seismicity mainly by reservoir compaction and (poroelastic) stressing on faults (e.g., gas production from porous reservoirs in case of CHE).
- Geothermal energy: Heat or electricity production using circulating fluids by combined injection and extraction of fluids with net balance in fluid mass that may lead to induced seismicity by local pressure, temperature and stress changes.

**Surface spills, leaks and emissions from well site operations**

The SECURe project mainly focussed on subsurface risks leading to leakage or induced seismicity. Surface causes for leakage are therefore not explicitly (or only indirectly) addressed. The reason to include them in this summary is threefold: (1) Analysis of causes for contamination aquifers, soils or surface environment associated with UHE identified spills and leaks from surface infrastructure (such as pipelines and storage tanks) as one of the most important causes of contamination (see Ter Heege, 2017 and references therein), (2) the direct link between $CO_2$ and $CH_4$ emissions and carbon footprint of geoenergy applications that is important considering the overarching objective of the SECURe project to help reducing the carbon footprint by extending the knowledge base and developing innovative technologies, and (3) the surface risks of leakage and emissions are an important consideration in stakeholder engagement and participatory monitoring.

The following main risks and impacts associated with HSE can be distinguished:

- Reduced air quality due to emissions to air (**R2**): Local air quality around geoenergy operations can be affected, for example due to fossil fuel combustion to operate equipment (e.g., $CO_x$, SOx, NOx), gas treatment (e.g., volatile organic compounds) and well pad construction (particulate matter). Release of gases through wells and gas migration due to loss of subsurface containment (e.g., $CO_2$ or $CH_4$), mentioned above can also contribute to reduction in air quality. This risk is particularly relevant for geoenergy application that require large scale of operations such as UHE in the US.A. and Canada.
- Greenhouse gas emissions that affect the global carbon footprint (**R2**): Emissions of greenhouse gases ($CO_2$ or $CH_4$) from subsurface or surface sources contribute to the global climate change. Important considerations are local versus global costs and benefits of geoenergy applications (e.g., local effects of a CCS project contributing to reduction in greenhouse gas emissions globally). This risk is of prime concern for CGE, UHE and CCS.
- Contamination due to surface spills & leaks associated with the transport, storage or handling of hazardous substances (**R4**): Spills and leaks may occur due to human error or failure of equipment or infrastructure. This risk is considered the main source of surface contamination associated with UHE in the US.A. and Canada where large volumes of drilling or hydraulic fracturing fluids need to be transported, stored and handled. It is likely less relevant for other geoenergy applications, although public concerns of $CO_2$ leakage from surface infrastructure have been important for CCS projects.

**Lack of a social license to operate**

The SECURe project mainly addressed this risk through studies of stakeholder engagement, participatory monitoring and outreach. A social license to operate is critical in geoenergy applications. It can be considered as a series of conditions covering both social and technical aspects that enable ongoing acceptance of geoenergy operations by local communities, general public and other stakeholders. Many examples exist where the lack of a social license to operate has significantly delayed or permanently suspended geoenergy projects. The risk is most prominent for geoenergy applications with large scale of operations (i.e. mainly UHE in the U.S.A. and Canada) and associated impacts on local environments, or for operations in densely populated areas. However, as some impact on local environment is inevitable, virtually all geoenergy applications are affected by issues related to social license to operate and stakeholder perceptions to some degree.

Besides the risks mentioned in previous sections, the following important risks and factors associated with HSE that are critical in stakeholder engagement, participatory monitoring establishing a social license to operate:

- Reduced general safety around well site operations due to accidents related to well site construction, transportation of materials and traffic (**R1**): Important considerations are the safety of workers at well sites, traffic to and from well sites, and impacts of operations on local communities. Some accidents mostly affect personnel occupied by geoenergy operators (e.g., well site accidents), while other may also impact local communities (e.g., traffic to/from well sites). As accidents have a direct impact on HSE, general safety is usually a prominent consideration in risks management protocols for geoenergy operations.
- Disturbance of landscape & environment due to changes in land or water use, interference with wildlife or impacts on biotopes and local communities (**R6, R7**): Geoenergy operations inevitably lead to some disturbance of local environment as it requires change of land use and surface

infrastructure. Some disturbance can be permanent and continuous (e.g., well site development), while it also can be temporary or infrequently (e.g., noise related to well site activities).

- Understanding of risks and consensus on acceptable risks: Perceptions and understanding of risks are generally challenging concepts in stakeholder engagement and discussions on a social license to operate for geoenergy applications. While risks are associated with any (industrial) activity, risks associated with geoenergy applications are often perceived as unique in areas without prior activities or considered as cumulative in areas with other industrial activities. Also, some risks are intuitively accepted based on experience (like driving a car), while risks associated with geoenergy applications are often perceived differently due to lack of experience or control. Besides understanding of technical risks, perception of risks may also have negative side effects, such as lower value of real estate. Because of these aspects risks associated with geoenergy applications are more readily considered unacceptable by local communities. Establishing a shared understanding and definition of acceptable risks including considerations of their relative importance compared to other risks are therefore important aspects in stakeholder engagement and defining conditions for a social license to operate. Of course, the result of such process can be that risks are considered too high to obtain a social license to operate, but it may be more easily to outline alternative options or locations based on the engagement process.
- Balance in costs and benefits: For many geoenergy applications impacts are local (e.g., well site construction), while benefits are national (e.g., improving economics) or global (e.g., mitigating climate change). Balancing costs and benefits can help in establishing a social license operate. Note that not only financial compensation should be considered (and is sometimes negatively perceived as pay-off), but other types of benefits (e.g., better roads or better access to facilities) should be considered as well.

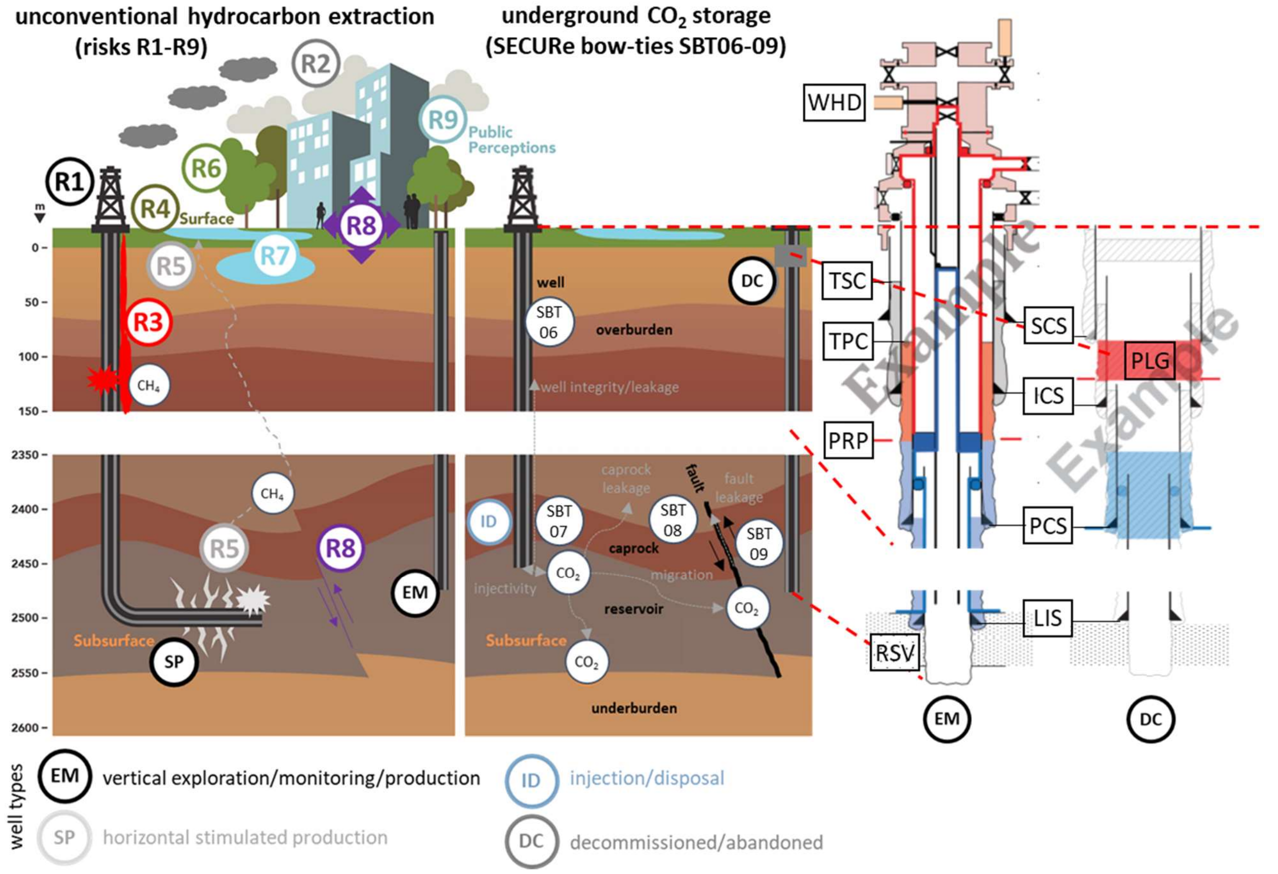


**Figure 2-1. Schematic diagram showing (1) unconventional hydrocarbon extraction [UHE] (*left*) with some important risks (*R1-R9*; modified after Ter Heege et al., 2017) and underground $CO_2$ storage [CCS] (*right*) with bow-ties defined in the SECURe project (*SBT06-SBT09*), (2) relevant types of wellbores (EM, SP, ID, DC), and (3) examples of wellbores with primary (*in blue colours*) and secondary (*in red colours*) well barriers (*right*) with some key underground well barrier elements (*boxed text*, modified after ISO, 2017). Note that well designs and depths may vary. The diagrams of well barrier schematics (*right figures*) are indicated to illustrate complexity of well designs, for example multiple cemented casing at shallow depths. Risks R1-R9 are defined for UHE in terms of effects on human health, safety & environment: R1- Reduced general safety around well site operations due to accidents related to well site construction, transportation of materials and traffic. R2- Reduced air quality & global climate footprint due to emissions to air. R3- Contamination due to loss of well integrity & leakage associated with drilling, construction, completion, operation, decommissioning or abandonment of wells, R4- Contamination due to surface spills & leaks associated with the transport, storage or handling of hazardous substances, R5- Contamination due to the loss of geological containment associated with fracturing and/or migration of hazardous substances through geological seals such as caprocks or faults, R6- Disturbance of landscape & environment due to changes in land or water use, interference with wildlife or impacts on biotopes and local communities, R7- Reduced water availability & quality due to extensive water use in operations, R8- Structural damage due to induced seismicity associated with fluid injection (e.g., hydraulic fracturing, waste water disposal), R9- Lack of stakeholder engagement & social license to operate. SECURe bow-ties *SBT06-SBT09*: see text for definition. LIS- liner shoe, PCS- production casing shoe, ICS- intermediate casing shoe, PLG- cement (pancake) plug (isolating milled out section of casing, cement and formation), PRP- production packer, RSV- reservoir, SCS- surface casing shoe, TPC- top production cement, TSC- top surface casing cement, WHD- wellhead.**

## 2.3 CROSSOVER LESSONS LEARNED AND GENERAL IMPLICATIONS FOR RISKS ASSOCIATED WITH DIFFERENT GEOENERGY APPLICATIONS

The risks associated with geoenergy applications are generally studied for a specific application with limited focus on crossover lessons learned between similar subsurface operations performed for different applications. Below, unique aspects and some crossover lessons learned that may help mitigating risks are discussed for different geoenergy applications. Three primary energy sources (CHE, UHE, GEE), subsurface $CO_2$ injection (CCS), and hydrogen energy buffering systems (UHS) are considered. It focusses on some important overarching aspects relevant to the research performed in the SECURe project (with reference to the risks and concepts discussed in section 2.2) rather than on compiling a comprehensive list of lessons learned for each individual application.

**Conventional hydrocarbon extraction [CHE]**

Because of the long track record of CHE in many countries worldwide, many current concepts and good practices for subsurface operations were originally developed for CHE. The long history of operations is particularly valuable for assessing long term impacts and risks of geoenergy applications, although evolution of good practices over time should be taken into account. For example, isotopic compositions of methane gas were studied for samples at a site (Sleen, the Netherlands) that experienced underground well blowout in the 1960s and demonstrated thermogenic source of the gas based on isotopic composition. It shows that isotopic fingerprinting can be used to perform long term monitoring of release of gas from gas reservoirs. It can also be used to distinguish thermogenic and biogenic methane which is important in discussion on causal relations between operations and methane leakage and in better assessing leakage risks. CHE is also one of the few geoenergy applications where long term integrity of decommissioned and abandoned wells can be studied in detail by monitoring potential leakage and emissions above abandoned well sites. By comparing leakage or emissions for a large number of sites, valuable data on the efficiency of well decommissioning practices can be collected and used to improve good practices.
Experience with CHE in Europe also offers some valuable lessons learned for establishing a social license to operate, and good practices for participatory monitoring and stakeholder engagement. For example, public opposition following induced seismicity associated with gas production in the Slochteren field (Groningen, the Netherlands) has led to a decision to permanently suspend gas production before 2030. It present an interesting study case on the importance of a social license to operate for sustainable subsurface operations.

**Unconventional hydrocarbon extraction [UHE]**

Unique to UHE is the large scale of operations and efficiency of (horizontal) drilling and multistage hydraulic fracturing in the U.S.A. and Canada. As regulations for the design, drilling, construction, completion, operation, decommissioning and abandonment of wells can vary between states in the U.S.A., the vast amount of data allows relations between regulations, well characteristics and release of fluids or gas to be established. Experience with horizontal drilling and multistage fracturing provides valuable information on critical thresholds for pressure and temperature changes and associated well stresses leading to integrity issues. Also the relative importance of (1) release of fluids or gases through wells, (2) fluid or gas migration due to loss of subsurface containment, and (3) surface spills, leaks and emissions can be assessed. For UHE, potential issues with fluid or gas migration are mostly associated with fractures or a fracture disturbed zone that extend beyond the shale reservoir. The extent of fractures or fracture disturbed zone critically depends on injected volumes of fracturing fluids. Previous reviews suggest that improper well construction and surface spills and leaks are more important than loss of subsurface integrity and containment (see Ter Heege 2017 and references therein). This information can be used to prioritize risk mitigation measure, for example by focussing on improving surface infrastructure for transport and storage of fracturing fluids or hydrocarbons.
Besides leakage risks, induced seismicity risks are an important concern for UHE. Felt induced seismicity ($M > 2$) is occasionally associated with hydraulic fracturing (mainly in Western Canada). Felt and damaging induced seismicity is associated with waste water disposal in some cases with where high volumes of fluids are injected (mainly in Oklahoma, U.S.A.). These and other injection data are the basis for relations between observed maximum magnitudes of seismic events and cumulative injection volume in reservoirs. Although many other geological and operational factors affect magnitudes of seismic events as well, these relations can be used as a first order screening of induced seismicity risks. Within the SECURe project, a statistical method was used to better describe the spatial and temporal distribution of seismic events for the Oklahoma waste water injection case. Also, an optimization modelling workflow that uses Oklahoma seismicity data to develop scenarios with optimum distribution of fluid injection over many wells with the aim to achieve maximum waste water injection volumes while maintaining seismicity rates below a predefined threshold. This workflow can be modified to study, for example, maximum gas production or $CO_2$ injection while limiting induced seismicity in fields with many wells.
In Europe, costs and benefits of UHE have been subject to debate. It can be argued that the lack of a social license to operate is one of the main causes for the current absence of UHE in European Member States. Experiences with UHE can provide lessons learned for other new (sustainable) energy applications, in particular concerning communication or risks.

**Geothermal energy extraction [GEE]**

Geothermal energy is the only sustainable primary energy source considered in this summary. For GEE, it is important to distinguish the type of geothermal system, i.e. hydrothermal systems usually targeting volcanic rock types (HVS), enhanced geothermal systems (EGS) that use hydraulic fracturing to produce heat or electricity, and hot sedimentary aquifers (HSA) (Buijze et al. 2019). EGS requires reservoir stimulation which may lead to fluid migration, but scale of fracturing, rock types and type of fracturing fluids are different than for UHE. As HSA are generally targeting porous reservoirs with comparable properties as hydrocarbon reservoirs, only these systems are in more detail considered here. As in HSA energy is produced from circulating hot water using doublet systems, risks related with release or migration of potentially hazardous fluids or gases are less prominent (but not always absent). Net injected/extracted volume is negligible. Continuous re-injection of cold water, however, does introduce local stress changes by pressure and temperature changes. The effect of temperature is more prominent than for CGE and UHE (except maybe for waste water injection), and much can be learned on the relation between pressure, temperature and stress changes that can lead to induced seismicity. Induced seismicity is a prime concern for GEE, but felt or damaging seismicity is usually not occurring for HSA (Buijze et al. 2019). Pressure, temperature and stress changes and associated induced seismicity are determined by a combination of geological and operational factors. Important geological factors are depth, rock properties, presence and properties of faults and fractures, proximity of wells to faults, and local stress state in formations and faults (e.g., tectonically active versus tectonically inactive regions). Important operational factors affecting pressure, temperature and stress changes for different geoenergy applications are extraction or injection rates and volumes, and injection temperature. The combination of direct pressure (i.e. local pore pressure changes), poroelastic (i.e. contraction or expansion of porous rocks due to pore pressure changes) and thermoelastic (i.e. contraction or expansion of porous rocks due to temperature changes) results in local stress changes, mainly around injection wells.

In Europe, induced seismicity is a prime concern in GEE projects, in particular for obtaining a (social) license to operate.

**Subsurface storage of $CO_2$ [CCS]**

CCS involves long term injection of (usually) cold $CO_2$ which leads to significant pressure and temperature changes. A prime concern is the long term containment of $CO_2$ in storage reservoirs that requires long term zonal isolations of (decommissioned) wells and integrity of the subsurface storage complex. Pressure and temperature changes affect local stresses at top seals and faults by the same mechanisms as discussed for GEE above. These stress changes may affect seal integrity by fracturing of caprock or and permeability changes or induced seismicity due to reactivation of faults. Additional considerations in CCS are reactive flow of $CO_2$ that may alter rock properties of reservoir and seals. As these properties determine the transfer of stresses, they may change seal integrity or induced seismicity risks.
Considering the relation observed maximum magnitudes of seismic events and cumulative injection volume in reservoirs as derived from fluid injection operations (mainly for hydraulic fracturing and fluid disposal for UHE and hydraulic fracturing for GEE) and the effects of temperature changes, upscaling of CCS has the potential to lead to induced seismicity. Up to now, only ($M < 2$) seismicity has been recorded for $CO_2$ injection (see Ter Heege et al. 2021 and references therein) but it is an important consideration to maintain a social license to operate if onshore $CO_2$ storage is upscaled following the Paris Agreement. Technology developed in the SECURe project, such as the optimization workflow for maximizing injection volumes while maintaining a threshold in induced seismicity, may support tackling these challenges.
In Europe, larger scale CCS projects are looking at upscaling $CO_2$ injection using offshore deep saline formations (e.g., Net Zero Teeside in the U.K. and Northern Lights in Norway) or offshore depleted gas fields (e.g., Porthos in the Netherlands, cf. Ter Heege at al. 2021 and references therein)

**Underground hydrogen storage [UHS]**

Unique to UHS are the repeated injection and extraction cycles required for buffering demand and supply of (sustainable) energy. These cycles result in cyclic stress changes on wells and seals of the storage complex. Other important aspects are that hydrogen is not naturally occurring in large volumes in subsurface reservoirs (contrary to $CH_4$ and $CO_2$), is reactive with some rock and well materials, highly mobile, and is known to promote microbial activity in the subsurface. Accordingly, the interaction with subsurface and wells may be different. Alterations of the hydrogen storage system due to (microbial-influenced) reactions between hydrogen and rock properties can affect the integrity and containment required to efficiently use UHS as an energy buffering system. As UHS projects targeting porous reservoirs are mostly in pilot phase (cf. section 1.2), experiences from other geoeenergy applications are invaluable to mitigate risks. Lessons learned from cyclic injection and extraction associated with seasonal storage of natural gas can feed into good practices for UHS.

Lessons learned from injecting $CO_2$ can be considered in developing good practices for UHS as well, but characteristics of geochemical interaction will be different. One of the most important aspects that is not covered in studies to risks associated with other geoenergy applications is the combination and *interaction* of cyclic injection/extraction, reactivity and mobility of hydrogen in UHS operations. Further studies and assessment of risks should consider this knowledge gap.
Issues around a social license to operate for UHS projects are likely similar as for CCS projects, and much can be learned from experiences with CCS. It would be beneficial to take the knowledge base and lessons learned from CCS experience as a basis for stakeholder engagement in UHS projects. The (perceived) explosive characteristics under specific conditions may be an added concern in stakeholder engagement.

## 2.4 OVERARCHING RECOMMENDATIONS FOR ENVIRONMENTAL MONITORING AS A MEANS TO MITIGATE RISKS ASSOCIATED WITH GEOENERGY APPLICATIONS

Recommendations for good practice for unconventional hydrocarbon production and geological $CO_2$ storage based on SECURe research are reflected in a series of factsheets (BGS, 2021a, b). Below some overarching recommendations for environmental monitoring are outlined that can be used to assess and mitigate risks associated with geoenergy applications in general. They focus on different application domains, impact areas and tools or methods (Figure 2-2). They are based on the comparison of risks and crossover lessons learned described in the previous sections rather than a repetition of recommendations in the factsheets. As such they do not reflect the detailed research findings of individual research tasks in the SECURe project. They outline more general recommendations for environmental monitoring in a broad sense that are linked to but not always explicitly described in the deliverable reports.

The following overarching recommendations, suggestions and examples can be considered:

- **Social license to operate**- Establish conditions to obtain a social license to operate that include a definition of acceptable risks using stakeholder engagement and participatory monitoring:
    - Early and frequent stakeholders engagement (preferably before or as part of license application)
    - Focus on obtaining a vision on prerequisites for a license to operate shared by all stakeholders rather than on convincing stakeholder of existing plans
    - Objective information on risks, uncertainties associated with risk assessment, and practical limitations of monitoring approaches

- **Regulations, design, planning and procedures**- Follow good industry practices and implement them both in regulations and internal procedures:
    - Risk assessment and management that outline measures to prevent incidents and control impacts based on predefined critical conditions and thresholds of risk indicators
    - Regulations and procedures that are practically feasible considering technical as well as economic considerations
    - Possibilities to modify (improve) regulations and procedures based on experience in (ongoing) projects

- **Scale of operations-** Reduce the scale of operations where possible:
    - Options to achieve similar operational goals (e.g., energy extraction or injection volumes) while minimizing impacts (i.e. more attention to optimization of operations)
    - Re-use of existing infrastructure
    - Special attention to surface infrastructure, transportation and impacts in general

- **Surface and subsurface characterization-** Perform as much characterization as practically feasible prior to operations:
    - Assessment of surface characteristics (e.g., land use, population density, existing infrastructure) in planning of projects
    - Subsurface characterization, preferably by combining field, laboratory and modelling studies to assess the response of reservoir, seals and faults to operations (e.g., characterization of sealing caprocks)
    - Assessment or forecasts of dynamic changes in the subsurface (e.g., changes in stress and rock properties)

- **Environmental baselines-** Determine practical baselines that help demonstrating (absence of) causal relations between operations and risks:
  - Monitoring for baselines that starts well before commencement of operations and acknowledges interaction with other industrial activities
  - Baselines that include critical thresholds for risk detection (e.g., critical $CO_2$ concentrations indicating leakage or natural seismicity), uncertainty in assessment of indicators of risks and consideration of acceptable risks
  - Baselines that account for changing conditions unrelated to operations (as surface and subsurface conditions can change over time and subsurface reservoirs are dynamic systems)

- **Chemical or isotopic fingerprinting of fluids or gases-** Chemical fingerprinting rather than focussing on changing concentrations for leakage detection:
  - Deployment of new techniques that can pinpoint source of leakage or causes of elevated concentrations (e.g., clumped isotopes to distinguish biogenic and thermogenic methane)
  - Incorporation of chemical fingerprinting in baseline assessment and characterization of leakage sources help demonstrating (absence of) causal relations between operations and leakage
  - Spatial and temporal distribution of chemically fingerprinted fluids or gases to better assess the impacts of leakage

- **Well cementation and decommissioning-** Focus on improving well cementation and plugging of abandoned wells to reduce well leakage risks:
  - Development of in situ stress in well cement during curing and effects on zonal isolation
  - Cyclic thermal and pressure loads on well systems and effects of cement failure
  - Accounting for (long term) dynamic interaction of wells with formations and formation and injected fluids or gases during all operational phases of wells

- **Induced seismicity and ground motions-** Early warning signals for problematic seismicity with focus on impacts to mitigate induced seismicity risks:
  - Traffic light systems for induced seismicity that implement more characteristics of seismicity rather than seismic magnitudes alone (e.g., peak ground velocities, peak ground accelerations, alignment of hypocentres, changes in frequency-magnitude relations)
  - Risk assessment using modelling workflows that cover source to surface causes and effects of induced seismicity
  - Extensive deployment of flexible, low-cost micro-seismic monitoring to characterize the effect of operations in the subsurface

- **Monitoring-** Optimizing and prioritize monitoring efforts based on experience with operations and regular assessment of risks:
  - Focus on most prominent risks rather than comprehensive monitoring campaigns, fine-tuning efforts based on experience with operation in running projects
  - Traffic light systems for leakage based on continuous monitoring of aquifer or groundwater compositions, analogous in use to traffic light systems used for managing induced seismicity risks
  - More flexible, temporary, re-usable monitoring networks that can be deployed for different periods in different areas

- **Modelling forecasts**
  - Focus on validation of model forecasts with field or laboratory data
  - Application of probabilistic (fast semi-analytical) modelling approaches to assess uncertainties in model forecasts and deterministic (slower finite element) modelling approaches to assess complexity in geology and interaction or coupling of processes
  - Incorporation of model forecasts, coupled with (real time ) monitoring in risk management procedures

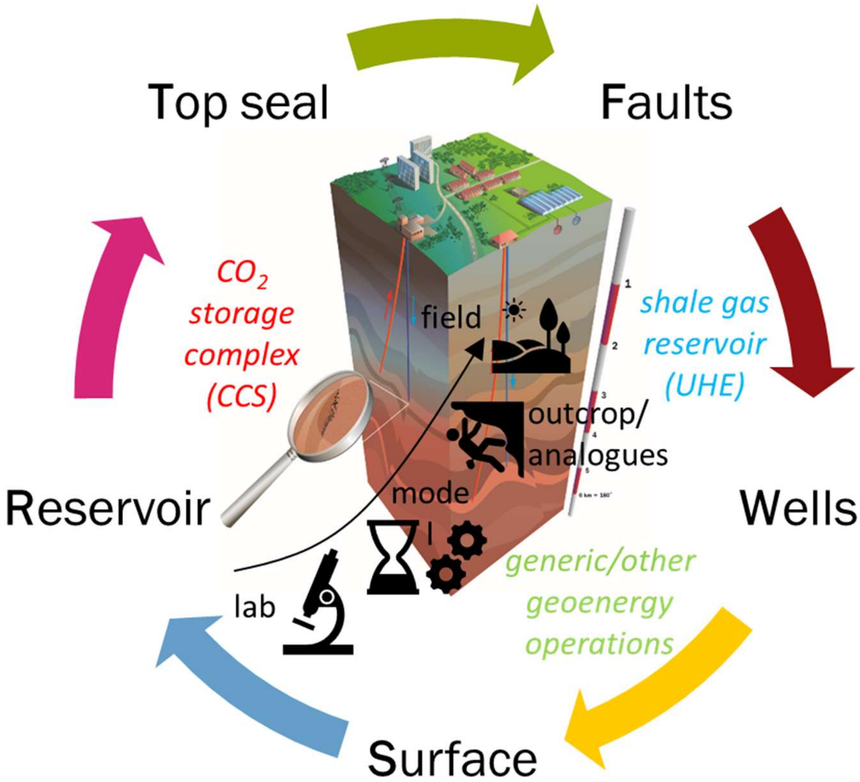


**Figure 2-2. Application domains ($CO_2$ storage complex, shale gas reservoir and generic/other geo-energy operations), Topics or impact areas/risk receptor (R-Reservoir, T-Top seal, F-Faults, W-Wells, S-Surface), and Tools or methods (lab experiments, modelling, field cases- as indicated by symbols and text in figure). Recommendations for environmental monitoring can be considered for these application domains, impact areas and tools or methods.**

# 3 References


BGS, 2021a. Best practice recommendations for the environmental monitoring of CO2 storage operations in Europe. SECURe factsheets, D6.8.

BGS, 2021b. Best practice recommendations for the environmental monitoring of shale gas operations in Europe. SECURe factsheets, D6.9.

Buijze, L., van Bijsterveldt, L., Cremer, H., Paap, B., Veldkamp, H., Wassing, B., van Wees, J.-D., van Yperen, G., ter Heege J., Jaarsma, B., 2019 Review of induced seismicity in geothermal systems worldwide and implications for geothermal systems in the Netherlands. Netherlands Journal of Geosciences, 98, https://doi.org/10.1017/njg.2019.6.

Heinemann, N., Alcalde, J., Miocic, J., Hangx, S., Kallmeyer, J., Ostertag-Henning, C., Hassanpouryouzband, A., Thaysen, E., Strobel, G., Schmidt-Hattenberger, C. Edlmann, K., Wilkinson, M., Bentham, M., Haszeldine, S., Carbonell, R., Rudloff, A., 2021. Enabling large-scale hydrogen storage in porous media – the scientific challenges. Energy Environ. Sci. 14, 853.

ISO, 2017. Petroleum and natural gas industries — Well integrity Part 1: Life cycle governance. ISO 16530-1:2017.

Ter Heege, J. 2017. Inventory of quantified risks and impacts of shale gas exploration and exploitation. M4ShaleGas Project Report, D21.3. www.m4shalegas.eu.

Ter Heege, J., Van Unen, M., Brunner, L., Moghadam, A., Orlic, B., Wassing, B., Fokker, P., Szott, W., Lubaś, J., Wojnicki, M., Łetkowski, P., Beeson, M., Kupoluyi, M., Cerasi, P., Ghaderi, A., Taghipour, A Bhuiyan, M., Todorovic, J., Rizzo, R., Busch, A., Fazeli, H., Doster, F., Forbes Inskip, N., Castanedo Neto, R., Bobek, K., Wójcicki, A., Le Guenan, T., Aochi, H., Jakobsen, R., Dahl-Jensen, T., Larsen, T.B., Voss, P.H., 2021. Guidelines for risk assessment for leakage and induced seismicity risks in $CO_2$ storage and unconventional gas production. SECURe Project Report, D2.6. www.securegeoenergy.eu.

# Glossary

| | |
|---|---|
| *CCS* | Carbon capture and storage |
| *CHE* | Conventional hydrocarbon extraction |
| *EGS* | Enhanced geothermal system |
| *GEE* | Geothermal energy extraction |
| *HSA* | Hot sedimentary aquifer |
| *HVS* | Hydrothermal volcanic system |
| *ISO* | International Organization for Standardization |
| *SBT* | SECURe bow-tie |
| *UGS* | Underground gas storage |
| *UHE* | Unconventional hydrocarbon extraction |
| *UHS* | Underground hydrogen storage |
| *WP* | Work package |