Project Acronym and Title:

M4ShaleGas - Measuring, monitoring, mitigating and managing the environmental impact of shale gas

Integrated review of best practices of subsurface operations in U.S.A. and Canada

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Public introduction

M4ShaleGas stands for *Measuring, monitoring, mitigating and managing the environmental impact of shale gas* and is funded by the *European Union's Horizon 2020 Research and Innovation Programme*. The main goal of the M4ShaleGas project is to study and evaluate potential risks and impacts of shale gas exploration and exploitation. The focus lies on four main areas of potential impact: the subsurface, the surface, the atmosphere, and social impacts.

The European Commission's Energy Roadmap 2050 identifies gas as a critical fuel for the transformation of the energy system in the direction of lower CO_2 emissions and more renewable energy. Shale gas may contribute to this transformation.

Shale gas is – by definition – a natural gas found trapped in shale, a fine grained sedimentary rock composed of mud. There are several concerns related to shale gas exploration and production, many of them being associated with hydraulic fracturing operations that are performed to stimulate gas flow in the shales. Potential risks and concerns include for example the fate of chemical compounds in the used hydraulic fracturing and drilling fluids and their potential impact on shallow ground water. The fracturing process may also induce small magnitude earthquakes. There is also an ongoing debate on greenhouse gas emissions of shale gas (CO_2 and methane) and its energy efficiency compared to other energy sources

There is a strong need for a better European knowledge base on shale gas operations and their environmental impacts particularly, if shale gas shall play a role in Europe's energy mix in the coming decennia. M4ShaleGas' main goal is to build such a knowledge base, including an inventory of best practices that minimise risks and impacts of shale gas exploration and production in Europe, as well as best practices for public engagement.

The M4ShaleGas project is carried out by 18 European research institutions and is coordinated by TNO-Netherlands Organization for Applied Scientific Research.

Executive Report Summary

This report provides an integrated summary of the main risks and impacts of **subsurface** operations, and discusses best practice operations that mitigate these risks based on reviews of operations that are current practice in the U.S.A. and Canada. Risks are defined as the combination of the likelihood of an incident or hazardous event (e.g., loss of zonal isolation) and the effects the incident has on human health, safety and natural environment (e.g., the contamination of a shallow aquifer). It has been identified that the main risks of **subsurface** shale gas operations in the U.S.A. and Canada are associated with drilling and well integrity, hydraulic fracturing, and induced seismicity. Poor zonal isolation of wells has been identified as one of the main hazards for subsurface operations that may lead to risks associated with contamination of shallow aquifers. It is unlikely that hydraulic fracturing operations result in direct pathways of enhanced migration between stimulated fracture disturbed rock volume and shallow aquifers, but operations may jeopardize well integrity or induce seismicity. There is a growing concern regarding induced seismicity related to injection of waste water in the subsurface which is associated with high magnitude (up to M_L 5.7) earthquakes, and regarding high volume hydraulic fracturing operations, mainly in western Canada (up to M_L 4.4). Best practice subsurface shale gas operations that mitigate these risks ideally consist of (1) a planning phase to establish baselines and minimize the scale of operations that includes site-specific subsurface characterization, data collection and modelling, (2) an operational phase to minimize subsurface impact that includes monitoring of wells to detect potential leakage and micro-seismic monitoring of hydraulic fracturing operations to determine the spatial extent of stimulated fracture disturbed rock volume, and (3) an abandonment phase to minimize the permanent footprints of shale gas exploitation that includes evaluation of decommissioned wells and long term monitoring of abandoned wells in terms of well integrity and zonal isolation. New technological developments that may further mitigate risks for subsurface operations mainly focus on extending and integrating current mitigation approaches, developing better sensors or data processing techniques, apply alternative drilling or well construction techniques, and further optimize hydraulic fracturing operations.

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1 INTRODUCTION

1.1 Context of M4ShaleGas

Shale gas source rocks are widely distributed around the world and many countries have now started to investigate their shale gas potential. Some argue that shale gas has already proved to be a game changer in the U.S. energy market (EIA 2015[1]). The European Commission's Energy Roadmap 2050 identifies gas as a critical energy source for the transformation of the energy system to a system with lower CO_2 emissions that combines gas with increasing contributions of renewable energy and increasing energy efficiency. It may be argued that in Europe, natural gas replacing coal and oil will contribute to emissions reduction on the short and medium terms.

There are, however, several concerns related to shale gas exploration and production, many of them being associated with the process of hydraulic fracturing. There is also a debate on the greenhouse gas emissions of shale gas (CO_2 and methane) and its energy return on investment compared to other energy sources. Questions are raised about the specific environmental footprint of shale gas in Europe as a whole as well as in individual Member States. Shale gas basins are unevenly distributed among the European Member States and are not restricted within national borders, which makes close cooperation between the involved Member States essential. There is relatively little knowledge on the footprint in regions with a variety of geological and geopolitical settings as are present in Europe. Concerns and risks are clustered in the following four areas: subsurface, surface, atmosphere and society. As the European continent is densely populated, it is most certainly of vital importance to understand public perceptions of shale gas and for European publics to be fully engaged in the debate about its potential development.

Accordingly, Europe has a strong need for a comprehensive knowledge base on potential environmental, societal and economic consequences of shale gas exploration and exploitation. Knowledge needs to be science-based, needs to be developed by research institutes with a strong track record in shale gas studies, and needs to cover the different attitudes and approaches to shale gas exploration and exploitation in Europe. The M4ShaleGas project is seeking to provide such a scientific knowledge base, integrating the scientific outcome of 18 research institutes across Europe. It addresses the issues raised in the Horizon 2020 call LCE 16 – 2014 on *Understanding, preventing and mitigating the potential environmental risks and impacts of shale gas exploration and exploitation.*

[1] EIA (2015). Annual Energy Outlook 2015 with projections to 2040. U.S. Energy Information Administration (*www.eia.gov*).

1.2 Study objectives for this report

The main objective of this report is to summarize and integrate reviews of data and current practices of subsurface operations for shale gas exploitation. As commercial shale gas exploitation is mainly limited to the U.S.A. and Canada, this report is largely based on experience and data from shale gas operations in North America. Where relevant, European data and implications for Europe are incorporated. It has been identified that the main risks of shale gas operations *in the subsurface* are associated with (1) drilling and well integrity, (2) hydraulic fracturing, and (3) induced seismicity. The risks are described, existing knowledge is reviewed, and practical examples are discussed. Current practices of subsurface operations, risk mitigation measures and technology developments are reviewed that contribute to reducing the impacts and risks of different operations. The review aids in identifying potential knowledge gaps related to impacts and risks of subsurface shale gas operations, specifically when applied to Europe. Accordingly, the work contributes to building a European knowledge base on the subsurface risks, impacts and scientific recommendations for best practices of subsurface operations.

1.3 Aims of this report

The report aims to disseminate a concise, integrated review of impacts and risks related to *subsurface shale gas operations* with current practices for operations from the U.S.A. and Canada, including comparison and links between different impacts, best practices and risks.

1.4 Scope

The M4ShaleGas project studies and evaluates the potential risks and impacts of shale gas exploration and exploitation in four main areas of potential impact: the subsurface, the surface, the atmosphere, and social impacts. This report focusses on the potential risks and impacts of *subsurface* operations. It deals with subsurface operations that start when drilling of the first shale gas well is commenced and end after the well is long abandoned. The analysis is restricted to the risks for human health, safety and natural environment that are associated with subsurface operations. Other risks, such as economic risks associated with subsurface shale gas operations are not covered in the current report. This report focusses on comparing the most important risks, current practices and mitigation measures that have been identified. This focus is chosen to keep the report concise and avoid overlap with more comprehensive reviews of the individual risks and mitigation measures in the subsurface that are also performed in the M4ShaleGas project (Bohnhoff and Malin 2015; Cuss et al. 2015; Garcia et al. 2015; Gawel et al. 2015; Osinga et al. 2015). Although there are strong links with surface operations, for example concerning transport and handling of fracturing fluids or methane emissions from pipelines, risks associated with surface activities are not explicitly incorporated in the report. Analysis and integration of risks associated with surface activities is the prime objective of other research activities in the M4ShaleGas project[2].

[2] M4ShaleGas (http://www.m4shalegas.eu).

2 RISKS AND BEST PRACTICES OF SUBSURFACE OPERATIONS

2.1 Definition of best practices, impacts, hazards, footprint and risks

Within the context of this report, current practices, activities, techniques or studies that are frequently applied in shale gas operations are described. In some cases, *best practices* can be identified that are defined as operations aiming to reduce or mitigate impacts, hazards, footprint and risks. *Impacts* are considered as direct effects resulting from operations, *hazards* as incidents caused by operations that *may* affect human health, safety and natural environment, and *footprints* as the permanent long term effects on the natural environment. For appropriate risk assessment, it is important to emphasize the difference between hazards, risks, incidents, the likelihood of an incident, and the effects the incident has (e.g., Okrent 1980; Smith 2013). Throughout the report risks are defined as the combination of the *likelihood* of an incident or hazardous event (e.g., loss of zonal isolation) and the *effects* the incident has on human health, safety and natural environment (e.g., the contamination of a shallow aquifer). The risk assessment of shale gas operations needs to acknowledge the *scale of operations*. If the likelihood of an incident is constant for a specific type of operation, the number of incidents will be expected to increase if the number of operations increases. Accordingly, local effects of shale gas operations and therefore the risks will be expected to increase if the scale of operations increase. Moreover, it is also useful to compare risks associated with shale gas operations with risks associated with *other energy resources* such as conventional gas which have been around for a longer period of time in order to get a better picture of their relative importance.

2.2 Most prominent hazards and risks of subsurface operations

The main impacts and risks of shale gas operations *in the subsurface* are associated with (1) zonal isolation and integrity of wellbore systems (Darrah et al. 2014; Davies et al. 2014), (2) the creation of migration pathways that allow upward migration of hazardous substances (Fisher and Warpinski 2012; Davies et al. 2012), and (3) the effect on reactivating existing large-scale faults that may lead to problematic or felt seismicity (Ellsworth 2013; Davies et al. 2013).

2.2.1 Drilling, well integrity and zonal isolation

Compared to conventional gas production, a multitude of wells are required for shale gas exploitation due to the low shale permeability and shale to well connectivity. Their main purpose in shale gas operations is to facilitate and control gas flow from the gas shale to surface infrastructure. Wellbores may create artificial pathways for migration of fluids from the subsurface to the surface along annuli, damaged tubing or through damaged cement sheath and surrounding rock affected by drilling induced damage (e.g., breakouts or washouts), regardless if the formations they penetrate are of negligible permeability. The typical life-cycle of a shale gas well includes four phases (1) drilling and cementing, (2) completion and stimulation, (3) gas production, re-stimulation and maintenance, and (4) plugging, decommissioning and abandonment (King 2012). The integrity and zonal isolation of wellbore systems need to be maintained during the entire life-cycle to minimize risks.

2.2.1.1 Overview of the main hazards and risks related to shale gas drilling and wells

It is important to distinguish hazards associated with shale gas drilling and wells from the risks these hazards may impose on human health, safety and natural environment. Drilling hazards include loss of borehole stability or loss of drilling fluids ("mud losses"). The main hazard associated with well cementation is a lack of zonal isolation due to a poor or incomplete cement sheath. Poor cementation may have different causes, including eccentric or damaged boreholes, open channels or drilling fluids that are encapsulated in the cement and de-bonding of cement-tubing-rock interfaces during curing of the cement. Subsequent stimulation and gas production from wells may affect well integrity and thereby zonal isolation due to pore pressure or temperature variations resulting from fracturing of the well, or due to interaction with the hydraulic fracturing operations from neighbouring wells. Plugging, decommissioning and abandonment of the well need to ensure long term zonal isolation, which may impose a hazard if it is improperly performed. All these hazards may lead to an increased, uncontrolled mobility of hazardous substances in the subsurface. Poor zonal isolation of wellbore systems may lead to increased upward migration of hazardous substances along wellbores and, consequently, leakage to shallow environments. The main risks for human health, safety and natural environment are associated with (1) migration of fluids containing drilling, fracturing or formation fluids along wellbores leading to hazardous contamination of aquifers that are used, for example for supply of drinking water or agricultural irrigation, and (2) migration of hydrocarbons along wellbores leading to emissions at the surface that lead to poor air quality and enhance climate footprint of shale gas exploitation. These risks are determined by the *likelihood* that upward migration to shallow depth or surface occurs, in combination with the *effects* of migration on shallow aquifer quality, air quality or emissions. The *likelihood* of migration to shallow aquifers is mainly determined by site-specific well construction operational parameters (such as injection volumes and rates), and the local state of the reservoirs and overburden (including the presence of natural fractures and faults). The *effects* at the surface depend on toxicity of migrating substances such as drilling, fracturing or formation fluids and gases.

2.2.1.2 Inventories and field cases of hazards and risks related to drilling and wells

Compared to conventional gas production risks related to drilling and wells are particularly important for shale gas exploitation due to the large number of closely-spaced wells and fracturing stages required for full-scale exploitation that is occurring in the US and Canada. Following the definition of risks adopted in this report (c.f. section 2.1), a higher number of wells and fracturing operations increases the probability of a hazardous event, even if the likelihood of an incident in individual wells is low. Another important aspect is the difference in hydrocarbon source rock between shale gas and conventional reservoirs. Whereas conventional reservoirs often consist of permeable rocks such as sandstones with low clay content, gas shales contain clays which dramatically changes the rock properties and behaviour around the producing part of the well. In particular, borehole stability may be affected by interaction between clays and drilling or fracturing fluids leading to clay swelling or by higher ductility and planes of weakness in the shales (depending on clay mineralogy). On the other hand, gas shales generally exhibit low matrix permeability and have the tendency to close migration pathways such as fractures and cement-rock annuli over time, in particular in shales with relative high ductility.

In a recent draft report, the Environmental Protection Agency (EPA[3]) assesses the potential impacts of hydraulic fracturing for oil and gas on drinking water resources, including an analysis of impacts and risks associated with well injection. Their findings are not quoted in this report because of their request not to cite or quote from the draft report (the reader is referred to the version published on their website for more information, EPA 2015). King (2012) states that problems with well construction are rare but are the dominant source of subsurface pollution apart from transport of materials to the well site. He estimates that 1-5% of shallow well completions requires a workover to repair to be able to drill deeper, and that regulations with respect to well barriers are “the primary reason for the near absence of incidents in producing shale gas wells”. Review of problems with shale gas wells in the US indicated that 3-6% of the wells experienced problems with well integrity (Davies et al. 2014; see also Stamford and Azapagic 2014 and the discussion by Westaway and Young 2015). These numbers only provide an indication of the likelihood of well integrity problems. To what extent these problems affect risks associated with well integrity also depends on the effect of these problems in the subsurface (e.g., on the amount of leaked fluids or migration rates).

Several recent studies investigated the relation between local shale gas exploitation and drinking water composition. Elevated concentrations of methane, ethane and propane in drinking water samples from 141 north-eastern Pennsylvanian drinking water wells showed a strong correlation with distance to gas wells in the Marcellus Shale (Jackson et al. 2013). Isotopic signatures, hydrocarbon ratios (methane to ethane and propane) and the ratio of the noble gas ^{4}He to CH_4 in groundwater were characteristic of a thermally mature Marcellus-like source in some cases. Seven discrete clusters of fugitive gas contamination in Pennsylvania and one in Texas showed increasing contamination through time, higher relative proportions of thermogenic hydrocarbon gas (e.g., CH_4, ^{4}He), and lower proportions of atmospheric gases (air-saturated water; e.g., N_2, ^{36}Ar) relative to background groundwater (Darrah et al. 2014). Contamination clusters were linked to gas leakage through failures of annulus cement, faulty production casings, and well failure. Contamination by upward migration through overlying geological strata triggered by horizontal drilling or hydraulic fracturing was deemed unlikely based on noble gas data. Llewelly et al. 2015 identified a complex mixture of organic compounds with signatures that were also observed in flowback water from Marcellus Shale gas wells in groundwater, together with a compound (2-n-butoxyethanol) also identified in the flowback water. The contamination was attributed to migration of stray natural gas and drilling or fracturing fluids along shallow to

[3] Environmental Protection Agency (http://www.epa.gov), sub-page ‘hfstudy’ (http://www.epa.gov/hfstudy), visited on 20 January 2016.

intermediate depth fractures to an aquifer, possibly in combination with leakage from a pit containing waste water at the nearest well pad. These studies indicate local evidence for contamination of shallow aquifers, groundwater and drinking water, but examples of widespread hazardous contamination of shallow aquifers that is uniquely correlated to drilling operations or improper well construction are absent in current literature. The lack of evidence may be caused by (1) low probability or limited effect of hazards associated with shale gas drilling and wells, (2) limited accessible data on water quality and baselines of groundwater composition, and (3) difficulty of linking chemical signatures of shallow aquifers with signatures of drilling, fracturing or formation fluids.

2.2.2 Hydraulic fracturing

In gas shales, hydraulic fracturing is performed to stimulate the flow of gas in the otherwise impermeable or low permeable shales. In most cases, it involves the injection of fracturing fluids into the shale through a perforated wellbore. It causes the tensile opening of new or existing fractures and the reactivation of existing faults accompanied by slip along the fault plane, creating a linked fracture network. The result is a stimulated fracture disturbed volume within and, in some cases, around the gas shale with enhanced permeability. While the stimulated fracture disturbed volume of shale (often referred to as stimulated reservoir volume in engineering studies) is of main importance for gas production, the entire stimulated fracture disturbed volume is important for assessing migration of hazardous substances from the gas shale.

2.2.2.1 Overview of the main hazards and risks related to hydraulic fracturing

Hazards associated with hydraulic fracturing *in the subsurface* include the loss of fracture containment around the gas shale that may lead to enhanced migration of hazardous substances from the gas shale and surrounding rock formations to shallow depth (see also section 2.2.2.2 on review of likelihood and relation with depth of operations in the US and Canada). These migration paths could occur if induced or reactivated faults and fractures extend from the gas shale and surrounding rock formations to shallow depths, or if a connection is made between induced or reactivated faults and fractures and wells with poor zonal isolation. This hazard may lead to an increased, uncontrolled mobility of hazardous substances in the subsurface and upward migration of hazardous substances. Other important hazards arise by effects of hydraulic fracturing on wellbore systems (c.f. section 2.2.1) or on faults and induced seismicity (c.f. section 2.2.3). One of the main risks for human health, safety and natural environment is associated with *surface* transport and handling of fracturing fluids, which is determined by the likelihood of surface spills and leakage, the amount and toxicity of fracturing fluids or chemicals that get in contact with the environment, and the specific interaction with the environment. In the *subsurface*, the main risks are associated with migration of fluids containing drilling, fracturing or formation fluids along induced or reactivated faults and fractures. If at sufficiently high rates, such migration may lead to hazardous contamination of shallow aquifers or poor air quality and enhance climate footprint by surface emissions of greenhouse gases. These risks are determined by the *likelihood* that upward migration to shallow depth or surface along induced or reactivated faults and fractures occurs, in combination with the *effects* of migration on shallow aquifer composition, air quality and emissions. The *likelihood* of migration of fracturing fluids to shallow aquifers *caused by hydraulic fracturing* is mainly determined by the local geological setting and operational parameters that determine the spatial extent of the stimulated fracture disturbed rock volume. This volume critically depends on operational parameters (e.g., injected volume of type of fracturing fluids) and site-specific geological setting (e.g., local stress field and depth). It should be noted that many European shales occur at depths below 1.5 km (also considering required gas maturity of prospective shales, c.f. Ter Heege et al. 2015), for which a hydraulic connection between stimulated fracture disturbed volume and shallow aquifers has not been demonstrated (Davies et al. 2012; c.f. section 2.2.2.2). Furthermore, operational parameters can be modified to limit height growth of induced fractures. Besides the economic benefit, increasing the efficiency of hydraulic fracturing operations can reduce some risks. If hydraulic fracturing can be performed more efficiently, less wells, less fracturing stages, and less fracturing fluids will be required for gas production. Accordingly, risks depending on the scale of operations will be reduced, such as risks associated with surface spills of fracturing fluids. The *effects* at the surface and in the subsurface largely depend on the injected volume and toxicity of fracturing fluids as well as the decay of toxicity with time in the subsurface. In addressing surface effects, it is important to note that toxicity is determined by the composition of the fracturing fluids as a whole rather than by the toxicity of the pure end member chemicals that are present in the fracturing fluids. It should also be noted that limiting injection volumes typically leads to less effective fracturing (smaller stimulated fracture disturbed rock volume) which in turn leads to smaller produced gas volumes. Optimization of hydraulic fracturing operations can be performed, focussing on maximum gas production with minimum injected fluid volume.

2.2.2.2 Inventories and field cases of hazards and risks related to hydraulic fracturing

Compared to conventional gas production, for example from tight sandstones, risks related to hydraulic fracturing are particularly important for shale gas exploitation due to the large number of fracturing operations required. Other important aspects include differences in composition and properties of the shale. In particular, differences in rock properties may yield large differences in the extent of individual fractures and volume of rock affected by hydraulic fracturing. As one the main hazards associated with hydraulic fracturing *in the subsurface* is enhanced migration along induced or reactivated faults and fractures, this section focusses on that hazard. Examples of natural seepage of hydrocarbons (i.e. hydrocarbon occurrences at the surface in areas *not affected by* hydrocarbon exploitation) show that under certain circumstances natural faults and fractures may act as migration pathways for hydrocarbons. However, considering the low natural permeability of gas shales, it is unlikely that migration of hazardous substances occurs provided that (1) the gas shale is located at depths below ~1500 meter which ensures that hydraulic fractures do not reach shallow aquifers, (2) no large-scale natural faults are present that may act as migration pathways after reactivation (i.e. a magnitude 4 earthquake requires a fault of ~1-4km and slip of several cm, c.f. Zoback and Gorelick 2012), and (3) hydraulic fracturing does not affect the zonal isolation of wellbore systems (c.f. section 2.2.1).

Micro-seismic monitoring during hydraulic fracturing operations in the US and Canada shows that height growth (i.e. the vertical extent of induced fractures or stimulated fracture disturbed volume) is limited (King 2012). Other studies have reviewed the maximum vertical distance between the horizontal well and the top of micro-seismic hypocenters for the Marcellus and Barnett Shale Formations in the US (Fisher en Warpinski 2012; Davies et al. 2012). These studies show no evidence that induced fractures have reached shallow groundwater-bearing formations or aquifers. In more than 99% of cases investigated the distance between the well and top of micro-seismic hypocenters is less than 350 meter and the distance between the top of micro-seismic hypocenters and shallow aquifers is more than 1000 meters. The maximum distance between the well and top of micro-seismic hypocenters is 536 meter for the Marcellus Shale and 588 for the Barnett Shale (Fisher en Warpinski 2012; Davies et al. 2012). Results of a survey of wells with shallow shale gas operations that include examples of distance between hydraulic fracturing and ground water resources below ~600 meter can be found in EPA (2015), which also includes statements on the potential impacts of hydraulic fracturing for oil and gas on drinking water resources. Recent studies attribute links between contamination of shallow aquifers, groundwater and drinking water and nearby shale gas operations to surface spills or problems with the zonal isolation of wells (Jackson et al. 2013; Darrah et al. 2014; Llewelly et al. 2015, c.f. section 2.2.1). It is important to emphasize that observations of limited fracture height growth and stimulated fracture disturbed volume are based on the monitoring of micro-seismic events (c.f. section 2.3.2.2). Micro-seismic monitoring is limited to imaging seismic deformation associated with hydraulic fracturing (mainly shear along planes of weakness). Aseismic deformation may also contribute to flow stimulation in the gas shale. Imaging aseismic deformation requires additional monitoring approaches, such as the use of tilt meters that capture the minute deformation of surface or borehole walls associated with fracture opening or shear along reactivated faults and fractures. Furthermore, there may be some bias resulting from that fact that micro-seismic monitoring is generally performed by shale gas operators to optimize hydraulic fracturing operations and gas production. Therefore, only a limited number of hydraulic fracturing operations are monitored in the US and Canada (estimated 3-5%, Van der Baan et al. 2013), and not all data for different shale plays are publically available.

2.2.3 Fault reactivation and induced seismicity

Hydraulic fracturing can involve the creation of new faults and fractures as well as the reactivation of existing faults and fractures. Movement along discontinuities such as faults or bedding planes can result in seismic events detectable by micro-seismic sensors. The occurrence of seismicity is mainly determined by (1) the natural stress conditions that results from the local geological setting, (2) the presence, dimensions and properties of faults and fractures, and (3) the local stress disturbance that results from subsurface operations. Most seismic events resulting from hydraulic fracturing operations are of relatively low magnitude that do not lead to risks at the surface (i.e. micro-seismicity with typical local magnitudes below $M_L < 1$, Warpinski 2012; Davies et al. 2013). Induced seismicity typically refers to seismicity with larger magnitudes (i.e. typically $M_L > 2$) that is the result of the reactivation of larger faults. Of particular interest to the assessment of seismic risk is 'felt' or 'problematic' induced seismicity, which refers to earthquakes that can be felt by people or lead to risks at the Earth's surface. This section focusses on seismic risks associated with the occurrence of *problematic induced seismicity*.

2.2.3.1 Overview of the main seismic hazards and risks

It is important to distinguish seismic hazards and risks they impose on human health, safety and natural environment. Seismic hazard is defined as the probability that specific ground motion (i.e. Peak Ground Acceleration, PGA, or Peak Ground Velocity, PGV) occurs in an area over a certain timespan (e.g., Giardini et al. 2013). PGA and PGV are not solely dependent on magnitude, but also depend on wave dampening/amplification in the (shallow) subsurface, the depth of the hypocentre and the distance from the epicentre. For example, a seismic hazard map has been compiled that displays PGA in Europe that are expected to be reached or exceeded with a 10% probability in 50 years, and distinguished between low (PGA≤0.1g), moderate (0.1<PGA≤0.25g) and high hazard (PGA>0.25g) areas (Woessner et al. 2015). Whereas most inventories of induced seismicity related to subsurface operations focus on earthquake magnitudes (McGarr 2002; Davies et al. 2013), ground motion resulting from earthquakes determines the damage at the Earth's surface. The risks associated with induced seismicity resulting from shale gas operations are determined by the *likelihood* that problematic seismicity occurs, in combination with the *effects* at the Earth's surface (e.g., the damage caused by the seismic event). Therefore, ground motion (i.e. PGA) is more directly linked to seismic risks. The *likelihood* that problematic seismicity occurs in an area is often described by relations between earthquake frequency and magnitude (e.g., Gutenberg-Richter relationship, Guttenberg and Richter 2010). The most important *effects* of problematic seismicity include: (1) structural damage to buildings, infrastructure and direct environmental damage, (2) damage to wellbores, (3) secondary damage caused by collapsing infrastructure, and (4) safety of the general public around shale gas operations (including both perceived and actual seismic risks). These effects may impact the general population and surface environments, for example due to destabilization of buildings or surface contamination by leakage due to failed well site infrastructure.

2.2.3.2 Inventories and field cases of seismic hazards and risks

The seismic hazards and risks of a specific area are caused by the combined effects of natural and induced seismicity. Natural seismicity is indicative of active faulting and may thus be useful to identify active faults. The occurrence of *natural* seismicity is indicative for the stress regime and tectonic loading rates (Woessner et al. 2015), but the relationship with *induced* seismicity is not well-constrained. Injection-induced earthquakes may take place in aseismic areas, with almost no or limited tectonic earthquakes recorded over the monitoring period. Statistical analysis of induced seismicity related to enhanced geothermal reservoirs suggests that in regions of very low peak ground acceleration (PGA), indicating low *natural* seismic hazard, magnitudes of *induced* seismicity are also limited (Evans et al. 2012). However, large scale waste water injection in the U.S.A. in regions with very low PGA resulted in large magnitude earthquakes (Keranen et al. 2014; National Research Council 2013). It suggests that injection volume as well as dimensions of fluid-affected area are important in controlling the maximum magnitudes of seismic events. In general, larger injected volume have been shown to correspond to higher magnitude induced earthquakes. However, the relation between injection parameter such as injected volume and flow rate can be complex. For example, at the Salton Sea Geothermal Field the observed seismicity shows a positive correlation with the net fluid volume (which accounts for both extracted and injected volume) rather than the injection volume alone (Brodsky and Lajoie 2013).

In some studies (e.g., McGarr 2002), the distinction is made between '*induced* seismicity' and '*triggered* seismicity'. The term '*induced* seismicity' is then used to refer to seismicity resulting from an activity that causes a stress change of comparable magnitude to the ambient shear stress acting on the slip plane, while the term '*triggered* seismicity' is reserved for cases where the imposed stress change is much smaller than the ambient shear stress. However, it is often difficult to differentiate between these two end-members. Here, the term '*induced* seismicity' is used to refer to any seismic activity that is the result of human activity.

The main seismic risks for shale gas operations are associated with high volume hydraulic fracturing (for example as observed in the Horn River Basin, Canada, BCOGC 2012) or injection of waste water originating from shale gas operations (for example as observed in Oklahoma, USA, Keranen et al. 2014). Problematic seismicity is not necessarily restricted to high volume (typically total injection volumes above 100000 m^3, NRC 2013) or intermediate to high local magnitudes (typically $M_L > 3$). Problematic seismicity have been observed to occur at lower injection volumes, for example if faults are critically stressed. Moreover, seismicity with a maximum magnitude of M_L 2.3 associated with hydraulic fracturing of the Bowland Shale, near Blackpool (United Kingdom) can be considered problematic as it has raised public concern and affected shale gas operations. Although waste water injection is strictly not a necessary operation for shale gas exploitation, induced seismicity due to waste water injection is included in this report because of its importance for shale gas operations in the U.S.A. and Canada. Shale gas operations consists often produce large volumes of waste water, consisting of fracturing fluids, flowback water and produced water from shale formations. Disposal of waste water by injection into deep permeable formations is often current practice in the U.S.A. and Canada. In some jurisdictions subsurface injection is the only approved method of shale gas wastewater disposal (BCOGC 2014). Different regulations exist for different European Member States regarding subsurface disposal of waste water from oil & gas operations, and it is questionable whether widespread injection of waste water from shale gas operations will be permitted in Europe. Typical magnitudes for the seismic events associated with the creation of hydraulic fractures range from M_W -4 to M_W 1 (with M_W indicating moment magnitudes, Downie et al. 2010; Warpinski 2012; Davies et al. 2013), which are not felt at the surface. In 2013, in the U.S.A. alone, there were approximately 35,000 wells in operation that used hydraulic fracturing for shale gas production; only one case of felt seismicity (a number of seismic events with a maximum of M_W 2.8) is known to be caused by hydraulic fracturing for shale gas (National Research Council 2013). Worldwide, there are several more cases of felt induced seismicity caused by hydraulic fracturing for shale gas, mostly in western Canada.

One of the largest recorded earthquake that has been linked to hydraulic fracturing occurred near the town of Fox Creek, Alberta, Canada and had a maximum magnitude of M_L 4.4 (with M_L indicating local magnitudes, Schultz et al. 2015). Following hydraulic fracturing of the Duvenay Formation on November 26th 2013, a new series of seismic event was registered on regional seismic monitoring networks, commencing 5 days after the initiation of hydraulic fracturing. More than 160 seismic events recorded in 2014 could be statistically compared to the timing of hydraulic fracturing operations in the area, indicating a temporal correlation >99.99% (Schultz et al. 2015). In January 2015, 24 events of M >2.0 were recorded, one of which had a magnitude of M_L 4.4 (Atkinson et al. 2015). In the Bowland Shale, near Blackpool, United Kingdom, seismic events were recorded during five hydraulic fracturing stages between 31st of March and the end of May 2011 at different depths ranging from 2670 – 3080 m in the Preese Hall 1 (De Pater and Baisch 2011; Green et al. 2012). Seismicity occurred mainly during stage 2 and 4, with a maximum magnitude of M_L 2.3 which occurred during the shut-in phase of the well after stage 2, and a M_L 1.5 during shut-in of the well after stage 4. Total volumes injected during stage 2 and 4 were 2300 m^3 and 1650 m^3 respectively, with a maximum injection pressures at the wellhead of 37 and 30 MPa. Hypocentres were located in the vicinity of the well, but the relative location of most events could not be determined due to poor seismometer station coverage. During stage 4 a local seismic array was employed, and a few events could be located, placing them at 300-500 m from the well. The focal mechanism indicated mainly strike-slip (Harper 2011). The bedding plane, which dips 30 - 79 degrees across the well interval perforated, may have played a role in the generation of the seismicity either by accommodating seismogenic slip or by facilitating the migration of fluids to a larger fault structure further away from the well. Casing deformation indicated that bedding plane slip could have occurred, but it remains unclear whether this slip was seismogenic (De Pater & Baisch 2011; Harper 2011). The Preese Hall 1 well is located in a seismically quiet area with only a few events were recorded in the area over the past decades, before hydraulic fracturing commenced.

The risk of inducing earthquakes by subsurface injection of waste water from shale gas operation is a growing concern in the U.S.A. In Oklahoma, the number of $M \geq 3.0$ earthquakes in Oklahoma has increased significantly since 2009. This increase in seismicity has been linked to the disposal of wastewater in the Arbuckle Group, an often dolomitized limestone that sits directly above the crystalline basement (Walsh and Zoback 2015). The increased amount of wastewater disposal is directly linked to the development of the Woodford Shale gas play. Injection of wastewater (95% formation brine, 5% fracking fluid on average) has led to a lowering of the effective normal stress on critically stressed faults in the crystalline basement, which causes slip of the faults and the associated seismicity (Walsh and Zoback 2015). The earthquake with the largest magnitude occurred in 2011 near the city of Prague, Oklahoma. The M_W 5.7 earthquake destroyed 14 residential homes, injured 2 people and caused damage to a large number of buildings and pavement (Keranen et al. 2013). This earthquake was felt 1000 km away in Chicago, Illinois (Ellsworth 2013). Although the Prague earthquake was the largest earthquake in Oklahoma since seismic monitoring started (Keranen et al. 2013), both the injection rate and the total injected volume in the Prague area are an order of magnitude lower than in some other parts of Oklahoma (Walsh and Zoback 2015). This example shows that diffusion of a pressure front can trigger large earthquakes at relatively small changes in pore pressure over time if larger critically stressed faults are reached. This notion is supported by a hydrogeological model of the region, which indicates that an earthquake swarm that occurred in 2010 near Jones, Oklahoma only required a pore pressure change in of the order of 0.1 MPa (Keranen et al. 2014).

2.3 Current practices of subsurface operations, risk mitigation measures and current technology developments

Best practice shale gas operations in the *subsurface* ideally account for risks for human health, safety and natural environment during the planning, operational and decommissioning phases of development. Best practices that help mitigate impacts, hazards, footprints and risks include four main activities: (1) upfront characterization of the subsurface to establish baselines for monitoring, to obtain site-specific data, to model impacts and to tailor operations, (2) monitoring of operations to measure impact and to control operations, (3) data interpretation to validate predictions, to improve models and to optimize operations, and (4) development of appropriate well closure and decommissioning strategies.
Although this approach can be performed using current technology, datasets and practices, development of innovative technology may further reduce impacts, hazards, risks and footprint of shale gas exploitation.

2.3.1 Characterization of the subsurface

Risks associated with subsurface shale gas operations can be mitigated if site-specific surface and subsurface conditions are analysed upfront, i.e. before large-scale exploitation has commenced. Upfront analysis enables tailoring operations to achieve safe and efficient procedures that comply with local, national and international regulations and best practices.

2.3.1.1 Characterization of baselines for the composition of shallow aquifers

Local evidence for contamination of shallow aquifers, groundwater and drinking water resulting from shale gas operations is often difficult to obtain (EPA 2015). In many cases, limited accessible data on water quality and baselines of groundwater composition hamper causal relations between shale gas operations and groundwater composition. For example, groundwater may contain high natural concentrations of biogenic methane so that methane concentrations itself are not a good indicator of contamination (King 2012). Hydrocarbon abundance in combination with chemical fingerprinting of hydrocarbon and noble gas isotope compositions (Darrah et al. 2014) or organic compounds mixtures (Llewelly et al. 2015) are required to pinpoint sources of groundwater contamination. It is crucial to establish potential causal relations between shale gas operations and groundwater compositions to identify the most prominent hazards and risks associated with shale gas operations, determine optimum mitigation measures and implement proper regulations.

2.3.1.2 *Characterization of the site-specific geological setting and geomechanical conditions in the subsurface*

Detailed characterization of the geology, spatial distribution and properties of gas shales can aid upfront predictions of borehole stability and well integrity. It can also be used to assess the impact of hydraulic fracturing and gas production, for example by improving estimates of local stress conditions and shale properties in models that predict dimensions of hydraulic fractures and volumes of stimulated fracture disturbed rock. The potential maximum earthquake magnitude and probability of inducing an earthquake can be assessed by combining data on the location and orientation of large faults, the in-situ stress state and mechanical properties of the rock. In this way critically-stressed faults can be identified and the potential for reactivation due to fluid injection assessed. Seismic risks can be assessed by combining site-specific analysis of the shallow subsurface and surface conditions in terms of slope stability, presence of water-retaining structures such as dams and dykes, population density, building density, construction quality, presence of vulnerable infrastructure, and potential for ecological and environmental damage in case of a seismic event, with reference to potential ground velocities associated with seismic events.

Best practices of subsurface characterization include interpretation of well logs from existing wells, well tests and passive seismic data. Well log correlation (e.g., based on gamma ray logs) can be used to determine depth and thickness of the shale and formations in the over- and underburden. The combination of density and dipole sonic logs can be used to determine elastic properties of the shale and provide an estimate of the local stress state, in particular the vertical stress. Well tests, such as extended leakoff tests (XLOT) where fluid is injected to determine the injection pressure at which hydraulic fractures are induced, can further constrain the local stress state as the fracturing pressure provides an estimate of the minimum horizontal stress. Passive seismic surveys can be used to map out the regional distribution of the shale in the subsurface. Multicomponent seismic data from passive seismic surveys can be used to map out rock properties, such as Young’s modulus and Poisson’s ratio over large areas covered by the shale.

Developments of characterization approaches that may further mitigate risks associated with subsurface shale gas operations include:

- Better shale characterization approaches by improving relations between measurements and shale properties, expanding existing approaches and integrating different disciplines.
- Laboratory hydraulic fracturing experiments on core samples of gas shales to determine the relation between fluid injection and fracture development.
- More accurate models for development of stimulated fracture disturbed rock volume that can simulate the interaction between tensile and shear fracture, and the interaction of induced fractures with wellbore systems and existing geological structures such as faults or bedding planes and natural fractures.

2.3.2 Monitoring of subsurface operations

Continuous monitoring of shale gas operations can mitigate risks in two main ways: (1) early detection of incidents or unwanted impact expands possibilities and time window for implementing mitigation measures, and (2) more detailed data on subsurface impact can be used to increase safety and efficiency of shale gas operations, thereby reducing the scale of operations (e.g., the number of wells and fracturing stages and required volume of fracturing fluids).

2.3.2.1 Monitoring of zonal isolation and integrity of wells

The risk of shallow aquifer contamination due to migration of hazardous substances along wells can be reduced by continuous monitoring of zonal isolation and integrity of wells. Best practices for monitoring the zonal isolation and integrity of wells involves both logging tools and permanent sensors that are placed in the well. Initially well integrity can be tested by so-called Formation Pressure Tests (FPT) that monitors the response of well pressure at the surface to pressurization of the well to pressure above the lithostatic pressure at depth. A drop in surface pressure can indicate leakage of the well along the wellbore. The quality of well cementation can be inspected using a Cement Bond Log (CBL). CBL provides a rough indication of the local cement thickness, presence of annuli between the tubing and cement sheath, and de-bonding of the cement-tubing interface. Continuous monitoring of annulus pressure can be used to detect the absence of adequate zonal isolation (continuous high annulus pressure) or sudden leakage along the wellbore (sudden or gradual increase of annulus pressure). Damage to the tubing can be detected using a Multifinger Caliper Log (MCP) that uses a video camera to image the inner side of the tubing.

Developments of monitoring approaches that may further mitigate risks associated with the drilling, construction, operation, decommissioning and abandonment of shale gas wells include:

- New types of permanent sensors for continuous monitoring, for example based on fiber optics technology (Pearce et al. 2009, Rassenfoss 2013). The main advantages of fibre optics are that pressure (Distributed Pressure Sensing, DPS), temperature (Distributed Temperature Sensing, DTS), strain (Distributed Strain Sensing, DSS) or acoustic signals (Distributed Acoustic Sensing, DAS) can be monitored at high resolution over the entire length of the well (Hull et al. 2010). DAS can detect local changes in flow regime and thereby detect well leakage (Johannessen et al. 2012). Local changes in pressure or temperature can indicate migration pathways between rock formations at depth and shallower parts of the well. Strong extension or compression of the well that may lead to loss of well integrity can be measured by DSS. Further development of fibre optic sensing technology in combination with fast data processing techniques are required to make the technology cost-effective and enable widespread application.
- New techniques to inspect the quality of tubing and cement sheaths, for example improved acoustic CBL tools or new methods to use these tools in long horizontal well sections (Nurhayati en Foianini 2013).
- Long term monitoring of zonal isolation and integrity of wells after abandonment. Post-abandonment monitoring is currently not routinely applied in the US and Canada. However, it may help to mitigate risks of contamination, in particular considering the large number of wells in shale gas exploitation.

2.3.2.2 Monitoring of hydraulic fracturing

Monitoring of hydraulic fracturing operations can reduce risks associated with (1) interaction of the stimulated fracture disturbed volume with wellbore systems, (2) migration of hazardous substances along faults or fracture networks, and (3) fault reactivation and problematic seismicity. Best practices mainly involve micro-seismic monitoring which is one of the key monitoring techniques to determine the subsurface impact of hydraulic fracturing and gas production. Micro-seismic monitoring is widely applied to improve hydraulic fracturing and thereby increasing the efficiency of shale gas operations as well as to reduce the risks associated with hydraulic fracturing (Green et al. 2012; Warpinski 2012; Van der Baan et al. 2013). The dimensions of individual hydraulic fractures and stimulated fracture disturbed volume can be mapped using networks of seismic sensors at the surface or in monitoring wells as long as the fracturing process involves seismic deformation. The spatial and temporal distribution of seismic events during hydraulic fracturing and gas production can be used to detect unwanted out-of-zone fracturing, lack of fracture containment or interaction of induced fractures with wellbore systems. Dense seismic arrays and micro-seismic arrays can be used to locate faults that are difficult to detect using reflection seismic, such as small faults and strike-slip faults (BCOGC 2012; 2014). In particular, the distribution of seismic events can indicate when large-scale faults are reactivated (Wolhart et al. 2006). In order to mitigate seismic risks, micro-seismic monitoring can be used to implement a “traffic light system” in which shale gas operations are suspended or stopped if observed seismicity exceeds a pre-defined magnitude or frequency threshold, or changes its characteristics (Bommer et al. 2006; Green et al. 2012). Sudden or local increase in magnitudes, change in frequency-magnitude relations and micro-seismicity lining up in a direction other than the expected fracture direction are all indicative of reactivation of larger faults (Downie et al. 2010; Wolhart et al. 2006). Traffic light systems can also be based on ground motion measurements that can be better indicators of seismic hazards than seismic magnitudes.

In addition to micro-seismic monitoring, subsurface deformation due to hydraulic fracturing can also be monitored using networks of tilt meters near the surface or in monitoring wells. Tilt meters record all deformation in the subsurface, including both seismic and aseismic deformation of both natural and anthropogenic origin. Therefore, it can be used in addition to micro-seismic data to improve data on subsurface impact.

Developments of monitoring techniques that may further mitigate risks associated with hydraulic fracturing include:

- Better design of seismic monitoring networks and improving the resolution of seismic sensors.
- Real time high resolution micro-seismic monitoring. Considering the general short duration of hydraulic fracturing operations, development of fast data processing techniques are required (Bohnhoff and Malin 2015).
- Time-lapse seismic monitoring starting before and ending after hydraulic fracturing operations to image changes in subsurface geology.

2.3.2.3 Monitoring the composition of groundwater or shallow aquifers

Migration of hazardous substances from the subsurface may be detected at an early stage by continuously monitoring the chemical composition of groundwater or aquifers at shallow or intermediate depths. Current best practices are mainly based on sampling water samples and laboratory analysis. Development of chemical sensors that can detect chemical tracers or changes in chemical composition can be used to indicate migration of hazardous substances. As causal relations between shale gas operations and groundwater composition currently require chemical fingerprinting (Darrah et al. 2014; Llewelly et al. 2015), continuous monitoring requires identification of suitable tracers or chemical signatures to detect pollution from shale gas operations in combination with design and implementation of subsurface sensors and monitoring networks. Integration of different monitoring techniques, for example based on chemical tracers, temperature anomalies, electrical conductivity or acoustic signals provides added value in detecting migration of hazardous substances provided they can be implemented in a cost-efficient way. Continuous monitoring of groundwater or aquifer compositions may be used to implement a “traffic light system” for hazardous migration which is used to modify, suspend or stop shale gas operations if the concentrations of certain chemical proxies exceed a pre-defined threshold or if specific pre-defined chemical fingerprints or chemical concentrations are detected.

2.3.3 Optimization and implementation of safe and efficient subsurface operations

Subsurface operations can be specifically designed to increase their efficiency. Besides the economic benefit, increasing the efficiency of hydraulic fracturing operations can also reduce risks by reducing the scale of operations.

2.3.3.1 Drilling, construction, operation, decommissioning and abandonment of wells

Best practices for shale gas well construction and operations account for the entire life-cycle of a shale gas well, i.e. from planning to abandonment. Field development planning of well locations should take into account important geological features such as in-situ stress field, and large-scale faults that may affect well integrity and safe spacing between new, operational and abandoned wells. Drilling fluid composition may be chosen as to mitigate the impacts and risks of drilling. Best practices include oil- and water-based muds as drilling fluids. Oil-based muds have some advantages for drilling efficiency compared to water-based muds (e.g., reduced drilling time due to shale instabilities), but surface spills and leaks are potentially more hazardous than water-based muds. If prior knowledge on pressure and temperature fluctuations around the well is available, the design of individual wells should take into account planned hydraulic fracturing operations. Proper design involves multiple well barriers, in particular near shallow aquifers. Typically, well barriers at shallow depth involve 2-5 layers of steel casing surrounded by cement (King 2012). Risks associated with contamination of shallow aquifers can be mitigated by increasing the number of well barriers at aquifer depth (typically 3-5). Wells should be tested and monitored during completion, operation and after abandonment to ensure zonal isolation and well

integrity (c.f. section 2.2.1). Implementing proper regulations plays an important role in mitigating risks associated with the drilling, construction, operation, decommissioning and abandonment of shale gas wells such as contamination of shallow aquifers (King 2012; EPA 2015).
Developments of approaches that may further mitigate risks associated with shale gas drilling and wells include:

- Implementing procedures that are tailored to site-specific conditions by detailed modelling of borehole conditions and cementing process to further reduce the likelihood of migrating hazardous substances along wellbore systems (McDaniel et al. 2014; Yadav et al. 2014).
- Special cementing procedures that improve the settling and bonding of cement to tubing and surrounding rock to increase zonal isolation and well integrity. For example, the tubing may be rotated or moved in a controlled manner to improve cementing (Holt en Lahoti 2012).
- The use of innovative materials that improve zonal isolation and well integrity. Examples include flushing fluids designed to better remove drill cuttings and fluids from the well (Benkley and Brenneis 2013) and cement with different composition or additives (e.g., resins) that improve settling of cement, bonding to tubing and surrounding rock or closure of holes or fractures (‘self-healing cement’, Taoutaou et al. 2011), especially in zones of borehole instability (breakouts or washouts).
- Improving well decommissioning and abandonment procedures. Recent developments include the use of time-dependent deformation (“creep”) of salt- or clay-rich formations above the gas shale to improve the permanent seal at milled-out or perforated wellbore sections (Orlic and Buijze 2014).

2.3.3.2 Hydraulic fracturing

Best practices for hydraulic fracturing operations focus on safe and efficient stimulation to optimize gas production. Maximizing production on the basis of increasing injected volumes (i.e. high volume hydraulic fracturing) and resulting stimulated fracture disturbed volumes increases risks associated with aquifer contamination and induced seismicity. In contrast, more efficient hydraulic fracturing reduces the injected volume of fracturing fluids, and thereby helps reducing the scale of operations. Therefore, designing and implementing a hydraulic fracturing scheme that minimizes the amount of fluid helps mitigate risks associated with aquifer contamination and induced seismicity. The most prominent technique to monitor the subsurface impact of hydraulic fracturing is micro-seismic monitoring, which can be used to optimize operations (c.f. section 2.3.2.2). Recent developments that contribute to more efficient hydraulic fracturing include the so-called “zipper” fracturing with simultaneous or sequential fracturing stages along two parallel horizontal wellbores to account for stress shadows around the stimulated fracture disturbed volume (Nagel et al. 2013, Pierce and Bunge 2015), and cyclic injection of fracturing fluids that increase fracture complexity and shale to well connectivity (Urbancic et al. 2014). Other techniques, such as thermal or

pneumatic fracturing are in an experimental phase (e.g., Gandossi 2013), as are water-free or reduced water fracture technologies.
Alternative fracturing fluids may also aid in reducing risks of contamination by increasing the efficiency of hydraulic fracturing operations to reduce the scale of operations or by modifying the chemical composition to yield less toxic fracturing fluids. Increasing the efficiency of hydraulic fracturing is one of the main goals of research performed by the shale gas industry, and fracturing fluids that are tailored to specific shale compositions or properties are available (King 2012). Some studies also focus on reducing the amount of chemicals or replacing toxic chemicals with less toxic, more sustainable or bio-degradable alternatives. A screening of the toxicity of used fracturing chemicals can reduce risks if it is used to replace toxic chemicals with less toxic or non-toxic alternatives or if concentrations of the most toxic chemicals are lowered, while maintaining efficiency of hydraulic fracturing. In areas with water scarcity, risks of water shortage may be reduced by replacing water as the main constituents of fracturing fluids. Known alternatives for water that are already used for hydraulic fracturing include CO_2, LPG and propane. In particular, increased efficiency of hydraulic fracturing and gas production has been reported when using CO_2 as the fracturing fluid (Yost and Mazza 1993; Mazza 2004). Part of the increased gas production may be caused by desorption of methane due to replacement by adsorbed CO_2 in the gas shales. Increased efficiency is also reported for use of LPG and propane, but these substances are also hazardous and can contaminate shallow aquifers. Although some risks may be reduced compared to conventional fracturing fluids due to increased efficiency and absence of additional chemicals, other risks associated with required surface infrastructure, transport and availability of the alternatives may be introduced. In general, routine application of alternative fracturing fluids in operational field cases is lacking, i.e. their effects have not been tested outside laboratory environments. In order to assess the effect and risk of alternative fracturing chemicals and fluids they should be tested under relevant conditions in relevant environments at the relevant scale of the reservoir or stimulated well volume.
Seismic risks can be mitigated by reducing the injected volume of fracturing fluids and by designing the hydraulic fracturing operations to take place at a safe distance from large pre-existing faults, acknowledging the existing in-situ stress field. This safe distance is dependent on the volume of injected fluid, the existence of fluid pathways from the injection site to the fault, the bulk permeability of the surrounding rock, the injection pressure and the initial criticality of the fault. Actively pumping fracking fluid back to the surface or allowing rapid flow back immediately after the injection phase can also reduce the risk of induced seismicity by limiting the rock volume that is influence by the pore pressure change (De Pater & Baisch 2011; Green et al. 2012). Minimizing the amount of fracking fluid that stays in the subsurface reduces the pore pressure gradient and limits the distance the fracking fluid can travel through the rock volume. This technique appeared to be effective in reducing seismicity in the Montney Shale in Canada (BCOGC 2014).
There are large differences in regulations and practices of hydraulic fracturing between operators, states and fields in the U.S.A. and Canada. Public disclosure of procedures

and the chemical make-up of the fracturing fluids in the U.S.A. and Canada has become part of current practices (FracFocus[4]; EPA 2015). In Europe, regulations differ between Member States. For examples, the United Kingdom's onshore operator's group has published (non-mandatory, voluntary) industry guidelines covering best practices for shale well operations that include the hydraulic fracturing process and public disclosure of the chemical make-up of the fracturing fluids (UKOOG 2015). Such guidelines can be implemented in addition to the mandatory regulations and permits imposed by planning, licensing and environmental organisations. Current practice in the U.S.A. and Canada is that shale gas operations are largely unregulated with respect to induced seismicity, although there are differences between operators, states and fields. Some jurisdictions use a "traffic light" systems (Colorado, U.S.A and British Columbia, Canada) and Ohio requires accurate seismic monitoring in designated "high risk zones" (BCOGC 2014).

Developments of approaches that may further mitigate risks associated with hydraulic fracturing of shale gas wells include:

- Applying alternative drilling or reservoir stimulation techniques. Examples include the use of radial wells where a series of smaller wells is drilled from a central main well into parts of the gas shale or needle wells where a series of short, thin wells are jetted in different directions from a central main well. These techniques have shown promising results for increasing gas production in tight sandstone reservoirs (Egberts and Peters 2015). As gas shales generally have lower permeability than tight sandstone reservoirs, hydraulic fracturing may still be required, but the scale of fracturing operations may be reduced.
- Designing fracturing fluids that require a reduced amount of chemicals or replace toxic with less toxic chemicals, such as more sustainable or bio-degradable alternatives (King 2012; Gandossi 2013).
- Implementing a trial hydraulic fracturing phase with a small injection volume and micro-seismic monitoring. Uncertainties in upfront analysis of risks and impacts can be accounted for by comparing compare observed and predicted response in the trial phase. This approach can improve hydraulic fracturing designs and control on stimulated fracture disturbed rock volume and induced seismicity (Green et al. 2012).

[4] FracFocus (http://www.fracfocus.org), Chemical Disclosure Registry, visited on 10 February 2016.

3 CONCLUSIONS

In this report, the main impacts, hazards, footprint, risks and current practices for shale gas operations in the subsurface are reviewed. The main focus is on risks for human health, safety and natural environment. The main objectives are to provide an integrated review that allow comparison and links between different hazards and risks, and to summarize best practice operations from US & Canada that may affect these hazards and risks.

The review shows that the main risks of shale gas operations *in the subsurface* are associated with (1) zonal isolation and integrity of wellbore systems, (2) the creation of migration pathways that allow upward migration of hazardous substances, (3) the use of hazardous chemicals in drilling and fracturing fluids that may pollute subsurface aquifers, and (4) the effect on reactivating existing large-scale faults that may lead to problematic seismicity.

Best practice subsurface shale gas operations that mitigate risks for human health, safety and natural environment *ideally* include the following phases and activities from planning to post-abandonment phases:

- A planning phase which aims at minimizing the scale of operations (i.e. the number of wells and fracturing stages). This phase includes upfront characterization of the subsurface to obtain site-specific data for modelling impacts and designing operations and to obtain baselines of for the composition of shallow aquifers.
- An operational phase which aims at minimizing the subsurface impact and ensuring safe and efficient operations. This phase includes monitoring of the zonal isolation and integrity of wells to detect potential leakage of substances to shallow aquifers and micro-seismic monitoring of hydraulic fracturing to determine the spatial extent of stimulated fracture disturbed rock volume.
- An abandonment phase which aims at minimizing permanent footprints of shale gas exploitation. This phase includes evaluating the zonal isolation of plugged wells and long term monitoring of abandoned wells to detect the potential accumulation of hazardous substances in aquifers or cumulative emissions to air.

New technological developments that further mitigate risks associated with subsurface shale gas operations mainly extend or integrate current approaches, focus on developing new sensors, better sensor networks or data processing techniques, apply alternative drilling or well construction techniques, optimize hydraulic fracturing operations, or use alternative materials or chemicals for drilling, well construction and hydraulic fracturing.

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