Project Acronym and Title:

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

Integrated review of data and best practices for shale gas operations in the USA and Canada

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Disclaimer

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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 hazards, risks, best practices and public perceptions of shale gas operations based on current practices in the USA and Canada. Hazards and risks associated with operations in the subsurface and on the surface, and associated with emissions to air are reviewed. Available data on the occurrence and potential effects of hazards have also been summarized to give a rough indication of the relative importance of hazards and risks. 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 might have on human health, safety and natural environment (e.g., the contamination of a shallow aquifer). It is therefore noted that identified hazards do not necessarily lead to significant risks, i.e. high risks require frequent occurrence of incidents and significant effects on human health, safety or natural environment. It has been identified that the most prominent risks of shale gas operations in the USA and Canada are associated with (1) loss of zonal isolation and integrity of wellbore systems, (2) the creation of migration pathways that allow upward migration of potentially hazardous substances, (3) the occurrence of problematic seismicity, (4) incidents related to well site construction, storage and transportation, (5) spills and leaks of potentially hazardous substances, (6) reduction in water quality or availability, (7) landscape disturbance with negatively impacts on biotopes, wildlife or local communities, (8) reduction of local or regional air quality, and (9) negative impact on the global climate by elevated greenhouse gas emissions. Best practice operations that help mitigating these risks are discussed. These focus on (1) upfront characterization to obtain site-specific data on the subsurface and environmental baselines and to reduce the scale of operations by optimizing operations, (2) monitoring of operations to measure impact and to control operations, (3) analysis of data acquired during operations to improve knowledge and predictive models, and to further optimize operations, (4) appropriate well decommissioning and abandonment strategies, and (5) full disclosure of data, procedures and substances pertinent to risk mitigation procedures. The most prominent findings related to public perceptions of shale gas are also reviewed based on comparison between USA, Canada and Europe, and based on observations from other large scale energy technologies. A key insight from research on other large scale energy technologies is that it would be wrong to think that all that government and industry need do is provide the public with the 'right' information to ensure public acceptance.

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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, a range of concerns related to shale gas exploration and production, many of them being associated with the process of hydraulic fracturing. There is also a debate around 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 regulatory 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 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 Objectives, aims and scope

The main objective of this report is to summarize and integrate reviews of data and current practices for shale gas exploitation. As commercial shale gas exploitation is mainly limited to the USA and Canada, this report is largely based on experience and data from shale gas operations in North America. The report aims to disseminate a concise, integrated review of data, best practices and risks associated with shale gas operations. It focusses on integrating knowledge and comparing the most important risks, current practices and mitigation measures. Therefore, short summarizing statements and key references are given rather than in depth analysis of data, risks and best practices. This focus is chosen to keep the report concise and avoid overlap with more comprehensive reviews of the individual risks and mitigation measures for the four main areas of potential impact addressed in the different sub-programmes of the M4ShaleGas project (see references in the relevant sections). The report summarizes and integrates the more comprehensive reviews for the different impact areas, i.e. the subsurface, the surface, the atmosphere, and social impacts (see reviews by Ter Heege 2016, Król et al. 2016, Costa et al. 2016 and Bradshaw 2016, and the studies underpinning these reviews performed in the different work packages[2]). The reviews aid in identifying potential knowledge gaps related to impacts and risks of shale gas operations. Accordingly, the work contributes to building a European knowledge base on the risks, impacts and scientific recommendations for best practices of shale gas operations.

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

2 RISKS AND BEST PRACTICES OF SHALE GAS 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. Where possible or relevant, *best practices* 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 incidents, hazards and risks (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., spill of fracturing fluid or an earthquake) and the *effects* the incident might have on human health, safety and natural environment (e.g., the contamination of a shallow aquifer or damage to a building). It means that the significance of risks associated with these hazards may vary depending on the frequency of occurrence and impacts, i.e. risks are only high if hazardous events occur frequently and have a strong impact on human health, safety or natural environment. For example, some chemicals in hydraulic fracturing are regarded as "potentially hazardous substances", but they only really are a hazard or risk to human health, safety and natural environment if an incident causes them to pollute surface environments.

The risk assessment of shale gas operations needs to acknowledge the *scale of operations.* Following the definition of risk above, 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 other industrial activities, in particular *comparison to other large scale energy technologies* such as conventional gas which have been around for a longer period of time. This comparison is important to get a better picture of the relative importance of risks. In the report data on the occurrence of incidents and reported effects are reviewed that together give a rough indication on the relative importance of different hazardous events and associated risks.

2.2 Most prominent risks and best practices of subsurface operations

This integrated review on risks and best practices of subsurface operations has been compiled by Ter Heege (2016). It summarizes five studies that examined (1) hydraulic fracturing (Cuss et al. 2015), (2) induced seismicity related to global shale gas operations (Osinga et al. 2015), (3) seismic monitoring network design, waveform processing procedures (Bohnhoff and Malin 2015), (4) monitoring well leakage (Garcia et al. 2015), and (5) shale gas well drilling, completion, production and abandonment operations (Gawel et al. 2015).

2.2.1 The main hazards and risks associated with subsurface operations

The review shows that the main risks of subsurface shale gas operations for human health, safety and natural environment are associated with drilling and well integrity, hydraulic fracturing, and induced seismicity. The main hazards that have been identified based on experiences in the USA and Canada include (1) loss of zonal isolation and integrity of wellbore systems, (2) the creation of migration pathways that allow upward migration of potentially hazardous substances, and (3) the effect on reactivating existing large-scale faults that may lead to problematic 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 (i.e. it is estimated that 3-6% of the wells in the USA experienced problems with well integrity, although the severity of problems may differ, Davies et al. 2014). 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. King estimates that 1-5% of shallow well completions require 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". In a recent draft report, the US Environmental Protection Agency (EPA 2015[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. Examples of *widespread, systemic* impacts on drinking water resources that is related to problems with well integrity are absent in the current literature. The lack of evidence may be caused by low probability or limited effect of hazards associated with shale gas drilling and wells, limited accessibility of data on water quality and baselines of groundwater composition, and difficulty of linking chemical signatures of shallow aquifers with signatures of drilling, fracturing or formation fluids. Several recent studies indicate *local* evidence for contamination of shallow aquifers, groundwater and drinking water (Llewelly et al. 2015).

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[3]. Migration of potentially hazardous substances is particular unlikely if (1) the gas shale is located at depths below ~1500 meters which ensures that hydraulic fractures do not reach shallow aquifers, (2) large-scale natural faults that may act as migration pathways after reactivation are absent, and (3) the zonal isolation of wellbore systems is not affected by hydraulic fracturing. Micro-seismic monitoring during hydraulic fracturing operations in the USA 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 USA (Fisher and Warpinski 2012). These studies show no evidence that induced fractures

[3] Environmental Protection Agency (http://www.epa.gov), sub-page 'hfstudy' (http://www.epa.gov/hfstudy), visited on 20 January 2016. Note that the report is marked as a draft for review purposes and may be subject to changes.

have reached shallow groundwater-bearing formations or aquifers. They state that in more than 99% of studied cases, 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. A survey of wells with shallow shale gas operations that include examples of distance between hydraulic fracturing and ground water resources below ~600 meters have been performed by the EPA[3]. 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. 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 the 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 USA and Canada (estimated 3-5%, Van der Baan et al. 2013), and not all data for different shale plays are publically available.

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, Keranen et al. 2014) earthquakes, and regarding high volume hydraulic fracturing operations, mainly in western Canada (up to M_L 4.4, Schultz et al. 2015). The occurrence of induced seismicity is mainly determined by the natural stress conditions that result from the local geological setting, the presence, dimensions and properties of faults and fractures, and the local stress disturbance resulting from subsurface operations. 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. Although the occurrence of *natural* seismicity is indicative for the stress regime and tectonic loading rates (Woessner et al. 2015), 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. However, large scale waste water injection in the USA in regions with very low PGA resulted in large magnitude earthquakes (Keranen et al. 2014). 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 has been shown to correspond to higher magnitude induced earthquakes. Most seismic events resulting from hydraulic fracturing operations are of relatively low magnitudes, which does not lead to risks at the surface (i.e., micro-seismicity with typical local magnitudes below $M_L < 1$, 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.

2.2.2 Focus of best practices for subsurface operations

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

- A planning phase which focusses on 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 for the composition of shallow aquifers, groundwater or drinking water.
- An operational phase which focusses 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.
- A decommissioning and abandonment phase which focusses 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 potentially hazardous substances in aquifers and long term emissions to air.

2.2.3 Current practices and new technological developments for subsurface operations

Current practices for upfront characterization generally include analysis of the site-specific geological setting and geomechanical conditions. In many cases, limited accessible data is available on local water quality and baselines of groundwater composition (EPA 2015[3]). Upfront modelling of operations and their effect is usually performed to increase the efficiency of operations, and thereby help reducing the scale of operations.

Monitoring of zonal isolation and integrity of wells integrity is often performed by acquiring a Cement Bond Log (CBL) which 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. Formation Pressure Tests (FPT) that monitor the response of well pressure at the surface to pressurization of the well are also current practice. Current practices for monitoring of hydraulic fracturing mainly involves micro-seismic monitoring that indicate the subsurface impact of hydraulic fracturing and gas production by detecting small seismic events indicative of seismic slip along faults and fractures. Monitoring of the chemical composition of groundwater or aquifers is mainly based on water sampling and laboratory analysis. Continuous monitoring using permanent sensors in groundwater or aquifers is generally not performed.

Evaluation of the zonal isolation of wells after decommissioning and abandonment is not generally current practice. Long term monitoring of integrity, migration or emissions is rare.
New technological developments that further mitigate risks associated with subsurface shale gas operations mainly (1) extend or integrate current mitigation approaches, (2) focus on developing new sensors, better sensor networks or data processing techniques, (3) apply alternative drilling or well construction techniques, (4) optimize hydraulic fracturing operations, or (5) use alternative materials or chemicals for drilling, well construction and hydraulic fracturing.

2.3 Most prominent risks and best practices of surface operations

This integrated review on risks and best practices of surface operations has been based on Król et al. (2016). It summarizes six studies that examined (1) soil and water monitoring systems (Fajfer et al. 2015), (2) risk assessment of impacts on groundwater quantity and quality induced seismicity related to global shale gas operations (Jacobsen et al. 2015), (3) water management (Vadillo Fernández et al. 2015), (4) drilling materials and management of wastes (Kukulska-Zając et al. 2015), and (5) compositions of operational fluids and flowback in hydraulic fracturing (Vieth-Hillebrand and Schmid 2015), and well site infrastructure (Clancy et al. 2015).

2.3.1 The main hazards and risks associated with surface operations

The main risks of surface shale gas operations for human health, safety and natural environment are associated with general public safety around well sites, surface spills, leaks and emissions, availability and quality of water resources, and changes to landscapes or biotopes. The main hazards that have been identified based on experiences in the USA and Canada include (1) incidents or impacts related to well site storage and transportation (e.g., traffic accidents), (2) spills and leaks of potentially hazardous substances (e.g., some of the chemicals in hydraulic fracturing fluids such as biocides), (3) reduction in water quality or availability (e.g., in arid regions), (4) landscape disturbance that negatively affect biotopes, wildlife or local communities (e.g., in forests).
Well site storage and transportation pose a risk to public safety, in particular if transport occurs for long distances on public roads. Exploration and exploitation of gas from shale formations requires a broad spectrum of chemical substances and mixtures, which are present both in materials used in the work and in generated waste. In addition to public risks associated with transport, as with other outdoor activities, well pad sites are exposed to extreme weather and environmental conditions (e.g. heavy rainstorms, severe windstorms, floods and freezing conditions) which makes working on those sites difficult. The presence and operation of heavy equipment and the large quantities of potentially hazardous chemicals used on shale gas sites present similar risks to other industrial facilities, thus making the site secure is extremely important to ensure public safety of personnel as well as local communities in the vicinity of the well site. Well sites and their associated infrastructure should be treated like any other industrial site and made to adhere to securing these facilities so they can operate in a safe manner

(Eshleman and Elmore, 2013). The impact of traffic generated by shale gas activities on general traffic networks (primarily roads but also possibly rail or other modes) needs to be considered. In general, these impacts fall into the following categories: direct road and traffic management concerns (e.g., additional disruption, congestion and delay to other road users, damage to pavement surfaces), pollution concerns (e.g., Greenhouse Gas Emissions, noise and vibration) and additional concerns (e.g., changes to the employment opportunities, culture or heritage of a region, Goodman et al. 2016).
Working conditions at well pads elevate the risk of *accidents, spills or leakages*. Unless these spills and accidents are prevented and/or quickly and carefully contained, contamination of land, surface water and groundwater may result, which, if severe, may lead to potentially highly toxic chemicals being exposed to humans and natural ecosystems (Eshleman and Elmore, 2013). Well site infrastructure such as pipelines and boreholes need to be properly constructed, monitored and maintained to avoid leakage into surface water and groundwater, for there are some references about the American experiences of migration of hydrocarbons into the water. Within the U.S. the frequency of spillage events related to shale gas developments is not well known, there have been a number of media reports citing spills but there is a lack of robust data on the frequency, cause and impact on public safety of such events (see EPA 2015[3], for recent available data). Typically, spills and leaks tend to occur near the drilling location, with occurrence and frequency linked to the density of the shale gas drilling developments. Spills and leaks of hydraulic fracturing and flowback water (often containing organics, salts, metals, and other constituents) can pollute soil, surface water, and shallow groundwater (Vengosh et al. 2014).
Examples of *widespread, systemic* impacts on *drinking water resources* that is related to shale gas exploitation are absent in current literature (EPA 2015[3]). The lack of evidence may be caused by low probability or limited effect of hazards associated with shale gas drilling and wells, limited accessible data on water quality and baselines of groundwater composition, and difficulty of linking chemical signatures of shallow aquifers with signatures of drilling, fracturing or formation fluids. Several recent studies indicate *local* evidence for contamination of shallow aquifers, groundwater and drinking water (Llewelly et al. 2015). Shale gas operations may affect local availability of water resources if resources are not properly managed, not protected by legislation, or not properly accounted for by operations (EPA, 2015[3]). Water consumption during hydraulic fracturing is large and variable, depending on the type of geological formation, the vertical depth of a well and the length of a horizontal well. Exploration and exploitation of unconventional hydrocarbon deposits generate various types of waste that may contaminate water near the surface, including drilling waste and waste associated with hydraulic fracturing (i.e., flowback fluids). Waste generated during the initial drilling of the well typically maintains the characteristics of the drilling fluid but also contains additional solids and dissolved constituents related to the geological formations. The composition of flowback fluids is related to the composition of the initial fracturing fluid, the composition of the natural formation water of the shale and the possible interactions between fracturing fluid and shale system over time at the in-situ conditions. Initially flowback fluid is mostly fracturing fluid, but with time it becomes more similar to the natural formation water (e.g., there is an increase in salinity and a decrease in dissolved organic carbon concentration, Cluff et al. 2014). At this later

stage, fluid composition becomes similar to so-called produced water. With regard to the composition of flowback and produced water, inorganic constituents (metals, salts), organic compounds (hydrocarbons, organic acids) and naturally occurring radioactive material (NORM) are present. Some of these constituents are present in the form of total dissolved solids (TDS) and total suspended solids (TSS), which are bulk parameters routinely used in water characterisation studies.

Landscape disturbance includes the impact of land use and land cover change and the accompanying ecological, physical and aesthetic changes that can result from well site development and associated infrastructure. With the development of shale gas, landscape disturbance is inevitable as numerous wells from many well pads are required to intersect the gas bearing formation(s) in order to be economic. The amount of land disturbed will vary depending on the spatial footprint of a well pad site, e.g., the well pad size, number of wells per pad, well pad density and specifics of the shale play that is being developed (Baranzelli et al., 2015). However, even with technological advancements the footprint from well site infrastructure is generally still significant, especially in natural areas that are not industrialized. It may cause considerable changes to natural landscapes, and may have a substantial impact on agricultural and forested land.

2.3.2 Focus of best practices for surface operations

Best practice surface shale gas operations that mitigate risks for human health, safety and natural environment are mainly related to:

- Well site infrastructure and transport with a focus on procedures to prevent incidents and increase public safety based on safety protocols for industrial facilities with an excellent track record on managing health, safety and environment, and reducing the scale of activities, for example by utilisation of existing infrastructure (e.g., existing water supply networks) and re-using well site infrastructure for multiple well sites.
- Spills and leaks of potentially hazardous substances with a focus on well site designs that ensure containment of used substances, and working guidelines and regulations that minimize spills and leaks.
- Water and soil monitoring with a focus on establishing baseline conditions of the water sources, and site-specific regulations for the frequency of water tests, the scope and method of data collecting, and disclosing of data.
- Water management with a focus on dedicated water treatment, disposal of flowback and produced waters, and wastewater recycling that is based on specific knowledge of chemical compositions of flowback fluids.
- Waste management with a focus on including uniform requirements for the quality of waste, guidelines for their treatment, transportation, disposal and storage, and disclosure of harmfulness of wastes.
- Disclosure of applied chemicals and chemical compositions of operational fluids with a focus on the applied chemicals in and compositions of drilling and hydraulic fracturing fluids, and their fate over the full lifetime of shale gas exploitation including interactions between them, alterations in the subsurface and (altered) chemical compositions of flowback and waste water.

- Landscape disturbance with a focus on field and well site development that minimizes the impact on land use and land cover change as well as ecological, physical and aesthetic changes.

2.3.3 Current practices for regulating surface operations

Current practices for surface shale gas operations that mitigate risks for human health, safety and natural environment are closely linked to regulatory frameworks imposed. The review has shown that as far as the influence of surface operations on environmental compartments is concerned, the most important current practices and developments are related to standardization, systematization and regulation of monitoring and disclosure of chemicals used for shale gas exploitation.
In the USA, regulations on monitoring ground and surface water and soil as well as on disclosure of chemicals used for shale gas exploitation vary between different States or jurisdictions. Continuous ground or surface water testing and full disclosure of chemicals is generally not required by regulation. Agencies or regulators imposing regulations, or promoting monitoring or disclosure of chemicals include (1) the US Environmental Protection Agency (EPA) that assessed the potential impacts of hydraulic fracturing for oil and gas on drinking water resources[3], (2) the Emergency Planning and Community Right to Know Act (EPCRA) that establishes requirements regarding emergency planning and reporting on hazardous and toxic chemicals[4], (4) the Bureau of Land Management (BLM) that may require water testing and monitoring and encourages baseline water testing as a best management practice[5], (5) FracFocus, managed by the Ground Water Protection Council and Interstate Oil and Gas Compact Commission, that is currently in use in 23 states as a mean of chemical disclosure of hydraulic fracturing fluids[6], and (6) the American Petroleum Institute (API) that recommends baseline water quality assessment of both surface and ground water prior to hydraulic fracturing[7]. Wastes generated from crude oil and natural gas exploration and production are generally subject to waste regulation of the Resource Conservation and Recovery Act (RCRA), but wastes from produced water, drilling fluids, drill cuttings and well completion, treatment and stimulation fluids are on the list with wastes from hydrocarbon exploration and production that are excluded from federal hazardous waste regulations[8].

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[4] Environmental Protection Agency (http://www.epa.gov), sub-page (https://www.epa.gov/epcra/what-epcra), visited on 22 March 2016.
[5] Bureau of Land Management (https://www.govinfo.gov/), sub-page 'Hydraulic Fracturing on Federal and Indian Lands; Final Rule, 2015, Federal Register, Vol. 80, No. 58, Part III Department of the Interior, Oil and Gas' (https://www.govinfo.gov/content/pkg/FR-2015-03-26/pdf/2015-06658.pdf), visited on 16 March 2016.
[6] FracFocus (http://fracfocus.org/), visited on 22 March 2016.
[7] American Petroleum Institute (http://www.api.org), sub-page 'Water Management Associated with Hydraulic Fracturing, API guidance document HF2 First Edition, 2010' (http://www.api.org/~/media/Files/Policy/Exploration/HF2_e1.pdf), visited on 16 March 2016.
[8] Environmental Protection Agency (http://www.epa.gov), sub-page 'Exemption of Oil and Gas Exploration and Production Wastes from Federal Hazardous Waste Regulations' (https://www3.epa.gov/epawaste/nonhaz/industrial/special/oil/oil-gas.pdf), visited on 22 March 2016.

In Canada, there are no legal requirements demanding groundwater monitoring at well pads. In terms of surface water monitoring, monitoring networks that provide information on hydrological parameters at the local scale are few, i.e. only large rivers are monitored for flow and water quality monitoring is minimal[9]. More is known about surface waters and the fresh groundwater zone than for the deeper zones because these parts of the hydrological cycle have been well studied in terms of other types of environmental impacts. Chemical substances produced or used in Canada are regulated by the federal government under the Canadian Environmental Protection Act (CEPA)[10]. The FracFocus Chemical Disclosure Registry website also exists for Canada[11]. Similar to the United States, the federal-provincial structure in Canada allocates primary authority to ten provinces and three territories over the relevant areas of regulation with regard to shale gas. Although Canada has strong provincial and federal regulations concerning operational practices to protect the environment, these regulations are not specific to the shale gas industry. The National Energy Board (NEB) regulates oil and gas exploration and production activities[12].

2.4 Most prominent risks and best practices related to emissions to air and carbon footprint

This integrated review on risks and best practices related to emissions to air and carbon footprint is based on based on Costa et al. 2016. It summarizes two studies that examined (1) gas emissions to air related to shale gas operations (Costa et al. 2015) and (2) the carbon footprint from shale gas exploitation (Hauck and Denier van der Gon 2015).

2.4.1 The main hazards and risks associated with emissions to air and carbon footprint

The review showed that the main risks of subsurface shale gas operations for human health, safety and natural environment are associated with air pollutant emissions and emissions of greenhouse gases (GHG). The main hazards that have been identified based on experiences in the USA and Canada include (1) reduction of local or regional air quality due to pollutant emissions and (2) negative impact on the global climate by elevated greenhouse gas emissions.

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[9] Council of Canadian Academies (http://www.scienceadvice.ca), sub-page ‘Environmental Impacts of Shale Gas Extraction in Canada. Ottawa (ON): The Expert Panel on Harnessing Science and Technology to Understand the Environmental Impacts of Shale Gas Extraction, Council of Canadian Academies, 2014’ (http://www.scienceadvice.ca/en/assessments/completed/shale-gas.aspx), visited on 16 March 2016.

[10] Government of Canada Justice Laws Website (http://laws-lois.justice.gc.ca/eng/), sub-page ‘Canadian Environmental Protection Act, 1999 ‘(http://laws-lois.justice.gc.ca/PDF/C-15.31.pdf), visited on 22 March 2016.

[11] FracFocus (http://fracfocus.ca/), visited on 22 March 2016.

[12] Government of Canada Justice Laws Website (http://laws-lois.justice.gc.ca/eng/), sub-page ‘Canada Oil and Gas Operations Act, 1985 ‘(http://laws-lois.justice.gc.ca/PDF/O-7.pdf), visited on 22 March 2016.

The main current concern of emissions at shale gas well sites are the greenhouse gases (mainly CH_4, CO_2), but more attention should be given to the air pollutant emissions in the future. The evaluation of the different shale gas-related emissions should account for all air emissions related to the (1) pre-production, (2) production, transportation, distribution and end-use of shale gas, (3) end of exploitation and well decommissioning. The different sources and types of emissions associated with the various phases of shale gas production can be classified in main categories, i.e. methane (CH_4), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), benzene, hazardous air pollutants (HAPs[13]), and ozone (O_3). The most significant sources of GHG and air pollutants emissions during the pre-production phase are associated with well completion and gas treatment. Emissions from combustion sources are also important. CO_2, SO_x and NO_x are the main emissions during fossil fuel combustion to provide energy to equipment, such as diesel engines used for drilling, hydraulic fracturing and natural gas compression and during flaring operations. Incomplete combustion can also result in other emissions such as CO, methane, VOCs and PM. Furthermore, natural gas fired engines can be a significant source of formaldehyde, which is considered a secondary pollutant (DOE 2009). The reaction of NO_x and VOCs in the presence of sunlight can produce ozone (O_3), which can be associated with exploration and production operations. Primary PM is mainly formed during combustion, but can also appear from dust or soil entering the air during pad construction, due to earth movement, and traffic on access roads (DOE 2009). Emission of CH_4 is the main concern in vented (for example due to the release of gases during flowback) and fugitive emissions as it is the principal component of natural gas. CH_4 may be released as a fugitive emission from gas processing equipment (such as pneumatic controls, valves, well heads and others), or it may escape into ground water due to problems with well integrity (c.f. section 2.2). VOCs are formed during the incomplete combustion, but can also be emitted during the dehydration step of natural gas (DOE 2009). It is also associated with fugitive emissions and flaring from shale gas extraction, but generally in small concentrations (Zammerilli et al. 2014). The HAPs are associated with fugitive emissions, but their presence in general emissions is considered to be small as they were not detected in significant amounts in the gas stream. Nevertheless, accumulated emissions of HAPs may be significant over the entire lifetime of a well. The gas treatments (e.g., treatments to remove CO_2, N_2 and sulphur compounds) applied to the produced gas can reduce the presence of some of these pollutants (Foster and Perks 2012).

The carbon footprint of energy production is a way to quantify and compare climate impact. Different greenhouse gases can be compared by expressing the emissions of each gas in CO_2 equivalents based on their Global Warming Potentials. Several studies indicate that the carbon footprint of generating electricity using shale gas as a fuel ranges from 420-850 g CO_2-eq/kWh, close to the range reported for conventional gas (480-750 kg CO_2-eq/kWh) in the United States. In general, power plant efficiencies are

[13] Environmental Protection Agency (http://www.epa.gov), sub-page 'Initial List of Hazardous Air Pollutants with Modifications' (https://www.epa.gov/haps/initial-list-hazardous-air-pollutants-modifications), visited on 4 April 2016.

important in determining carbon footprints as combustion of gas in power plants generally contributes to about 80% of total GHG emissions. The total gas production (i.e. Estimated Ultimate Recovery, EUR) of a well is identified as one of the largest unknowns for the relative assessment of the carbon footprint of shale gas. A general conclusion is that well integrity remains the weak spot in the system, being the primary concern in environmental protection issues. More attention needs to be given to this issue (see also Balcombe et al. 2015).

2.4.2 Focus of best practices for reducing emissions

The different phases from planning to post-abandonment with main focus for reduction of emissions can be summarized as follows:

- Site preparation phase with a focus on efficient use of resources, minimization of transport and efficient well site operations.
- Drilling phase with a focus on reduction of combustion-related emissions of pollutants and well designs that minimize methane leakage by ensuring zonal isolation and wellbore integrity.
- Hydraulic fracturing phase with a focus on reduction of combustion-related emissions, reduction of methane leakage from wells and well site infrastructure, and capture or flaring of fugitive gas rather than venting to the atmosphere.
- Well completion phase with a focus on reduction of methane emissions from flowback fluids.
- Gas production, transport, distribution and storage phase with a focus on reducing emissions from conventional equipment (e.g. dehydration equipment, pumps and compressors) and leakage from gas distribution pipes.
- Decommissioning and abandonment phase with a focus on reducing long term emissions of plugged and abandoned wells and long term monitoring of abandoned wells.

2.4.3 Current practices and new technological developments for reducing emissions

Several current practices reduce both greenhouse gases and air pollutant emissions to atmosphere. In general, efficient use of resources, minimization of transport and efficient well site operations can reduce emissions of both greenhouse gas and air pollutant emissions to atmosphere. Optimization procedures can be implemented that optimize gas recovery, that minimize drilling and well completions, flowback water, rig or vehicle movements, or that maximize the use of local sources for materials, equipment and personnel, and the efficiency of transport engines. In particular, reduction of emissions associated with the well site construction can be achieved by using existing infrastructure such as roads and pipeline access to water resources and local facilities to recycle and dispose waste. Also, transportable tanks can be used instead of permanent reservoirs for on-site storage of water, hydraulic fracturing or flowback fluids to reduce emissions related to well site construction.
The most prominent mitigation option for reduction of methane emissions is the capture (and use) of fugitive gas, instead of venting to the atmosphere as done by implementing

Reduced Emission Completions or Green Completions (RECs) options. Another option is flaring of the gas, which reduces methane emissions, but releases CO_2 by combustion (Foster and Perks 2012). However, to facilitate the recovery of the gas, the separation of the phases in the flowback fluid that is a mixture of a liquid hydrocarbon, produced water and fracturing fluids, proppants (sieved sand or ceramic solids) and natural gas has to be performed. EPA assumes that for the USA, RECs can capture up to 90% of the initial gas flows, reducing the need for flaring (EPA 2009). GAO (2010) states that available measures, which capture emissions from completions, liquid unloading or venting from pneumatic devices and optimization of plunger lifts could reduce vented and flared emission of shale gas in general by about 40% in the USA. Nevertheless, the variation of methane emissions between different plays remains large (0.2–4% of the lifetime production of a shale gas well) and is still not well understood. In general, more legislation or “good practices”, such as avoiding operating of pneumatic valves on shale gas, has resulted in a decrease in the leakage rates in recent years (2014-2015) compared to earlier shale gas exploitation. The reduction of emissions due to leakage from gas distribution pipes will involve improvements in the gas supply infrastructure off-site. Leak reduction via leak detection and reduction programs can have reported efficiencies of 45-96%. The emissions from storage tanks of produced water can occur due to the volatilization of the gases present in the liquids with the changes in temperature or pressure of the tank. These emissions can be reduced by, approximately, 95% using vapour recovery units (see Alvarez et al. 2012, and references therein). Regarding mitigation of combustion-related emissions, reducing fuel consumption at well sites or the use of alternative energy sources such as gas engines or electricity instead of diesel-fired internal combustion engines is beneficial. For example, local gas from existing wells could be used as an energy source for drilling and completing new wells or for re-fracturing of existing wells. Alternatively, electricity-driven equipment can be used to replace combustion-driven equipment if connections to power grids can be made. The use of three-way catalytic oxidizers on drilling rig engines or injection pumps for hydraulic fracturing can reduce non-CO_2 emissions.

2.5 Summary of data for hazards associated with shale gas operations

This summary briefly lists available data from the USA and Canada on the occurrence of main hazards identified for operations in the subsurface and on the surface, and for emissions to air in the different reviews (Table 1). Only the hazards that are most prominent in the different reviews are listed. More comprehensive lists may be found in the integrated reviews for the different M4ShaleGas sub-programmes or in external literature.

Table 1: Summary of the main hazards associated with shale gas operations, with key statistics on occurrence of incidents and reported effects, impacts or concerns based on available data from the USA and Canada. Note that the summary should be regarded as a rough indication of the relative importance of hazards rather than a definite ranking, and the data cannot be directly applied to other regions.

Potential hazard	Key statistics or findings relevant for the occurrence of incidents	Reported effects, impacts or concerns
subsurface		
loss of zonal isolation or integrity of wells	typically <6.3% well integrity problems, 1.3% leak to surface[a] ; 3% lack cement around parts of casings at groundwater levels[b]	no widespread, systemic impacts on drinking water resources[b]; some examples of local drinking water contamination[c]
migration of potentially hazardous substances to surface through fractured disturbed zone[d]	vertical extent of fractures above horizontal well sections from micro-seismics: typically 1% > 350 m, max. 588 m[e,f]	no documented examples of direct migration, concerns for shales < 1000 m depth and for effects on integrity of nearby wells[b]
induced seismicity related to hydraulic fracturing[d]	typically $M_w < 1$[g,h]; some examples of $M_L > 2$[g,h]; USA: max. $M_w = 2.8$[i], Canada: max. $M_L = 4.4$[j]	seismicity felt at surface (western Canada), well damage possible[k,l]
induced seismicity related to wastewater disposal[d]	some examples of problematic seismicity $M_L > 2$, max. $M_w = 5.7$ (OK, USA)[m]	seismicity felt and structural damage at surface[m]
surface		
incidents related to well site storage and transportation	likely increase of occurrence, no quantitative data on comparison of industries[n]	impacts linked to local settings, methods used, scale of operations and preventive measures[n]
spills and leaks of potentially hazardous substances	typically 0.4-12.2 spills for every 100 wells, 1% of spills linked to hydraulic fracturing on or near the well pad, 0.4% are chemicals, additives, or fracturing fluids[b]	9% of chemicals, additives, or fracturing fluids spills reached surface water, 64% reached soil, none reached groundwater (but may reach groundwater over time)
landscape disturbance due to well site construction	some level of landscape changes are inevitable, depending on scale of operations and field development planning[o]	different levels of ecological, physical and aesthetic landscape changes depending on well site designs[o]
emissions to air		
reduction of air quality due to pollutant emissions	emissions (mg/MJ): CH_4 800, VOC 80 (uncaptured venting); NO_x 52-69, CO 4.6-6.0, PM 0.01 (combustion)[p]	health effects from smog with ground-level ozone (VOC+NOx), CO, fine particles (PM); soil or surface water acidification (SO_2)[p]
greenhouse gas emissions affecting the global climate	carbon footprint for generating electricity: 420-850 CO_2-eq/kWh[q]; total life cycle GHG emissions for shale gas: 65-100 g CO_2/MJ[p-r]	contributes to global warming, level depends on local energy sources (impact depends on comparison with coal, conventional gas, etc.)[p-r]

[a]Davies et al. (2014), Marcellus Shale only, 8030 wells (note that other statistics from this study are not quoted because offshore, mixed with conventional, or lower percentage); [b]EPA (2015), review of 23000 wells in 2009-2010 for well integrity, review of 36000 spills in 2006-2012 (note that the report is marked as a draft for review purposes and statistics may be subject to changes pending review); [c]Llewellyn et al. (2015); [d]Vertical extent fractures and induced seismicity related to hydraulic fracturing based on micro`-seismic monitoring (note that in estimated 3-5% of hydraulic fracturing operations micro-seismic monitoring has been performed, Van der Baan et al. 2013); [e]Fischer and Warpinski (2012) and [f]Davies et al. (2012) for the Barnett and Marcellus shales; [g]Warpinski et al. (2012), M_w-moment magnitudes; [h]Davies et al. (2013), M_L-local magnitudes; [i]NRC (2014), 35000 wells; [j]Schultz et al. (2015); [k]BCOGC (2014); [l]Green et al. (2012); [m]Keranen et al. (2014); [n]Eshleman and Elmore (2013); [o]Baranzelli et al. (2015); [p]Zammerli et al. (2014), uncaptured venting (CH_4, VOC) and combustion (NO_x, CO, PM) in Barnett and Marcellus shales; [q]see references in Hauck and Denier van der Gon(2016); [r]Forster and Perks (2012).

Risks are defined as the combination of the likelihood of an incident or hazardous event and the effects the incident might have on human health, safety and natural environment. Therefore, the summary can be used as a rough indication of the relative importance of risks.

It should be noted that lack of evidence for the occurrence of incidents may have several causes, i.e. it may be caused by low probability or limited effect of hazardous events associated with shale gas operations or limited accessible data (EPA 2015)[3]. Also, the likelihood of incidents is strongly linked to local, regional and national best practices and regulatory frameworks in-place. Site-specific conditions, practices and regulations will ultimately determine the importance of these hazards, and the data is therefore only directly applicable to the different regions and current practices in the USA and Canada.

3 PUBLIC PERCEPTIONS OF SHALE GAS

This integrated review on public perceptions of shale gas has been compiled by Bradshaw (2016). It pulls together the findings of three studies that examined (1) public perceptions of shale gas/oil operations in the USA and Canada (Thomas et al. 2015), (2) existing European data on public perceptions of shale gas (Lis et al. 2015), and (3) the lessons learned on public perceptions and engagement of large scale energy technologies (CCS, nuclear and onshore wind, Mastop and Rietkerk 2015). The review is organised around three themes: acceptability and awareness, risks and benefits and trust and information.

3.1.1 Public perceptions in the USA and Canada compared to Europe

In the case of *North America*, it is important to understand that the body of research that has been reviewed reflected the situation in 2012-13, before recent changes in the price of oil there and the change in the fortunes of the oil and gas industry globally. Even so, research shows substantial regional variations in levels of acceptability with the level of awareness being greatest in areas of actual commercial development. Although studies using national samples suggest slightly more support than opposition, there is some evidence of opposition growing over time in North America, while more locally-based studies there show that the situation regarding ‘support/opposition’ is much more nuanced at regional and local levels.

In *Europe*, there is a much greater level of variation in national attitudes towards shale gas development and many member states have banned development or have a moratorium in place. The study that is reviewed focused on: Poland, the UK, Germany and the Netherlands. Poland was the obvious outlier with a high level of public acceptance, the UK is divided with many still undecided, in Germany opposition seems to be the dominant attitude, and in the Netherlands the lack of detailed research makes it difficult to reach a conclusion. In all cases the public professes a lack of knowledge and feels that they lack sufficient information to make informed decisions.

When it comes to risks and benefits there seems commonality between research findings in the USA and Europe. In both regions the benefits are largely seen as economic in nature, while the risks are seen as both environmental and social. The similarity is not surprising given that the experience in North America is forming the evidence base for the debate in Europe. However, in the European context greater currency appears to be given to the wider issues of energy security and climate change. When it comes to trust and information, it is clear that where people get their information from is important, with the local media being a key source in the USA. In Europe there have been very effective campaigns by environmental groups that have stressed the risks associated with shale gas development and people seem uncertain where to obtain independent views, though scientists are seen as one source of such information. When it comes to trust, it would seem that in the USA few organisations, groups and individuals are trusted. Mistrust of industry is common place and government is often perceived to be too closely aligned to industry. Much can be learnt about matters of trust and knowledge from studying the experience of other large-scale energy technologies and this will be the subject of further work.

3.1.2 Public perceptions in other large scale energy technologies

The review of other large scale energy technologies raises the issue of 'pseudo decisions' whereby people form a strong opinion on the basis of limited knowledge. However, experience warns against assuming that those holding opposing views will change their minds if provided with more information.

3.1.3 Main observations for public perceptions of shale gas

Four observations are made by way of conclusions:

- Evidence from national studies conducted in North America suggest that while there are varied proportions of the public who voice opposition or alternatively support, a significant share of the public remains undecided. This means that shale gas remains both a divisive issue and the focus of ongoing debate there.
- There appears to be a lack of trust of key stakeholders, particularly government and industry, and a concern about a lack of transparency and the availability of independent information. There is some ambiguity over the role of environmental NGOs, but scientists and institutes tend to be seen as relatively impartial and trustworthy, though there are concerns about industry funding their research.
- National and local context matters a great deal in shaping public opinion; particularly in those regions where there is the possibility of development. This also means that there is often a difference between the nature of public attitudes as revealed by national surveys and studies conducted in the potential shale gas regions. At the regional/local level there is a much higher level of opposition and concern about the negative impacts on environment and society. This may be related to a strong sense of place attachment and a view that shale gas development is not compatible with the existing landscape and community (but more research is required to understand this issue).
- In Europe is clear that public awareness of the issues of shale gas is growing. The growing public awareness about the issue of shale gas development in the EU Member States is not surprising given the level of media coverage in many States. More systematic primary research is now needed on how public attitudes are forming in different European countries.

3.1.4 Future research activities

There are four areas of future research activity that lead from this review (1) already there are important lessons that can be learnt about best practice from the North American experience, but there is a need to continue to monitor research outputs from North America to gain new insights into changing public attitudes and assessment of the risk/benefit profile as the fortunes of the industry are changing, (2) things in the EU are also in a state of flux—particularly in the UK and Poland—and there is a need to continue to monitor developments, particularly in relation to changing public attitudes and assessments of the risks and benefits of commercial development at the regional/local scale, (3) comparative surveys across member states in the EU are instructive, but there is a clear lack of comparative research at the regional/local scale that adopts a more experimental approach to provide insights into the reasoning behind the regional variations in perceptions and attitudes (i.e. surveys such as the Flash Eurobarometer 420 report tell us what people think, but not why they have those attitudes, how they reach them, and how they might change in the future), and (4) the consideration of lessons learned from other large scale energy technologies shows that many of the challenges related to public perceptions of shale gas are not new; thus, there is real value in continuing to place shale gas research and policy making in this comparative perspective.

4 CONCLUSIONS

In this report, the main hazards, risks and current practices for shale gas operations are summarized based on existing reviews for subsurface operations, surface operations, and emissions to air and global footprint. Trends in technological developments and existing regulatory frameworks in the USA and Canada are also briefly addressed. The main focus in the review of shale gas operations is on best practices that reduce risks for human health, safety and natural environment from the USA 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 might have on human health, safety and natural environment (e.g., the contamination of a shallow aquifer). It is therefore noted that identified hazards do not necessarily lead to significant risks, i.e. high risks require frequent occurrence of incidents and significant effects on human health, safety or natural environment. The main objective is to provide a systematic, integrated review that allows comparison and links between different hazards, risks and best practice operations for shale gas exploitation.

The following best practices and main hazards have been identified based on experiences in the USA and Canada:

- In general, best practices for shale gas operations should focus on (1) upfront characterization to obtain site-specific data on the subsurface and environmental baselines and to reduce the scale of operations by optimizing operations, (2) monitoring of operations to measure impact and to control operations, (3) analysis of data acquired during operations to improve knowledge and predictive models, and to further optimize operations, (4) appropriate well decommissioning and abandonment strategies, and (5) full disclosure of data, procedures and substances pertinent to risk mitigation procedures
- Specific hazards and associated mitigation options for subsurface operations include:
    1. *Loss of zonal isolation and integrity of wellbore systems* that can be mitigated by continuous monitoring of shallow aquifer composition to detect potential leakage of substances.
    2. *The creation of migration pathways that allow upward migration of potentially hazardous substances* that can be mitigated by micro-seismic monitoring of hydraulic fracturing to determine the spatial extent of stimulated fracture disturbed rock volume.
    3. *The effect on reactivating existing large-scale faults that may lead to problematic seismicity* that can be mitigated by micro-seismic monitoring of hydraulic fracturing to detect the effect of stimulated fracture disturbed rock volume on existing faults.
- Specific hazards and associated mitigation options for surface operations include:
    4. *Incidents or impacts related to well site construction, storage and transportation* that can be mitigated by optimizing safety protocols and using or re-using existing infrastructure

5. *Spills and leaks of potentially hazardous substances* that can be mitigated by dedicated use of alternatives for potentially hazardous chemicals, waste management procedures, well site designs that ensure containment of used substances, and working guidelines and regulations that minimize spills and leaks.
6. *Reduction in water quality or availability* that can be mitigated by establishing baseline conditions of the water sources, continuous monitoring of water and soils following standardized and regulated protocols, and dedicated water management procedures focussing on water recycling and sustainable water use
7. *Landscape disturbance* with negative impacts on biotopes, wildlife or local communities that can be mitigated by field and well site development focussing on minimizing the impact on land use and land cover change as well as ecological, physical and aesthetic changes.

- Specific hazards and associated mitigation options for emissions to air include:

8. *Reduction of local or regional air quality due to pollutant emissions* that can be mitigated by efficient use of resources, transport and well site operations, by using alternatives for diesel-fired internal combustion engines, by ensuring containment of stored or transported substances.
9. *Negative impact on the global climate by elevated greenhouse gas emissions* that can be mitigated by reducing methane leakage from wells and well site infrastructure (e.g., flowback storage facilities and gas distribution pipelines), capture or flaring of fugitive gas rather than venting to the atmosphere, and proper well decommissioning and abandonment.

Observations of public perceptions towards shale gas and public engagement in the USA, Canada and Europe are also reviewed. The following main observations have been made:

- Evidence from national studies conducted in North America suggest that while there are varied proportions of the public who voice opposition or alternatively support, a significant share of the public remains undecided. This means that shale gas remains both a divisive issue and the focus of ongoing debate there. There also appears to be a lack of trust of key stakeholders, particularly government and industry, and a concern about a lack of transparency and the availability of independent information. National and local context matters a great deal in shaping public opinion in North America; particularly in those regions where there is the possibility of development. This also means that there is often a difference between the nature of public attitudes as revealed by national surveys and studies conducted in the potential shale gas regions. At the regional/local level there is a much higher level of opposition and concern about the negative impacts on environment and society.
- In Europe it is clear that public awareness of the issues of shale gas development is growing. This growing public awareness in the EU Member States is not surprising given the level of media coverage in many States.

> However, we do not yet have a systematic comparative picture of how public attitudes are forming across different European nations.

It should be noted that only the most prominent hazards, best practices and findings of public perceptions are listed as the report aims to provide a concise review, avoiding overlap with more comprehensive reviews performed in the different sub-programmes of the M4ShaleGas project or in external literature.

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