Project Acronym and Title:

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

RISKS AND IMPACTS OF SURFACE SHALE GAS OPERATIONS ON WATER, SOIL, WASTE AND INFRASTRUCTURE IN EUROPE

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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 groundwater. 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

Environmental impacts of surface operations related to exploration and exploitation of gas from unconventional deposits are most often analysed with respect to water, soil, atmosphere and their impact on the quality of life of people in the areas covered by these works. The inevitable effect of shale gas exploitation is the occupation of a large area for the well pad, gas processing infrastructure, transport infrastructure and access roads. Possible threats related to the exploration and exploitation of unconventional hydrocarbon deposits include the possibility of contamination of surface water and groundwater, soil, the possibility of emission of pollutants to air, increased water consumption for drilling muds and fracturing fluids, as well as the risks associated with storage of fluids after fracturing. Europe lacks a broader assessment of the actual environmental impact of shale gas exploration and production, which makes it necessary to draw on the experience of its exploitation in North America. However, it should be emphasised that the production of gas from unconventional deposits in part of the process does not differ, or is slightly different, from the work on conventional deposits that has been carried out in Europe for more than a century. In addition, environmental regulation in Europe is much more restrictive than in the United States. This report briefly summarizes the work of six scientific teams engaged in studying the impact of surface operations related to shale gas exploration and exploitation on natural environmental elements: groundwater, surface water, soil, waste management, well site infrastructure and transport. The report presents possible risks and impacts of shale gas surface operations on quality of water, soil, waste and broadly defined infrastructure in Europe, based on the results of a study carried out as part of the M4ShaleGas project. Risk and impacts related to surface shale gas operations were defined based on literature reviews of current practices in the USA, Canada and Europe as well as dedicated experimental and modelling studies. In addition, the report also discusses the possibilities of reduction of the hazards, related to the exploration and production of unconventional hydrocarbon deposits for individual elements of the environment. The risks and impacts presented in the report, as well as the possibilities of their reduction, should increase public awareness and consequently contribute to reducing the environmental impact and public safety of the ongoing works, the methods used and the waste generated. In addition, it should be emphasized that respecting all possible security rules significantly reduces or eliminates defined risks and impacts of surface operations related to shale gas exploration and exploitation on natural environmental elements.

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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.*

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[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 collect and summarise the main risks and impacts of surface shale gas operations on quality of water, soil, waste and broadly defined infrastructure in Europe. This report summarizes research conducted by six scientific teams engaged in researching the impact of surface operations related to shale gas exploration and exploitation on elements of natural environment: groundwater and surface water, and soil. Teams involved in the M4ShaleGas project were also interested in researching the influence of such actions on correct waste management and well site infrastructure and transport.

Detailed results obtained by different research groups were presented and discussed in reports published on the M4Shalegas project website (http://www.m4shalegas.eu):

1. Monika Konieczyńska, Olga Lipińska, *Stakeholders views on monitoring groundwater and soils,* Polish Geological Institute - National Research Institute (Report D7.3)
2. Monika Konieczyńska, Olga Lipińska, Joanna Fajfer, Agnieszka Konon, Łukasz Wojcieszak, Paweł Kwecko, Józef Mikołajków, Krzysztof Jóźwiak, *Environmental monitoring for shale gas,* Polish Geological Institute - National Research Institute (Report D7.5)
3. Ole Stig Jacobsen, Peter Gravesen, *Handling fracking fluids and flowback for shale gas*, Geological Survey of Denmark and Greenland (Report D8.2)
4. Ole Stig Jacobsen, Jacob B. Kidmose, *Seepage shale gas waste in different geological conditions,* Geological Survey of Denmark and Greenland (Report D8.3)
5. Ole Stig Jacobsen, Anders Risbjerg Johnsen, Peter Gravesen, Niels Hemmingsen Schovsbo, Jacob B. Kidmose, *Minimizing pollution risks from drilling and production,* Geological Survey of Denmark and Greenland (Report D8.4)
6. Ole Stig Jacobsen, Anders Risbjerg Johnsen, Peter Gravesen, Niels Hemmingsen Schovsbo, Jacob B. Kidmose, *The impacts of fracking fluids on drinking water resources and quality,* , Geological Survey of Denmark and Greenland (Report D8.6)
7. Virginia Rodríguez Gómez, Lucas Vadillo Fernández, Francisco Javier Fernández Naranjo, *Sustainable alternatives for wastewater management related to shale gas activities in the european context,* Instituto Geológico y Minero de España (Report D9.2)
8. Francisco Javier Fernández-Naranjo, Lucas Vadillo-Fernández , Virginia Rodríguez-Gómez, *Improving water management and treatment in shale gas operations,* Instituto Geológico y Minero de España (Report D9.3)
9. Virginia Rodríguez-Gómez, Lucas Vadillo-Fernández, Francisco Javier Fernánde-Naranjo, *Sustainable water and liquid waste management in shale gas operations,* Instituto Geológico y Minero de España (Report D9.5)
10. Ewa Kukulska-Zając, Anna Król, Marta Dobrzańska, Monika Gajec, Jadwiga Holewa-Rataj, Justyna Mostowska, *Physicochemical parameters to assess the harmfulness of flowback water and waste relevant to shale gas operations,* Oil and Gas Institute - National Research Institute (Report D10.2)

11. Ewa Kukulska-Zając, Anna Król, Jadwiga Holewa-Rataj, Marta Dobrzańska, Monika Gajec, Justyna Mostowska, *Characteristics of fracturing fluids and flowback water with regard to their harmfulness and hazard*, Oil and Gas Institute - National Research Institute (Report D10.3)
12. Ewa Kukulska-Zając, Anna Król, Marta Dobrzańska, Monika Gajec, Jadwiga Holewa-Rataj, Justyna Mostowska-Stąsiek, *Composition and management of waste from shale gas operations in Europe*, Oil and Gas Institute - National Research Institute (Report D10.5)
13. Andrea Vieth-Hillebrand[1], Franziska E. Schmid[1], Juraj Francu[2], *Simulation of flowback water composition in lab experiments*, [1]GFZ German Research Centre for Geosciences, Helmholtz Centre Potsdam, Section Organic Geochemistry, [2]Czech Geological Survey (Report D11.2)
14. Michael Kühn[1], Andrea Vieth-Hillebrand[1], Franziska D.H. Wilke[1], Juraj Francu[2], *Chemical process simulation to characterize mobility of organic and inorganic compounds and prediction of flowback water composition for selected shale systems*, [1]GFZ German Research Centre for Geosciences, Helmholtz Centre Potsdam, Section Organic Geochemistry, [2]Czech Geological Survey (Report D11.3)
15. Andrea Vieth-Hillebrand[1], Franziska D.H. Wilke[1], Michael Kühn[1], Juraj Francu[2], *Simulating the potential composition and mobility of compounds in flowback water*, [1]GFZ German Research Centre for Geosciences, Helmholtz Centre Potsdam, Section Organic Geochemistry, [2]Czech Geological Survey (Report D11.5)
16. Sarah Antoinette Clancy, Fred Worrall, *Review of spills and leaks from normal shale gas operations*, Durham University (Report D12.2)
17. Sarah Antoinette Clancy, Fred Worrall, Paul Goodman and Neil Thorpe, *Mitigating impacts of infrastructure and transport on habitat*, Durham University (Report D12.3)
18. Fred Worrall[1], Sarah Antoinette Clancy[1], Paul Goodman[2], Neil Thorpe[2], Stephen Willis[1], *Final report on impact of well site infrastructure and transport*, [1]Durham University, [2] Newcastle University

1.3 Aims of this report

The objective of the report is to present and disseminate the integrated risks and impacts of surface shale gas operations on quality of water, soil, waste and broadly defined infrastructure in Europe based on research carried out within the M4ShaleGas project. The inventory allows comparison of risks and impacts from different surface operations for shale gas exploration and exploitation, specifically for Europe, and aids in assessing their relative importance.

2 RISKS AND IMPACTS OF SURFACE SHALE GAS OPERATIONS – REVIEW AND SYNTHESIS

The possibility of exploiting energy resources from new sources always awakens many expectations, mainly in terms of economic and financial benefits, but also raises a number of doubts and concerns among the public. The exploration and exploitation of gas from unconventional hydrocarbon deposits can undoubtedly have an impact on the environment and human safety. Possible threats related to the exploration and exploitation of unconventional hydrocarbon deposits include the possibility of contamination of surface water and groundwater, soil, the possibility of emission of pollutants to air, increased water consumption for drilling muds and fracturing fluids, as well as the risks associated with storage and treatment of fluids after fracturing. The following section presents the possible risks and impacts of surface shale gas operations on particular elements of the environment.

2.1 Risks and impacts of surface shale gas operations - water

Exploration and exploitation of shale gas from shale formations is a huge undertaking, requiring access to water at practically every stage of the work. Assessment of possible water sources, including water resources necessary for development, is necessary already in the planning phase. This evaluation should include an analysis of:

- the total volume of water required for hydraulic fracturing (m^3/year) per well and/or well pad,
- yearly water availability versus total water demand from all users, including expected demand to shale gas plays and
- accessibility of alternative water sources (its quantity and quality).

During shale gas operations, water is used during many stages of the work, among which are listed:

- construction of a well pad - water for social and living purposes,
- drilling of wells - water for preparing the drilling fluid (the amount of water used depends on the type of drilling fluid used and the length of the borehole),
- hydraulic fracturing - water is the basis for a fracturing fluid preparation,
- mining plant activity - water for social and living purposes of the employees on the well pad.

Proper water management in the process of exploration and exploitation of gas from unconventional hydrocarbon deposits is extremely important not only for the natural environment, but also for the local community. Pollution of groundwater and aquifers can occur mainly during the leakage of chemical substances (fracturing fluid) on the ground surface and due to fracture cracks and leakage of process fluids from pipes in case of faulty cementation of the cladding pipes during drilling. The work carried out may also pose a risk for hydrogeological balance due to imperfect insulation of the drilled aquifers, in particular the utility waters. It should be added, however, that risks to the soil and water environment occur not only during drilling, but also during the preparatory works, as a result of the storage of substances and chemicals, as well as a large volume of water. Transport and storage of large quantities of chemical substances is also a hazard to drinking water supplies.

The potential impact on the soil and water environment may be particularly visible during hydraulic fracturing operations. Excessive water exploitation during drilling can lead to local water shortages (*Nicot et al., 2012*), even in wetland areas (*Mitchell et al., 2013*). The risk of water depletion could have serious environmental impacts and could lead to conflicts among water consumers (*Shale Gas as seen, 2013*). In addition, activities related to the exploitation of unconventional hydrocarbon deposits may also affect the volume and quality of drinking water, groundwater, surface water and related ecosystems. Hydraulic fracturing also generates significant amounts of liquid waste, which should be managed in a rational way, as improper handling of this waste may pose a risk of contamination to water and soil.

Among the most important possible risks and impacts of surface shale gas operations on quality of surface water and groundwater are as follows:

- contamination due to migration of process fluids or gas in case of incorrect construction of the borehole or dilatation of local dislocation zones (jumps),
- contamination (e. g. petroleum-derived substances from working vehicles and machinery) from the ground surface to surface water and shallow groundwater, which is in hydraulic contact with surface water in the event of improper protection of the ground surface,
- unanticipated events (e. g. failure of drilling equipment and associated leakage of process fluids). The probability of adverse changes depends primarily on the distance from the elements of the environment (surface water and groundwater, natural habitats, residential areas, etc.) that may be affected by the unanticipated events. The degree of contamination due to leakage depends on the chemical composition and the amount of the spilled substance.
- the penetration of contaminants from the surface of the area (e. g. fracturing fluid spillage, leaks from flawed ground tanks for flowback and produced water),
- lifetime of exploitation, over time, can lead to corrosion of the cladding pipes and cement sealant, which may allow gas to penetrate the aquifers,
- gas emissions from the deposit,
- incorrect storage and transport of waste that may result in leakages and emissions of gases and volatile compounds,
- accidental discharge of liquid waste into water,
- permeation of contaminants from waste tanks or overfilling of waste storage tanks,
- surface flow carrying impurity loads (e. g. surface flow as a result of torrential rainfall in the absence of an adequate drainage network at the drilling rig),
- preparation process of drilling mud. Drilling mud is most often prepared in the well pad area and then injected into the well to cool down and oil the drilling equipment. There is a risk of soil, surface water and groundwater contamination during the preparation of drilling mud. However, due to the increasing

substitution of hazardous substances that are a component of drilling muds for safer ones, the risk of environmental contamination can be reduced (*King, 2012*).
- well blowouts - that may also cause spills.

Contaminant transfer (e. g. for radium and barium) in the aquatic environment strongly depends on the geochemical conditions there, and the assessment of their transport is based on site specific factors. Some of the substances (chlorides, bromides) can be easily transported with water.

The risk and impact of work related to exploration and production of gas from unconventional deposits may be minimised in terms of groundwater resources, surface water resources and drinking water resources through the following:

- Correct recognition of the hydrogeological conditions by the geological construction operator (e. g. determination of flow directions for shallow groundwater and possible impacts of groundwaters on surface waters). Appropriate identification enables the borehole to be designed and constructed in a way that guarantees safety for groundwater. Seismic testing carried out in accordance with procedures does not pose a risk to underground water quality.
- Hydraulic fracturing operations have to use casing that are designed with sufficient strength to withstand the stresses there will evolve after installation, during fracturing, and later in production phases. The right casing of shale gas wells is crucial for the safety of the following operations. The casing must be resistant to corrosion from contact with any liquids that will be transported through the casing, e.g. hydraulic fracturing fluids, brines, and gas. Good practices bring several layers of impermeable cement and steel casing to isolate the well. In particular, it is important that the annulus is sealed so that nothing may be able to migrate outside of the borehole.
- Regardless of the depth and purpose of drilling, it is essential to minimise environmental impacts from the point of view of proper construction and execution of drilling wells, which should effectively eliminate the possibility of process fluids and gas entering the rock mass, including in particular aquifers. The correct construction of the well, confirmed by cement tightness tests, reduces the risk of contamination of groundwater by migration of process fluids or gas along the vertical section of the borehole.
- Securing the surface of the drilling pad with impermeable liners and concrete slabs in the immediate vicinity of the well and fuel and chemical tanks, as well as the use of an appropriate drainage and sewage of precipitation water from the well pad.
- Providing full qualitative and quantitative composition of the used fracturing fluid and all information on any additive (including trade name, supplier, purpose, CAS number, concentration and volume) that the operator intends to use to allow appropriate risk assessment in case of leakage and appropriate remedial action to be taken. It is also necessary to report changes in the composition of fluids during processes with them.

- Conducting geophysical tests by the operator before drilling the well. Correct analysis of results of geophysical tests and archival geological data reduces designing works in the zone of occurrence of local dislocation zones.
- The occurrence of natural large scale of sealing confinement formations (at least 3-4 km).
- Performing continuous monitoring of the quality of protection in the borehole during operation and liquidation.
- Execution in accordance with legal requirements for borehole liquidation (e. g. use of cement plugs or mechanical barriers to isolate the gas from aquifers.
- Use of alternative water resources (e. g. water from the local water system, water from sewage treatment plants, treated water from other industrial plants or water of low quality which cannot be used in the agricultural sector or for living and economic purposes). Developing technology allows us to use non-standard solutions that effectively reduce water consumption and allow rational management of water in the extraction process. One such solution is the reuse of treated flowback water or the preparation of fracturing fluid based on water that does not meet high quality standards. For this purpose, process waters (e. g. cooling waters), treated communal wastewater or so-called urban waters (i. e. rainwater), water from mine drains, brine, and, in the coastal zone, sea waters.
- Use of the closed flowback water circuit in subsequent fracturing operations, which would replace the use of surface water and groundwater resources for this purpose.
- Reducing the environmental impact of drilling muds by removing hazardous chemical substances from their composition and replacing them with less hazardous substances.
- Storage of chemicals and fracking fluids away from surface water, aquifers and other sensitive areas (e. g. protected areas). Buffer zones can be introduced to provide additional security for these areas.
- Laying of excavations with mesh systems, vapour recovery before waste water storage, installing a closed loop system.
- Maintaining a safe distance between exploration or exploitation activities and residential areas, water protection areas or other environments requiring special attention.

Member States should ensure that operators carry out characterisation and risk assessment of the exploration and production site for shale gas formations and the surrounding area including the underground area. The risk assessment should cover the potential exploration and production area and identify all possible ways of exposure, as well as the risks associated with leakage or migration of process fluids, hydraulic fracturing fluids, naturally occurring substances, hydrocarbons and well gases. The baseline shall be determined and the quality and characteristics of surface and groundwater flows and water quality at drinking water abstraction points shall be defined. Designation and assessment of risk and determination of the consequences of actions for the natural environment should be carried out on a case-by-case basis. The elements of the hydrological system that have to be taken into account in the risk assessment are groundwater, watercourses, masses of natural water, wetlands (including seasonal surfactants) and water reservoirs. In the groundwater contamination risk analysis as a result of hydraulic fracturing operations, the possibility of penetration of fracturing fluid or gas from a horizontal section of the well should not be overlooked. This could be the case in the event of an uncontrolled rock reaction, such as, for example, the disturbance of long range dislocation zones.

It is worth mentioning that contamination of the environment, including water, may also occur after the disposal stage due to unsealing of the borehole and migration of deposit gas to aquifers and towards the surface of the terrain. In such a situation, the operator should prepare a corrective action plan and cooperate with the relevant state authority in order to minimize the impact on the natural environment and quickly repair the tightness of the borehole.

2.2 Risks and impacts of surface shale gas operations - soils

The process of exploration and exploitation of gas from unconventional deposits requires the development of the area required to set up well pads and other equipment used for this purpose. In order to reduce the risk of soil contamination, the drill floor is sealed with concrete slabs and impermeable membranes are used to insulate the surface of the ground.

In the case of work on unconventional deposits, the utilised area is larger than in conventional fields, which results, among others, from the specific hydraulic fracturing operations, for the needs of which special reservoirs for fracturing fluid and material returning to the borehole (flowback and produced water) are created on the drilling site.

Drilling activity is periodical. Once exploration work is completed, the well's output is secured with a production head and the area around the spilled area is remediated. In the event of failure, the entire drilling area is completely remediated and restored to its pre-drilling condition.

The unfavourable impact of shale gas exploration and production on the soil lies primarily in the following:

- degradation of soils and exclusion of the area occupied by the well pad and access roads leading to it from its normal functions,
- necessity to create a water tank,
- necessity to abandon cultivation,
- local contamination of the soil and ground surface with gas, fuels, lubricants, solvents, cleaning agents and materials used for the production of drilling fluids and regulation of their technological parameters, as well as flowback and produced water, which constitutes a direct risk to the quality of soil, fauna and flora and indirectly adversely affects animals whose food are plants grown in the area. In addition, contaminated soil can affect surface water, subsoil and groundwater by transferring released chemicals through surface flow and infiltration of rainwater,
- soil deterioration as a result of mixing humus with deeper layers and imbalance disturbances that affect the humus, compaction and erosion,

- disposal and storage of the top soil layer during construction of the well pad. This is the most common method of levelling the ground surface as well as for soil protection. However, it can contribute to excessive water and wind erosion, leading to reduced soil fertility,
- the high subsoil density due to overburden from piles and well pad infrastructure, which can also significantly reduce future yields over several growing seasons.

Soil contamination from shale gas exploration and production may occur during gas production operations such as transportation of materials, including chemicals, to and from well pads, well preparation, drilling, well completion (including fracturing and flowback recovery), gas production (and other deposit fluids separation and collection) and well removal. The soil may be contaminated by incidents such as leaks, plant failures and emissions from production and maintenance equipment. Another possibility is fugitive emission of gases or liquids from drilled through geological loss via natural pathways (e. g. fault zones) or through borehole failures.

However, the impact of shale gas exploration and extraction activities on soil quality can be minimised by means of:

- collecting the humus layer of soil from the well pad and storing it in a way that minimizes the occurrence of adverse changes,
- appropriate protection of the terrain surface during the works against contamination by careful ground insulation,
- removal of equipment, drilling rigs, hardening and sealing elements after completion of work,
- terrain levelling,
- assessment of needs for remediation and carrying out remediation,
- conducting continuous monitoring of the quality of security measures in the borehole during the period of operation and disposal,
- execution in accordance with legal requirements for borehole removal (e. g. use of cement plugs or mechanical barriers to isolate the gas from aquifers),
- storage of chemicals and fracturing fluids and waste in closed containers.

Following the current safety procedures and the above recommendations should minimise the possible impact of surface shale gas operations on soil quality.

2.3 Risks and impacts of surface shale gas operations – waste

During drilling and hydraulic fracturing, various types of liquid and solid waste are generated. They are characterized by variable chemical composition, mechanical properties and potential harmfulness to the environment. The method of waste management resulting from exploration for and exploitation of gas from unconventional deposits depends on their physicochemical properties, environmental, legal (legally permissible methods), technical (available facilities for recovery or disposal) and logistic (economic transport of waste to these facilities) conditions.

Proper management of waste generated from the exploration and exploitation of shale gas is a key issue to be taken into account when assessing environmental safety. Significant amounts of waste generated, their complex and variable chemical composition, ecotoxicity and state of aggregation (primarily liquid or semi-liquid) can contribute to pollution of individual environmental elements in case of accidental release as well as improperly planned and conducted treatment and/or disposal. Contamination can occur not only near the well pad where waste is generated, but also wherever waste is transported, stored, treated or disposed.

The main risks associated with the generation of large amounts of waste during exploration and production of unconventional hydrocarbon fields include:

- poor knowledge of the characteristics and composition of flowback and produced water, as it is a relatively new type of waste in Europe,
- leakage or overflow from lined and unlined pits for the storage or disposal,
- breakage or failure of pipelines and valves,
- accidents in transporting waste from well pad,
- improper storage and transport of waste, which may result in leakages and emissions of gases and volatile compounds, with the consequent risk of air, soil and ground contamination in the vicinity of the well pad and leakage of harmful substances into water,
- fracturing fluid composition changes depending on local geological conditions as a result of contact with mineral salts and organic matter in different geological layers, which may result in flowback or produced water containing environmentally hazardous substances when returning to the ground,
- the content of naturally occurring radioactive materials (NORM) in shale and mudstones at different levels, such as e. g. thorium and uranium; during operations involving the extraction of gas from unconventional deposits, these substances may penetrate the ground and pose risks to the aquatic and land environment and human health,
- lack of a specific classification for new types of waste such as flowback and produced water, despite the fact that such waste may contain hazardous substances,
- lack of clear guidelines for handling waste such as flowback and produced water, including uniform requirements for testing/ characterization of this waste,
- flowback and produced waters have a much higher salinity than surface waters, so the introduction of even a small amount of this waste can have a significant impact on freshwater quality (*Vengosh et al., 2014*).
- spills or leaks of flowback and produced water can contaminate soil, surface water and shallow groundwater with organic substances (e.g. monoaromatic hydrocarbons (BTEX), salts (such as chlorides and bromides), metals and metalloids (such as Ba, Sr, Se, As) and other (radionuclides). Groundwater pollution also may occur as a result of the formation of toxic (carcinogenic) trihalomethanes (THMs), typically occurring in conjunction with high concentrations of halogens in saline waters (*Vengosh et al., 2014*).

The waste generated during shale gas operations can contaminate the environment, including water and soil, in a variety of different pathways. Subsurface pathways that may result in the release of fracking fluids to aquifers include failure of well integrity, improperly abandoned wells, and existing faults or fractures in geologic formations between the target formations and aquifers. The likelihood of groundwater contamination by these means is generally low. Surface pathways cover leaks during transport, storage and handling of fracturing fluid and flowback and produced water. Surface spills and releases are the more likely groundwater contamination pathway (*Rogers et al., 2015*).

On the other hand, the impacts and risks associated with shale gas from shale formations arising from exploration and production activities can be minimised by the following:

- using, during drilling, equipment purifying drilling mud - vibrating sieves and centrifuges,
- composing drilling fluids and process fluids from materials with the lowest possible environmental impact,
- use as few potentially harmful or toxic substances as possible and reduce the number and quantity of substances that may create dangerous transformation products during their use in technological processes related to mining activities,
- cost-efficient fluid and material management and closed circuits,
- appropriate, i. e. primarily legal and environmentally safe waste management, i. e. the use of recovery or disposal processes,
- strict control of any flowback and produced water treatment in locations where clay stone contain high levels of radioactive uranium and thorium; in particular, it would be advisable for flowback and produced water to be pre-treated on site in order to reduce radioactive elements in the resulting waste,
- disclosure full qualitative and quantitative composition of the fracturing fluid and all information on any additive that the operator intends to use (including trade name, supplier, target, CAS number, concentration and volume) to allow proper risk assessment in case of leakage and appropriate corrective action to be taken,
- collecting and storing information on the composition (quantitative and qualitative) of waste, as well as information on the method of further waste management, which in case of environmental contamination will allow to take appropriate corrective actions,
- purifying and reusing flowback water in the next on-site hydraulic fracturing process,
- transport waste to other locations or to mining waste disposal facilities in accordance with waste transport procedures.

In order to minimize the environmental risks and hazards associated with the use of fracking fluids, it is essential to know their composition. Only if this knowledge is available, it will be possible to assess the risk and determine the likelihood of reactions in the shale formation during which new hazardous transformation products may be produced and returned to the surface with flowback water, which pose a threat to the environment and human health.

2.4 Risks and impacts of surface shale gas operations – well site infrastructure and transport

Exploration and exploitation of shale gas from shale formations, like any industry branch, generates an impact on the infrastructure of the surrounding areas. The development of this branch of industry also generates changes in road traffic. The increase in road traffic associated with the need to transport technical equipment and technological materials (such as chemicals, large volumes of water) or the transport of generated waste can potentially cause changes in traffic congestion, may also necessitate the expansion of existing road infrastructure and may cause changes in the functioning of existing ecosystems and their pollution.

Significant risks and impacts of surface shale gas operations on the broadly understood infrastructure and ecosystems include above all the following:

- Disturbance of existing space and infrastructure, which is related to the fact that the extraction of gas from unconventional resources often requires the drilling of many wells on a relatively small area.
- Possibility of accidents on roads, resulting in spills and leaks of transported substances or waste.
- Possible occurrence of disturbances in the continuity of road traffic (block formation, accidents, road destruction).
- Possibility of soil and air pollution, which is related to the necessity of land transport of a number of chemical substances and wastes (mainly liquid waste), which must be transported often over long distances.
- Disturbance of existing ecosystems or pollution of them by harmful and toxic substances due to increased traffic and technology.
- Possibility of changing the structure of large areas free from human intervention, including industrial activities, and thus disturbing habitats of various animal species.
- Increasing the emission of noise, light and pollution of environmental elements by chemicals, with the risk of changing the behaviour and functioning of ecosystems surrounding the work area causing increased noise, light or chemical contamination. Noise, light and air pollution can all together contribute to the environmental impact of the areas involved in shale gas extraction activities. These factors can affect organisms at population level and cause changes in the behaviour of these populations.
- Light pollution that changes the natural cycles of light and darkness in the environment by producing artificial light in times of natural darkness, affecting both flora and fauna. Such artificial light production can cause biological orientation problems and can attract or repel species to light sources. Increasing artificial lighting can also change reproductive behaviour and communication in

species and affect the composition of the animal community (*Longcore and Rich, 2004*).

- Noise generated by exploration and production operations of shale gas from shale formations, which can mainly affect the behaviour of birds and other animals.
- Leaks or spills, mainly related to failures and accidents occurring in the area of extraction and exploitation of unconventional hydrocarbon deposits (equipment failures, deficiencies in the application of safety procedures).
- Disturbance of vegetation zones in areas where shale gas exploration and exploitation is carried out, thereby reducing food supply for vegetation pollinating insects.
- Changes in plant structure that may have the effect of reducing the population density of some birds and increasing the risk of predation in smaller mammals. Habitat losses associated with the development of shale gas operations may force populations to occupy smaller areas, increasing the grazing intensity of these areas. This may be particularly problematic in the vicinity of nature conservation sites. In this case, we will have to deal with the possibility of a higher number of big herbivores in protected areas, which can lead to the disturbance of important ecological processes. There is also a risk of the opposite (due to the need for migration in some areas, large predators may need to migrate, which may be a consequence of a change in grazing patterns and a reduction in the diversity of ecosystems).
- Influence on abundance and need to change the breeding areas of certain bird species.
- Disturbance of natural hydrological patterns and thus ecological balance of the water system due to intense water intake for shale gas operations from these systems. Excessive water uptake is associated with the risk of a collapse of freshwater communities, which may result in a change in the abundance of species living in aquatic ecosystems (fish, algae).
- Changes in water flow rates from streams and rivers due to intense exhausting. Such changes may occur both spatially and seasonally, and the survival of many species living in waters is determined by the rate of water flow and its natural fluctuations.
- Changes in the chemical composition of waters. Chemical contamination, as well as the presence of suspended particles in the water, adversely affects the eco-systems operating in the water. For example, an increase in the metal content (including mercury) in waters may increase the mortality of invertebrates and fish or the accumulation of metals in their bodies. On the other hand, an increase in total dissolved solids (TDS) results in a decrease in the number of macrobes. The increase in salinity in waters may affect amphibians living in waters.
- Storage of liquid waste, often containing hydrocarbons in open tanks, posing a risk to the health of birds, which are often exposed to hazardous or toxic substances when landing on these contaminated waste tanks.

When assessing the impact of well pads and any related infrastructure and transport on existing ecosystems, the impact of these factors on existing habitats, the potential for animal migration and possible disruption by the development of shale gas operations infrastructure should be taken into account. The impact on the functioning of aquatic ecosystems should also be taken into account.

On the other hand, limiting the impact of surface shale gas operations on broadly understood infrastructure and ecosystems can be achieved through:

- Prior to the commencement of the work, an analysis is carried out between the amount of forecast gas to be produced, the planned boreholes and the possibility of having a potential impact on the environment, as the magnitude of shale gas operations changes is dependent on a number of factors, including the geology of the drilled rock layers and the number of wells themselves.
- Reducing the risk of road accidents and thus reducing the number of potential chemical leaks to the environment associated with these accidents by regularly checking the technical condition of vehicles, taking care of the technical condition of vehicles, providing regular training for drivers, introducing appropriate safety instructions and applying them, selecting the right route and adjusting the set travel time to weather conditions.
- Obtain as much ecological information as possible on the area being transformed in order to reduce the risk of disturbances in ecosystems before starting work on shale gas exploration and production.
- Use the following measures to reduce or eliminate environmental noise:
  - ✓ location of the drilling rig at a safe distance from surrounding buildings or areas requiring protection,
  - ✓ building embankments or using sound absorbing screens around well pads to dampen noise,
  - ✓ using silent devices with sound screens installed,
  - ✓ using silencers for equipment and machinery,
  - ✓ using low sound power devices,
  - ✓ taking care of the efficiency and correct use of machines and equipment,
  - ✓ carrying out, as far as possible, works generating the greatest noise at the times that are least burdensome for the local population (i. e. during the daytime from 6:00 am to 10:00 pm),
  - ✓ reducing vehicle traffic from and to the drilling rig to a minimum.
- Using measures that reduce the risk of leakage or spillage, such as:
  - ✓ making the crew sensitive to adverse effects of neglect (both ecological and economic),
  - ✓ using in areas where leaks or spills are likely to occur,
  - ✓ providing the crew with the equipment to enable immediate ecommissioning of spills,
  - ✓ permanent control of packaging of materials and chemicals as well as of fuel and waste storage sites,
  - ✓ inspecting the site after drilling and analysing the results obtained.

- Light pollution from development sites should be tightly controlled wherever possible, with artificial light sources being minimised during hours of darkness as much as possible.
- To site well pads and related infrastructure safely, with as little environmental damage as possible, avoiding conflict with existing land uses, and trying to conserve biological diversity.

The impact of well site infrastructure and transport is important but comparable to the impact of other industries. It can be minimized while maintaining the basic precautionary measures and applying the relevant provisions. Infrastructure measures could be expected to be increasingly effective as the industry matures, economies of scale come into effect or as technology changes.

Operators should always use existing roads wherever possible, and avoid the construction of new roads so to minimise habitat fragmentation and avoidance behaviours. Traffic should also be minimised to the lowest possible level. Similarly, any seismic lines cut for resource exploration purposes should be as narrow as possible.

3 SUMMARY

Surface operations related to shale gas exploration and exploitation affect environmental elements such as groundwater and surface water and soil. Generated waste and the entire infrastructure associated with shale gas operations also have an influence on the environment and public safety. Possible hazards associated with the exploration and exploitation of unconventional hydrocarbon deposits include the possibility of contamination of underground water and groundwater, soil and ground, the possibility of emission of pollutants into the air, increased water consumption for drilling muds and fracturing fluids, as well as the hazards associated with storage of liquid waste. It should also be remembered that this type of work may also have an impact on the ecosystems operating in or near areas occupied by well pads. However, compliance with strict safety standards, procedures and environmental standards at every stage of the work will contribute to minimising the risk of possible environmental pollution and will allow rapid corrective action to be taken in the event of any accident or failure. Undoubtedly, monitoring of the environment is a very important and, at the same time, effective security control measure which allows to identify measures that minimize the impact of works related to exploration and production of hydrocarbons from unconventional deposits on the environment. Well-targeted monitoring programmes are also a source of data and contribute to the understanding of natural and industrial phenomena as well as to the determination of the scale of adverse environmental changes caused by the extraction of hydrocarbons from unconventional sources. It is important to mention that respecting security rules significantly minimizes or even eliminates defined risks and impacts of surface operations related to shale gas exploration and exploitation on natural environmental elements.

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