> Hydraulic Fracturing

A technology under debate

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EXECUTIVE SUMMARY

Hydraulic fracturing, commonly referred to as fracking, is a critically and controversially debated technology that divides opinion among both politicians and the general public. At the same time, hydraulic fracturing is a prerequisite for two applications significant in terms of economic and energy policy: the production of unconventional gas from shale formations (shale gas) and the utilisation of heat energy from petrothermal reservoirs deep underground. It is against this multi-layered background that acatech has elaborated this POSITION.

Addressing the various facets of fracking, the paper wishes to contribute to objectifying the debate. It aims at broadening the available information base by a comprehensive scientific and technical overview of the method and its risks and benefits. This will allow decision-makers from politics as well as interested members of the public to draw their own conclusions about hydraulic fracturing and to decide on the further use of the technology.

Fracking in the context of the energy transition and resource and climate policies

The German energy transition, European and international climate policies and the global availability of energy resources form the framework within which the exploitation of natural gas and deep geothermal energy must be addressed. The energy transition will remain one of the key challenges Germany will face over the coming decades. In this process, technological progress and competitiveness will play a crucial role. The requirements of the energy transition can only be met if the political echelons join forces with the industry, the scientific community and the public to find appropriate solutions and to set the right course.

There is no doubt that for the next decades, hydrocarbons will continue to play a significant role in Germany's energy supply system. Currently, natural gas covers around 22 percent of the country's primary energy demand. In 2012, domestically produced natural gas still accounted for 13 percent of this total. In about ten years' time, however, Germany's reserves of conventional gas will be exhausted. Without the production of unconventional shale gas, the country will then be totally dependent on natural gas imports. If, on the other hand, Germany were to use hydraulic fracturing to recover shale gas, it could sustain its domestic gas production at the current level for decades to come. Shale gas, incidentally the "cleanest" fossil energy source, could thus provide a bridging function.

The technology of deep geothermal energy seeks to recover the huge resources of heat energy locked deep underground for power and heat generation. Of all renewable energy sources, geothermal energy has the smallest ecological footprint. It can provide a sustainable, long-term supply with base-load power. Most of Germany's geothermal energy is stored in deep, hot rock, also known as petrothermal systems. Even with the current technology, these reservoirs could contribute substantially to covering Germany's demand of electric power and heat. An appropriate funding and development of the relevant technologies for the exploitation of petrothermal reservoirs by means of heat exchangers would largely enhance this potential. Deep geothermal energy could indeed become a major factor in the renewable energy portfolio that is to cover Germany's future energy demand.

Neither shale gas extraction nor the development of petrothermal systems are possible without hydraulic fracturing.

Hydraulic fracturing: processes and techniques

Hydraulic fracturing is a technology that uses water pressure to generate fractures in solid, low permeable rocks in the geologic subsurface. The method is carried out in deep wells and is usually applied through deliberately perforated sections of the cemented borehole casing. The objective of a fracking operation is to achieve a lasting improvement in the hydraulic permeability of the rock and to create highly conductive flowpaths for the transport of fluids (e.g. natural gas, oil and water). To this end, a so-called frac-fluid is pumped into the target rock. The injection of this fluid builds up sufficient pressure to either produce tensile fractures (hydraulic fracturing in the strict sense) or to trigger shear displacements along pre-existing faults or fissures in the rock (hydraulic stimulation). The shear fractures significantly enhance the hydraulic permeability of the rock. Hence, the frac-fluid usually used for conventional hydraulic stimulation in petrothermal reservoirs is water. If, however, hydraulic fracturing is employed to recover natural gas and oil reservoirs, the frac-fluid requires chemical additives as well as additional proppants like quartz sand or ceramic beads to keep the newly created tensile fractures open.

Typically, frac-fluids will contain 97.0 to 99.8 percent water and 0.2 to 3.0 percent additives. In Germany, the total number of chemical additives for tight gas extraction has already been reduced to around 30. Under current legislation, these 30 additives are not subject to any license restrictions. In the case of shale gas extraction, it appears possible to further reduce the number of additives to only two or three.

Seismic monitoring during fracking operations allows a permanent control of the fracprocess and ensures that the fractures do not extend beyond the target horizon of the reservoir. Whereas the horizontal extent of the fractures (length) ranges from a couple of ten to a few hundreds of metres, their height is generally much lower. The width of the fractures is often no more than a few millimetres and rarely exceeds one centimetre.

Hydraulic fracturing and the environment

Hydraulic fracturing is an established technology that has meanwhile been employed in over three million frac-operations worldwide. The technology was developed towards the end of the 1940s by the oil and gas industry in order to improve the productivity of conventional oil and gas deposits. Since then it has established itself as a key technology for the extraction of hydrocarbons from conventional deposits in low-permeable sandstones or carbonate rocks (tight gas/tight oil). In Germany, the fracking technology has been in use since 1961. In recent decades, it has primarily been employed to extract tight gas from deep reservoirs.

The outright opposition fracking is frequently met with can partly be attributed to media reports on incidents in connection with the production of shale gas in the United States. Such incidents occur in the context of the large-scale frac operations that have been carried out for over ten years in order to extract natural gas (and more recently also oil) from shale formations.

Whereas conventional gas and oil migrate through the Earth's upper crust and accumulate in geological structures acting as traps (conventional hydrocarbon deposits), shale gas is still stored in the rock where it was originally generated (source rock). These so-called unconventional hydrocarbon occurrences are widespread in some regions of the USA, but can also be found in other parts of the world – sometimes in quite substantial quantities. These resources, which usually have a large lateral extension, are accessed by deep boreholes that enter the deposit vertically before making a horizontal bend to run along the length of the shale formation.

There are several major environmental risks that are commonly attributed to fracking – particularly since reports on shale gas production in the United States fuelled the public debate. These risks include: contaminants infiltrating from the surface into drinking water horizons as a result of accidents or technical failures, toxic or environmentally hazardous substances and methane being released and ascending to the surface out of and along leaking boreholes as well as contaminants escaping from the fracked rock and rising up to the surface and emissions of methane into the atmosphere. Other concerns include the large land areas required for fracking, the significant amount of water used in the process, and, in particular, the phenomenon known as induced seismicity.

In Germany, groundwater protection is a particularly important issue in the debate on hydraulic fracturing. In this discussion, the terms “groundwater” and “drinking water” are often used as synonyms. However, once a depth of around 50 to a few hundred meters (depending on the regional geology) is surpassed, the naturally occurring groundwater is in fact undrinkable and unsuitable for economical utilisation. It frequently contains extremely high concentrations of salt (e.g. up to 30 percent or more in the North German Basin), high contents of trace metals and, occasionally, naturally occurring radioactive substances. Therefore, a clear distinction should be drawn between commercially viable shallow groundwater, medicinal water and formation water/deep saline brines without any potential for exploitation.

To date, there have been no reported environmental incidents caused by hydraulic fracturing in Germany. This is not least due to the high standards and comprehensive regulations that Germany has already introduced with regard to the design and monitoring of well sites/production facilities, the completion and casing of deep wells and the conduction of fracking operations. This position paper presents a number of recommendations and measures that could help to further improve safety, for instance in the field of site-specific risk assessments and well integrity management and monitoring.

The injection of fluids to create fractures in shale gas deposits or petrothermal reservoirs inevitably leads to the occurrence of induced (micro-) seismic events. However, these events are rarely perceptible at the Earth’s surface. Their magnitude and frequency are particularly dependent on the respective geological and technical parameters. It is, therefore, important to employ “soft” fracking techniques based on local seismic hazard analyses. The aim must be to develop standards for the injection process that limit the magnitude of the microseismic activity perceptible at the surface while still significantly improving the permeability of the reservoir. Although research efforts have already yielded a variety of possible approaches and methods, further research in this field is still required.

Public perception and social debate

In an open society, the future use of hydraulic fracturing will require the consent of the groups and residents affected by the operations. It is therefore essential that planning approval procedures ensure full transparency, providing for a comprehensive communication of the necessary measures and offering active participation in the planning process to those directly concerned. Scientifically monitored pilot/test projects as proposed in Chapter 9 can contribute to this end by showing and explaining the technical procedures of a frac operation. Such experiences are important to create a basic confidence and appreciation of the economic and ecological potential hydraulic fracturing offers. At the same time, pilot/test projects can also serve to curb excessive expectations and foster a sound level of scepticism.

Best Practice: Options and recommendations for hydraulic fracturing

acatech has drawn up a comprehensive list of best practice measures aimed at minimising any environmental risks that might arise in the context of hydraulic fracturing operations. These include:

- **Preparatory geological and geophysical studies and 3D-modelling of the subsurface:**
  Prior to every drilling operation, a 3D-image of the geological underground at the drilling site in question should be created. This can be achieved by combining all available geological data and information with the results of geophysical deep sounding methods and modelling techniques.

- **Site-specific risk assessment of the well site and drilling strategy:**
  Groundwater protection is to be guaranteed by designating water protection zones, identifying the boundary between drinking water/shallow groundwater and formation water/deep saline brines and establishing the overall hydrogeological situation, as well as by locating any geological barrier formations and tectonic fault zones. The risk of naturally occurring earthquakes must likewise be assessed.

- **Baseline measurements and long-term monitoring:**
  Regular monitoring of the near-surface groundwater (chemical composition and physico-chemical properties), the atmosphere (e.g. methane emissions) and natural seismicity (signal-to-noise ratios) is necessary both prior to and during pilot/test projects.

- **Frac-fluids:**
  All additives and relevant data pertaining to any frac-fluids intended for use are to be disclosed. Research and development efforts should be undertaken to reduce the number of additives and to replace potentially harmful substances with safe ones. Frac-fluids classified as toxic, hazardous or anything more than weakly water contaminating (Water Hazard Class 1) should not be used.

- **Flowback:**
  The so-called flowback fluids, discharged at the beginning of shale gas extraction immediately after a frac-operation, should be recycled and re-used. This measure substantially reduces the water consumption for fracking operations and largely avoids the necessity of fluid disposal.

- **Cluster drilling:**
  A significant reduction in land use can be achieved by exploiting shale gas deposits by clusters of 20 or more horizontally diverted boreholes issuing from a single drill site.

- **Induced seismicity/seismic monitoring:**
  Project-specific seismic monitoring should be carried out at the surface and, where possible, in adjacent observation wells, in order to provide a real-time record of fracture propagation during frac operations. Thus, accurate information is available at all times, allowing for immediate and appropriate measures to counteract any potential seismic hazards. A project-specific "traffic light system" should be developed to this end.

- **Well Integrity Management System:**
  A project-specific definition and establishment of minimum standards for a "Well Integrity Management System" is recommended. This should cover the entire life cycle of a deep well, from the planning and drilling stages to the exploration and exploitation of the resource and the plugging of the well once the project is finalised.

- **Well integrity monitoring:**
  The technical installations above ground (including the well site/production facility), the well integrity and the operations monitoring systems are to be regularly inspected.

- **Communication with the media and public:**
  It is important to engage in a transparent, dialogue-based information and communication process with the public and the media right from the earliest planning stages of any project that involves fracking.

Conclusion

Scientific or technical facts do not justify a general ban on hydraulic fracturing. Its use should, however, be subject to strict safety standards and requires clear regulations and comprehensive monitoring. In Germany, high technical standards are already in place for the various different process steps involved in drilling, reservoir engineering and fracking. These standards would also have to be observed for potential shale gas production or the recovery of deep geothermal energy.

In the current situation, scientifically monitored pilot/test projects can play an important role for the development of shale gas extraction as well as the utilisation of deep petrothermal systems. Such pilot projects should be carried out under clearly set conditions and in accordance with pre-defined standards and should address any unresolved issues in terms of risk assessment. At the same time, the fact that the operations are being permanently monitored and that the public is informed and involved into the processes from an early stage could help to enhance public confidence in the fracking technology.

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1 INTRODUCTION

“Scared stiff of fracking” ran the headline of a leader in the Frankfurter Allgemeine newspaper in March 2013.[1] And it would indeed be fair to say that in Germany fracking is currently dividing opinion among politicians and encountering more opposition in the public than almost any other technology.

This topic was taken up again by Germany’s current government in its Coalition Agreement of December 2013, where an entire section was devoted just to fracking. The text emphasises the considerable risk potential connected with the use of fracking for unconventional gas extraction. According to the agreement there is, as yet, no sufficient scientific understanding of the impacts of the technology on humans, nature und environment. It consequently stresses that the protection of groundwater and human health are the number one priorities. However, the text does not contain an outright ban of fracking, either. Rather the policy approach it appears to advocate could be summarised as: “moratorium” > research > final decision”.

Against this background, the present POSITION PAPER illuminates the various different facets of hydraulic fracturing. These include the environmental, legal, economic and energy policy aspects as well as issues pertaining to the field of communication and public acceptance. An integrated assessment of the technology, its benefits and risks rounds off the paper.

“Fracking” is the widely established shorthand term for “hydraulic fracturing”. It denotes a technique that uses water pressure to generate fractures in solid, lowpermeable rocks in the geologic subsurface. Prerequisite for the application of this method is the successful drilling of a deep well and the creation of a stable borehole in accordance with established standards. The objective is to achieve a lasting improvement in the fluid permeability of the rock and the generation of highly conductive flowpaths for the transport fluids such as natural gas, oil and water. A fracking operation usually involves pumping a frac-fluid through deliberately perforated and pressure-sealed sections of the cased and cemented borehole into the target rock. The frac-fluid consists of water which, depending on the application, may contain solid proppants to keep the fractures open, together with chemical additives.

Application of hydraulic fracturing for the extraction of oil and gas

The technology was first employed towards the end of the 1940s by the oil and gas industry in order to improve the productivity of conventional oil and gas deposits. Such economically viable accumulations of hydrocarbons (usually coming with water) are found in porous-permeable reservoir rocks, sealed off by impermeable barrier formations. Fracking has since become a key technology, particularly for the extraction of natural gas from relatively tight, low-permeable sandstones (tight gas) as well as from tight shale formations (shale gas). More than three million separate frac operations have already been carried out in wells all over the world. In Germany, fracking has been in use since 1961 to improve the flowrate of otherwise little productive conventional oil and gas occurrences. Since 1977, it has also been employed to extract tight gas from deep-seated sandstones.

Application of hydraulic fracturing for the extraction of deep geothermal energy

Hydraulic fracturing is also necessary to recover the huge resources of heat energy locked deep underground in so-called petrothermal reservoirs (“Enhanced Geothermal Systems”, EGS). Although more recent, this field of application is meanwhile also pursued worldwide. Under specific geological conditions, this type of deep geothermal energy can be recovered by means of hydraulic stimulation. The latter is a fracking variant in which solely water is injected to induce shear movements along already existing geological faults and fissures. In dense hot rocks without zones of weakness fracking sensu stricto has to be employed to create artificial heat exchangers deep underground (at depths below about four kilometres).

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[1] Cf. Mihm 2013.

Other fields of application for hydraulic fracturing

Fracking is occasionally used in groundwater and thermal water drillings or for the degassing of methane from coal beds. However, the method is also being employed for scientific purposes. In a number of national or international research drilling projects the method was employed to gain information on the geomechanical or hydrological properties and behaviour of underground rock and to investigate the natural seismic activity.

Owing to the former German Continental Deep Drilling Program (Kontinentales Tiefbohrprogramm, KTB), Germany has gained extensive research experience in the application of hydraulic fracturing. The method was employed to investigate how the tectonic stresses of the Earth's upper crust and the rock strength vary with depth as well as to obtain a quantitative understanding of the frac process and the generation and propagation of fracking-induced (micro)seismicity.

Between 1987 and 1994, two boreholes of 4,001 and 9,100 metres respectively were drilled as part of this large-scale national geoscientific research programme (jointly funded by the former Federal Ministry of Research and Technology (BMFT) and the German Research Foundation (DFG)). Both wells (the pilot and main borehole) are still available for use in experimental projects. In addition to tests for the further development of the fracking technology, several dozens of individual frac experiments for scientific research were carried out at depths between 1000 and 9100 metres in the main borehole. These resulted in thousands of induced microearthquakes that were recorded by a seismic monitoring network at the surface in combination with a borehole seismometer installed in the pilot hole at a depth of 4,000 metres. The analysis of the comprehensive data set has yielded crucial basic knowledge about the in-situ state of stress in the Earth's upper crust, the strength and fracture behaviour of the rocks as well as the factors and processes responsible for natural earthquakes.

Hydraulic fracturing for shale gas extraction in the public debate

Emotions tend to run high in discussions about fracking. Frequently, the technology is met with fundamental opposition. As often as not, such concerns can be attributed to media reports on incidents in connection with the production of shale gas in the United States, where large-scale fracking operations have been carried out for over ten years in order to extract natural gas (and more recently also oil) from tight shale formations. Whereas conventional gas and oil migrate through the Earth's upper crust until they get trapped in storage formations, shale gas is still contained in the rock where it was originally generated (source rock). These so-called unconventional hydrocarbon occurrences are widespread in some regions of the USA. However, they can also be found in other parts of the world – sometimes in quite considerable quantities. Usually, these shale formations are flat-lying and have a large lateral extension. Fracking operations for the production of hydrocarbons are therefore usually carried out through horizontally diverted boreholes that stretch along the length of the shale formation. In order to improve the yield, prevent corrosion and reduce energy consumption by lowering the flow resistance, the frac-fluids contain both proppants and a variety of chemical additives.

The afore-mentioned media reports about incidents in connection with shale gas fracking in the USA have resulted in a fundamental opposition to hydraulic fracturing, particularly among the European public. However, many reports about incidents connected with fracking have subsequently turned out to be exaggerated or even downright false. The fireballs blazing out of water-taps in private households in the movie "Gasland" are a case in point. The film fails to mention the fact that methane can make its way into near-surface groundwater as a result of natural processes not related to any fracking activities. Nevertheless, there still remain a number of questions, concerns, criticisms and possible risks connected with the application of the fracking technology that need to be addressed and discussed in a detailed and scientifically objective manner.

Themes addressed by this acatech POSITION PAPER

The principal focus of this paper is on the "Technological Aspects". They are dealt with comprehensively in Chapter 3, which looks at the key issues related to fracking and its application. The chapter covers everything from drilling techniques, fracking methods and frac-fluid compositions to fracture creation and propagation, including fracking-induced (micro-)seismicity and its recording and control.

Regionally, the paper centres on the economic use of hydraulic fracturing in Germany. The fields of application considered include both the potential extraction of shale gas and the utilisation of heat energy from deep geothermal systems (Chapter 2). Although an assessment based on the present state of knowledge can only be an approximation, it is sufficient to convey the importance of these energy sources in meeting Germany's energy demand. The deliberations can thus impress upon policymakers and the public why hydraulic fracturing is worth serious consideration.

Chapter 4 "Impacts on the Environment" takes a closer look at the potential dangers and risks associated with fracking. The following environmental impacts are discussed: the pollution of drinking water/groundwater due to harmful substances infiltrating into the near-surface underground (e.g. as a result of accidents), pollutants escaping from and ascending along wells (as a result of leaks), dispersal of contaminants contained in frac-fluids through overlying rock and the uncontrolled release and migration of methane. Other concerns include: induced seismicity, water consumption and land requirements.

Chapter 5 ("Regulatory Framework") presents the extensive regulations that already exist in Germany with regard to the extraction of natural gas and the utilisation of deep geothermal energy by means of hydraulic fracturing. The German government's plans for further additions and amendments to existing laws are also outlined.

There is no doubt that the future use of fracking will require the consent of the people affected by its application. Accordingly, Chapter 6 "Acceptance and Communication" discusses concepts for a comprehensive communication between stakeholders and local residents and proposes strategies for their active participation in the planning and decision-making processes. Surveys indicate that while a majority of those polled call for more public commitment in matters of environmental protection, they are not opposed to fracking in principle. The government should seek to establish effective preventive regulations but should not altogether ban fracking, especially not for research purposes. Balanced solutions are therefore required (including e.g. trade-offs between technological and social aspects) based on effective and environmentally friendly regulations. This will help to build trust and should make people more open towards the potential benefits of fracking as they gain more experience with the technology.

The "Best Practices" presented in Chapter 8 are key to any evaluation of the technology and its application. They could form the basis for future operational standards. In order to arrive at a decision on whether or not hydraulic fracturing should be allowed and the conditions under which it might be acceptable to further pursue the technology in Germany, it will therefore be necessary to consider the issue of acceptance and to carefully weigh the ecological and technical risks against the economic and energy political benefits.

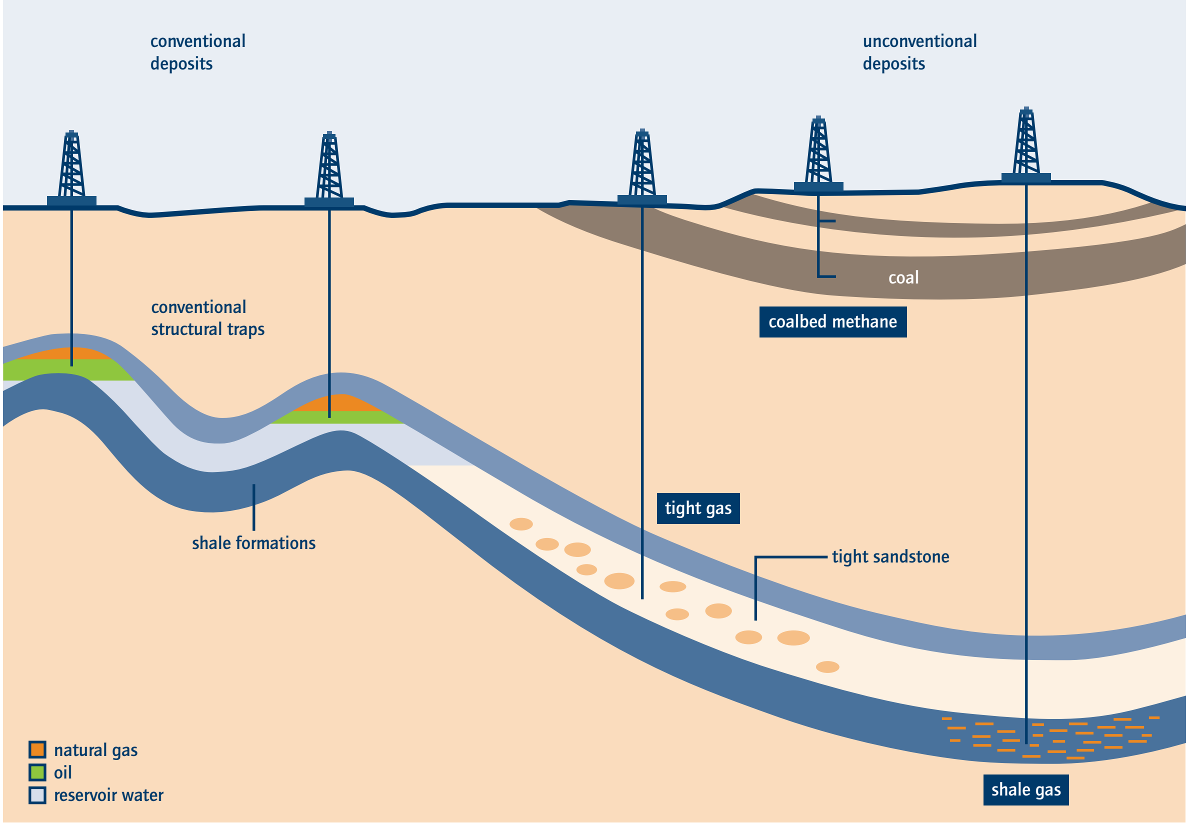
The aim of this POSITION PAPER is to provide a sound scientific and technical compilation and overview of the many different aspects to be considered in the context of hydraulic fracturing.

2 ECONOMIC ASPECTS

The decision to employ hydraulic fracturing largely depends on the economic potential it is estimated to open up. In this context it is important to distinguish between natural gas or oil production from tight sandstone or carbonate rocks (tight gas/tight oil) or from shale formations (shale gas and shale oil) on the one hand (cf. figure 1) and the extraction of geothermal energy from deep hot rock (petrothermal systems) on the other.

Although current knowledge allows only for a relatively rough assessment of the quantity of these geo-resources in Germany, their potential importance for the future energy supply is considerable. So far, there are no estimates available for tight oil/shale oil. Consequently, this chapter will concentrate on the application of hydraulic fracturing for the production of natural gas and the utilisation of deep geothermal energy. Natural gas occurrences in coal beds (coal bed methane) are likewise not considered in the present study.

Figure 1: Diagram of conventional and unconventional oil- and gas deposits[2]



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[2] Source: BGR 2012.

2.1 NATURAL GAS

Tight Gas

Tight gas occurrences are hydrocarbon deposits with relatively low fluid permeability. Hydraulic fracturing significantly increases the fluid permeability allowing for the profitable extraction of the natural gas. In Germany, tight gas has been extracted from relatively low-permeability sandstone and carbonate rock formations since the 1960s. Indeed, many tight gas occurrences are nowadays regarded as conventional hydrocarbon deposits. The criterion for distinction between (traditional) conventional gas and tight gas is based on the permeability of the target rock for fluids and gases. In Germany, this boundary is usually drawn at a permeability of 0.6 milliDarcy (mD). However, since it is often not possible to precisely determine the boundaries between less and more permeable reservoir rocks, an unequivocal differentiation between the two is not feasible.

The country's largest natural gas occurrences and the highest levels of production can be found in northern Germany. In 2012, Lower Saxony alone accounted for around 95 percent of domestic (raw) gas production. The natural gas reservoirs are primarily found in the Carboniferous, Rotliegend and Zechstein formations. At the end of 2012, Germany's natural gas reserves, i.e. known deposits that can be profitably exploited with current technologies, amounted to 123 billion cubic metres of raw gas. An unspecified percentage of this total can only be accessed via hydraulic fracturing. Tight gas accounts for around 30 percent of the total German gas production to date. The domestic conventional gas resources (assessment of the estimated economically viable occurrences) in the North German Basin amount to 150 billion cubic metres.

Since the annual demand for natural gas in Germany currently stands at about 90 billion cubic metres, most of it has to be imported. In 2012, the bulk of these imports came from the Russian Federation, Norway and the Netherlands. The total value of natural gas imports for 2012 amounted to 30.1 billion euros. That year, domestically produced natural gas still accounted for 13 percent of the total supply. However, domestic production and natural gas reserves have been declining steadily for several years. This is mainly due to the increasing exhaustion of the existing deposits and their advancing dilution by formation water. The drop in production has been further exacerbated by the fact that for several years now, companies operating in Germany have no longer been granted licences for fracking operations in deep deposits in the existing natural gas fields. Moreover, no significant new reserves have been discovered in recent years.

Shale gas

Shale gas is natural gas from tight shale formations, i.e. the rocks from which the gas originated (source rock). The only way by which shale gas can be produced from these unconventional deposits is by means of fracking. In a preliminary assessment of Germany's shale gas potential, the shale formations of the Lower Carboniferous, the Lower Jurassic (Posidonia Shale) and the Lower Cretaceous (Wealdon) were evaluated.[3] The quantity of hydrocarbons stored in the different source rocks depends on a variety of parameters. Along with the volume and type of the organic matter, these include the thermal maturity, thickness and depth of the respective formation. For each of these parameters we can assume minimum values required in any shale formation with potential for shale gas production. Results of recent research suggest that in many cases substantially more natural gas remained in the source rock than was previously supposed. This discovery has significantly enhanced the potential of these shale formations.

According to the evaluation mentioned above, the greatest potential for shale gas exists on the southern edge and in the eastern part of the Northwest German Basin, in the north-eastern regions of Germany and in the central area of the Upper Rhine Graben (red hatched section in figure 2). The total amount of shale gas presumably locked in the

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[3] Cf. BGR 2012.

Figure 2: Distribution of bituminous shale formations with potential for shale gas and with parameter values fulfilling the basic conditions for the formation of shale gas (grey areas). Promising areas for future exploitation are hatched in red.[4]

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[4] Source: BGR 2012.

investigated formations (so-called gas in place, GIP) lies somewhere between 7 trillion and 23 trillion cubic metres, with a median GIP value of approximately 13 trillion cubic metres. The greatest potential is found in the Lower Carboniferous shale formations, with a median value of approximately 8 trillion cubic metres.

As yet, no shale gas production has taken place in Germany. Therefore, no empirical data is available as to the percentage of the GIP that is technically recoverable. Production data from the US indicate that the recovery factor can range between 5 and 35 percent of the GIP. A study by the Federal Institute for Geosciences and Natural Resources[5] assumes a conservative ten percent of the GIP to be technically recoverable. Accordingly, the technically recoverable natural gas volume ranges between 0.7 trillion and 2.3 trillion cubic metres, with a median value of approximately 1.3 trillion cubic metres. This exceeds Germany's conventional natural gas reserves and resources (outlined above) significantly and amounts to one hundred times the country's current annual natural gas production.

Economic significance and environmental aspects

Without shale gas production, Germany's reserves of conventional gas will be completely exhausted in about ten years' time. The country would then be totally dependent on gas imports from abroad. The potential utilisation of shale gas enabled by the hydraulic fracturing technology is an option for reducing this dependency. Notwithstanding the continuing expansion of the renewable energy sector, natural gas will remain indispensable for Germany's energy supply system in the next decades. Assuming the current gas price and an annual production figure of twelve billion cubic metres, the economic value of Germany's natural gas occurrences amounts to four billion euros per annum.

Shale gas provides the "cleanest" energy of all fossil fuels, producing lower carbon emissions than coal and oil and no atmospheric pollutants such as carbon monoxide, sulphur and particulate matter. The comprehensive German standards, regulations and controls would ensure that any domestic gas production fulfils the requirements of eco-friendliness. Furthermore, the energy used to transport gas imports to Germany, often over thousands of kilometres, is not an issue for domestically produced gas. Domestic production also largely eliminates the risk of methane leaks at the production site or from the pipelines.

According to the German Oil and Gas Producers Association (Wirtschaftsverband Erdöl- und Erdgasgewinnung), the number of natural gas drillings carried out in 2012 and 2013 dropped by 50 percent compared to 2011.[6] Failure to grant licences has led to significant hold-ups in exploration activity. To this is added the risk of the service industry eventually moving elsewhere if their drill rigs are no longer used. This would result in the loss of thousands of jobs, not to speak of know-how – primarily in Lower Saxony. With a turnover of four billion euros in 2013, the oil and gas industry contributes notably to the German economy. In addition to annual royalties of around 670 million euros, revenues from corporate and local business taxes boost the federal, regional and local public budgets in those areas where oil and gas companies are active.[7]

2.2 DEEP GEOTHERMAL ENERGY

Deep geothermal energy is a comparatively young energy technology. It aims at recovering the huge thermal resources locked deep underground by means of boreholes and using it for the provision of heat and/or power. Deep geothermal systems offer a sustainable, steerable baseload energy that is independent of weather conditions. Geothermal facilities have a very small ecological footprint and can be operated in close proximity to residential areas, providing an option for decentralised energy supply

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[5] Cf. BGR 2012.

[6] Cf. WEG 2014.

[7] Cf. WEG 2013.

in local communities (for instance the geothermal heat and power plant in Unterhaching near Munich). Given appropriate support and technological development, deep geothermal energy could become an important element in the renewable energy portfolio that is to cover Germany's future energy demand.

Lessons of the last ten years

There has been a sharp rise in the number of deep geothermal projects for the generation of heat and power over the past few years. Important drivers of this trend were Federal Government initiatives, ranging from research funding measures to the Renewable Energy Sources Act and a market incentive programme. These initiatives also attracted substantial levels of private investment. Today, the deep geothermal energy industry possesses know-how, experience and technologies no one could even have dreamt of ten years ago.

Major scientific and technological advances have been achieved with regard to the exploration of geothermal resources, the drilling technology needed to recover them, reservoir management and surface installation technology. The long-running, in-depth research carried out by the European demonstration project at Soultz-sous-Forêts in France and the In-situ Geothermal Laboratory at Groß Schönebeck in Germany have ultimately paved the way for first commercial ventures into the exploitation of the deep basement rocks which form the largest petrothermal resource.

Reservoir types and geothermal potential

There are two basic types of reservoirs in Germany that are suitable for the use of deep geothermal energy: (1) permeable, hot-water-bearing sedimentary rock (= hydrothermal systems) and (2) hard rock and crystalline basement (= petrothermal systems). Petrothermal systems can be further subdivided into reservoirs with partly deep-reaching geological fault zones and fractured reservoirs consisting mainly of tight deep hot rock.

Current estimates regarding the potential of deep geothermal systems in Germany are based on a technology assessment study from 2003[8], the results of which have been confirmed by more recent work. The theoretical maximum electricity generation potential – based on reservoir temperatures of more than 100 degrees Celsius at depths below around three kilometres – was found to be approximately 600 times Germany's annual electricity demand. The vast majority of these resources (more than 90 percent) is found in petrothermal systems. Despite being of great importance locally, hydrothermal systems constitute but a relatively small resource from the federal perspective. This is due to the fact that they rely on natural anomalies, i.e. high fluid permeability at great depths underground. A particularly promising future field of application is the use of geothermal systems for the provision of heating energy, allowing for the economic utilisation of reservoir temperatures below 100 degrees Celsius.

Basic geological conditions

The temperature field and isotherm depths are key conditions for the localisation of geothermal projects. Areas with high temperature gradients are comparatively easier to access, since lower drilling depths suffice to reach the reservoirs. Extremely high temperature gradients are found in conventional geothermal steam reservoirs occurring in connection with active volcanoes, for instance in Iceland. In these reservoirs, temperatures of over 200 degrees Celsius can be found at a mere 500 metres below the surface. In Germany, there is significant regional variation in temperatures. Relatively high temperature gradients can be found in particular in the area of the Upper Rhine Graben, where strong tectonic forces are at play. Here, temperatures will occasionally reach 170 degrees Celsius at a depth of 3.5 kilometres. In other areas the same depth zone has much lower temperatures. Figure 3 shows this regional variation at depths of five kilometres.

The commercial viability of geothermal reservoirs depends not only on their temperature, but to an important degree

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[8] Cf. Paschen et al. 2003.

also on their hydro-geological factors, i.e. the flow conditions of the water acting as heat transport medium. Due to their lower temperatures, thermal hot water aquifers tend to be particularly dependent on hydrogeological conditions. Technologically, the production is easier to realise in hydrothermal reservoirs than in petrothermal systems.

20 of the 28 German geothermal plants (heat, power or combined) currently in operation are located in Bavaria. These are mostly doublet systems with a production and an injection well to access the natural hot formation water found in the aquifers of the South German Molasse Basin. At present, Bavaria has an installed electric capacity of 27 megawatts and an installed heat capacity of approximately 300 megawatts. The latter provides 1,000 gigawatt hours heat energy per annum which corresponds to an annual reduction of around 250,000 tonnes of carbon dioxide.

Geological fault zones are important tectonic structures offering major advantages in terms of flow conditions for both hydrothermal and petrothermal reservoirs. In these mostly steeply inclined structures, heat can rise due to thermal convection, transporting the deep hot formation water into more shallow depths. Fault zones are therefore typical exploration targets. Such fault systems created by tectonic forces in sedimentary and crystalline rock in the Earth's upper crust are found throughout Germany and can reach depths of more than eight kilometres. However, while principally qualifying for exploitation, these zones are frequently not per se eligible for commercial use, owing to the inadequacy of the naturally occurring hydraulic flow conditions. In these cases, hydraulic fracturing is required.

EGS systems

Systems requiring hydraulic stimulation measures are known as Enhanced (or Engineered) Geothermal Systems (EGS). There are currently three power plants on the German side of the Upper Rhine Graben that use EGS technology, with a total electrical output of about ten megawatts. With the goal of providing process heat, an EGS project is currently underway in Rittershoffen (Alsace), where two very successful deep boreholes have meanwhile been completed. This project could serve as a model for heat and power plants in similar geological structures associated with fault-zones on the German side of the Upper Rhine Graben, paving the way for first commercial ventures applying EGS-technology in Germany.

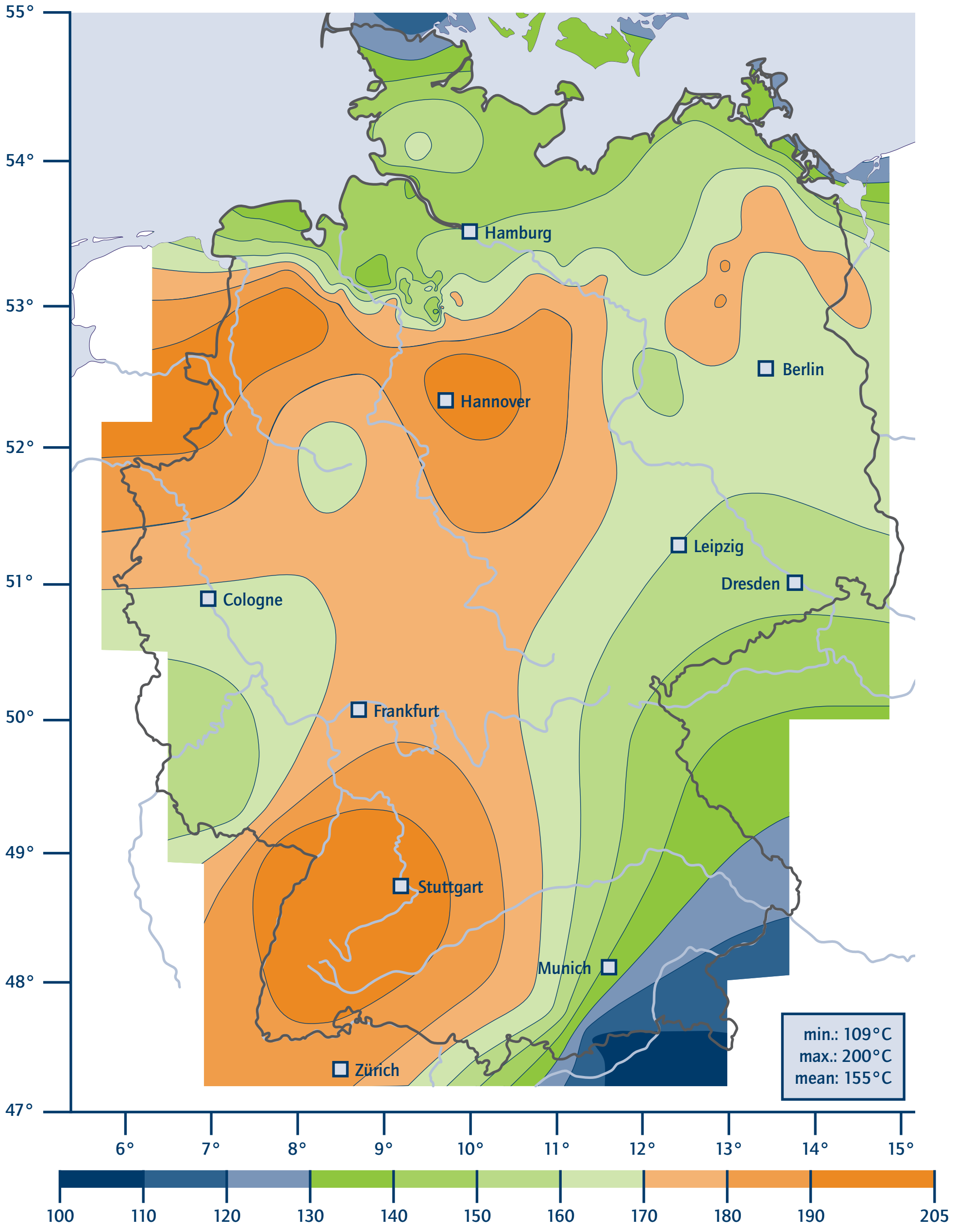
Future strategies

Applying the lessons learned from EGS in petrothermal systems associated with fault zones to tight petrothermal systems would have the advantage of minimising the exploration risk: The drilling depth could be chosen according to the target temperature, while the fracture systems required to extract the heat could be generated by means of hydraulic fracturing operations. Such petrothermal reservoirs (found in hard rock formations in the North German Basin and in crystalline basement rocks in central and southern Germany) have by far the greatest potential for geothermal energy generation. However, their large-scale exploitation will require the use of hydraulic fracturing along with further technical measures in order to create artificial "heat exchangers" in deep, hot rock.

One approach regarded as commercially promising in the medium term involves EGS-systems where several smaller reservoirs are created and linked together by a combination of horizontal drilling and multi-frac technology. Performing several small fracs instead of a single large stimulation (as in the project Deep Heat Mining Basel) has the added advantage of dramatically reducing the risk of induced seismicity, as seismic magnitude and shear fracture size are directly correlated.

A Swiss geothermal drilling programme scheduled for 2016–2017 could mark the first step in this direction. The plan is to drill strongly deviated wells and to employ multi-fracking in order to create a reservoir of numerous interconnected fracs.

Figure 3: Temperature distribution at a depth of five kilometres (in degrees Celsius)[9]



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[9] Source: Schellschmidt 2015.

In Germany, too, a number of similar projects are currently in the planning stage, providing for the use of technologies that have already been successfully tested in the shale gas industry. The crucial aim will be to prove the technical feasibility of horizontal wells with up to 50 (small) fracs in tight, deep rock formations, which is pivotal for the future development of deep geothermal energy.

2.3 THE IMPORTANCE OF HYDRAULIC FRACTURING FOR GERMANY'S ENERGY TRANSITION

The energy transition will remain one of the key challenges Germany has to cope with over the coming decades. Technological progress and competitiveness will both be crucial to the successful restructuring of the energy sector. In order to meet the requirements of the energy transition, it will be necessary for policymakers, industry, the scientific community and the public to find adequate solutions and make the right choices.

Hydrocarbons will undoubtedly remain an important component of both the German and the European energy supply system for the next few decades (natural gas currently covers 22 percent of Germany's primary energy demand). Comparatively "green" shale gas could therefore be used as a bridging technology in the process towards a future power supply based largely on renewable energy sources.

The hydraulic fracturing technology to produce shale gas is not a novel approach, but is, indeed, already widely used. In order to enable an objective, fact-based public debate it is therefore important to analyse and assess both the risks and the opportunities of hydraulic fracturing. By exploiting its national shale gas resources, Germany could mitigate its economic and political dependencies on third parties. This is of importance not least with regard to the interests of the German national economy, as it strengthens the industry, attracts investment, creates and protects jobs and reduces the currency drain.

As long as Germany still requires significant amounts of natural gas to meet its primary energy demand, it does make sense even from an environmental point of view to use this domestic potential. If the gas is extracted domestically, every step is subject to German standards, regulations and controls, ensuring the safety and sustainability of the procedures. This makes Germany independent of gas from countries with far lower environmental standards, enabling it, for instance, to virtually eliminate the risk of methane leaks. Furthermore, when gas is transported over great distances, often several thousand kilometres, a substantial proportion (estimated at between 7 and 15 percent) is used for the transportation process. Also, every compressor station along a pipeline emits considerable quantities of CO_2. The energy losses occurring during the distribution of domestically produced gas, on the other hand, are extremely low.

Deep petrothermal systems constitute another source of energy based on a domestic resource. As yet, their extensive implementation across Germany is a vision of the future. Their widespread use would dispense with the necessity to import raw materials for heating energy, while the economic value would remain in the region. In the process of developing the use of geothermal energy, a sustainable infrastructure could be created as a long-term investment for future generations. Also, deep geothermal district heating has the benefit of price stability, since it is largely unaffected by fluctuations in fossil fuel prices.

3 TECHNOLOGICAL ASPECTS

Hydraulic fracturing is a method of borehole stimulation by means of water pressure. Prerequisite for its employment is the successful drilling of a deep well and the creation of a stable borehole according to established standards. Only by application of hydraulic fracturing can natural gas be produced from tight gas or shale gas deposits and geothermal energy extracted from deep petrothermal reservoirs.

The target horizons for accessing these georesources are determined by Germany's geological characteristics. They range between depths of approximately 1.5 to 4.0 kilometres for shale gas, 2.5 to 5.0 kilometres for tight gas and 3.5 to over 6.0 kilometres for petrothermal energy.

The exploration and exploitation of these resources is realised by means of deep wells. Their main function is to create a sealed connection (pipes/casing) between the surface (well site/production facility) and the reservoir in order to restrict the transport of the fluids to the borehole and to prevent any leakage of fluids or exchange of matter between the well and its surroundings.[10] In principle, there is no difference between the drilling technology employed in deep geothermal systems and that used for the production of natural gas.

3.1 DEEP WELLS AND DRILLING TECHNOLOGIES

Pre-investigations and 3D-Modelling of the geological subsurface

Deep wells are technical constructions that require meticulous preparation in comprehensive pre-site studies. The principal objectives of such preparatory investigations are to identify any potential risks ex ante, to select a suitable well site, to carry out a site-specific risk assessment and to finalise the well design.[11] To this end, a systematic compilation and analysis of all available data and information is required. This must include the local geological and tectonic structures and lithology (rock type and sequence) as well as the hydrological and physical properties of the subsurface. A key component of such programmes is the indirect exploration of the underground terrain by means of geophysical deep sounding methods. The standard technique that has been systematically developed by the exploration industry over the past few decades is known as deep reflection seismics. In a first step, this method is applied to generate a large-scale physical map of the survey area by means of 2D-vertical sections, covering depths of up to six kilometres.

In a second step, the seismic profiles are consolidated to form a dense grid around the potential well site, complemented by additional deep sounding techniques and other geophysical measurements. Amongst these, magnetotellurics, i.e. the measurement of electrical conductivity of the underground terrain, is of particular importance, since it allows for the identification of e.g. groundwater-bearing rock formations, major tectonic faults and hydrogeothermal resources.

By means of modelling techniques, all available geophysical, geological and mineralogical information and results are processed into a 3D-model of the prognosticated "real" image of the underground terrain. This approach, which has recently been largely improved both methodologically and technologically, increases the planning security of deep boreholes substantially and allows for a much more effective, environmentally compatible and less risky implementation.

Well Site/Production Facility

For an average well site where the drilling of the well is followed by fracking operations and which is subsequently used as production facility for the extracted resources, an area about the size of a football pitch (0.7 to 1.0 hectares) is required.

In Germany, the construction, technical design and long-term operation of such well sites are subject to extensive legal provisions and regulations to protect human life and

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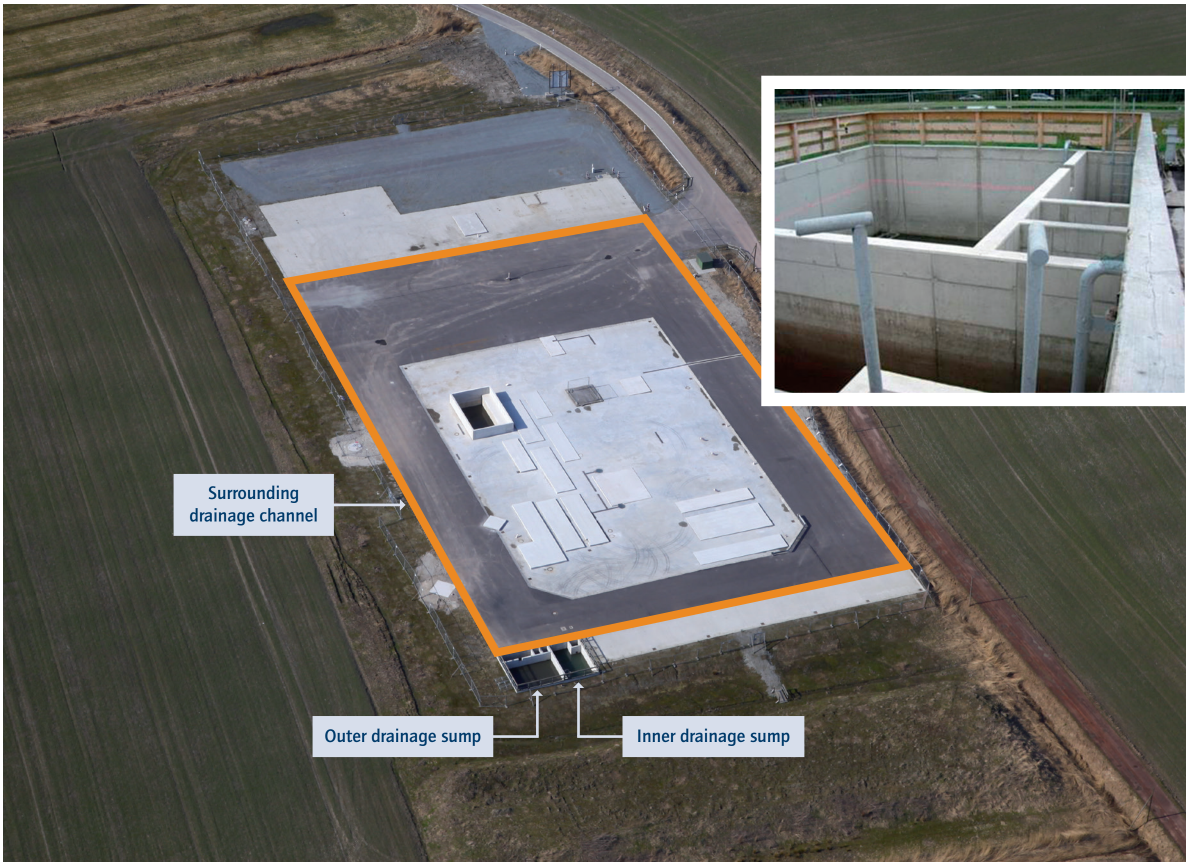
[10] Cf. Reinicke 2014a.

[11] Cf. Reinicke 2014a.

the environment against potential hazards, particularly against dangers arising from accidents or technical failures.

In order to protect drinking water/groundwater, the well site is divided into a (larger) inner area and an outer area (cf. Figure 4). The topsoil is removed and saved for later reuse. The inner area is paved with a layer of waterproof concrete to prevent any potential water contaminants from leaking underground. This includes all liquids, drilling fluids, hydraulic- and diesel oils and waste water, as well as drilling fluid additives and any other substances identified as potentially detrimental to groundwater. The outer area used for transporting and storing operating materials is paved with asphalt. Upstands and a system of drainage channels surrounding the well site ensure that all liquids, including rainwater, are collected for correct reprocessing and/or disposal.

Figure 4: Protection of well site/production facility by liquid collection and drainage system[12]



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[12] Source: acatech.

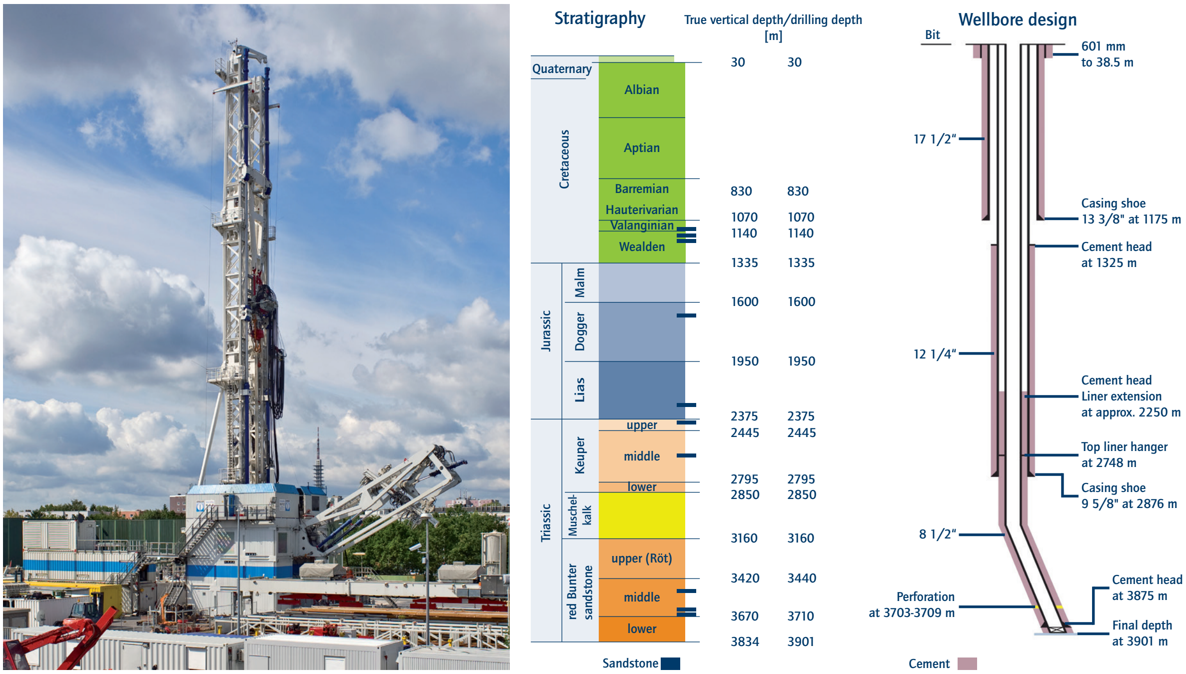
Drilling/Casing

In Germany, deep wells are drilled with modern rigs specially built for use in densely populated areas (cf. Figure 5). They are powered by electricity from the public electricity grid, which avoids problems connected with diesel generators, particularly noise and odour pollution.

Nowadays, oil, gas and geothermal wells are only rarely drilled vertically. Modern directional drilling systems are able to control the underground trajectory, viz. the direction and inclination of the wellbore. For instance, an initially vertical wellbore can be diverted horizontally once it has reached the required depth, extending the drilled section in the reservoir and giving access to a greater volume of natural gas or water. The directional drilling technology also allows for the sinking of two inclined wellbores from a single well site (doublets) in order to extract geothermal energy. Likewise, shale gas reservoirs can be accessed from a single site by a cluster of up to 20 wellbores, diverted so as to run horizontally through the reservoir for distances of up to three kilometres. Thus, an underground production area of more than ten square kilometres can be exploited.

The wellbore trajectory is constantly monitored during directional drilling. In addition, key reservoir parameters are permanently logged, for instance gas/water contacts or changes in rock composition, e.g. from shale to sandstone. Owing to these monitoring procedures (Measurement While Drilling and Logging While Drilling) the wellbore trajectory can nowadays be controlled to within a metre.

Figure 5: Well site with rig, geological profile of underground terrain and wellbore design of the GeneSys-Bohrung at the Geozentrum Hannover[13]



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[13] Source: BGR.

The wells are drilled in sections, each wellbores being subsequently cased with steel pipes. In order to provide permanent protection for near-surface drinking water/groundwater horizons and to prevent the rig foundations from being washed out, a surface casing or "conductor pipe" is run to a depth of approx. 50–70 metres and cemented in place. The first wellbore section is then drilled and cased (200 to 1,000 metres). This surface casing covers the lower-lying groundwater horizons. It is completely cemented right up to the surface and is used for the wellhead with the blowout preventers. If necessary, these devices allow for the wellbore to be closed rapidly and safely at any time.

Depending on the target depth and the geology of the site, the wellbore is then cased with up to seven casing strings consisting of special steels. The setting depth of these casings varies according to the geotectonics and hydrogeology of the site. Each casing string has a smaller diameter than the previous one, so that the wellbore tapers telescopically towards the bottom. The gap between the casing string and the wellbore wall – the so-called "annulus" – is filled with gas-tight and pressure-resistant cement. Besides ensuring that the casing strings are firmly anchored in the rock and protected against corrosion, this also prevents liquids or gases from leaking through the annulus and seeping into overlying rock strata. By means of measurements and pressure tests, the result of the cementations and, in particular, the successful creation of a secure, hydraulic seal preventing leakages into groundwater horizons (well integrity) must be proved to the responsible mining authority.

Figure 6: Model of wellbore casing and cementing[14]

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[14] Source: acatech.

The barrier-based approach described above (well site, drilling fluid, blowout preventers, casing strings) and strict compliance with the rules of a "Well Integrity Management System" can ensure that the drilling of deep wells and the subsequent exploitation of the respective resources does not pose any risk to humans and the environment.

3.2 FRACKING TECHNOLOGIES

Hydraulic borehole stimulation and frac-fluids

The objective of borehole stimulation is to generate a lasting improvement in the formation permeability of otherwise low-permeable rocks and to trigger the transport of natural gas, oil or water to the wellbore. This is done by pumping a so-called "frac-fluid" through deliberately perforated and pressure-tight isolated sections of the casing into the target horizon.

Until 20 years ago, tight gas in Germany was produced by means of vertical boreholes with just one frac-operation per well. Today, however, shale gas is usually extracted using a combination of horizontal drilling and multi-frac-operations. This involves deviating the direction of the borehole from vertical to horizontal once it has reached the target depth. It then runs horizontally along and within the reservoir rock. Once the horizontal part of the borehole is cased and cemented, sections of it are perforated and fracked.

The frac-fluid providing the pressure consists essentially of water. Depending on the field of application, it may also contain solid materials known as proppants, together with chemical additives. The recipe of a frac-fluid has to be determined on a case-by-case basis. It depends on the rock composition, the temperature and pressure conditions and other reservoir parameters as well as the respective technical requirements. Typically, frac-fluids will contain 97 to 99.8 percent water and 0.2 to 3.0 percent (chemical) additives; if proppants are added, these figures are reduced proportionally (proppants can account for 5 to 30 percent of the total).

Proppants (quartz sand or ceramic beads) are necessary in order to prevent the artificially created fractures from closing up completely once the frac-operation is over and the pressure drops. The term "flowback" denotes the fluid that is returned to the surface at the beginning of the production phase, having deposited most of its proppant cargo within the target rock formation. The additives have a number of important functions, e.g. to provide the carrying capacity for the transport of the proppants into the generated fractures (gelling by viscosifiers), to remove the gel after injection has been completed (gel breakers), to provide enhanced pumpability of the fluid (surfactants are employed to reduce frictional losses) and to maintain its temperature stability. The hydrocarbon industry is currently carrying out extensive R&D-work, seeking to eliminate any compounds of such additives that might threaten human health and the environment. In Germany, this has resulted in a review of the list of authorised additives and the systematic removal of potentially dangerous compounds. According to ExxonMobil (April 2014), the number of authorised additives could be reduced to 30, comprising a total of around 50 compounds. The published data and recent results of research in this field indicate that the additives the industry intends to employ would not be subject to any license restrictions under current legislation and confirm that the relevant frac-fluids are non-toxic, not polluting and no more than slightly hazardous to water (Water Hazard Class 1).

Hydraulic fracture-creation

Rocks of the continental crust display a complex geological deformation history and are subject to mechanical stresses known as "tectonic stresses". These are caused by the burden of the overlying rock mass on the one hand, and the horizontally acting plate-tectonic forces on the other. Consequently, the in-situ state of stress of a rock can be described by the magnitude of three principal, mutually perpendicular stresses (S). One of these three principal stresses is vertical (Sv) and can be calculated from the mass of the overlying rock column. The two other principal stresses run horizontally, with the maximum horizontal stress being designated as SH and the minimum horizontal stress as Sh. SH corresponds to the maximum value of plate tectonic compression, which in Germany largely runs in southeast-northwest direction (with an average SH orientation of 155 degrees north). Hence, the direction in which the fractures tend to propagate is well known. The in-situ state of stress of a rock together with its tectonic deformation pattern resulting from its geological past (fault zones, faults, fissures or cracks, depending on their size) are crucial in determining its behaviour when subjected to hydraulic fracturing.

Fracking involves injecting a frac-fluid at high flow rates, in order to build up sufficient pressure in the target rock to either create artificial fractures (hydraulic fracturing in the strict sense), or to trigger shear movements by reactivation of pre-existing faults or fissures (hydraulic stimulation). Depending on the geotectonic parameters and flow rates of the frac-fluid, the pumping pressures required at the wellhead will vary substantially.

When employing hydraulic fracturing sensu strictu, the injection pressure to be reached within the target formation (reservoir) must be greater than the minimum principal in-situ stress of the surrounding rock. This will result in a tensile fracture opening perpendicular to the direction of the minimum principal stress of the respective rock. In Germany, according to the general in-situ stress pattern of rocks below a depth of about 600 meters, Sh will always represent the least stress component. This means that the tensile fractures run vertically and extend in the direction of the maximal tectonic compression (SH). While the length of the fracs (horizontal extension) ranges between some ten and a few hundred meters, their height is generally less. The width of the fracs is often no more than a few millimetres and rarely exceeds one centimetre.

Fracking operations are scaled in such a way that the fracs are confined to the target horizon. By means of model calculations, mini-fracs (using small volumes of frac-fluid) and other hydraulic tests, the fracture propagation can be predicted before any fracking is carried out. Moreover, indirect information about the actual frac propagation can be obtained from the continuous monitoring and recording of the pressure development during the frac-operation. Direct monitoring of frac propagation by means of seismic techniques is only likely to succeed if observatory wellbores are used that have been drilled specifically for this purpose. This is owing to the fact that the seismic signals required for detection only occur as a weak secondary phenomenon resulting from stress changes on natural fractures in the immediate surroundings of the artificially created frac.

In the public discussion the concept of hydraulic stimulation which was developed for the utilisation of petrothermal systems is mostly lumped together with hydraulic fracturing under the umbrella term “fracking”. This concept builds upon experiences gained from projects in deep geothermal energy around the world which have demonstrated that highly permeable fractures can be created in hard rock simply by injecting water. The injection of water triggers shear events predominantly on already existing natural fractures.[15] The roughness of the reactivated new fracture plains is usually sufficient to ensure that the fractures do not close up completely after pressure release.

The injection pressure required for hydraulic stimulation is mostly lower than the “frac creating pressure” required for hydraulic fracturing, since shear movements can already be triggered at pressures below the limit necessary to open a new tensile fracture (>Sh). A recent review of observations related to the application of hydraulic stimulation in deep geothermal systems suggests that shearing alone cannot be responsible for all the highly conductive fractures observed.[16] Rather, it appears that a combination of hydraulic stimulation and fracturing took place and created shear as

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[15] Cf. Brown/Duchane 1999.

[16] Cf. Jung 2013.

well as tensile fractures. In contrast to hydraulic fracturing, in the case of hydraulic stimulation the newly generated (shear) fractures are kept open due to natural self-propping mechanisms. As a result, the frac-fluids usually do not require the addition of proppants and chemical additives. The volume of water injected during hydraulic stimulation is significantly higher than in hydraulic fracturing and is usually in the order of 10,000 cubic meters. Hands-on experience has shown that hydraulic stimulation requires fractures of a certain size in order to create the desired hydraulic properties in the reservoir.

Modelling

Numerical modelling is employed in hydraulic fracturing in order to predict the fracture propagation in space and time under a given operating plan and to optimise it with view to the intended application. It is of particular importance to assess the seismic risk associated with the injection of fluids before fracking commences and to monitor the entire frac-operation in real time.

In order to illustrate the frac-processes numerically, it is necessary to describe the undisturbed state of stress of the geologic subsurface, the induced spatial and temporal changes of the stress field and an appropriate failure criterion. It is especially important to jointly consider the hydraulic and mechanical conditions of the fracures and the rock matrix. Numerical techniques are employed to address this challenge. Different specialised computer programmes are employed to model tensile and shear fractures as they differ significantly in their generation and propagation.

In hydraulic fracturing, new fractures open up parallel to the direction of the maximum principal tectonic stress. Fracture propagation is a continuous process, since the tensile fracture propagates within a relatively homogeneous medium and grows steadily as the frac-fluid is pumped in. The spatial and temporal propagation of the newly created frac is predicted by means of numerical techniques.

The numerical description of a shear fracture is a greater challenge owing to the structural complexity of the already brittly deformed rocks.

Induced seismicity

Induced seismicity refers to shear stress release occurring on existing fracture surfaces or on newly created fractures as a result of underground activities. The crystalline continental crust, in particular, is intercalated by in some cases deep reaching steeply inclined faults. Due to the natural in-situ stresses, these are in a critical stress equilibrium, i.e. close to their fracture limit.[17] Even minor perturbations of the state of stress such as pore-pressure increase during frac-operations can result in "supercritical" conditions and a local release of shear stress generating induced seismicity.[18] In Germany, induced seismicity has already been observed in connection with salt-, coal- and ore-mining, natural gas and oil extraction (e.g. reinjection of reservoir water) and – locally – the extraction of geothermal energy.

In petrothermal systems, induced seismicity can even be desirable, since the reactivation of small faults and fractures causes a local increase in the reservoir's hydraulic permeability. Indeed, some enhanced geothermal system (EGS) plants can only operate profitably because of the induced seismicity triggered by hydraulic stimulation. As induced seismicity indicates where hydraulic conductivity has increased in the reservoir, it plays a key role in the spatial mapping of stimulated reservoir areas. Similarly, the induced seismicity caused by fracking operations in hydrocarbon deposits is used for mapping purposes. The formation of a tensile fracture (hydrofrac) does not itself produce a seismic signal, owing to the slow rate at which the artificial fracture opens up. However, induced seismicity can be detected as a secondary phenomenon, occurring due to changes in the stresses acting on natural fractures around the tensile fracture.

The magnitude and number of frac-induced (micro-)earthquakes is largely determined by the geological boundary

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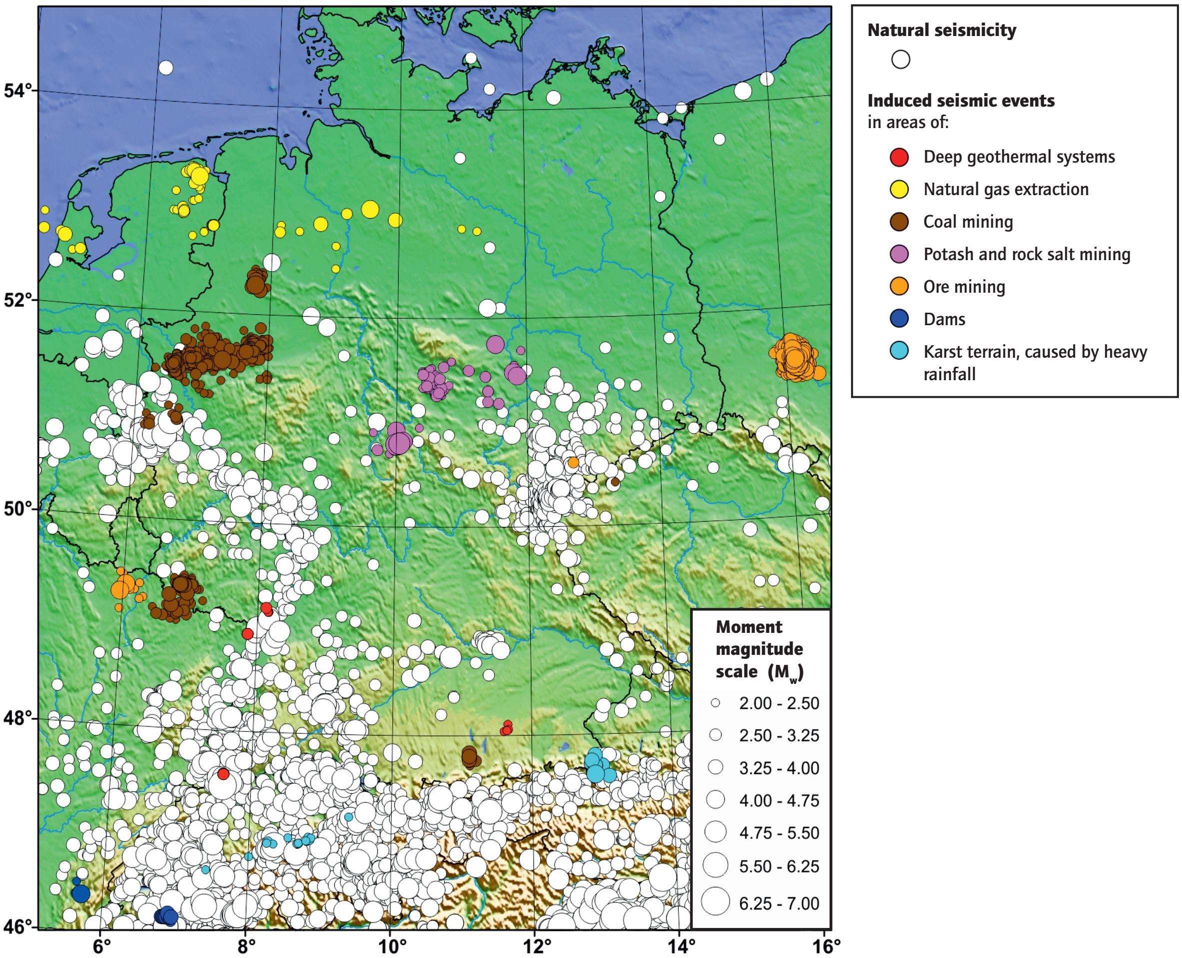
[17] Cf. Zoback/Harjes 1997.

[18] Cf. Hubbert/Rubey 1959.

Figure 7: Natural and induced seismicity in Central Europe[19]



conditions. Induced seismicity usually has larger magnitudes in crystalline rocks than in the softer sedimentary rock formations which display a lower shear strength and frequently aseismic behaviour. The number of detectable induced earthquakes depends on the sensitivity of the seismic network. Borehole geophones frequently record hundreds or even thousands of microearthquakes in connection with a frac operation. The vast majority of these events cannot be felt or even instrumentally detected at the surface. Of the several millions of frac operations in shale gas deposits, only a few tens of cases are known to have caused an earthquake perceptible at the Earth's

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[19] Source: Grünthal 2014.

surface.[20,21] Moreover, none of these earthquakes caused any material damage.

Nevertheless, there have recently been growing numbers of media accounts from North America, reporting an increase in perceivable seismicity in areas of extensive shale oil and shale gas extraction. This may be attributable to the frac-operations themselves or – more likely – to the massive reinjection of reservoir water or the socalled "flowback", respectively. Flowback is the fluid returned to the surface before the start of the production phase, having deposited most of its proppant cargo in the artificially created fractures in the reservoir rock.

Perceivable seismicity occurs more frequently in connection with hydraulic stimulation of geothermal systems, especially in production facilities located in tectonically active regions such as the Upper Rhine Rift System. In one case (the DHM geothermal project in Basel), hydraulic stimulation caused the plaster to crack on the walls of adjacent buildings. More serious structural damage did, however, not occur.

Seismologically controlled hydraulic borehole stimulation

Seismic monitoring, which is still a major research topic, constitutes the first basic step towards controlled hydraulic borehole stimulation. The technical requirements are, however, already fulfilled: Standard seismological techniques adopted from fundamental research ensure measurement accuracy as well as an operable seismographic network. In both hydraulic fracturing and hydraulic stimulation, a real-time analysis of the recorded seismic waves is essential to enable a swift response to any seismic hazards. Such a real-time analysis requires automated data processing.

Current knowledge does not yet allow to predict time and place of individual seismic events. Instead, seismic hazard analyses use recorded seismicity values to estimate the probability of undesirable major seismic events in the future. One of the key parameters is the magnitude-frequency relation, according to which each major earthquake is accompanied by several minor ones.

The seismic response profile ("traffic light system") compares current measurements with predefined limit values. The system also defines the measures to be taken in the event of an increase in earthquake magnitude of the induced seismic activity (e.g. reducing or altogether stopping hydraulic injections). The limits for the earthquake response system are currently based on the DIN 4150 standard that refers to structural vibrations in the construction industry. The DIN contains maximum peak ground velocity (PGV) values which, if complied with, should prevent structural damage to buildings. In Germany, the limits are set by the responsible mining authority. The great advantage of this response system is its simplicity – the seismogram displays the current hazard status as PGV value.

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[20] Cf. NRC 2012.

[21] Cf. Ellsworth 2013.

4 IMPACTS ON THE ENVIRONMENT

The threats and risks of hydraulic fracturing have received a lot of public attention, not least due to media reports on incidents in connection with the production of shale gas in the United States.

The key terms are often emotionally charged. Clear definitions are therefore the first prerequisite of a balanced discussion. In this chapter, a threat is defined as a potentially detrimental alteration in the condition of a protected good which cannot be excluded during an operation. Whether or not the operation in question is carried out in compliance with the legal provisions is immaterial for this purpose. In addition to this terminological definition, a general risk assessment should recognise that (1) risk estimation will invariably refer to comparable technologies with the same or similar application goals and that (2) risks can arise from actions or, indeed, the failure to act.

With regard to environmental risks connected with hydraulic fracturing, this approach raises a number of questions. For instance, is it riskier to import natural gas from countries with lower environmental standards than to produce it under the strict German regulation regime? Does the disadvantage of foregoing the billions of Euros of annual royalties weigh more heavily than the risks inherent to the extraction of natural gas? We can further objectify the discussion by a comparison with regard to the application goals. Does biogas production, for example, harbour less, greater or equal environmental risks to groundwater quality, the ecosystem or human health than the production of unconventional natural gas?

Unfortunately, very few sound studies were conducted in Germany and Europe on such overarching questions. As a result, the public debate tends to overestimate the threats and risks of certain technologies and underrates their potential benefits.

Taking only the environmental impacts of hydraulic fracturing into view, the public debate evolves around the threats to groundwater, human health, the landscape and the climate.

4.1 GROUNDWATER/DRINKING WATER: A LEGALLY PROTECTED RESOURCE

Citizens' initiatives, environmentalists, the water industry and local authorities fear above all the contamination of groundwater aquifers used for drinking water supply. It is worth noting, however, that in the public debate the terms groundwater and drinking water are mostly used as synonyms. In administrative law, however, as well as in the scientific definition, groundwater refers to all freely moving water filling up the hollow spaces in geological formations.

Below a depth of around 50 to a few hundred meters, groundwater – due to its chemical composition with sometimes extremely high concentrations of salt as well as high concentrations of trace metals and naturally occurring radioactive materials – is generally unsuitable for the utilisation as drinking water, although there are major regional differences.

Notwithstanding administrative court rulings to the contrary, from a scientific and technical point of view it is important to draw a clear terminological distinction between shallow (near-surface) groundwater occurrences suitable for utilisation as drinking water, groundwater with potential for medicinal use and formation water or deep saline brines without any direct application potential. Also, the general classification of activities involving hydrogeological formation water systems will need to be revised: Owing to the natural conditions and other factors, the current limits for solute concentrations and physicochemical parameters are not per se applicable in this case. A renewed discussion between scientific-technical experts and administrative law experts would therefore be desirable.

The debate on hydraulic fracturing is just one example of a general problem, viz. that we must take greater account of the natural conditions in deep geological formations – both from a terminological perspective and in terms of protection strategies. This topic will be gaining in importance in the context of a policy debate currently evolving around issues of spatial planning and the regulation of underground geological formations. The aim is to identify and regulate both the competing and the synergetic aspects of different uses of the geological underground.

Several recent studies have extensively addressed the potential threats and risks to which the protected resource of shallow groundwater is exposed by fracking operations.

At the national level, a number of studies seek to assess the risks connected with the use of hydraulic fracturing for natural gas production.[22,23,24,25] A further report commissioned by the Federal Environment Agency provides input on specific subtopics which the above-mentioned studies identified as significant with view to evaluating the negative impacts of gas production. These topics include monitoring strategies, a fracking chemicals registry, the disposal of flowback, emissions/climate footprint, microseismicity and land use.

Assessments[27,28,29] from one of the studies[30] suggest an approach to risk assessment envisaging the possible transport of substances classified as potentially hazardous to water into underground strata. To this end, the transport of chemical components of frac-fluids was simulated. The parameter being highly uncertain, a conservative approach was adopted, basing the calculations on the cumulative effect of adverse factors (high permeability, the presence of permeable fault zones, high potential differences etc.).

These assessments come to the following important conclusion: The risk of groundwater contamination does not so much arise from a possible leakage of frac-fluids into deep groundwater. The danger is, indeed, much more pronounced where increased surface activity takes place (e.g. HGV-transportation, pipelines, handling of chemicals and flowback[31]) – cases, in short, that qualify as "traditional" contamination scenarios.

Most of the studies agree that for risk assessment purposes, the following risk scenarios should be considered:

Risk of frac-fluids/flowback leaking into groundwater as a result of aboveground on-site accidents

The above-cited studies agree that shallow groundwater is mainly threatened by leaks resulting from accidents involving aboveground on-site surface installations. During regular operation, however, this risk is considered to be negligible – under the condition that the national standards are complied with. The probability of such a scenario is, indeed, not significantly higher for hydraulic fracturing than for normal handling of similar substances. Moreover, provided that timely and appropriate counteraction is taken, any damage would be minor and locally limited. There is an easy and realistic baseline available for the risk to groundwater via this contamination path, viz. industrial facilities handling comparable quantities of potentially polluting substances that can be assigned to

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[22] Cf. Ewen et al. 2012.
[23] Cf. UBA 2012.
[24] Cf. NRW 2012.
[25] Cf. SRU 2013.
[26] Cf. UBA 2014.
[27] Cf. Sauter et al. 2012.
[28] Cf. Lange et al. 2013.
[29] Cf. Kissinger et al. 2013.
[30] Cf. Ewen et al. 2012.
[31] Cf. Warner et al. 2013.

similar water hazard categories. Should an accident result in local contamination of leakage water and groundwater, we can therefore resort to a wealth of experience in the remediation of contaminated sites, from investigation to monitoring and, possibly, decontamination.

Risk of frac-fluids/flowback leaking through the borehole into shallow groundwater

The second, somewhat less important risk path the studies have identified for shallow groundwater involves pathways along the well. These could occur as a consequence of faulty annulus cementing or leaks in the casing rings. The studies refer to the results of sporadic hydrochemical investigations of wells in shale gas fracking zones as a baseline for the likelihood of leaks occurring along the wellbore. To the authors' knowledge, however, there are, as yet, no studies investigating the level of groundwater contamination potentially attributable to this risk path. An empirical assessment of the risk claiming a minimum of robustness is impossible without knowing the extent of the contamination. This, in turn, correlates roughly with the quantity of leaked pollutants. Here, further research is required. This should, for instance, include participating in research projects in areas with longstanding experiences with shale gas fracking.

Also required are numerical scenario analyses, calculating the propagation of leaks in aquifers with different monitoring systems and, possibly, response- and decontamination measures, always assuming representative geological conditions and compliance with the national standards for oil and gas extraction facilities.

Risk of frac-fluids leaking into shallow groundwater via pathways (artificial fractures, fault zones) in the overlying strata

The third risk path considers possible pathways leading from the casing perforations in the fracked shale gas formations to shallow aquifers via the artificially created fractures and permeable fault zones and covering distances of more than a thousand metres. Experts agree that the risk of this type of contamination is extremely low. This assessment is partly based on mathematical modelling. For one thing, there are usually no appropriate potential gradients (driving fluid flow) allowing for the transport of formation water or frac-fluids through low-permeability rock strata. For another, large-scale hydraulic fracturing-induced gas transport appears highly unlikely. Fluid flow monitoring along this risk path should concentrate on fracture propagation during the fracking process.

Risk of flowback from disposal formations leaking into groundwater

Fracking operations generate flowback when frac-fluids are returned to the surface before the start of the production phase. In the United States, most of these flowback fluids are disposed of by reinjecting them into permeable rock formations. The large volumes of reinjected fluids can significantly alter the pressure regime in the disposal formations. This, in turn, could induce formation water transportation processes. However, should the German legislator permit the use of hydraulic fracturing for shale gas extraction, it can be assumed that the treatment and reuse of flowback in subsequent fracking operations will be mandatory. Therefore, there will be no disposal of fluids by reinjection. What is still needed, however, is a solution to a different though related problem, i.e. the question of how to deal with the formation water brought to the surface during conventional gas extraction. At present, this fluid is reinjected into exhausted reservoirs or into deep saline aquifers where it can,for instance, lead to induced seismicity.

Several papers addressing the risks of fracking assume that during shale gas production, higher quantities of metal-polluted formation water are brought to the surface. While this is indeed true for conventional natural gas extraction, the reservoir properties in shale gas formations make the occurrence of formation water highly improbable.

Risk of shale gas fracking causing a significant drop in the groundwater level

Fracking operations require a certain amount of water. Occasionally, concerns are expressed that the high water consumption could lead to a harmful drop in the groundwater level. With its generally high supply of groundwater, Germany does certainly not qualify as a water shortage area. Moreover, clear legal provisions on groundwater use exclude any potentially harmful extractions of groundwater. This issue could be more relevant in (semi-)arid regions with only weak legal groundwater protection, although even here there are now technological alternatives to the use of drinking-water-quality groundwater. For instance, brackish water, saltwater and some types of industrial wastewater can principally be used as frac-fluids. In addition, the recycling of flowback fluids can significantly reduce water consumption.

4.2 DIRECT THREATS TO HUMAN HEALTH

Other possible direct threats to human health, e.g. due to work-related or transport accidents are not specific to shale gas extraction. Consequently, they can be addressed by the proven measures used in the hydrocarbon industry. Another threat that cannot be completely ruled out involves air pollution as a consequence of accidents. In this case, the same evaluation criterions apply as for industrial (chemical) facilities, biogas plants etc.

A concern frequently voiced in the public debate regards risks to human health, buildings and infrastructure as a result of “earthquakes”. However, with view to the mechanical properties of shale gas reservoirs and the technology of small multi-fracs, it appears rather unlikely that shale gas fracking should induce seismic movements to that extent (cf. Chapter 8). Also, most seismicity is triggered by the reinjection of flowback fluids underground. Since shale gas fracking flowback, unlike the fluids used in conventional oil and gas extraction, can be recycled, there will be no disposal by reinjection.

5 REGULATORY FRAMEWORK

All technical measures connected with the exploration and exploitation of oil and gas resources and deep geothermal reservoirs are subject to a complex administrative licensing process. This covers geophysical investigations of the geological underground, the drilling of boreholes and the use of frac fluids. Along with the provisions of mining law, the Water Resources Act (Wasserhaushaltsgesetz) and the associated ordinances as well as further regional water protection regulations constitute the core of the comprehensive framework for the protection of water and other protected goods.

Mining law

Under German mining law, the licensing process for mining projects covers several stages. First, a mining permit is required (Sec. 7 cf. of the Federal Mining Act – Bundesberggesetz), which comprises an authorisation for the exploration of a reservoir as well as a licence for the extraction of the natural resource. In the second stage, the details of the mining operation, i.e. the implementation of individual technical measures, need to be specified in the mining operating plan procedures (Arts. 51 ff. Federal Mining Act). For mining projects requiring an environmental impact assessment (EIA), a mandatory general operating plan will have to be approved in a separate planning procedure. In this case, the planning permission process is carried out according to the Administrative Procedures Act (Verwaltungsverfahrensgesetz) involving both the relevant authorities and the public.

The operations plans contain details of the planned measures, for example the employment of geophysical deep sounding methods, well site construction, well drilling, fracking operations, etc. A careful site selection can minimise, or altogether prevent, potential conflicts with public and private interests and requirements at an early stage. The licensing conditions under German mining law (Sec. 55 Federal Mining Act) stipulate that (1) the operations plan contain measures to safeguard against threats to human life and health and damage to material goods and that (2) there be no indications as to any effects detrimental to public welfare. The operations plan must also provide proof that the relevant licensing conditions have been complied with (Sec. 52.4 Federal Mining Act). Accordingly, the project developers must include measures in the operations plan to guarantee the protection of legal interests. Part of the process for approving the operations plan involves evaluating the projects' potential impacts based on feedback obtained in the stakeholder consultation procedures. If necessary, special conditions may be imposed during the licensing process or ex post. Should operations be shut down, a closure plan must be worked out. This should, in particular, provide details of measures regarding the long-term safety of the boreholes, the removal of surface installations and the reconversion of the respective well site area to a condition allowing for alternative uses.

Additional permits and regulations

Depending on the circumstances, a project may require additional permissions as stipulated by further specific laws. For instance, dispensations and exemptions from nature conservation provisions may be necessary. If the project involves any of the water uses listed under Sec. 9 of the Water Resources Act, a special permit according to said act will have to be obtained. Any "non-standard" uses as defined by Sec. 9.2 of the Water Resources Act will likewise require authorisation. "Non-standard" uses include measures capable of causing lasting or significant adverse effects on the water quality.

If the use of water is provided for in an operations plan governed by German mining law, the issuance of a water use permit is subject to a joint decision of the mining and the water authorities. The water use permit may stipulate restrictions or additional requirements should they be deemed necessary to prevent or mitigate any adverse impacts (Sec. 13 Water Resources Act). The water use permit also regulates the monitoring of the water use with view to its predicted impacts. This enables a rapid reaction should any adverse effects in the water quality become apparent. If new findings suggest the necessity of restrictions or further safety measures, according provisions can be added ex post.

The Federal Government's plans

With view to the widespread public concerns about the use and impacts of hydraulic fracturing, the ruling parties committed to draw up, without delay, a range of amendment proposals to the Water Resources Act and the Ordinance on Environmental Impact Assessments for Mining Projects (Verordnung über die Umweltverträglichkeitsprüfung – UVP-V Bergbau). This engagement was duly recorded in the Coalition Agreement. On this basis, the respective Federal Ministers for Environment and for Economic Affairs published a joint document on 4th July 2014, containing a series of key points for the regulation of fracking.

The proposed legal changes involve in particular:

- compulsory EIAs for fracking operations
- clarifications with regard to the water uses covered by the Water Resources Act and the application of the duty of care principle (Besorgnisgrundsatz)
- a ban on fracking in certain locations (water protection areas, medicinal spring protection areas, catchment areas of dam reservoirs and lakes used for drinking water)
- permitted concentrations of different substances and the obligation to disclose the substances used
- the preparation of a baseline report
- regulations on the handling of flowback and reservoir water
- underground and surface monitoring
- eporting obligations
- reversing the burden of proof for mining damage resulting from fracking/deep wells

With these changes, the government seeks to strengthen the existing water protection measures and to ensure a thorough investigation and assessment of the impacts of fracking. It further aims at a better level of public information and more transparency in the decision making processes.

The legislative and regulatory proposals on fracking technology were published at the end of 2014 by the Federal Ministries for Economic Affairs and Energy and for the Environment and were subsequently discussed with stakeholder organisations and regional governments at a hearing in spring 2015. The according feedback has been analysed and will be considered in the revision of the draft regulations. Once the relevant ministries have agreed to the amendments, the draft bills will be submitted to the Cabinet for approval. They will then have to pass the parliamentary process before they become law.

6 ACCEPTANCE AND COMMUNICATION

The extraction of shale gas by hydraulic fracturing is currently subject to controversial debates. The public perception of this technology is largely determined by the way its essential features, particularly its opportunities and risks are communicated. If acceptance is doubtful, the actual subject of the communication is often neglected in the public debate, as project initiators and approving authorities tend to focus on the forms and techniques of communication. However, the formats and techniques of successful risk communication are well known among experts and professional communication offices are highly proficient in this field. In most cases, therefore, it is the contents rather than the packaging that must be blamed for communications failures. Hence, the following chapter examines more closely the contents to be communicated.

6.1 KEY PRINCIPLES OF RISK COMMUNICATION FOR HYDRAULIC FRACTURING

Transparency: The hallmark of successful science communication

Decision-makers in the field of hydraulic fracturing have an unfortunate tendency to beat about the bush. However, risks and uncertainties should not be glossed over, but stated clearly and openly. Equally frankness is required with regard to the opportunities inherent to hydraulic fracturing and the various scientifically promising concepts for minimising its risks. At the same time, false problems or assumptions that do not bear scrutiny must be revealed as such and explained – whether they serve to support or, indeed, oppose hydraulic fracturing. Where there is no scientific evidence, speculations or reassurances are out of place. People can cope with a certain amount of uncertainty. Rather than issuing inconsistent and contradictory recommendations, all parties concerned should agree to a "joint fact finding"-process. The results obtained in this process are then to be communicated to a larger public without playing down risks or overstating opportunities. Once the majority of the stakeholders can resort to a jointly supported knowledge base, the largely speculative attitude towards hydraulic fracturing will give way to a more evidence-based perspective. In addition, the addressees of this information should be briefed as to where further reliable and independent scientific information can be procured.

Results of acceptance research

We know that large-scale industrial plants and systems invariably give rise to scepticism and fear in the population – particularly amongst the residents around the site in question. The reasons are varied and include the complex effects of such plants on the environment, health and society, their disaster potential, the unequal distribution of benefits (enjoyed by the entire population) and risks (borne by the local residents) and the fear of being controlled by outside interests infringing upon municipal and individual autonomy. The controversies regarding nuclear energy, chemical plants and similar issues provide a blueprint of what is to come: Fracking will meet with a similar opposition and for the same reasons. Unlike the development we witnessed in mobile communications, it is not to be expected that habit or the experience of personal benefits will increase the acceptance of fracking.

Many citizens perceive fracking as a potential threat to various aspects of their personal lives without deriving any apparent personal benefits from it. The immediate advantages for the industry and the economy are more abstract in nature. Accordingly, social science research suggests that communication strategies should fulfil the following four requirements:

- Belief in the necessity of the investment: Acceptance is more likely to be gained if fracking is perceived as necessary to achieve important societal goals (such as the energy transition). Everyone wants to know how fracking will affect him or her and what he or she can expect from it. This includes considering possible alternatives and appreciating why they were rejected. At the same time citizens call for transparency, wishing to comprehend the reasoning behind a political decision.

- Self-efficacy: People tend to oppose interferences in their living conditions if they perceive them as potential threat to their personal freedom and the independence of their lifestyle habits. To many people, interferences in guise of new infrastructure projects or the construction of large-scale industrial plants constitute an unacceptable infringement of their sovereignty. The more a fracking operation gives the impression of restricting individual freedom, the lower the acceptance rate to be expected.
- Positive risk-benefit balance: The more the planned measures benefit a person or his or her friends and relations, the more acceptance he or she can be expected to show. Measures contributing to the common welfare will also receive a higher acceptance rate. Local residents invariably wish to know whether the benefits of the fracking project outweigh the risks of its implementation – as far as they are concerned as well as with regard to their friends and relations. It is indeed difficult to assess the desirability of project plans without information about their benefits and risks.
- Identity: People are more willing to accept a measure if they can identify with it emotionally. It is important for new projects to provide such information as will allow the local community to associate fracking with ongoing local developments and will help them to assess the extent to which the plans fit in with their own and others' perception of their social and cultural environment. One approach might involve experimenting with new operator and ownership models (such as cooperatives, issuing share certificates, profit-sharing arrangements, etc.), banking on the fact that ownership or rights of use will create an emotional bond from which a sense of identification can evolve.

Assuming these four aspects to be promising levers to foster acceptance of the planned projects, the respective information and communication strategies must obviously address them all on an equal footing. Acceptance will not increase unless we succeed in pointing out the added individual and general benefits of the planned projects and the potential they offer in terms of positive identification.

Designing recommendations with view to political and social feasibility

The addressee of a recommendation must be able to realise its legal, technical, economic and political purport within the scope of his or her responsibilities. Collectively binding decisions are difficult to implement in a democratic system unless the different stakeholders share at least some basic understanding. This is best achieved in face-to-face discussions or negotiations, because only in direct contact can we fully appreciate and adequately respond to the various concerns amongst those affected.

Many "pro-fracking"-campaigns hit that very snag: Despite being attractive in terms of communicative skills, they fail to convince people because their offer of dialogue does not extend to substantial issues and controversies. The somewhat contradictory consequence is that precisely those campaigns that set great store by a professional and slick impression frequently cause people to withdraw their acceptance. Communication programmes need to bring forward sound arguments and offer credible answers to the issues people are concerned with. Most importantly, they should not anticipate what opinion people will form on the basis of the information they receive. The challenge is to obtain judgments based on evidence rather than on hearsay and prejudices. If possible, examples should refer to past experiences, e.g. previous fracking projects, since this allows for the easy verification of every statement.

Striking the balance between old and new facts

While taking up the population's anxieties and concerns, such recommendations should also – wherever possible – contain an element of surprise. People are particularly keen on new findings in the field of hydraulic fracturing; this curiosity can be used to raise people's interest in the subject and to make them appreciate where risk management has succeeded or, indeed, failed.

Tailoring communication strategies to the priorities of stakeholders and local residents

A communication strategy should hinge on the specific concerns of stakeholders and local residents. Are they concerned with possible earthquakes or rather with a potential contamination of the ground water? Do they fear that the use of hydraulic fracturing might counteract the goals of the energy transition? Also, we frequently find rather indirect consequences at the bottom of a growing scepticism towards hydraulic fracturing. Many people, for instance, set great store by issues of social justice and demand a fair distribution of the benefits and risks. Fairness usually ranks higher in people's individual set of values than an optimal use of resources (in this case energy resources).

The individually perceived quality of life is often rated higher than increases in standard of living – though correlated, the two notions are not identical. A successful risk communication for hydraulic fracturing must therefore invariably address the individual and collective beliefs and values of the respective target group.

6.2 PSYCHOLOGICAL PITFALLS IN RISK COMMUNICATION

In complex matters where probabilities outweigh the solid facts, mechanisms of intuitive plausibility tend to fail. People's reactions to new information frequently follow a pattern of cognitive processes of information reception and evaluation acquired over the years. While such patterns have their merits in the interpretation of everyday events, they can, however, lead to cognitive biases in complex cases. Thus, individual events are often regarded as evidence of a trend; certain effects (such as methane leaking from a tap) are immediately attributed to specific causes (e.g. fracking) that are, indeed, unconnected with the incident in question; any uncertainties that may occur are attributed to the involved scientists' lack of integrity ("They know what is really going on, but they won't tell us."). By determining how a message is perceived, processed and assimilated, such psychological mechanisms influence people's behaviour, lead to conflicts and misunderstandings, shape conflict resolution strategies and affect people's decisions and actions. Indeed, the stronger the effects of such mechanisms, the less likely people are to give credence to scientific evidence Simply providing "objective" facts will therefore not suffice to break through these mechanisms. Successful risk communication will rather focus on exposing the psychological mechanisms of perception and risk evaluation in conversations or information events. If we resort to easily comprehensible examples to explain the distorting effects of intuitive conclusions, people will tend to scrutinise their line of reasoning with a more critical eye. By no means, however, should facts be oversimplified for the sake of easy comprehension.

Consequently, the primary goal of risk communication should not be to increase people's acceptance or approval of a technology but rather to increase their ability to form their own judgement of a risk. In other words, a person is enabled to form a consistent and balanced opinion on the basis of adequate information and his or her own values. This ability can be nurtured by several practical means, including structured dialogues or methods of stakeholder and public involvement.

6.3 RISK COMMUNICATION FOR HYDRAULIC FRACTURING AS PART OF THE RISK-GOVERNANCE SYSTEM

Processes of risk communication for hydraulic fracturing operations are part of a comprehensive risk governance system including four central subsystems of society: the market, the public authorities, civil society and the scientists and experts providing the necessary knowledge. In hydraulic fracturing, like in other fields, none of the four sub-systems can claim to succeed in governing the effects and conditions of systemic risks singlehandedly. Only in a process of mutual cooperation and dialogue can their respective contributions develop a potential for effective governance. Such a coordinated risk communication effort creates the cooperative atmosphere necessary for a rational and fair assessment of the advantages and disadvantages of hydraulic fracturing.

7 RELATED STUDIES: AN OVERVIEW

All scientific institutions in Europe and worldwide with an in-depth knowledge of the geological subsurface and the technologies required to explore, develop and exploit its resources, have so far come to the conclusion that there are no scientific reasons for a general ban on hydraulic fracturing. However, they unanimously call for clear regulations and standards in order to ensure that the technology is employed in compliance with environmental and social requirements. All available studies and reports published by these institutions conclude that given thorough preparatory and accompanying research, precise instructions, appropriate technical measures and comprehensive supervision by the relevant authorities, the remaining environmental risks are very low (cf. e.g. the US Geological Survey, US Department of Energy, US Environmental Protection Agency, Australian Academy of Humanities, British Geological Survey, British Geological Society, Royal Society, Royal Academy of Engineering, Bureau de Recherches Géologiques et Minières, Académie des Sciences de France and Swiss Academies of Arts and Sciences).

In a joint statement issued in 2013, EuroGeoSurveys[32], the network of the national geological surveys in Europe, declared that the use of fossil fuels with a comparatively low emission of greenhouse gases – for instance natural gas from conventional and unconventional deposits – could serve as a bridging technology. The findings of meticulously conducted research should enable policymakers and industry to decide upon measures allowing further exploration. Decisions should be based on expert assessments of the resource itself and of any environmental impacts that might occur in connection with its exploitation. These evaluations are to be carried out by independent institutions such as the National Geological Surveys.

Also in 2013, the State Geological Surveys of Germany and the German Federal Institute for Geosciences and Natural Resources published a position paper entitled "Opinion on the Earth Science Conclusions of the UBA Report[33], the NRW study[34] and the Risk Study from the ExxonMobil Information and Dialogue Process[35] on the subject of Fracking".[36] These three studies on the subject of fracking were analysed from a geoscientific perspective by the German Federal/State Committee on Soil Research (Bund-Länder-Ausschuss Bodenforschung).

The principal aim of this analysis was to verify the geoscientific conclusions and recommendations the studies provide. Despite some weaknesses, none of the studies advocates a general banning of fracking. Provided that the relevant statutory regulations are complied with and that each individual case observes regionally agreed procedures, the necessary quality-, environmental and safety standards can be met. Under certain conditions, the exploration and extraction of unconventional natural gas can be compatible with environmental- and water protection requirements. Central conditions involve detailed geoscientific pre-investigations and precise regulations of the distances to be observed.

In November 2014, the European Academies Science Advisory Council (EASAC) published a statement[37] on hydraulic fracturing entitled "Shale gas extraction: issues of particular relevance to the European Union". The statement is based on an expert study and addresses the European Commission and the governments of the European Member States. Whereas the present acatech POSITION PAPER undertakes a detailed analysis and assessment of the technology, the EASAC study concentrates primarily on shale gas extraction, addressing the following three issues: (1) the implications of the use of hydraulic fracturing with regard to the high population density throughout Europe (including the water usage implications), (2) greenhouse gas emissions and the problem of methane leakage and (3) the challenge of (local) public acceptance.

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[32] Cf. EGS 2014.
[33] Cf. UBA 2012.
[34] Cf. NRW 2012.
[35] Cf. Ewen et al. 2012.
[36] Cf. SGD 2013.
[37] Cf. EASAC 2014.

The statement comes to the following central conclusions:

- There is no basis for a ban on hydraulic fracturing on scientific and technical grounds. However, EASAC supports efforts towards clear and comprehensive regulations in the health, safety and environment sectors.
- Here, the existing European rules for minimising health-, safety- and environment impacts of conventional gas production provide a very good basis. A few amendments will suffice to adapt them to the specificities of unconventional gas production.
- The best practice methods the industry is currently resorting to have already greatly reduced the environmental footprint of hydraulic fracturing. The most important of these include the replacement or elimination of potentially harmful frac-fluid additives, the recycling of flowback fluids, the reduction of land use by means of cluster drilling and high well integrity standards. If these conditions are fulfilled, the risks appear to be manageable.
- A reduction in greenhouse gas emissions by means of increased natural gas production to replace e.g. coal can only be achieved if methane leakage is prevented during drilling, extraction and transport.
- Public acceptance requires complete transparency and the close involvement of local residents. By means of pilot projects, the potential of fracking and the reliability and safety of the methods can be demonstrated.
- The quantity of shale gas resources in Europe and their economic viability remain to be determined more precisely. Further exploration will be necessary before the importance of shale gas for Europe's future energy supply can be reliably assessed.

8 BEST PRACTICE: OPTIONS AND RECOMMENDATIONS

The use of deep wells and hydraulic fracturing for accessing and exploiting the geo-resources natural gas and geothermal energy must be meticulously prepared and continuously monitored once production is under way. Top priority in all operations must be to exclude any risks to human health, prevent harmful environmental impacts and generally minimise any adverse effects. This chapter on best practices describes options and recommendations for actions and measures which can help to achieve this goal.

Geological and geophysical pre-site investigations

Any project for the production of shale gas or utilisation of geothermal energy has to be prepared meticulously by a comprehensive programme of pre-investigations. Central component of such a program is the geophysical mapping of the subsurface along 2D sections by means of seismic deep sounding techniques. Over the past decades, the exploration companies of the hydrocarbon industry have gained extensive experience with the method of deep reflection seismics and the processing and interpretation of the data obtained. This means that proven technologies are available for geophysical pre-investigations of gas-prospective shale formations.

For the exploration of petrothermal reservoirs and the assessment of their economic potential we recommend a significant expansion of the geophysical pre-site investigations compared to current practice. This is not least advisable with view to reducing the exploration risk and enhancing the profitability of individual projects. Depending on the geological conditions, this might involve employing additional geophysical deep sounding methods, such as gravimetry or magnetotellurics. Magnetotellurics, for instance, might help to obtain valuable additional hydrological, hydrogeological and structural information.

Geophysical measurements are generally performed at the Earth's surface and do not leave behind any lasting traces. In Germany, their execution is strictly regulated by the relevant DIN standards. It is advisable to clearly communicate the planned field tests and their results to the public and not to shirk open discussions.

Site-specific risk assessments and 3D-modelling of the geologic subsurface

The process of well-planning as well as the exploration of shale gas and petrothermal reservoirs require a detailed, site-specific risk assessment. To this end, a realistic 3D-model of the architecture, rock composition and tectonic structures of the underground needs to be drafted by means of modelling techniques combining all available geological and geophysical data and information. In the specific case of petrothermal systems, the identification of major inclined faults (geological fracture zones) and their spatial orientation and depth is of paramount importance. In shale gas projects, on the other hand, accurate information as to a reservoir's depth, vertical thickness and spatial distribution is crucial. The same goes for the identification of geological "barrier formations" in the overlying sedimentary rock sequences. Further necessary measures include a detailed examination of the local hydrology and hydrogeology, the localisation of the exact boundary between shallow groundwater and saline deep formation water as well as the identification of any fault zones in the overlying strata that might be of hydraulic significance.

The locally varying depth ranges of commercially viable groundwater horizons suggest that a minimum vertical distance of one kilometre between the shale gas formation intended for production and the surface of the earth is advisable.[38] Past experiences corroborate this necessity.

Well site/production facility

In Germany, the construction and technical design of well sites are subject to extensive legal provisions and regulations to protect human life and the environment against potential hazards. Compliance is supervised by the relevant authorities, in particular the responsible mining authority.

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[38] Cf. Reinicke 2014b.

Efforts centre upon groundwater protection, i.e. preventing pollutants from leaking into shallow groundwater (for instance as a result of accidents occurring during the handling of chemicals on the surface).

The following measures can contribute to achieving this goal:

- paving the inner well site area and the later production facility with a layer of waterproof concrete as stipulated by the guideline for watertight concrete structures (WU-Richtlinie) of the German Committee for Reinforced Concrete (Deutscher Ausschuss für Stahlbeton),
- installing a circumferential drainage system in order to collect all liquids, including rainwater, for recycling or disposal
- protecting near-surface groundwater/drinking water by means of a standpipe and anchor casing.

Environmental impact assessments

The planning and construction of deep wells and the subsequent exploitation of the reservoir/resource are governed by a comprehensive regulatory framework, with compliance being supervised by the responsible authorities. The relevant legislation includes the Federal Mining Act, the Federal Emission Control Act, the Noise Control Act, the Water Resources Act, the Federal Soil Protection Act and the EU Habitats Directive.

Mandatory environmental impact assessments (EIAs) are recommended for deep wells where hydraulic fracturing is employed in order to gauge the potential effects on human health and the environment ex ante, i.e. before a project is approved. EIAs will also enhance public acceptance.

Deep wells and well integrity

Deep wells for the extraction of shale gas or the exploitation of petrothermal reservoirs are drilled in sections. Each section of the wellbore is secured with a special-steel pipe (known as a casing string). The gap between the casing string and the wellbore wall – the so-called "annulus" – is sealed with a layer of gas-tight and pressure-resistant cement, in order to prevent liquids or gases (especially methane) from leaking into the annulus and being transported along the well.

Secured by several casing strings and cement-sealed gaps, these deep wells are to create a sealed connection between the well site/production facility and the resource in question. In other words, they are designed to ensure that the transported matter (fluids and solids) remains within the pipes, to prevent any exchange of matter between the borehole and its surroundings and to exclude any unwanted substances being transported along the casing. These key environmental requirements can only be fulfilled if the well integrity can be vouchsafed at all times.

Well Integrity Management

In order to ensure compliance with the relevant laws and regulations, the industry has developed so-called Well Integrity Management Systems (WIMS). These cover the entire life cycle of a deep well, from the planning and drilling stages to the exploitation of the resource and the plugging of the well once the project is completed. The scope and requirements of WIMS are not standardised and vary internationally between the different companies. For projects in Germany employing hydraulic fracturing it is strongly recommended to establish a set of minimum standards for a Well Integrity Management System in cooperation with the mining authority.

Minimum WIMS standards should include the following criteria regarding well construction, resource exploitation and project termination:

- relevant laws and technical regulations
- standards for technical equipment, testing and inspection frequencies

- detailed description of the surface barrier strategy and its individual components (well site, production facilities, blowout preventer, wellhead)
- detailed description of the underground barrier concept and its individual components (drilling fluid, drilling string, pipes, cementing)
- detailed description of the operational barrier concept for drilling operations, wellbore testing, completion, production and special operations such as directional drilling, well logging, pumping-, wireline- and coiled tubing operations
- a pipe design taking into account all conceivable scenarios of static and dynamic strain, particularly with regard to thermal factors
- selection of suitable, gas-tight pipe couplings
- selection of suitable, thermally stable cements
- application of the fibre optic technology and installation of fibre optic cables behind the casing
- development of a water management- and environmental monitoring strategy before the start of the project and its incremental implementation throughout the project's duration
- pressure monitoring of the annuluses between the casing strings
- specification of all measurement parameters and of their processing and archiving
- risk analyses, alternative scenarios and emergency plans
- description and regulation of recultivation measures at the end of the project
- unequivocal definition of the roles and responsibilities of all parties involved throughout the project's life cycle

The installation of fibre optic cables behind the casing allows for high-resolution temperature measurements, which are regarded as a particularly effective means of permanent real-time well integrity monitoring.[39] This innovative technology should therefore be tested in the recommended pilot/test projects.

Well integrity monitoring

Based on the respective project-specific well management concept well integrity should be monitored throughout the entire lifecycle of a project. Recommended actions include:

- monitoring the annulus pressure to ensure permanent tightness of the cementation
- if necessary, monitoring of the integrity of the production tubing by means of fibre optic temperature measurements
- wall thickness measurements of the casing pipes using corrosion monitoring techniques

In accordance with the German Federal Mining Act, the respective mining authority is responsible for the supervision of all mining-specific measures. We suggest a possible involvement of an independent institution such as the German Technical Inspectorate (Technischer Überwachungsverein TÜV). The essential point is that a continuous supervision of the well integrity control measures is secured. Here, representatives of the industry, the scientific community and the public authorities should join forces to develop a concept adapted to the specific characteristics of shale gas production and the utilisation of deep geothermal energy.

Baseline measurements and long-term monitoring of environmental parameters

In order to enable assessment and classification of any potential damage to the environment as a result of hydraulic fracturing, the naturally occurring (baseline) values for the relevant parameters and factors have to be determined in advance. Such measurements should be started at least a year before any geotechnical measures are undertaken, so as to ensure that natural variations can be taken into account. This includes measuring hydrological, hydrogeological and near-surface atmospheric parameters (e.g. CO_2 or CH_4-level) and analysing their variation over the course

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[39] Cf. Reinsch/Henninges 2014.

of the year. For hydrological and hydrogeological investigations, measurement points (e.g. wells) must be established. They are to record the chemical and physical parameters of the near-surface groundwater as well as its hydrogeological properties such as flow direction and, possibly, flow rate. Due to respective technical developments in the last few years, a variety of tried-and-tested airborne measurement techniques to record atmospheric parameters are meanwhile available.

The measuring points and infrastructure set up to record the baseline values should continue to be used during the subsequent drilling and production phase for the long term monitoring of the selected environmental parameters. The specific parameters and factors to be recorded and documented are to be defined individually for each case, according to e.g. the nature and size of the project or the basic geological and technical conditions.

We recommend the appointment of separate expert groups for shale gas- and deep geothermal projects, including representatives from the scientific and applied research communities and the industry. These groups should define standards and guidelines for a minimum measurement- and monitoring programme.

Induced seismicity and seismic monitoring

Seismic monitoring provides the necessary basis to assess the seismic risk connected with a fracking operation. Seismic noise measurement should be started well in advance of drilling operations in order to establish a baseline value for naturally occurring local/regional seismicity. The surveillance network (seismological and immission networks) should be designed so as to enable full recording of induced seismicity even well below the human perception threshold for seismic activity. For both hydraulic fracturing and hydraulic stimulation, a real-time analysis of the recorded seismic waves is crucial with view to a swift detection of any potential seismic hazards.

In any case, a reaction scheme (a so-called traffic light system) needs to be developed with which current measurements can be contrasted with predefined limit values. This allows for an immediate response to any increased seismicity and for appropriate countermeasures such as reducing injection pressure or stopping fluid injection altogether.

The magnitude of the induced seismicity is best estimated on the basis of peak ground velocity measurements: This enables a direct comparison with the limit values established by the DIN 4150 standard which refers to structural vibrations in civil engineering. This DIN norm defines peak ground velocities (PGV) below which there is no risk of structural damages to buildings. In Germany, the limits are set by the responsible mining authority. The great advantage of this response system is its simplicity – the seismogram displays the current hazard status as PGV value, enabling an immediate response if necessary. Immission measurement devices for recording peak ground velocities should be employed to preserve evidence and allow rapid reaction in the event of damage.

In the specific case of hydraulic stimulations in Enhanced Geothermal Systems (EGS), we recommend the use of a multi-frac strategy in conjunction with cyclical stimulation in order to reduce the risk of seismic activity perceptible to humans.

Seismic monitoring is necessary throughout the lifecycle of all projects involving hydraulic fracturing. According measures should be started at an early stage, i.e. before the beginning of the actual project, in order to gain reliable information about the local/regional (natural) background seismicity. The scope and level of the monitoring will depend on various factors, including the regional geology and naturally occurring seismicity, as well as the nature and extent of the fracking operations (e.g. flow rate, injection pressure and fluid volume). Both the general design of seismic monitoring programmes and the development of project-specific versions with particular consideration of cost and feasibility aspects should resort to the know-how of the expert group on "Induced Seismicity" of the "Forschungskollegium Physik des Erdkörpers" (FKPE).[40]

Frac-fluids

Frac-fluids are composed mainly of water; depending on their field of application, they may also contain proppants and chemical additives. For hydraulic stimulation in petrothermal reservoirs, the frac-fluid is usually pure water. In Germany, the total number of additives to be employed in frac-fluids for tight gas extraction has been reduced to around 30. Under current legislation, these 30 additives are not subject to any license restrictions. They are non-toxic, not hazardous to the environment and at the most only weakly water contaminating (none being classified any higher than Water Hazard Class 1).

According to recent information by ExxonMobil (October 2014), the number of additives for shale gas extraction in Germany can be further reduced to only two or three substances. These additives are non-toxic, do not pose any threat to human health or the environment and are no more than slightly water polluting (Water Hazard Class 1).

Despite recent advances, the following key demands remain: (1) disclosure of all additives and the relevant data (safety data sheets), along with further reductions in additives and the replacement of potentially harmful substances and (2) a ban on all frac-fluids classified as toxic, hazardous to the environment or anything more than slightly water polluting.

Flowback/water consumption

A fracking operation for shale gas extraction typically requires around 1,000 cubic metres of frac-fluid that is returned to the surface as so-called flowback at the beginning of the production phase. Since shale gas deposits are relatively dry compared to conventional gas reservoirs, the flowback contains almost no formation water and only a small additional amount of condensate water. Flowback fluids can therefore be easily recycled, just as the drilling fluids. We therefore advocate recycling the flowback, something that is not least simplified by the now widespread use of cluster drilling. Recycling has the added advantage of significantly reducing water consumption.

Cluster drilling/land requirements

In the early days of shale gas exploitation, the deposits were accessed via separate vertical wells (or separate inclined wells) drilled at intervals of a few hundred metres from each other. Today, however, this approach has been replaced by cluster drilling of up to 20 wells at a single site. Once they have reached the required depth, these wells are usually diverted so as to follow the gas-bearing formation. In every such well, 30 or more fracs can be realised. This means that from a single well/production site covering a surface area of approximately one hectare, an area of ten or more square kilometres of underground shale formations can be accessed. Cluster drilling does not only significantly reduce land use but also improves efficiency and profitability by allowing for a concentration of surface installations (e.g. power supply, treatment plants, etc.). This has radically reduced the ecological footprint of shale gas production sites.

Involving local communities and communicating with the public and media

In view of the serious concerns among the population regarding projects that involve hydraulic fracturing, a transparent, dialogue-based information and communication campaign is required early on, particularly engaging the directly affected local residents into the process.

By involving local municipalities in the granting procedures for mining permits, the necessary local dialogue process can be launched at an early planning stage. In addition, project developers are encouraged, in the interest

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[40] Cf. Zimmermann et al. 2014.

of an early public participation, to inform the public about a planned project and its potential impacts before initiating any formal participation process. This involves discussing the residents' concerns as well as any suggestions they might make, and considering their feedback in the subsequent planning process. This approach will help to facilitate timely public involvement, open dialogue and conflict management.

9 PILOT/TEST PROJECTS AS BEST PRACTICE EXAMPLES

Scientifically and technically monitored pilot/test projects could serve as best practice examples, thus playing a decisive role for a future use of fracking in Germany. Their principal functions would include:

- demonstrating that hydraulic fracturing can be employed safely, profitably and without harming the environment under the respective local conditions,
- providing the responsible authorities with a test case for the regulation of future shale gas and geothermal energy projects,
- obtaining additional data and information allowing for a better assessment of the potential and economic viability of the resources,
- developing monitoring systems and standardised procedures for every project phase, from the pre-investigations to the exploitation of the resource and
- communicating the individual steps and results to the public in a clear and transparent information campaign and demonstrating how the public can be involved in the decision-making processes.

The implementation of the pilot/test projects should closely follow the recommendations and standards outlined in the chapter on “Best Practice”, although some of the issues will require further research and development (R&D).

It is more specifically recommended that the fields of application “extraction of natural gas from shale formations” and “generation of electricity and heat from petrothermal reservoirs” should be tested in at least two separate projects each. In the case of shale gas, the projects should focus on the exploration and development of the Posidonia Shale as a potential shale gas resource. Two different regions should be selected in order to ascertain the extent to which findings and results from one region are applicable elsewhere. It is up to the hydrocarbon industry to submit according project proposals which should, incidentally, provide for the participation of a small group of external experts for scientific and technical monitoring purposes.

The development of petrothermal systems could be promoted by launching a pilot project in the Upper Rhine Rift region. With its combination of tight, hot rock and steeply inclined geotectonic fault zones, the region offers an ideal setting for the exemplary exploration and exploitation of an EGS system. According preliminary works in the Upper Rhine region have yielded concepts and strategies as well as extensive expertise; there is hence no further obstacle to the application of the Enhanced Geothermal Systems-technology for commercial purposes. A second pilot project could focus on the potential exploitation of tight, hot geothermal reservoirs found all over Germany at depths of four kilometres and below. Here, the principal R&D issue is to create artificial heat exchangers. Established research collaborations with comprehensive expertise have already carried out extensive preparatory work in this field, particularly in Lower Saxony and northeastern Bavaria. As regards deep geothermal energy, acatech has already joined forces with the relevant stakeholders and developed a concept for the commercial exploitation of deep-seated petrothermal reservoirs.

If the proposed scientifically monitored pilot/test projects are realised, a steering committee should be established to determine the strategic and conceptual approach and ensure that the individual projects are professionally implemented. This body would further be responsible for translating the conclusions from the projects into policy recommendations for political decision-makers. The steering committee should include representatives of the relevant institutions and authorities as well as a sufficient number of independent experts from the key R&D fields.

10 CONCLUSION

In the light of this overall evaluation of the technology and its potential risks, acatech comes to the conclusion that scientific or technical facts do not justify a general ban on hydraulic fracturing – whether it is used for shale gas-extraction or for the utilisation of deep geothermal energy. Its use must, however, be subject to strict safety standards and requires clear regulations and comprehensive monitoring. In Germany, very high technical standards are already in place for the various different process steps involved in drilling, fracking and reservoir engineering. As long as the prescribed procedures are properly applied, the employment of the technology could be extended.

Scientifically monitored pilot/test projects, therefore, are key to the further advancement of the technology and the process of political decision-making. If implemented under strict conditions and in accordance with clearly defined standards, such projects enable a controlled, step-by-step approach allowing for immediate amendments. In addition, the close cooperation between industry, science, authorities and the population can also significantly enhance public confidence in the fracking technology.

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