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Impacts of shale gas and shale oil extraction on the environment and on human health

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DIRECTORATE GENERAL FOR INTERNAL POLICIES

POLICY DEPARTMENT A: ECONOMIC AND SCIENTIFIC POLICY

Impacts of shale gas and shale oil extraction on the environment and on human health

STUDY

Abstract

This study discusses the possible impacts of hydraulic fracturing on the environment and on human health. Quantitative data and qualitative impacts are taken from US experience since shale gas extraction in Europe still is in its infancy, while the USA have more than 40 years of experience already having drilled more than 50,000 wells. Greenhouse gas emissions are also assessed based on a critical review of existing literature and own calculations. European legislation is reviewed with respect to hydraulic fracturing activities and recommendations for further work are given. The potential gas resources and future availability of shale gas is discussed in face of the present conventional gas supply and its probable future development.

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LIST OF ABBREVIATIONS

ACP Africa, Caribbean and Pacific

ac-ft acre-foot (1 acre foot =1215 m^2)

ADR Agreement Concerning the International Carriage of Dangerous Goods by Road

AGS Arkansas Geological Survey

BAT Best Available Technique

bbl Barrel (159 litre)

bcm Billion m^3

BREF Best Available Technique Reference

CBM coalbed methane

CO Carbon monoxide

CO_2 Carbon dioxide

D Darcy (Measure for Permeability)

EIA Environmental Impact Assessment

EU European Union

EUR Estimated ultimate recovery (amoun of oil which is believed to be recovered ultimatly

Gb Gigabarrel (10^9 bbl)

GHG Greenhouse gases

GIP gas in place, amount of gas contained in a gas shale

IEA International Energy Agency

IPPC Integrated Pollution Prevention and Control

km Killometre

kt	Kiloton
LCA	Life Cycle Analysis
m	Metre
m^3	Cubic meter
MJ	Megajoule
MMscf	Million standard cubic feet
Mt	Million tons
MW	Mining Waste
NEEI	Non-energy-extracting-industries
NMVOC	Non methane volative organic compounds
NORM	Normally occuring radioactive substances (often also abbreviated as N.O.R.M.)
NO_x	Nitrogen oxide
OGP	International Association of Oil & Gas Producers
PA DEP	Pennsylvania Department of Environmental Protection
PLTA	Pennsylvania Land Trust Association
PM	Particulates
ppb	Parts per billion
ppm	Parts per million
Scf	Standard cubic feet (1000 Scf = 28.3 m^3)
SO_2	Sulfur dioxide
SPE	Society of Petroleum Engineers
TCEQ	Texas Commission on Environmental Quality
Tm^3	Tera cubicmeter (10^{12} m^3)

TOC Total organic carbon

UK United Kingdom

UNECE United Nations Economic Commission for Europe

US-EIA United States Energy Information Administrtion

USGS United States Geological Survey

VOC Volatile organic compounds

WEO World Energy Outlook

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EXECUTIVE SUMMARY

RECOMMENDATIONS

- There is no comprehensive directive providing for a European mining law. A publicly available, comprehensive and detailed analysis of the European regulatory framework concerning shale gas and tight oil extraction is not available and should be developed.
- The current EU regulatory framework concerning hydraulic fracturing, which is the core element in shale gas and tight oil extraction, has a number of gaps. Most importantly, the threshold for Environmental Impact Assessments to be carried out on hydraulic fracturing activities in hydrocarbon extraction is set far above any potential industrial activities of this kind, and thus should be lowered substantially.
- The coverage of the water framework Directive should be re-assessed with special focus on fracturing activities and their possible impacts on surface water.
- In the framework of a Life Cycle Analysis (LCA), a thorough cost/benefit analysis could be a tool to assess the overall benefits for society and its citizens. A harmonized approach to be applied throughout EU27 should be developed, based on which responsible authorities can perform their LCA assessments and discuss them with the public.
- It should be assessed whether the use of toxic chemicals for injection should be banned in general. At least, all chemicals to be used should be disclosed publicly, the number of allowed chemicals should be restricted and its use should be monitored. Statistics about the injected quantities and number of projects should be collected at European level.
- Regional authorities should be strengthened to take decisions on the permission of projects which involve hydraulic fracturing. Public participation and LCA-assessments should be mandatory in finding these decisions.
- Where project permits are granted, the monitoring of surface water flows and air emissions should be mandatory.
- Statistics on accidents and complaints should be collected and analysed at European level. Where projects are permitted, an independent authority should collect and review complaints.
- Because of the complex nature of possible impacts and risks to the environment and to human health of hydraulic fracturing consideration should be given to developing a new directive at European level regulating all issues in this area comprehensively.

Environmental Impacts

An unavoidable impact of shale gas and tight oil extraction is a high land occupation due to drilling pads, parking and manouvering areas for trucks, equipment, gas processing and transporting facilities as well as access roads. Major possible impacts are air emissions of pollutants, groundwater contamination due to uncontrolled gas or fluid flows due to blowouts or spills, leaking fracturing fluid, and uncontrolled waste water discharge. Fracturing fluids contain hazardous substances, and flow-back in addition contains heavy metals and radioactive materials from the deposit. Experience from the USA shows that many accidents happen, which can be harmful to the environment and to human health. The recorded violations of legal requirements amount to about 1-2 percent of all drilling permits. Many of these accidents are due to improper handling or leaking equipment. Furthermore, groundwater contamination by methane, in extreme cases leading to explosion of residential buildings, and potassium chloride leading to salinization of drinking water is reported in the vicinity of gas wells. The impacts add up as shale formations are developed with a high well density of up to six well pads per km^2.

GHG Emissions

Fugitive Methane emissions from hydraulic fracturing processes can have a huge impact on the greenhouse gas balance. Existing assessments give a range of 18 to 23 g CO2-equivalent per MJ from the development and production of unconventional natural gas. The emissions due to methane intrusion of aquifers are not yet assessed. However, project specific emissions might vary up to a factor of ten, depending on the methane production of the well.

Depending on several factors, greenhouse gas emissions of shale gas relative to its energy content are as low as those of conventional gas transported over long distances or as high as those of hard coal over the entire life cycle from extraction to combustion.

EU Regulatory Framework

The purpose of a mining law is to provide a legal framework for mining activities in general. The aim is to facilitate a prosperous industry sector, a secure energy supply and to secure sufficient protection for health, safety and the environment. At EU level, there is no comprehensive mining framework.

However, four Directives specifically designed for mining do exist. Additionally, there is a plenitude of non-mining-specific Directives and Regulations affecting the extractive industry. Focussing on regulatory acts concerning the environment and human health, the 36 most relevant Directives from the following fields of legislation were identified: water, protection of environment, safety at work, radiation protection, waste, chemicals and associated accidents.

Due to the multitude of relevant legislation from various fields, the specific risks of hydraulic fracturing are not sufficiently covered. Nine major gaps were identified: 1. lack of a mining framework Directive, 2. insufficient threshold in the Environmental Impact Assessment (EIA) Directive for natural gas extraction, 3. declaration of hazardous materials not mandatory, 4. approval of chemicals remaining in the ground not required, 5. no Best Available Technique Reference (BREF) on hydraulic fracturing, 6. The waste water treatment requirements are insufficiently defined, and the capacities of water processing facilities are probably insufficient if underground injection and disposal is to be banned, 7. insufficient public participation in decision-making at regional level, 8. effectiveness of water framework directive insufficient, and 9. LCA not mandatory.

Availability of shale gas resources and role in a low-carbon economy

The potential of unconventional gas availability must be seen in the context of conventional gas production:

- European gas production has been in steep decline for several years and is expected to decline by another 30 per cent or more until 2035;
- European demand is expected to rise further until 2035;
- Imports of natural gas will unavoidably rise further if these trends become reality;
- It is by no means guaranteed that required additional imports in the order of 100 billion m^3 per year or more can be realised.

The resources for unconventional gas in Europe are too small to have any substantial influence on these trends. This holds even more as the typical production profiles will allow extracting only a certain share of these resources. In addition, greenhouse gas emissions from unconventional gas supply are significantly higher than from conventional gas supply. Environmental obligations will also increase project costs and delay their development. This will reduce the potential impact further.

It is very likely that investments in shale gas projects – if at all – might have a short-living impact on gas supply which could be counterproductive , as it would provide the impression of an ensured gas supply at a time when the signal to consumers should be to reduce this dependency by savings, efficiency measures and substitution.

Conclusions

At a time when sustainability is key to future operations it can be questioned whether the injection of toxic chemicals in the underground should be allowed, or whether it should be banned as such a practice would restrict or exclude any later use of the contaminated layer (e.g. for geothermal purposes) and as long-term effects are not investigated. In an active shale gas extraction area, about 0.1-0.5 litres of chemicals are injected per square metre.

This holds even more as the potential shale gas plays are too small to have a substantial impact on the European gas supply situation.

The present privileges of oil and gas exploration and extraction should be reassessed in view of the fact that the environmental risks and burdens are not compensated for by a corresponding potential benefit as the specific gas production is very low.

1. INTRODUCTION

This study[1] gives a survey of unconventional hydrocarbon activities and their potential environmental impacts. The focus is on future activities in the European Union. The assessments of this study concentrate predominantly on shale gas, briefly touching shale oil and tight oil.

The first chapter gives a short survey of the characteristics of production technologies, mainly the process of hydraulic fracturing. This is followed by a brief review of experiences from the USA as this is the only country where hydraulic fracturing has been applied increasingly at large scale since many decades.

The second chapter concentrates on the evaluation of greenhouse gas emissions associated with natural gas produced with hydraulic fracturing methods. Existing assessments are reviewed and extended by an own analysis.

The third chapter reviews the legislative framework at EU level relevant for hydraulic fracturing. After reviewing the legislative framework covering mining laws, the focus lies on directives protecting the environment and human health. The legislative deficits concerning the potential environmental impacts of hydraulic fracturing are outlined and discussed.

The fourth chapter gives resource assessments and discusses the possible impact of shale gas extraction on European gas supply. For that reason experiences from US shale gas production are analysed and the common characteristics of production profiles are used to sketch a typical shale development. Concerning European gas production and demand, the probable role of shale gas extraction is discussed in relation to present production and supply with extrapolations to the next decades.

The final chapter draws conclusions and gives recommendations on how to deal with the specific risks of hydraulic fracturing.

1.1. Shale gas

1.1.1. What is shale gas?

Geological hydrocarbon formations are created under specific conditions from organic compounds of marine sediments. Conventional oil and gas originate from the thermo-chemical cracking of organic material in sedimentary rocks, the so-called source rocks. With increasing burial below other rocks these formations were heated, on an average 30 °C every 1 km increment, and the organic material decomposed into oil once a temperature of about 60 °C was attained, and later gas. Depth, temperature and exposure time determined the grade of decomposition. The higher the temperature and the longer the exposure time, the more the complex organic molecules were cracked, finally being decomposed into its simplest constituent methane with one carbon and 4 hydrogen atoms.

[1] We gratefully acknowledge the critical reading and helpful comments on chapter 4 (EU regulatory framework) by Dr. Jürgen Glückert (Heinemann & Partner Rechtsanwälte, Essen, Germany) and Mr. Teßmer (Rechtsanwälte Philipp-Gerlach + Teßmer, Frankfurt, Germany).

Fruitful discussions with Prof. Blendinger, Jean Laherrere, and Jean-Marie Bourdaire, and valuable comments are gratefully acknowledged.

Depending on the geological formation, the emerging liquid or gaseous hydrocarbons escaped from the source rock and migrated generally upwards into porous and permeable strata, which in turn had to be covered by impermeable rock, the so-called seal in order to create a hydrocarbon accumulation. These hydrocarbon accumulations form the conventional oil and gas fields. The relatively high oil content, the position within a few kilometres from the surface, and easy access on land make them easy to extract by drilling wells.

Some hydrocarbon accumulations exist in reservoir rocks with very low porosity and permeability. These occurrences are called tight oil or tight gas. Typically the permeability is 10-100 times smaller than in conventional fields.

Hydrocarbons can also be stored in large volumes in rocks which are in principle not reservoir rocks at all, but shales and other very fine grained rocks in which the volume necessary for storage is provided by small fractures and extremely small pore spaces. Such rocks possess extremely low permeability. This is called shale gas or shale oil. The latter do not contain mature hydrocarbons , but only the precursor called kerogene, which can be transformed into synthetic crude oil in chemical installations.

A third group of unconventional gas is coal bed methane, which is confined in the pores of coal deposits.

Depending on the deposit characteristics the gas contains different constituents in varying shares, including methane, carbon dioxide, hydrogen sulphide, radioactive radon etc.

All unconventional deposits have in common that the gas or oil content per rock volume is small compared to conventional fields, that they are dispersed over a large area of tens of thousand of square kilometres and that the permeability is very low. Therefore, special methods are necessary to extract that oil or gas. In addition, due to the low hydrocarbon content of the source rocks, the extraction per well is much smaller than in conventional fields, making their economic production much more challenging. It is not the gas itself that is unconventional, but the extraction methods are. These methods need sophisticated technologies, lots of water and the injection of additives, which may be harmful to the environment.

There is a no sharp distinction between conventional and unconventional gas or oil deposits. Rather, there is a continuous transition from conventional gas or oil production from fields with high specific gas content, high porosity and permeability over tight gas fields with worse performance parameters to shale gas extraction from deposits with small specific gas content, low porosity and very low permeability. Especially, the distinction between conventional and tight gas production is not always clear, as in former times the official statistics did not clearly distinguish these two methods. The unavoidable side effects concerning water use, environmental risks etc. also increase along this chain of extraction methods. For instance, hydraulic fracturing in tight gas formations typically needs several hundred thousand litres of water per well for each fracturing process mixed with proppants and chemicals while hydraulic fracturing in shale gas formations consumes several million litres of water per well. [ExxonMobil 2010]

1.1.2. Recent development of unconventional gas extraction

North American experience

Due to the maturity of conventional gas plays in the United States companies have more and more been forced to drill in less productive formations. In the beginning well pads were extended to the vicinity of conventional formations, producing from slightly less permeable formations. During this gradual shift the number of wells increased while the specific production volume declined. More and more dense formations were explored. This phase started in the 1970ies. The wells in tight gas formations were not separated from conventional statistics as there was no clear criterion differentiating them.

The reduction of the methane emissions is a target since the climate change debate has started. Though the theoretical resource of coal bed methane (CBM) is huge, the contribution rose only slowly in the USA over the last two decades to about 10 percent until 2010. Due to the inhomogeneous development in different coal regimes, some US states discovered this source of energy faster than others. New Mexico was the largest producer of coal bed methane during the 1990ies. However, it passed peak production in 1997 being substituted by the developments in Colorado – peaking in 2004 – and Wyoming which at present is the largest CBM producer.

The most challenging gas prospects are developed last. These are the shale gas deposits which are almost impermeable, or at least less permeable than other gas containing structures. Its development was triggered by technological progress in horizontal drilling and hydraulic fracturing using chemical additives on the one hand, but probably even more important by the exemption of hydrocarbon industry activities with hydraulic fracturing from the Safe Drinking Water Act [SDWA 1974], as legalised with the Energy Policy Act of 2005 [EPA 2005]. In Section 322 of the Energy Policy Act of 2005 hydraulic fracturing was exempted from majorEPA regulations.

Early activities already started decades ago with the development of the Bossier Shale during the 1970s and the Antrim shale during the 1990s. But the fast access to shale gas plays started around 2005 with the development of the Barnett Shale in Texas. Within 5 years almost 15,000 wells have been drilled there. A side effect of this economic success story is the selection of small companies like Chesapeake, XTO, or others who performed the drilling. The companies grew up with this boom becoming multi billion dollar companies attracting the attention of big companies like ExxonMobil or BHP Billiton. XTO was sold for more than $ 40 billion to ExxonMobil in 2009, Chesapeake sold its Fayetteville assets for $ 5 billion in 2011.

During this time the environmental side effects became more and more obvious to citizens and regional politicians. Most prominently, the development of the Marcellus shale has been discussed as this play covers large parts of the state of New York. Its development is suspected to be in conflict with areas protected for the water supply of the city of New York. At present, the US Environmental Protection Agency performs a study on the risks associated with hydraulic fracturing, the technology of choice for the development of unconventional gas fields. The results of this study will probably be published in the course of 2012 [EPA 2009].

European development

In Europe, these developments are delayed by several decades compared to the USA. Tight gas formations have been developed with hydraulic fracturing in Germany for about 15 years (Söhlingen), though at a very low level. The total European production volume of unconventional gas is in the order of several million m^3 per year compared to several hundred billion m^3 per year in the USA [Kern 2010]. However, since late 2009 the activities have been increasing. Most exploration concessions are granted in Poland [WEO 2011, p. 58], but corresponding activities also started in Austria (Vienna Basin), France (Paris basin and South East Basin), Germany and the Netherlands (North Sea-German Basin), Sweden (Scandinavia Region) and UK (Northern and Southern Petroleum System). For instance, in October 2010, the State mining authority of the German land of North-Rhine-Westphalia granted exploration authorisations[2] for an area covering 17,000 km^2, half of the state area.

Triggered by the information from the USA, public opposition against these projects has risen fast. For instance, in France the National Assembly set a moratorium for such drilling activities and banned hydraulic fracturing. The proposed law passed the National Assembly in May, but was not adopted by the Senate. The French industry minister proposes a different bill which would allow hydraulic fracturing only for scientific reasons under strict control of a committee composed of lawmakers, government representatives, NGOs and local citizens [Patel 2011]. This modified law was approved by the Senate in June.

In the German state of North Rhine-Westphalia, affected citizens, local politicians from almost all parties and representatives from water supply authorities and mineral water companies raised their concerns opposing hydraulic fracturing. The State Parliament of North Rhine-Westphalia also pledged for a moratorium until improved knowledge would be available. A first step was to set water protection at the same level as mining laws and to ensure that permits are not granted until water authorities agree. The discussion process is not yet finalised. Also, the most strongly involved company ExxonMobil started an open dialogue-process to discuss the concerns of the citizens and to assess the possible impact.

1.2. Shale oil

1.2.1. What is shale oil and tight oil?

Like shale gas, shale oil consists of hydrocarbons being trapped in the pores of the source rock. The oil itself is still in a premature status, called kerogen. To transform kerogen into oil it needs to be heated up to 450 °C. Therefore, the production of shale oil rather compares to conventional mining of shales, followed by the heat treatment. Its early uses trace back more than 100 years. Today, Estonia is the only country with a large share of shale oil on its energy balance (~50%).

Very often, the kerogen is mixed with layers of already mature oil in structures in between the source rocks with low permeability. This oil is classified as tight oil, though very often the separation is unclear and the transition is fluent by gradual changes of maturity. In its pure state, tight oil is mature oil trapped in layers of impermeable rock of low porosity. Thus, tight oil extraction in general requires hydraulic fracturing techniques.

[2] „Aufsuchungserlaubnis“

1.2.2. Recent development of tight oil extraction

USA

Projects of unconventional oil production from oil shale first started in North America around the year 2000 with the development of the Bakken Shale, which is located in North Dakota and Montana and covers an area of more than 500,000 km² [Nordquist 1953]. The Bakken formation contains a combination of kerogen rich shales and tight oil layers in between.

France/Europe

Besides the shale oil production in Estonia, the Paris Basin in France received new attention when a small company, Toreador, acquired exploration licences and announced that it starts to develop the tight oil reservoirs within this basin by means of many wells with hydraulic fracturing. Since the basin covers a large area including Paris and the vine rich area close to Champagne, opposition rose despite the fact that the basin has already been developed with conventional oil wells for about 50 years. [Leteurtrois 2011]

2. ENVIRONMENTAL IMPACTS

KEY FINDINGS

- Unavoidable impacts are area consumption due to drilling pads, parking and manouvering areas for trucks, equipment, gas processing and transporting facilities as well as access roads.
- Major possible impacts are air emissions of pollutants, groundwater contamination due to uncontrolled gas or fluid flows due to blowouts or spills, leaking fracturing fluid, and uncontrolled waste water discharge.
- Fracturing fluids contain hazardous substances, and flow-back in addition contains heavy metals and radioactive materials from the deposit.
- Experience from the USA shows that many accidents happen, which can be harmful to the environment and to human health. The recorded violations of legal requirements amount to about 1-2 percent of all drilling permits. Many of these accidents are due to improper handling or leaking equipments.
- Groundwater contamination by methane, in extreme cases leading to explosion of residential buildings, and potassium chloride leading to salinization of drinking water is reported in the vicinity of gas wells.
- The impacts add up as shale formations are developed with a high well density (up to six wells per km²).

2.1. Hydraulic fracturing and its possible impacts on the environment

Dense hydrocarbon containing geological formations have in common their low permeability. For that reason, the production methods for the extraction of shale gas, tight gas and even coalbed methane are quite similar. Nonetheless, they differ on the quantitative level. Since shale gas formations are by far the most impermeable structures, the effort required to get access to the gas pores is the highest. This results in the highest risk for environmental impacts from the development of these formations. However, there is a continuous transition from the permeable conventional gas containing structures, over tight gas to the almost impermeable gas shales.

The common characteristic is that the contact between the drilled wells and the pores must be enhanced artificially. This is done by the so called hydraulic fracturing, which sometimes is called “stimulation” or in short “fracing” or “fracking”.

Figure 1 shows a cross section of a typical well. The rig drills vertically into the gas bearing layer. Depending on the thickness of that layer only vertical wells are drilled or these are turned into horizontal wells in order to maximize the contact with the gas layer.

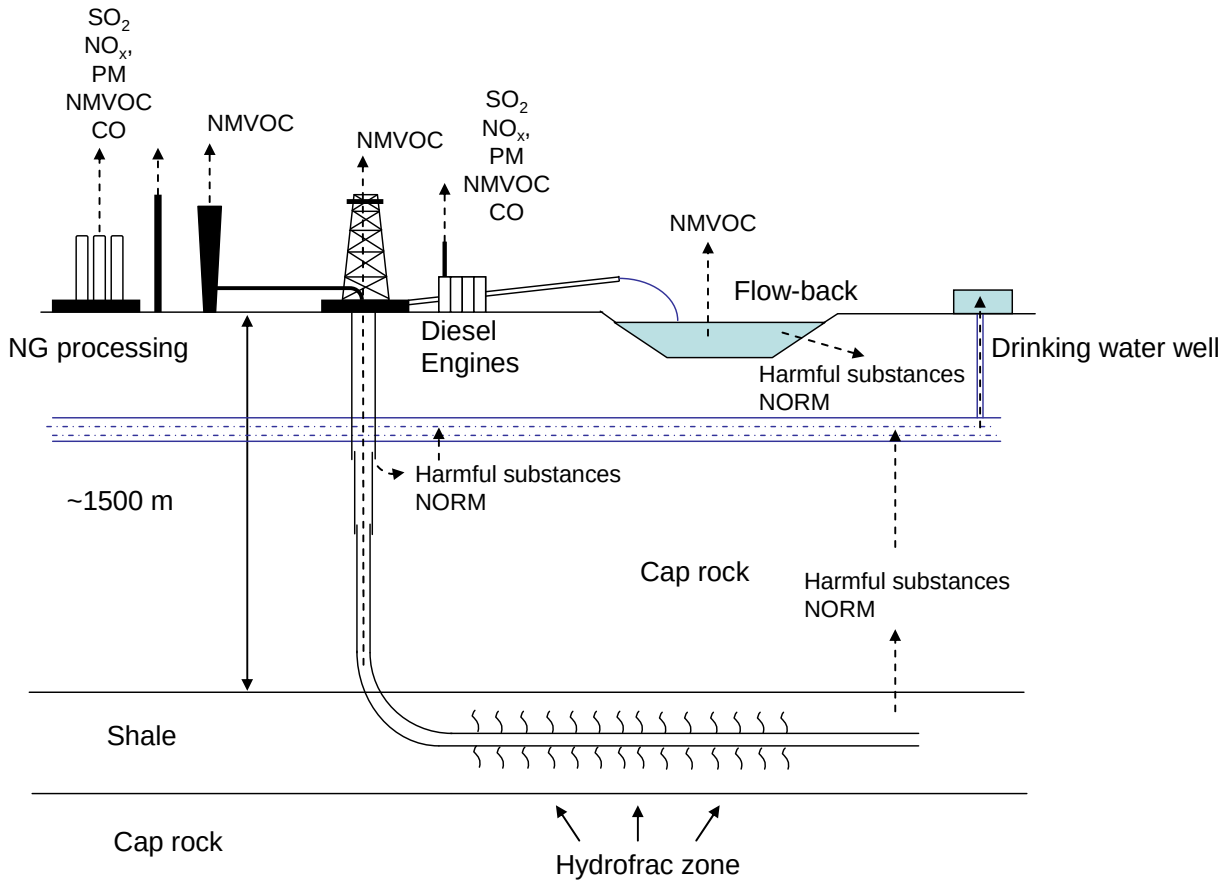
Within the layer explosives are used to create small fractures by perforating the casing. These fractures are artificially widened by means of filling with over pressurized water. The number of artificial fractures, their length and their positioning within the layer (horizontal or vertical) depend on the details of the formation. These details have an impact on the length of the artificial cracks, on the well spacing (vertical wells are more densely drilled than horizontal wells) and on the water consumption.

The over pressurized water opens the fractures gaining access to as many pores as possible. Once the pressure is reduced the waste water mixed with heavy or radioactive metals from the rock formation reflows to the surface including the gas. Proppants, usually grains of sand, are mixed to the water. These work as spline to keep the cracks open and to allow for further gas extraction. Chemicals are added to this mixture in order to achieve a homogeneous distribution of the proppant by forming a gel, to reduce friction and finally to break the gel structure at the end of the fracturing process for the backflow of the fluid.

Figure 1 might be used to identify the possible impacts on the environment along this way. These are

- Consumption of landscape as the rig pads need space for technical equipment, fluid storage and road access for their delivery.
- Air and noise pollution as the machinery is operated by combustion engines, the fluids (also waste water) might allow harmful substances to evaporate into the air, the trucks with frequent transport activity might emit volatile organic compounds, other air pollutants and noise.
- The water might be contaminated with chemicals from the fracturing process, but also with waste water from the deposit that contains heavy metals (e.g. arsenic or mercury) or radioactive particles. Possible migration paths to ground and surface waters could be accidents by truck transport, leaks of gathering lines, waste water ponds, compressors etc., spills from accidents (e.g. blow out with a fountain of fracturing fluid or waste water), damages to the cementation and casing or simply uncontrolled subsurface flows through artificial or natural cracks of formations.
- Earthquakes induced by the hydraulic fracturing process or waste water injection.
- The mobilization of radioactive particles from the underground.
- Finally, the huge natural and technical resources consumption with respect to the recoverable gas or oil must be assessed in a cost/benefit analysis of such operations.
- Impacts on biodiversity could be possible, though at present none are documented.

Figure 1: Potential flows of air pollutant emissions, harmful substances into water and soil, and naturally occurring radioactive materials (NORM)



Source: own source based on [SUMI 2008]

2.2. Impacts on Landscape

Experiences in North America

The development of gas shales requires well pads allowing for the storage of technical equipment, the trucks with compressors, chemicals, proppant, water and containers for waste water if these are not delivered from local water wells and collected in ponds.

A typical multi-well pad size in Pennsylvania during the drilling and fracturing is about 4-5 acres (16,200-20,250 m²). After partial restoration the production pad size might average between 1 – 3 acres (4,050-12,150 m²). [SGEIS 2009]

For comparison, if such an area (~10,000 m²) would be occupied by a solar power plant, about 400,000 kWh of electricity could be generated per year[3], corresponding to about 70,000 m³ of natural gas per year if this would be converted to electricity at 58% efficiency. The typical gas production of wells in the Barnett shale (Texas, USA) amounts to about 11 Mio. m³ per well in the first year, but only about 80,000 m³ in the 9th year and about 40,000 m³ in the 10th year [Quicksilver 2005]. In contrast to fossil energy extraction, the solar power plant generates electricity for more than 20 years. At the end of its life time the solar plant can be substituted by a new one without additional land consumption.

[3] Solar irradiation: 1000 kWh per m² and year; efficiency photovoltaic panel: 15%; performance ratio: 80%; panel area: 33% of land area

The development of shale or tight gas formations requires a dense spacing of these well pads. In the USA the well spacing depends on the state's regulations. Typical spacing in conventional fields in the USA is one well per 640 acre (1 well per 2.6 km²). In the Barnett shale the typical spacing in the beginning was reduced to one well per 160 acres (1.5 wells per km²). Later-on so called "infill wells" were permitted and drilled at 40 acre spacing (~6 wells per km²). This seems common practise in most shales when these are intensively developed. [Sumi 2008; SGEIS 2009]

By the end of 2010, almost 15,000 wells had been drilled in the Barnett Shale, while the total shale extends over an area of 13,000 km² [RRC 2011; ALL-consulting 2008]. This results in an average well density of 1.15 wells per km².

Figure 2 shows wells for the production of tight gas in the USA. In case of tight gas production the wells are surface well pads with up to 6 wells per pad. The spacing is tighter than in the case of the Barnett shale because most of the tight gas wells are drilled vertically.

Figure 2: Tight-gas sandstone drilling

Source: Photograpf by EcoFlight, courtesy of SkyTruth – www.skytruth.org

The well pads are connected with roads for truck transport, which further increases land consumption. In the USA, surface area is also consumed for waste water ponds collecting the back flowing waste water before it is disposed of or removed by truck or pipe. These areas are not yet included in the well pad sizes sketched above. Including them could easily double the area consumed by gas producing operations.

After extraction, the gas must be transported to the distribution grids. As most wells have a small production rate with a steep decline profile, very often the gas is stored at the well pad and periodically loaded on trucks. If the well density is high enough gathering networks with compressor stations are built. Which storage or transport mode is chosen and whether the lines are built above or below ground depends on the specific parameters of the projects and on the applicable regulations.

Transferability to European conditions and open questions

The permission of well pads is granted by mining authorities based on relevant laws and regulations (see chapter 4). These might determine the minimum allowed spacing of wells. This may follow the practise in the USA to start the shale development with larger spacing and to increase the density the more exhausted the producing wells become. As outlined in chapter 5, the typical amount of gas resources per area in most European shales is probably comparable to those of the Barnett or Fayetteville shales in the USA.

Completed wells must be interconnected with gathering networks. Whether these lines will be constructed above or below ground will depend on corresponding regulations and economic considerations. Here, existing regulations should be adapted and maybe harmonized.

2.3. Air Pollutant Emissions and Soil Contamination

The emissions potentially originate from the following sources:

- Emissions from trucks and drilling equipment (noise, particulates, SO_2, NO_x, NMVOC and CO);
- Emissions from natural gas processing and transportation (noise, particulates, SO_2, NO_x, NMVOC and CO);
- Evaporative emissions of chemicals from waste water ponds;
- Emissions due to spills and well blow outs (dispersion of drilling or fracturing fluids combined with particulates from the deposit).

The operation of drilling equipment consumes large amounts of fuels which are burnt to emit CO_2. Also, some fugitive emissions of methane, a greenhouse gas, might occur during production, processing and transport. These are assessed in the following chapter 4 which is dedicated to greenhouse gas emissions.

2.3.1. Air pollutants from regular operations

Experiences in North America

Many complaints of human illnesses and even animal deaths around the small city of Dish, Texas, forced the Mayor of the city to commission an independent consultant to undertake an air quality study of the impacts of gas operations within and around the city [Michaels 2010, and references therein]. Though such complaints are also reported from other sites, the investigations in Dish are the best referenced. As there are no other industrial activity in that region, natural gas extraction activities in and around the city are believed to be the only source of these impacts.

The study, conducted in August 2009, confirmed "the presence in high concentrations of carcinogenic and neurotoxin compounds in ambient air and/or residential properties." And further on: "…Many of these compounds verified in laboratory analysis were metabolites of known human carcinogens and exceeded both, short-term and long-term effective screening levels according to TECQ regulations. Of particular concern are those compounds with potential for disaster as defined by TECQ [Texas Commission on Environmental Quality]". [Wolf 2009]

According to the study, also "numerous complaints had been made to the Town in regards to the constant noise and vibration emanating from the compressor stations as well as foul odours". "Of particular concern", according to the study "were reports of young horses becoming gravely ill and several deaths over the years 2007-2008 with unknown etiology". [Wolf 2009].

Also the region around Dallas-Fort Worth has seen dramatic impacts on its air quality from natural gas drilling in the Barnett Shale, according to [Michaels 2010]. A comprehensive study on "Emissions from Natural Gas Production in the Barnett Shale Area and Opportunities for Cost-Effective Improvements" was published in 2009. [Armendariz 2009] According to the analysis, five of the investigated 21 counties where almost 90% of all natural gas and oil activities take place dominate the emissions by far. For instance, the portion of smog-forming compounds originating from these five counties was calculated at 165 tons per day during peak in summer 2009 compared to 191 tons per day peak summer emission from all oil and gas sources (including transport) in these 21 counties. [Armendariz 2009] Thus, state average values conceal the fact that in the five most active counties, air pollutant emissions are very much higher than average leading to poor air quality levels.

The Texas Commission on Environmental Quality (TCEQ) has established a monitoring program, partly confirming extraordinarily high hydrocarbon vapours escaping from drilling equipment and storage tanks, and significant levels of benzene in some locations [Michaels 2009]. In January 2010, the TCEQ published an interoffice memorandum on its monitoring program. Some of their key findings are [TCEQ 2010]:

- "Thirty-five chemicals were detected above appropriate short-term comparison values in one instantaneous canister sample collected at Devon Energy natural gas well-head with a benzene concentration of 15,000 ppb." This air sample close to the well-head - 5 feet from the source - was taken as reference.
- In addition to the benzene concentration in the sample collected at the well-head, benzene was detected above the short-term health-based comparison value of 180 ppb at one of the 64 monitoring sites.
- The Toxicology Division has some concerns about areas where benzene was detected above the long-term health-based comparison value of 1.4 ppb. "Benzene was detected above the long-term health-based comparison value at 21 monitoring sites."

Transferability to European conditions

The emissions of aromatic compounds such as benzene and xylene observed in Texas predominantly come from the natural gas compression and processing where the heavier components are discharged into the atmosphere. In the EU the emissions of such substances are limited by law.

The machines used for the drilling and extraction processes such as diesel engines are probably the same, and also the air pollutants emitted by these machines. Table 1 shows the emission of air pollutants from stationary diesel engines used for drilling, hydraulic fracturing and well completion based on diesel engine emission data from [GEMIS 2010], the diesel requirement and a natural gas yield assumed for the Barnett Shale in [Horwarth et al 2011].

Table 1: Typical specific emissions of air pollutants from stationary diesel engines used for drilling, hydraulic fracturing and completion

	Emissions per engine mechanical output [g/kWh$_{mech}$]	Emissions per engine fuel input [g/kWh$_{diesel}$]	Emissions per natural gas throughput of well [g/kWh$_{NG}$]
SO_2	0.767	0.253	0.004
NOx	10.568	3.487	0.059
PM	0.881	0.291	0.005
CO	2.290	0.756	0.013
NMVOC	0.033	0.011	0.000

It is recommended that besides emission factors also their total impact is restricted as the emissions from multiple drilling pads will add up when a shale is developed with one or even more wells per km². The emissions during development need to be restricted and monitored as well as emissions from gas processing and transportation later-on when many gathering lines add up.

These aspects should be included in the discussion of relevant directives, e.g. the Proposal for a Directive of the European Parliament and of the Council amending Directive 97/68/EC on emissions of gaseous and particulate pollutants from engines in non-road mobile machinery.

2.3.2. Pollutants from well blowouts or accidents at drilling sites

Experiences in North America

Experiences in the USA show that several serious well blowouts have occurred. Most of them are documented in [Michaels 2010]. Excerpts of that reference list are:

- On June 3, 2010 a gas well blow-out in Clearfield County, Pennsylvania, sent at least 35,000 gallons of wastewater and natural gas spewing into the air for 16 hours.
- In June 2010 an explosion at a gas well in Marshall County, West Virginia, sent seven injured workers to hospital.
- On April 1, 2010 both a tank and an open pit used to store hydraulic fracturing fluid caught fire at an Atlas well pad. The flames were at least 100 feet (33 m) high and 50 feet (15 m) wide.

In all of the above-mentioned cases the involved companies were fined. It turns out that these accidents are mostly related to incorrect handling, either by untrained personal or through incorrect behaviour. Moreover, it seems that there are significant differences between individual companies. Further accidents are listed in the following subchapters.

Transferability to European conditions

In order to minimize the risk of spills in Europe, strict regulations and their strict monitoring are recommended. Specifically, it is recommended to collect the statistics about accidents at European level, to analyse the causes of the accidents and to draw corresponding consequences. In case specific companies have particularly negative track records it may be considered to exclude them from further exploration or production rights. These cases are being discussed in the European Parliament in relation to offshore oil and gas activities. An own initiative report on this issue will be voted on in the Committee on Industry, Research and Energy in July 2011.

2.4. Surface and ground water

2.4.1. Water consumption

Large volumes of water are consumed during conventional drilling of the bore hole in order to cool and lubricate the drilling head, but also to remove the drilling mud. About a factor of ten more water is consumed in hydraulic fracturing for the stimulation of the well by injecting over pressurized water for the creation of the cracks.

A comprehensive study of the water demand for the development of the Barnett shale has been performed on behalf of the Texas Water Development Board [Harden 2007]. This study contains a literature review about the specific water consumption: Elder uncemented horizontal wells with a single frac-stage needed about 4 MGal (~15 million litres) of water. Newer cemented horizontal wells usually perform the fracturing job at multi stages on several perforation clusters at once. A typical distance between two fracturing stages at the same horizontal well is 400-600 ft (130-200 m). Typically, a horizontal well has about 3 fracturing stages, but this is not mandatory. Statistical analysis from about 400 wells resulted in a typical water consumption of 2000-2400 gal/ft (25-30 m^3/m) for water fracs [Grieser 2006] and about 3900 gal/ft (~42 m^3/m) for slickwater fracs which are used more recently where the distance is the length covered by the horizontal part of the well. [Schein 2004]

This study from 2007 also includes scenarios on the water consumption for the Barnett Shale exploration in 2010 and 2025. For 2010, the water demand was estimated at 10,000-20,000 ac-ft (12-24 Mio. m^3) further developing until 2020 to 5,000-20,000 ac-ft (6-24 Mio. m^3), depending on future exploration activities.

Table 2 lists more recently available data for typical new wells. For a rough upscaling, 15,000 m^3 per well seem to be realistic in the Barnett Shale. Based on these numbers, the 1146 newly developed wells in 2010 (see chapter 4) would result in a water consumption of about 17 billion litres in 2010. This is coherent with the above-cited forecast for 2010. This consumption must be compared with the water consumption of all other consumers, which was about 50 billion litres [Harden 2007]. For that comparison, the water consumption of those counties was used where the drilling activities predominantly took place (Denton, Hood, Johnson, Parker, Tarrant and Wise).

Table 2: Water demand of various wells for shale gas production (m^3)

Site/Region	Total (per well)	Only Fracturing	Source
Barnett Shale	17000		Chesapeake Energy 2011
Barnett Shale	14000		Chesapeake Energy 2011
Barnett Shale	no data	4500 -13250	Duncan 2010
Barnett Shale	22500		Burnett 2009
Horn River Basin (Canada)	40000		PTAC 2011
Marcellus Shale	15000		Arthur et al. 2010
Marcellus Shale	1500 – 45000	1135 – 34000	NYCDEP 2009
Utica shale, Québec	13000	12000	Questerre Energy 2010

Furthermore, wells drilled for producing shale gas may have to be fractured several times over the course of their operation time. Each additional fracture operation may require more water than the previous one [Sumi 2008]. In some cases, the wells are refractured up to 10 times [Ineson 2010].

2.4.2. Water contamination

Experiences in North America

Possible water contaminations might be induced by

- Spills of drilling mud, flowback and brine, from tailings or storage tanks causing water contamination and salinization.
- Leaks or accidents from surface activities, e.g. leaking fluid or waste water pipes or ponds, unprofessional handling or old equipment.
- Leaks from inadequate cementing of the wells.
- Leaks through geological structures, either through natural or through artificial cracks or pathways.

Actually, most of the complaints against hydraulic fracturing are because of possible groundwater contamination. Basically, besides specific spills and accidents the intrusion of fracturing fluids or methane from the deeper structures is in the focus.

A detailed analysis was performed in 2008 for Garfield County, Colorado. The 'Colorado Oil and Gas Conservation Commission' maintains records of reported spills from oil and gas activities. In the period from January 2003 to March 2008 a total of 1549 spills is referenced. [COGCC 2007; referenced in Witter 2008] Twenty percent of the spills involved water contamination. It is noteworthy that the number of spills was increasing. For instance, while five spills are reported in Garfiled County in the year 2003, 55 spills are reported in 2007.

A subsequent study on ground water contamination identified that "there is a temporal trend of increasing methane in groundwater samples over the last seven years that is coincident with the increased number of gas wells installed in the Mamm Creek Field. Pre-drilling values of methane in groundwater established natural background was less than 1 ppm, except in cases of biogenic methane that is confined to ponds and stream bottoms. … The isotopic data for methane samples show that the most samples with elevated methane are thermogenic origin. Concurrent with the increasing methane concentration there has been an increase in groundwater wells with elevated chloride that can be correlated to the number of gas wells." [Thyne 2008] Obviously, there is a clear coincidence in space and time: Methane levels are higher in areas with a high density of wells and methane levels increased over time coinciding with the increasing number of wells.

A more recent study by [Osborne 2011] confirms such findings in aquifers overlaying the Marcellus and Utica shale formations of north eastern Pennsylvania and upstate New York. In active gas extraction areas, the average methane concentrations in drinking-water wells was 19.2 mg/litre with maximum levels up to 64 mg/litre, a potential explosion hazard. Background concentration in neighbouring non-gas extracting regions of similar geological structure was 1.1 mg/litre. [Osborn 2011]

In total, more than 1000 complaints of drinking water contamination are documented. A report which claims to be based on Pennsylvania Department of Environmental Protection data records counts 1614 violations of state oil and gas laws during drilling operation in the Marcellus Shale over a two-and-a-half-year-period [PLTA 2010], two-thirds of them are "most likely to harm the environment". Some of them are included in [Michaels 2010].

The most impressive documented accident was the explosion of a dwelling house which was caused by drilling operations and subsequent methane invasion into the house's water system [ODNR 2008]. The Department of Natural Resources report identified three factors which led to the explosion of the house: (i) inadequate cementing of the production casing, (ii) the decision to proceed with hydraulic fracturing of the well without addressing inadequate cementing of the casing, and, most significantly, (iii) the 31-day period after the fracturing, during which the annular space between the surface and production casings was "mostly shut in" (quoted after [Michaels 2010]).

In most cases, methane or Chloride contamination of water could be shown, while the intrusion of benzene or other fracturing fluids rarely can be proven. However, sampling of drinking water wells in Wyoming by the Environmental Protection Agency in 2009 detected chemicals which are widely used in hydraulic fracturing: "Region VIII earlier this month released its results of water well sampling in Pavillion, WY – requested by local residents – showing drilling contaminants in 11 of 39 wells tested, including the chemical 2-butoxyethanol (2-BE), a known constituent in hydraulic fracturing fluids, in three of the wells tested, as well as the presence of methane, diesel range organics and a type of hydrocarbon known as adameantenes". [EPA 2009]

In many cases, companies are already fined for violating state laws. For instance, Cabot Oil & Gas received a note from the Pennsylvania Department of Environmental Protection stating: “Cabot has caused or allowed gas from lower formations to enter fresh groundwater”. [Lobbins 2009]

Based on historical data in New York State an accident rate of 1 to 2% was estimated. [Bishop 2010] This sounds plausible. However, the above mentioned more than 1600 violations only in the Pennsylvania part of the Marcellus shale suggest a much larger rate when compared to about 2300 wells, drilled there until the end of 2010.

Transferability to European conditions

Most of the accidents and ground water intrusions seem to be due to incorrect handling, which could be avoided. Regulations exist in the USA, but monitoring and supervision of operations is rather poor, be it for lack of available budgets of public authorities or for other reasons. Therefore, the basic problem is not inadequate regulation, but their enforcement through adequate supervision. It must be guaranteed that best practice is not only available, but also commonly applied.

In addition, a certain risk remains that undetected pathways (e.g. old abandoned, but not registered wells with incorrect cementing, unpredictable risks due to earthquakes etc.) pave the way for methane or chemicals into groundwater levels.

2.4.3. Waste water disposal

The fracturing fluids are injected into the geological formations at high pressure. Once the pressure is released, a mixture of fracturing fluid, methane, compounds and additional water from the deposit flow back to the surface. This water must be collected and properly disposed of. According to industry sources, between 20% and 50% of the water used for hydro-fracing gas wells returns to the surface as flowback. Part of this water will be recycled to fracture future wells. [Questerre Energy 2010] According to other sources, between 9% and 35% recover to the surface. [Sumi 2008]

Experiences in North America

The proper disposal of waste water seems to be a major issue in North America. The core problem is the huge quantity of waste water and the improper configuration of sewage plants. Though recycling might be possible, this would increase project costs. Many problems associated with the improper disposal are reported. For instance:

- In August 2010 ‘Talisman Energy’ was fined in Pennsylvania for a spill in 2009 that sent over 4200 gallons (~16 m^3) of hydraulic fracturing flow-back fluid into a wetland and a tributary of Webier Creek, which drains into the Tioga River, a coldwater fishery. [Talisman 2011]
- In January 2010 ‘Atlas Resources’ was fined for violating environmental laws at 13 well sites in south-western Pennsylvania, USA. Atlas Resources failed to implement proper erosion and sedimentation control measures, which led to turbid discharges. Furthermore, Atlas Resources discharged diesel fuel and hydraulic fracturing fluids into the ground. Atlas Resources holds more than 250 permits for Marcellus wells. [PA DEP 2010]
- ‘Range Resources’ was fined for an October 6, 2009 spill of 250 barrels (~40 m^3) of diluted hydraulic fracturing fluid. The reason for the spill was a broken joint in a transmission line. The fluid leaked into a tributary of Brush Run, in Hopewell Township in Pennsylvania. [PA DEP 2009]

- In August 2010, 'Atlas Resources' was fined in Pennsylvania for allowing a hydraulic fracturing fluid overflow from a wastewater pit contaminating a high-quality watershed in Washington County. [Pickels 2010]
- At a drilling pad with three gas wells in Troy, Pennsylvania, 'Fortune Energy' illegally discharged flow-back fluids into a drainage ditch and through a vegetated area, eventually reaching a tributary of Sugar Creek (quoted after [Michaels 2010]).
- In June 2010, the West Virgina Department of Environmental Protection (DEP) released a report concluding that in August 2009 'Tapo Energy' discharged an unknown quantity of a 'petroleum based material' associated with drilling activities into a tributary of Buckeye Creek in Doddridge County. The spill contaminated a thee-mile-long segment of the creek (quoted after [Michaels 2010]).

Transferability to European conditions

Again, most of these water contaminations are due to improper practices. Therefore, very strict handling of these issues is mandatory. Also in Europe,e.g. in Germany, accidents have already happened in hydraulic fracturing operations. For instance, waste water pipes from the tight gas field "Söhlingen" in Germany leaked in 2007. This caused groundwater contamination with benzene and mercury. Though the corresponding Mining Agency of Lower Saxony ("Landesbergbehörde") was correctly informed, the public noticed the accident only in 2011 when the company started to replace the agricultural soil where the fluids had leaked into the ground. [NDR 2011; Kummetz 2011]

2.5. Earthquakes

It is well known that hydraulic fracturing can induce small earthquakes in the order of 1 – 3 at the Richter scale. [Aduschkin 2000] For instance, in Arkansas, USA, the rate of small earthquakes has increased over the last years tenfold. [AGS 2011] Concerns rose that these are induced by the steep increase in drilling activities in the Fayetteville Shale. Also, the Fort Worth region has experienced at least 18 smaller earthquakes since December 2008. The city of Cleburne alone experienced 7 earthquakes between June and July 2009 in an area where during the 140 years before no earthquake at all was registered. [Michaels 2010]

In April 2011, the city of Blackpool in the UK experienced a small earthquake (1.5 at the Richter scale) which was followed in June 2011 by a larger one (2.5 at the Richter scale). The company 'Cuadrilla Resources' which was conducting hydraulic fracturing operations in the earth quake area, stopped its operations and commissioned an investigation of the issue. It announced that it would cease its operations in case a relation of the earthquakes to its drilling activities would be shown. [Nonnenmacher 2011]

2.6. Chemicals, Radioactivity and Impacts on Human Health

2.6.1. Radioactive Materials

Naturally occurring radioactive materials (so called N.O.R.M.) are part of any geological formation, though with a very small share in the ppm to ppb range. Most black shales in the USA have uranium contents in the range of 0.0016-0.002 per cent. [Swanson 1960]

Through the hydraulic fracturing process, these naturally occurring radioactive materials such as uranium, thorium and radium bound in the rock are transported to the surface with the flow-back fluid. Sometimes, radioactive particles are injected with the fluids for special purposes (e.g. as tracer). N.O.R.M. can also move through the cracks in the rock into the ground and surface water. Usually, N.O.R.M. accumulates in pipes, tanks and pits.

The amount of radioactive substances differs from shale to shale. The Marcellus shale, e.g., contains more radioactive particles than other geological formations. During gas processing activities, N.O.R.M. can occur as radon gas in the natural gas stream. Radon decays to 210Pb (a lead isotope), then to 210Bi (a bismuth isotope), 210Po (a polonium isotope), and finally to stable 206Pb (lead).

Radon decay elements deposit as a film on the inner surface of inlet lines, treating units, pumps, and valves principally associated with propylene, ethane, and propane processing streams. Because the radioactive materials become concentrated on oil and gas-field equipment, the highest risk of exposure to oil and gas N.O.R.M. is to workers employed to cut and ream oilfield pipe, remove solids from tanks and pits, and refurbish gas processing equipment. [Sumi 2008]

Experiences in North America

In Onondaga County, New York, the radioactive substance radon (222Rn) was measured in indoor air in the basements of 210 homes. All of the homes underlain by Marcellus shale had indoor air levels of 222Rn above 148 Bq/m³, and the average concentration in these homes was 326 Bq/m³[4], which is more than twice the U.S. Environmental Protection Agency's (EPA) 'action level' (i.e. the level at which it is recommended that homeowners try to reduce the radon concentration) of 148 Bq/m³. The average indoor radon level in the USA is 48 Bq/m³. [Sumi 2008] An increase by 100 Bq/m³ of air leads to an increase of lung cancer of 10%. [Zeeb et al 2009]

Rock cuttings from shale gas development at the Marcellus Shale are highly radioactive (25 times higher than surface background). Partly, the waste has been spread over the soil. Measurements of soils in 1999 show a 137Cs (a radioactive caesium isotope) concentration of 74 Bq per kg of soil. [NYDEC 2010] 137Cs is used for the analysis of a geological formation during shale gas exploration.

Transferability to European conditions

Naturally occurring radioactive materials (N.O.R.M.) also occur in Europe. Therefore, the same problems with N.O.R.M. may occur in Europe. However, the amount of N.O.R.M. differs from location to location. Therefore, the relevance of radioactive particles has to be evaluated at each individual shale and tight gas basin separately.

For that reason the composition of a core sample of a specific shale under investigation should be disclosed before any production permission is granted.

2.6.2. Chemicals to be used

The fracturing fluid typically consists of about 98% water and sand, and 2% chemical additives. The chemical additives include toxic, allergenic, mutagenic, and carcinogenic substances.

Experiences in North America

Because of trade secrets the composition of the additives is not fully disclosed to the public. [Wood et al 2011] An analysis of a list of 260 substances provided by the New York State leads to the following results:

- 58 of the 260 substances have one or more properties that may give rise to concern.

[4] Converted from picocuries per liter to Bq per m³, 1 Ci = 3.7 1010 Bq

- 6 are present in list 1 of lists 1-4 of priority substances, which the European Commission has published for substances requiring immediate attention because of their potential effects to man or the environment: Acrylamide, Benzene, Ethyl Benzene, Isopropylbenzene (cumene), Naphthalene, Tetrasodium Ethylenediaminetetraacetate.
- One substance (Naphthalene bis (1-methylethyl) is currently under investigation as persistent, bioaccumulative and toxic (PBT).
- 2 substances (Naphthalene and Benzene) are present on the first list of 33 priority substances established under Annex X of the Water Framework Directive (WFD) 2000/60/EC - now Annex II to the Directive on Priority Substances (Directive 2008/105/EC).
- 17 are classified as being toxic to aquatic organisms (acute and/or chronic).
- 38 are classified as being acute toxins (human health) such as 2-butoxy ethanol.
- 8 substances are classified as known carcinogens such as benzene (GHS classification: Carc. 1A) and acryl amide, ethylene oxide, and various petroleum based solvents containing aromatic substances (GHS[5] classification: Carc. 1B).
- 6 are classified as suspected carcinogens (Carc. 2) such as Hydroxylamine hydrochloride.
- 7 are classified as mutagenic (Muta. 1B) such as benzene and ethylene oxide.
- 5 are classified as having reproductive effects (Repr. 1B, Repr. 2).

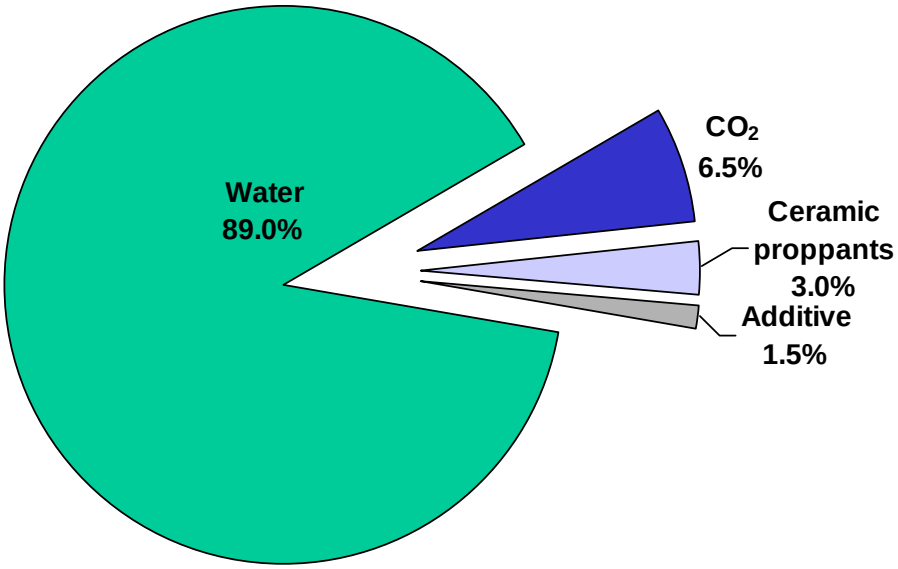
2-butoxy ethanol (also called ethylene glycol monobutyl ether) is often used as chemical additive. [Bode 2011], [Wood et al 2011] It is toxic at relatively low levels of exposure. The half-life of 2-butoxy ethanol in natural surface waters ranges from 7 to 28 days. With an aerobic biodegradation rate this slow, humans, wildlife and domestic animals could come into direct contact with 2-butoxy ethanol through ingestion, inhalation, dermal sorption, and the eye in its liquid or vapour form, as the entrapped water reaches the surface. Aerobic biodegradation requires oxygen, which means that the deeper 2-butoxy ethanol is injected into underground layers the longer it will persist. [Colborn 2007]

Transferability to European conditions

Figure 3 shows the composition of the fracturing fluid (6405 m^3) used at the tight gas well 'Goldenstedt Z23' in Lower Saxony in Germany.

[5] Global Harmonized System of Classification and Labeling of Chemicals

Figure 3:Composition of the fracturing fluid used at 'Goldenstedt Z23' in Lower Saxony in Germany



The fractions fluid contains 0.25% of toxic substances, 1.02% of substances which are harmful or toxic to human health (where 0.77% are classified as harmful 'Xn' and 0.25% are classified as acute toxic 'T'), and 0.19% substances which are harmful to the environment. At the well 'Goldenstedt Z23' in Lower Saxony in Germany, a total of about 65 m^3 (more than the equivalent of two road tankers with a gross weight of 40 t and a net payload of 26 t) of substances which are harmful to human health have been applied, thereof about 16 t of acute toxic substances.

Often, the detailed composition of the chemical additives is confidential and therefore not published. One of the substances is tetramethylammoniumchloride which is toxic and harmful for drinking water already if small amounts are released. According to [Bode 2011], toxic substances such as such as 2-butoxy ethanol, 5-Chloro-2-methyl-4-isothiazolin-3-one, and 2-Methylisothiazol-3(2H)-one have been used as chemical additives for hydraulic fracturing in Lower Saxony, Germany.

Table 3: Selected substances used as chemical additives for fracturing fluids in Lower Saxony in Germany

CAS number	Substance	Formula	Health effect	Classification GHS
111-76-2	2-butoxy ethanol	$C_6H_{14}O_2$	toxic	GHS07
26172-55-4	5-Chloro-2-methyl-4-isothiazolin-3-one	C_4H_4ClNOS	toxic	GHS05 GHS08 GHS09
2682-20-4	2-Methylisothiazol-3(2H)-one	C_4H_5NOS	toxic	GHS05 GHS08 GHS09
9016-45-9	Nonylphenol-ethoxylate	C_mH2_{m+1}-$C_6H_4OH(CH_3CH_2O)_n$	toxic	GHS05 GHS07 GHS09
75-57-0	Tetramethyl-ammoniumchloride	$C_4H_{12}ClN$	toxic	GHS06 GHS07

Source: GHS: Global Harmonised System (GHS)

Furthermore, hydraulic fracturing may affect the mobility of naturally occurring toxic substances present in the subsurface such as mercury, lead and arsenic. These substances can find a pathway to an underground source of drinking water if fractures extend beyond the target formation, or if the casing or cement around the drilling fails under the pressures exerted during hydraulic fracturing. Other toxic substances may be formed by complex biogeochemical reactions with chemical additives used for the fracturing fluid. [EPA 2011]

The naturally occurring toxic substances can also be found in the flow-back. Knowledge about the efficacy of current treatment processes for adequately removing certain flow-back and produced water constituents. [EPA 2011]

2.6.3. Impacts on human health

Possible health effects are mainly caused by the impacts of the relevant emissions into air or water. These are predominantly headache and long-term effects from volatile organic compounds. Groundwater contamination may be dangerous when inhabitants come into contact with contaminated water. For instance, when small children are frequently washed with contaminated water this may have an effect on allergies and health. Also, wastewater pits and blow out fluids are a matter of concern when the skin is exposed.

Experiences in North America

Beyond potential effects actual health effects and their direct link to hydraulic fracturing activities are rarely documented. Usually, reports on headaches are leading the list.

In the vicinity of the community of Dish, Texas, USA, the illness and deaths of young horses are documented as already cited in chapter 2.3. [Wolf 2009]

Two extreme examples are quoted in the following as these are documented fairly well, though the relation to gas drilling activities cannot be proven. The first one is stated in a written testimony to the House Committee on Oversight and Government Reform, USA:

"A woman [Laura Amos] from Silt, Garfield County, Colorado called to tell me that she had developed a very rare adrenal tumor and had to have the tumor and her adrenal gland removed. One of the effects of 2-BE [2-butoxy ethanol] was adrenal tumors. She told me that she lived within 900 feet of a busy gas well pad where frac'ing took place frequently. During one frac'ing episode her domestic water well erupted. She also began describing the health problems of others who lived near her". [Colborn 2007]

and:

"In mid–August [2008] the Colorado debate intensified when news broke that Cathy Behr, an emergency room nurse in Durango, Colorado, had almost died after treating a wildcatter who had been splashed in a fracking fluid spill at a BP natural gas rig. Behr stripped the man and stuffed his clothes into plastic bags…. A few days later Behr lay in critical condition facing multiple organ failure." [Lustgarten 2008]

2.7. Possible long term ecological benefits

There are no obvious potential long term ecological benefits of shale gas extraction with the exception of possible greenhouse gas emission reductions. The latter may occur in case more strongly polluting fossil resources, notably coal and oil, are replaced by shale gas, and shale gas extraction proves to have lower greenhouse gas emissions along the entire fuel chain than coal and oil. Results of chapter 3 indicate that this may not be the case, or only to a limited extent. Results of chapter 5 show that shale gas can only make small or even marginal contributions to European energy supply.

The impacts described in the the above sections demonstrate that a number of serious risks to the environment are associated to shale gas extraction. Consequently, a reduced risk compared to conventional oil and gas operations including the risk of large scale accidental pollutions such as the recent catastrophe in the Gulf of Mexico cannot be claimed. It must be emphasized here that risks types, risk probabilities and potential impacts are quantitatively and qualitatively different. A detailed appreciation is beyond the scope of the present analysis.

2.8. Discussion of risks in public debates

A number of arguments are put forward in public debates of hydraulic fracturing aimed at weakening the assessment of environmental impacts described above. These include the following:

- *Proven accidents and violations are due to bad practises by companies, which are predominantly small companies and which are not involved in European activities.* This political argument may be seen to underline the importance of independent monitoring of possible risks and impacts of hydraulic fracturing operations.
- *Groundwater contamination by methane is due to natural methane levels from the decomposition of biogenic methane in the underground.* Scientific analysis of isotope composition and statistical analyses of correlations between increasing methane levels and increasing fracturing activities unambiguously prove that methane contaminations of groundwater are caused by fossil methane from geological formations.
- *There is no clear evidence that groundwater contamination is related to hydraulic fracturing activities.* Obviously, it is very complex to prove direct relations between specific contaminations and individual activities. Nonetheless, there are some instances where such proof has been found, and there are many cases of circumstantial evidence demonstrating the correlation…
- *When state-of-the-art technology and trained personal is used the accidents and problems known from US activities can and will be avoided in Europe.* It is a major objective of the present analysis to assess the potential impacts and risks in order to allow Europe to avoid them. It should be noted, however, that necessary requirements will come at a certain cost and will decelerate developments which may make shale gas extraction economically unattractive and may reduce the energetic contribution to marginal levels.
- *Remaining (small) risks must be balanced against the economic benefits of developing domestic natural gas fields.* The economics of shale gas extraction are beyond the scope of the present analysis. Nonetheless, it should be pointed out the hydraulic fracturing activities are much more costly than conventional extraction. The economic attractiveness of European shale gas development has not yet been proven. A cost benefit analysis including all aspects in an LCA should be done for each well as a prerequisite of granting extraction permits.

2.9. Resources consumption

Experiences in North America

Table 4 summarises the materials and truck movements for activities associated with natural gas developments.

Table 4: Estimated quantities of materials and truck movements for activities associated with natural gas development [NYCDEP 2009]

Activity	Material/waste	Quantities (1)	Associated truck trips
Single-well pad with total well length of 1500 to 4000 m, consisting of 900 to 2100 m depth and 600 to 1800 m of lateral length with a 6 inch diameter production casing and 8 inch diameter borehole. Lateral is cased but not grouted.			
Site access and drill pad construction	Cleared vegetation and earthwork	0.8 to 2.0 ha site, plus access roads as needed	20 to 40
Drill rig setup	Equipment		40
Drilling chemicals	Various chemicals		
Drilling water	Water	40's to 400's of m^3	5 to 50
Casing	Pipe	2100 to 4600 m (60 to 130 t) of casing	25 to 50
	Cement (grout)	14 to 28 m^3	5 to 10
Drill cuttings	Rock/earth/formation material	71 to 156 m^3	Depends on fate of cuttings
Drilling waste water	Waste drilling fields	40's to 400's of m^3	5 to 50
Stimulation setup	Equipment		40
Casing Perforation	Explosives	Single charge ~25 g, no estimate on number of charges per length of lateral	
Fracturing fluid - water	Water	11,355 to 34,065 m^3	350 to 1,000
Fracturing fluid - chemicals	Various chemicals	Assuming 1 to 2% of fracture fluid volume is comprised of chemicals yields 114 to 681 m^3	5 to 20
Fracturing fluid waste water	Waste fracturing fluids	11,355 to 34,065 m^3	350 to 1000
Well-pad completion	Equipment		10
Gas collection	Produced water	57 m^3 per year and per well average	2 to 3
Total estimated truck trips per well			800 to over 2000

(1) US units converted to metric units

Transferability to European conditions

The information available so far leads to the conclusion that the resources consumption, the energy requirements (and the associated GHG emissions – see chapter 3) for shale gas field development are higher than for conventional natural gas field development. There is a large bandwidth concerning the natural gas yield per well with a spread of more than a factor of ten. Thus, the specific resources and energy consumption and the associated GHG emissions per m^3 of natural gas extracted vary by more than a factor of ten. Consequently, an individual assessment for each shale gas formation needs to be carried out in order to get relevant and reliable data.

3. GREENHOUSE GAS BALANCE

KEY FINDINGS

- Fugitive methane emissions have a huge impact on the greenhouse gas balance.
- Existing assessments give a range of 18-23 g CO_2-equivalent per MJ as indirect GHG emissions from the production and processing of unconventional natural gas.
- The potential emissions due to methane intrusion of aquifers are not yet assessed.
- However, project specific emissions might vary up to a factor of ten, depending on the total methane production of the well.
- Depending on several factors, greenhouse gas emissions of shale gas relative to its energy content are as low as those of conventional gas transported over long distances or as high as those of hard coal over the entire life cycle from extraction to combustion.

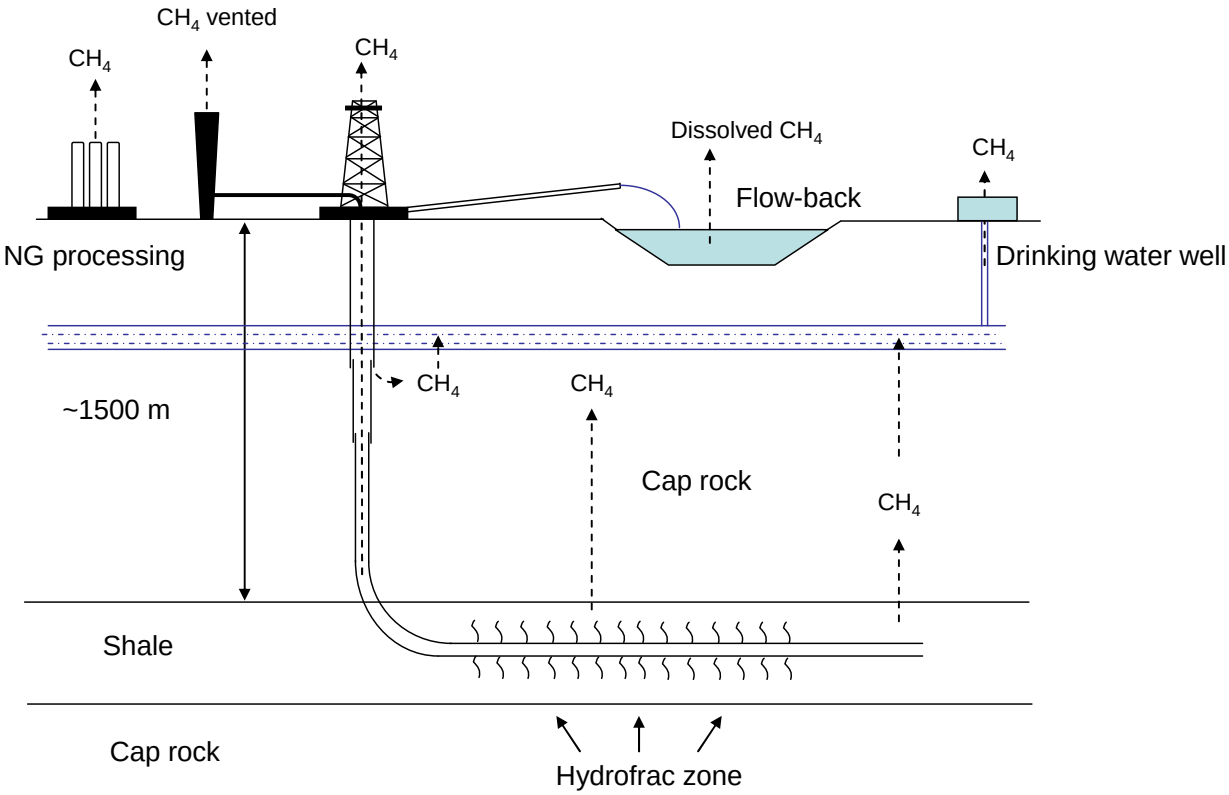
3.1. Shale and tight gas

3.1.1. Experiences in North America

CO_2 emissions occur during combustion processes in gas turbines, diesel engines and boilers required for shale gas exploration, extraction and processing. Depending on the CO_2 content of the extracted natural gas non-combustion CO_2 emissions can also occur in the natural gas processing stage. The CO_2 content of the extracted gas can amount up to 30% [Goodman et al 2008] which would lead to specific emissions of about 24 g CO_2 per MJ of extracted gas.

Furthermore, methane is released which has a global warming potential of 25 g CO_2 equivalent per g of CH_4 (according to IPCC for a time horizon of 100 years). During the exploration and development phase, methane emissions occur during drilling ('shallow' gas vented), during flow back of the liquids from the hydraulic fracturing process and from plug drill-out after the hydraulic fracturing process. During the extraction and processing phase methane is leaking from valves and compressors, during liquid unloading (unloading of separated liquid hydrocarbons), and natural gas processing. Furthermore, methane can be emitted from damaged drillings. It is estimated that in the USA about 15 to 25% of the drillings are not tight.

Figure 4: CH_4 emissions from shale gas exploration, extraction and processing



Source: own source based on [SUMI 2008]The shale gas exploration and development (initial drilling and completion), which includes the flow-back procedure, contributes to a large extent to the overall methane emissions. Table 5 shows the methane emissions from the flow-back procedure at four unconventional wells.

Table 5: Methane emissions from flow-back fluids for four unconventional natural gas wells

Basin	Emission during flow-back [10^3 m³ CH_4]	Lifetime production of well [10^6 m³]	Flow-back emissions as % of life-time production	Flow back emissions in g CO_2 eq/MJ (1)
Haynesville (Louisiana shale)	6,800	210 *(75)*	3.2%	20.1
Barnet (Texas shale)	370	35	1.1%	6.6
Piceance (Colorado, tight sand)	710	55	1.3%	7.9
Uinta (Utah, tight sand)	255	40	0.6%	3.8

(1) 25 g CO_2 equivalent per g CH_4 based on a time horizon of 100 years according to IPCC

Source: [Cook et al 2010], [Howarth et al 2011]

The average methane emissions from flow-back fluids of the four unconventional wells in Table 5 amount to about 1.6% of the extracted natural gas. Additionally, drill-out, which is carried out after the hydraulic fracturing, leads to methane emissions of about 0.3% of the extracted natural gas summing up to total methane emissions of 1.9% from exploration and development. The methane can be partly captured and flared to reduce the emissions of methane. Typically, about 50% of the emitted methane can be captured and flared. Furthermore, [Howarth et al 2011] assumes the content of methane of the extracted natural gas to be 78.8% for the conversion of the volume related methane losses to energy related methane losses.

It has to be noted that the specific GHG emissions from drilling combustion strongly depend on the amount of natural gas which can be extracted. The amount of CO_2 combusted during drilling depends on the depth of the drilling. The lower the natural gas yield per well the higher the GHG emissions per MJ of extracted natural gas. For the Haynesville Louisiana shale the lifetime natural gas production per well indicated by [Howarth et al 2011] is surprisingly high (210 million m^3 instead of 35 to 55 million m^3 indicated for the other shale and tight gas fields). According to [Cook et al 2010] the mean value for the lifetime production per well at the Haynesville Louisiana shale is about 75 million m^3 instead of 210 million m^3 indicated in [Howarth et al 2011]. If the 75 million m^3 are realistic and the methane emissions from flow-back would be constant the specific methane emissions would be 9.0% instead of the 3.2% indicated in Table 5. The GHG emissions from flow-back at the Haynesville Louisiana shale would increase from about 20 g/MJ to about 57 g/MJ of extracted natural gas.

Table 6 shows the GHG emissions from the exploration, extraction, and processing of shale and tight gas assessed in the USA[6]. The methane emissions from flow-back (which are included in the methane emissions from “completion”) have been derived from the average of the wells indicated in Table 5.

Table 6: Emissions of shale gas exploration, extraction and processing related to the LHV of the produced gas

	CO_2 [g/MJ]	CH_4 [g/MJ]	N_2O [g/MJ]	g CO_2 eq/MJ (1)
Site clearing:				
Disturbance	0.018	-	-	0.018
Land clearing	0.018	<0.01	<0.01	0.018
Resource consumption	0.550	<0.01	-	0.550
Exploration and development:				
Drilling combustion (RIG and FRAC)	0.660 *(0.878)*	<0.01	<0.01	0.827 (1.045)
Drilling combustion (mobile)	0.293 *(0.493)*	<0.01	<0.01	0.460 (0.660)
Completion (50% flare, 50% vent)	0.733 *(1.145)*	0.254 *(0.417)*	-	7.077 (11.578)
Gas production:				

[6] converted from g C for CO_2 and CH_4 presented in the literature source to g CO_2 and CH_4

Combustion	2.089	-	-	2.089
Brine tank	-	<0.01	-	
Misc. fugitives	-	0.147	-	3.673
Processing:				
Combustion	1.905	<0.01	-	2.239
Fugitives	0.330	0.027	-	0.998
Total	6.60 *(7.43)*	0.454 *(0.618)*	0.00	17.9 *(22.9)*

(1) 25 g CO_2 equivalent per g CH_4 based on a time horizon of 100 years according to IPCC Values in brackets: calculated for a lower yield at Haynesville according to Cook et al. 2010. S**rce:** [Cook et al 2010], [Howarth et al 2011]

If the yield for the Hayensville Louisiana shale indicated in [Cook et al 2010] were applied and the methane emissions from flow-back were kept constant the overall GHG emissions for shale gas exploration, extraction and processing for the mix of the four unconventional natural gas wells would increase from 17.9 g/MJ to 22.9 g/MJ.

Furthermore, methane can leak into groundwater resources. In aquifers overlying the Marcellus and Utica shale formations of North-Eastern Pennsylvania and upstate New York, there is evidence for methane contamination of drinking water associated with fracturing [Osborn et al 2011]. This methane may also be released to the atmosphere during water use leading to additional GHG emissions. These emissions as well as methane emissions from venting during drilling are not included in Table 6.

In Ohio, USA, natural gas was entering homes via water wells. A house in the Bainbridge Township of Geauga County exploded. Two residents in the house at the time of the explosion were not injured, but the house was significantly damaged. [ODNR 2008] Therefore, it can be concluded that significant amounts of methane can migrate into the groundwater and finally into the atmosphere in this way.

If the CO_2 content of the extracted natural gas is higher than assumed in Table 6 the CO_2 emissions at the natural gas processing stage would be higher (up to 23.5 g/MJ instead of 0.33 g/MJ for a CO_2 content of 30%). Since the methane content would be 70% instead of the 78.8% indicated in [Howarth et al 2011] all other values also would increase leading to a value of about 43.3 g/MJ instead of 17.9 g/MJ.

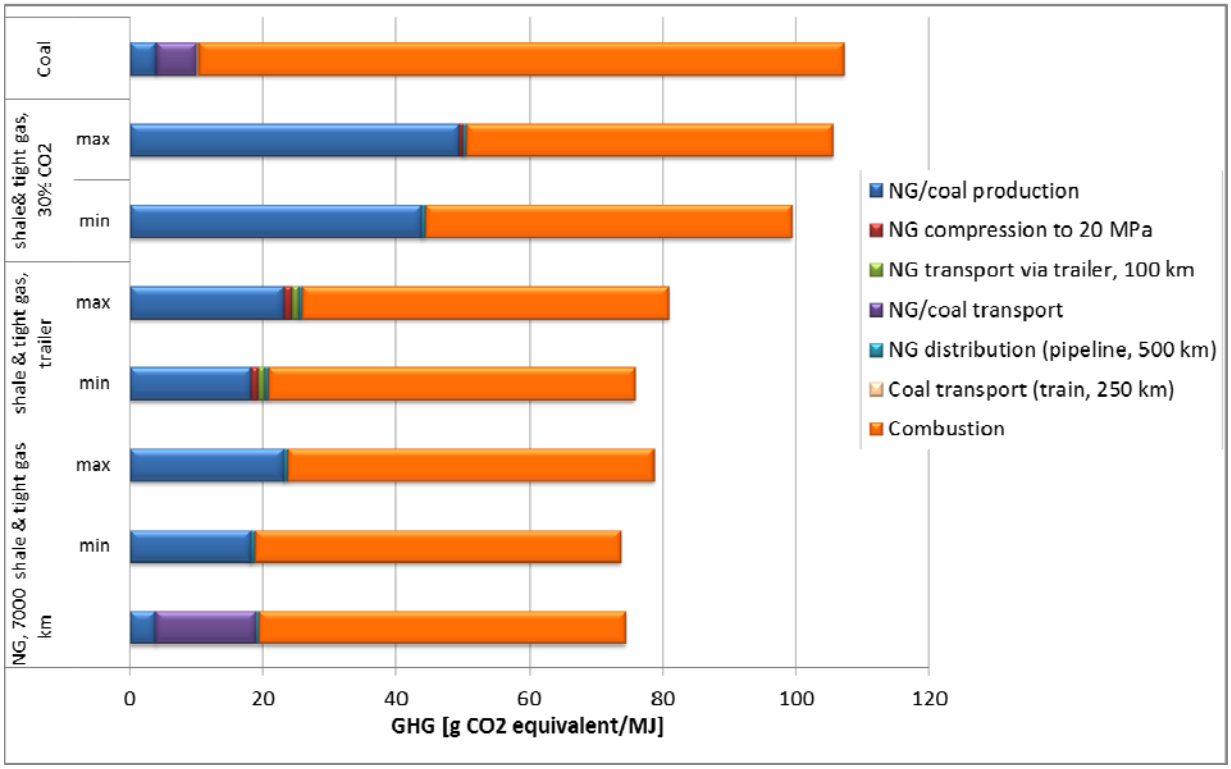
Another issue to be taken into account is the transport of the natural gas from the well to the natural gas grid. In case of small natural gas yields per well the natural gas is transported in compressed form by truck using a CNG trailer.

3.1.2. Transferability to European conditions

There are a few non-conventional natural gas projects in the EU. Fracturing is not only applied for shale gas, but also for coal bed methane and for tight gas. As an example, ExxonMobil plans to produce coal bed methane in North Rhine-Westphalia, Germany.

The greenhouse gas emissions of shale and tight gas development, extraction, distribution and combustion as estimated above are presented in Figure 5. Depending on the assumptions chosen, tight and shale gas at the lower end has similar overall GHG emissions as conventional natural gas transported over long distances, or at the upper end has GHG emissions close to hard coal.

Figure 5: Greenhouse gas emissions of shale and tight gas production, distribution and combustion compared to conventional natural gas and coal



Source: own source

If the methane loss into the ground water were avoided and if it were assumed that the shale gas is combusted in a combined cycle gas turbine (CCGT) power plant with an efficiency of 57.5% the overall GHG emissions from natural gas supply and use would amount to 460 per kWh of electricity (shale gas production: 113.5 g/kWh of electricity; NG distribution: 3.6 g/kWh of electricity; combustion: 344.3 g/kWh of electricity) if the same GHG emissions for shale gas production were assumed as in the USA. If the CO_2 content of the extracted gas amounted to 30% and the specific methane emissions from flow-back were higher due to a lower natural gas yields the overall GHG emissions would increase to about 660 g per kWh of electricity. For comparison: natural gas based power production from long distance pipeline transport (7000 km) would lead to about 470 g per kWh of electricity. Coal from Australia combusted in a new coal steam turbine (ST) power station with an efficiency of 46% leads to about 850 g per kWh of electricity.

Table 7: GHG from the supply of electricity from natural gas CCGT from various NG sources compared with the supply of electricity from coal in g CO_2 equivalent per kWh of electricity

	CCGT (shale & tight gas)		CCGT (shale & tight gas, trailer)		CCGT (shale & tight gas, 30% CO_2)		CCGT (NG, 7000 km)	Coal ST
NG/coal production	113.5	144.6 [(1)]	113.5	144.6 [(1)]	274.1	309.1 [(1)]	24.1	31.1
NG compression to 20 MPa	-	-	7.2	7.7	-	3.6	-	-
NG transport via trailer, 100 km	-	-	6.2	6.2	-	-	-	-
NG/coal transport	-	-	-	-	-	-	94.0	47.7
NG distribution (pipeline, 500 km)	3.6	3.6	3.6	3.6	3.6	3.6	3.6	-
Coal transport (train, 250 km)	-	-	-	-	-	-	-	2.3
Combustion	344.3	344.3	344.3	344.3	344.3	344.3	344.3	772.8
Total	**461**	**493**	**475**	**506**	**622**	**661**	**466**	**854**

[(1)] The upper value represents the higher specific methane emissions due to lower natural gas yield than indicated in [Howarth et al 2011]

The reason for the huge GHG emissions from the supply and use of shale gas in the USA (almost as high as coal supply and use) indicated in [Horwarth et al 2011] and [Osborn et al 2011] is that there are extremely high methane emissions from the transport, storage and distribution of natural gas in the USA (1.4 to 3.6% adding 7.0 to 18.0 g CO_2 equivalent per MJ to the 17.9 g/MJ from Table 6), mainly due to the poor quality of the equipment in the USA. On the other hand, methane leaks into the groundwater and the inclusion of methane emissions from venting during drilling can lead to significantly higher GHG emissions than described above.

In case of conventional natural gas the methane losses in the EU are generally lower than in the USA due to better equipment (tightness of pipelines, valves, etc.). Concerning the non-conventional gas specific processes it is not known whether or to what extent the GHG emissions are lower in the EU than in the USA. The fracturing process includes the risk of release of methane into the drinking water and as a result into the atmosphere (as occurred in the USA).

According to expert statements, monitoring of the cementation of the drilling is mandatory in Germany reducing the risk of methane losses and contamination of groundwater by toxic substances. Furthermore, closed systems instead of open ponds for the back-flow are planned for projects in North Rhine-Westphalia, Germany. Therefore, the variant “50% flared, 50% vent” in [Horwarth et al 2011] selected for the GHG emissions shown in Table 6 could be realistic for Europe.

3.1.3. Open issues

It has to be noted that there is a considerable uncertainty concerning emission data from shale and tight gas production due to a lack of reliable data. Every well is different and the best wells (where most of the data come from) will be developed first. Thus, published data tend to overestimate the average amount of recoverable methane from a well.

The assessment of the amount of methane from the fracturing process leaking into water and as a result into the atmosphere is also still an open issue.

3.2. Tight oil

The differentiation between conventional oil production and the production of tight oil is not always well defined; the transition from conventional oil production to tight oil production is gradual. As an example, there are conventional crude oil fields where hydraulic fracturing is applied to enhance the oil recovery. Since for the production of tight oil hydraulic fracturing is applied methane emissions from flow-back can occur in the same way as for shale and tight gas. There are no publicly available data on methane emissions from tight oil production.

3.2.1. Experiences in Europe

The production of tight oil must not be mistaken for shale oil production. In Estonia oil shale has been mined since 1921 (via open pit as well as via underground mining). The shale oil is extracted via so-called ‘retorting’ which is in fact a pyrolysis process generating shale oil and shale gas. In contrast, tight oil is produced by drilling and applying hydraulic fracturing.

In the Paris Basin in France 5 million barrels of oil have been extracted from 2000 wells, equivalent to 2500 barrels of oil per well. [Anderson 2011] This has been conventional oil extraction without the use of hydraulic fracturing. Based on the LHV of the extracted crude oil 2500 barrels of oil per well over the entire lifetime have approximately the same energy content as 0.5 million Nm^3 of natural gas.

If the Paris Basin were considered as typical for tight oil extraction the amount of energy which could be extracted per well is far lower than that for shale gas (0.4 million Nm^3 instead of 35 million Nm^3 per well in the case of the Barnet Texas shale). If these wells are typical for tight oil the overall GHG emissions from drilling and hydraulic fracturing would be higher than for conventional oil extraction, and also higher than for the production of shale and tight gas.

4. EU REGULATORY FRAMEWORK

KEY FINDINGS

- There is no EU (framework) directive governing mining activities.
- A publicly available, comprehensive and detailed analysis of the European regulatory framework concerning shale gas and tight oil extraction has not yet been developed.
- The current EU regulatory framework concerning hydraulic fracturing contains a number of gaps. Most importantly, the threshold for Environmental Impact Assessments to be carried out on hydraulic fracturing activities in natural gas or tight oil extraction is set far above any potential industrial activities of this kind, and thus should be lowered substantially. Along with this, the scope of the water framework Directive should be reassessed.
- A detailed and comprehensive analysis of declaration requirements for hazardous materials used in hydraulic fracturing needs to be carried out.
- In the framework of a Life Cycle Analysis (LCA), a thorough cost/benefit analysis could be a tool to assess the overall benefits for each individual Member State and its citizens.

The aim of this chapter is to provide an overview of the current regulatory framework of EU legislation concerning

- the extraction of shale gas, tight gas, and tight oil, and
- whether it has adequate provisions to guard against the specific potential risks to the environment and human health resulting from these activities.

In chapter 4.1 the four European Directives specifically targeting mining activities are presented. The following chapter 4.2 gives at first an overview of further 10 Directives mentioned in today's literature as relevant for mining activities. The second part of this chapter (chapter 4.2.2) focuses on the approximately 40 Directives relating to shale gas and tight oil specific risks. Finally, nine major gaps in current EU legislation are identified. These concern specific potential risks for the environment, water and human health associated with hydraulic fracturing. Some reflect the difficulties experienced in the USA, some are currently discussed in the Member States of the EU.

4.1. Extractive Industry specific Directives

The purpose of a mining law is to provide a legal framework to facilitate a prosperous industry sector, a secure energy supply and to secure sufficient protection for health, safety and the environment.

At EU-level, there is no comprehensive mining framework. [Safak 2006] Currently, mining law is to a very large extent the responsibility of the Member States and in most countries legislation is historical and does not necessarily reflect today's requirements. [Tiess 2011] The European Commission's Directorate Generale for Enterprise and Industry has a sector named "Metals, Minerals, Raw Materials" which state on their website, that there are only three Directives developed specifically for the extractive industry [EC 2010 MMM]. In Table 8 these three Directives are supplemented by a fourth Directive according to [Kullmann 2006].

Table 8: All EU Directives developed specifically for the extractive industries

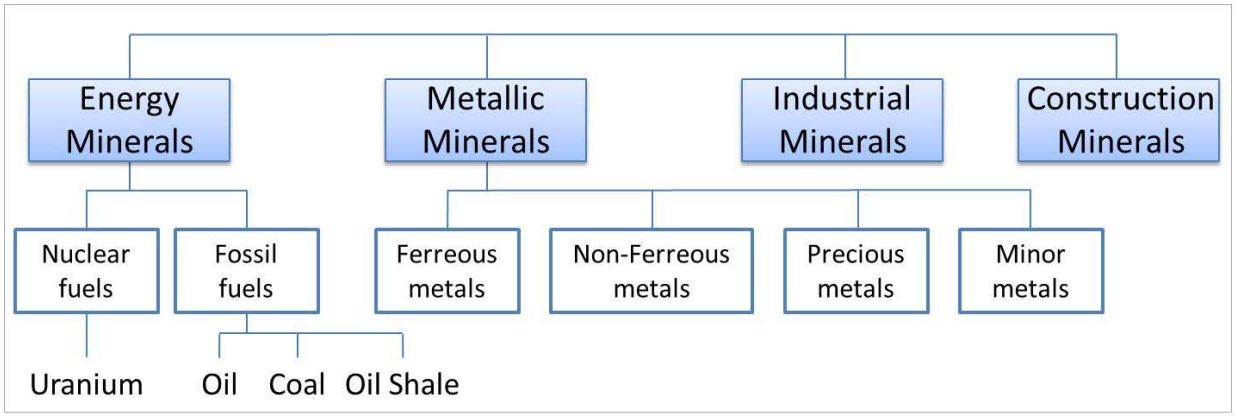
Directive	Directives on Mining
2006/21/EC	Directive on the management of waste from extractive industries **Mining Waste Directive**
1992/104/EEC	Directive on the minimum requirements for improving the safety and health protection of workers in surface and underground mineral-extracting industries (twelfth individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)
1992/91/EEC	Directive concerning the minimum requirements for improving the safety and health protection of workers in the mineral-extracting industries through drilling (eleventh individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)
1994/22/EC	Directive concerning the conditions for granting and using authorizations for the prospection, exploration and production of hydrocarbons

Source: [EC 2010, Kullmann 2006]

A by-product of hydraulic fracturing is a large quantity of water contaminated with carcinogens, biocides, radioactive Radon and further hazardous chemicals (see chapter 2.6). The mining waste directive is fundamental for the safe handling of this accumulating mixture. For hydraulic fracturing as for every major drilling activity, heavy machinery is required which is operated by workers. Legal aspects on safety and health protection of workers specifically in a mining environment are defined in two further directives, as listed in Table 8. The fourth mining-specific directive governs sovereignty of the Member States in granting exploration licences of hydrocarbons.

Apart from these Directives, there are several Acts clarifying especially the competitive environment e.g. the opening of domestic markets of the new Member States. An example is the Declaration on the restructuring of the oil shale market in Estonia: 12003T/AFI/DCL/08. As the scope of this study is the legal framework concerning the potential risks to the environment and human health, the regulation of markets is not elaborated further here.

Figure 6: Structure of the extractive industry



Source: [Papoulias 2006]

From a legal perspective, the extractive industry as shown in

Figure 6 comprises two categories:

- the non-energy extractive industries (NEEI) exploiting metallic, industrial and construction minerals, and
- industries exploiting energy minerals (including shale gas and tight oil).

It is common, that legislation and the work of the European Commission explicitly focus on NEEI and therefore do not cover the exploitation of natural gas [EC NEEI].

4.2. Non-specific Directives (focus: environment and human health)

There is a plenitude of non-mining-specific Directives and Regulations affecting the extractive industry. This paragraph focuses on regulatory Acts concerning the environment and human health. In paragraph 4.2.1 the result of a literature review yields the seven to twelve most relevant Directives and the reference to a comprehensive and well-structured data base with hundreds of EU regulatory Acts. So far, no literature source exists on the EU regulatory framework with the scope of this study; therefore the collection in paragraph 4.2.2 is the result of dedicated research for the present study. Around 40 directives are identified as relevant for safety aspects accompanying hydraulic fracturing.

4.2.1. General Mining Risks covered by EU-Directives

As presented in chapter 4.1, there are only four EU Directives that were tailored for the specific requirements of the extractive industry. Nevertheless, there is further legislation especially in the areas of environment and health and safety that also covers the issues of mining [Safak 2006].

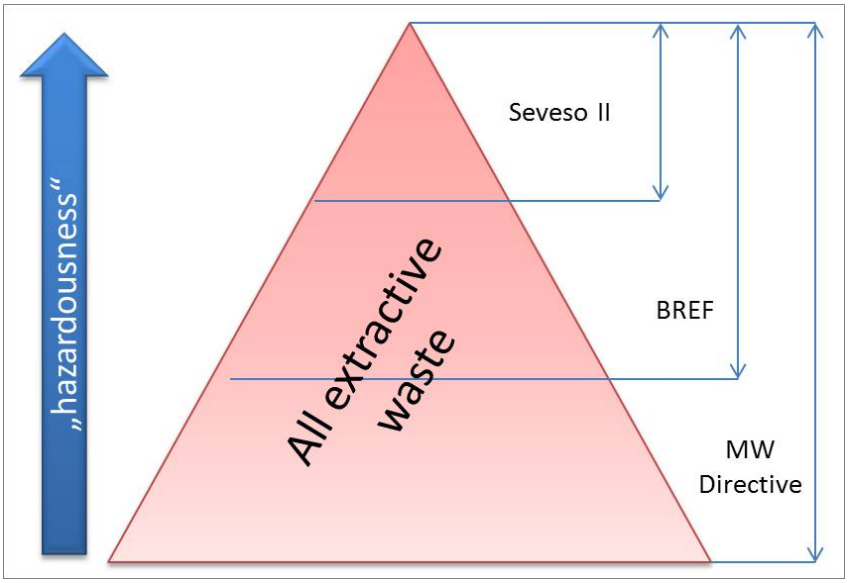
Table 9 gives a first impression on the multitude of different general legislation from various different fields.

Table 9: Most relevant legislation affecting the extractive industries

Most relevant legislation affecting the extractive industries	
Mining Waste Directive	Natura 2000
Ambient Air Quality	Ground Water Directive
BAT Note (BRAF)	Habitats & Bird Directives
Seveso II	Ambient Air Strategy
EIA Directive	Water Framework Directive
REACH	Environmental Liability

An important aspect is that the mining specific Directives are not necessarily the strictest ones. Due to major incidents in the past, there is more stringent legislation especially concerning hazardous chemicals. Figure 7 demonstrates that the Mining Waste Directive has a much broader scope than e.g. the Seveso II directive[7] [Papoulias 2006].

Figure 7: Most important EU Directives effective on extractive waste



Source: [Papoulias 2006]

[7] The Seveso II Directive is currently under review.

The most up-to-date literature lists the following number of legislative acts as relevant for mining purposes:

- 7 items [EC 2010 Grantham and Schuetz 2010],
- 9 items [Weber 2006],
- Up to 18 items [Hejny 2006**Error! Reference source not found.**],
- 12 items [Kullmann 2006].

At the other extreme, there is a fascinating overarching collection of all EU environmental legislation sorted by topics [UWS GmbH]. For EU-legislation on waste alone, 36 directives, regulations, recommendations and the like are listed. In total, this collection probably comprises hundreds of documents relevant for environmental aspects.

In order to assess the current EU regulatory framework focussing on hydraulic fracturing, the lists of up to 12 directives are not exhaustive, while the collection of hundreds of regulatory documents is too encyclopaedic. Nevertheless, some of the lists were especially composed to give an overview of the EU regulatory framework relevant for the exploitation of shale gas, e.g. [Schuetz 2010] listing the following seven Directives:

1. Water framework Directive
2. Groundwater Directive
3. REACH
4. Natura2000
5. EIA
6. Waste framework Directive
7. Noise Directive

4.2.2. Specific shale gas and tight oil risks covered by EU-Directives

A number of possible dangers originating from the exploitation of shale gas, tight gas and tight oil are in principle the same as for conventional energy sources. Therefore, the existing legislation does cover many risks sufficiently. Nonetheless, unconventional gas is associated with unconventional risks. These may not be sufficiently covered and may originate from the

- tremendous quantity of chemicals used during the process of hydraulic fracturing,
- selection of chemicals including toxic, carcinogenic and mutagenic substances, and substances harmful to the environment used as additives for fracturing fluids (e. g. biocides),
- amount of flow back water contaminated with radioactive substances such as radon and uranium and other additional subsurface materials (e.g. heavy metals),
- large number of drilling sites,
- infrastructure e.g. network of gathering pipes,
- high amount of water used for the fracturing fluid, and
- potentially high emissions of methane from well completion.

For further details on the specific risks please refer to chapter 2. The following compendium of the 36 most relevant EU Directives gives a unique basis for further detailed research.

The Directives are sorted by relevance within each table. Not all of these Directives are necessarily effective as of today due to possible delays in (correct) transposition into national law. First studies on the chemicals used during hydraulic fracturing in the USA [Waxman 2011] gives a good basis to survey the appropriateness of EU legislation with respect to chemicals.

The major concern about hydraulic fracturing is usually the possible effects on water quality. The critical points are (see chapter 2.4.2):

- Regular fracturing process: chemicals remaining in the underground which might reach aquifers.
- Accidents during hydraulic fracturing: cracks in the installed equipment allow direct access to ground water and surface water.
- Depending on the number of wells, huge amounts of fresh water are consumed (refer to Table 2).

Table 10 lists the six most relevant Directives on water that are or probably should be relevant for hydraulic fracturing activities. For more detailed analyses, these should be evaluated.

Table 10: Relevant EU-Directives on Water

	Directive	Title
1.	2000/60/EC	Directive establishing a framework for Community action in the field of water policy (**Water framework directive**)
2.	1980/68/EEC	Directive on the protection of groundwater against pollution caused by certain dangerous substances (repealed by 2000/60/EC with effect from 22 December 2013)
3.	2006/118/EC	Directive on the protection of groundwater against pollution and deterioration
4.	1986/280/EEC	Council Directive on limit values and quality objectives for discharges of certain dangerous substances included in List I of the Annex to Directive 76/464/EEC
5.	2006/11/EC	Directive on pollution caused by certain dangerous substances discharged into the aquatic environment of the Community (Codified version)
6.	1998/83/EC	Directive on the quality of water intended for human consumption.

The risk of polluted water is inseparably linked to the risk of a polluted environment. These risks form a subset of the total environmental risks which can roughly be split into the following areas:

- Emissions to the ground
    - drinking and ground water contamination
    - Land contamination
- Emissions to the air
    - Exhausts
    - Noise
    - Chemicals
- Accidents outside the operating sites
    - Transport on roads
    - Landfill of waste

This list focusses on the influences on the environment under regular operating conditions. In all of these areas, there is of course also the risk of accidents. Table 11 gives the nine most relevant Directives regulating the influences under regular and accident conditions.

Table 11: Relevant EU Directives on the Protection of the Environment

	Directive	Title
7.	2010/75/EU	Directive on industrial emissions (integrated pollution prevention and control) **IPPC-Directive**
8.	2008/1/EC	Directive concerning integrated pollution prevention and control (codified version)
-	Decision 2000/479/EC	Decision on the implementation of a European pollutant emission register (EPER) according to Article 15 of Council Directive 96/61/EC concerning integrated pollution prevention and control (IPPC). Annex A1: List of pollutants to be reported if threshold value is exceeded.
9.	1985/337/EEC	Environmental Impact Assessment Directive **EIA Directive**
10.	2003/35/EC	Directive providing for public participation in respect of the drawing up of certain plans and programmes relating to the environment and amending with regard to public participation and access to justice Council Directives 85/337/EEC and 96/61/EC
11.	2001/42/EC	Directive on the assessment of the effects of certain plans and programmes on the environment **Strategic Environmental Assessment (SEA)**
12.	2004/35/EC	Directive on environmental liability with regard to the prevention and remedying of environmental damage
13.	1992/43/EEC	Directive on the conservation of natural habitats and of wild fauna and flora **Natura 2000**
14.	1979/409/EEC	Directive on the conservation of wild birds
15.	1996/62/EC	Directive on ambient air quality assessment and management

Hydraulic fracturing always goes hand in hand with the use of heavy machinery (see chapter 2.3) and hazardous chemicals. Citizens have to be protected as well as the workers operating these materials and machinery on a daily basis. There are comprehensive EU Directives on safety at work. Table 12 provides a list of nine relevant Directives that protect workers especially in the mining industry operating with dangerous chemicals.

Table 12: Relevant EU Directives on safety at work

	Directive	Title
16.	1989/391/EEC	Directive on the introduction of measures to encourage improvements in the **safety and health of workers** at work.
17.	1992/91/EEC	Directive concerning the minimum requirements for improving the safety and health protection of workers in the mineral-extracting industries through drilling.
18.	1992/104/EEC	Directive on the minimum requirements for improving the safety and health protection of workers in surface and underground mineral-extracting industries.
19.	2004/37/EC	Directive on the protection of workers from the risks related to exposure to carcinogens or mutagens at work (codified version)
20.	1991/322/EEC	Directive on establishing indicative limit values by implementing Council Directive 80/1107/EEC on the protection of workers from the risks related to exposure to chemical, physical and biological agents at work.
21.	1993/67/EEC	Directive laying down the principles for assessment of risks to man and the environment of substances notified in accordance with Council Directive 67/548/EEC
22.	1996/94/EC	Directive establishing a second list of indicative limit values in implementation of Council Directive 80/1107/EEC on the protection of workers from the risks related to exposure to chemical, physical and biological agents at work
23.	1980/1107/EEC	Council Directive of 27 November 1980 on the protection of workers from the risks related to exposure to chemical, physical and biological agents at work
24.	2003/10/EC	Directive on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise)

Most rock formations contain “Naturally Occurring Radioactive Materials” (N.O.R.M.). In the majority of cases, natural gas contains radioactive radon which is a decay product of uranium. The International Association of Oil & Gas Producers (OGP) describes this negative side-effect of exploitation of natural gas as follows:

“Radon is a radioactive gas, which is present in varying degrees in natural gas in oil & gas formations. In the absence of natural gas, radon dissolves in the (light) hydrocarbon and aqueous phase. When produced with the oil and gas, radon will usually follow the gas stream. […] NORM waste disposal must adhere to applicable regulations pertaining to the disposal of radioactive waste.” [OGP 2008]

Not only the natural gas contains radon, but also the huge amounts of flow-back water after hydraulic fracturing. There is a Euratom directive specifically focussing on safety standards around N.O.R.M.:

Table 13: Relevant Directive on Radiation Protection

	Directive	Title
25.	1996/29/Euratom	Directive laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation. **N.O.R.M.** (naturally occurring radioactive material) Directive

As already mentioned in section 4.1, there is a Directive on waste especially tailored to the extractive industries. Several more Directives and especially several Decisions defining limit values are relevant here (for details on waste issues see chapter 2). These four Directives and four Decisions are listed in Table 14. Further legislation on mining waste including financial guarantee aspects can be found on the mining waste specific website of the European Commission. [EC 2011 MW]

Table 14: Relevant EU Directives on Waste

	Directive	Title
26.	2006/21/EC	Directive on the management of waste from extractive industries and amending Directive 2004/35/EC **Mining Waste Directive**
-	Commission Decision 2009/359/EC	Decision completing the definition of inert waste in implementation of Article 22(1)(f) of Directive 2006/21/EC concerning the management of waste from extractive industries.
27.	2006/12/EC	Directive on waste **Waste Framework Directive**
28.	1999/31/EC	Directive on the landfill of waste
-	Commission Decision 2000/532/EC	Decision establishing a list of (hazardous) wastes pursuant of several Directives (replacing Decision 94/3/EC)
-	Commission Decision 2009/360/EC	Decision completing the technical requirements for waste characterisation laid down by Directive 2006/21/EC on the management of waste from extractive industries
-	Commission Decision 2009/337/EC	Decision on the definition of the criteria for the classification of waste facilities in accordance with Annex III of Directive 2006/21/EC concerning the management of waste from extractive industries
29.	Decision 2002/1600/EC	Decision laying down the Sixth Community Environment Action Programme (Article 6 (2)(b): "...developing further measures to help prevent the major accident hazards with special regards to those arising from pipelines, mining, marine transport of hazardous substances and developing measures on mining waste...")

In April 2011, a first comprehensive study on "Chemicals used in hydraulic fracturing" in the USA was published. One of their results is the quantity and quality of chemicals used:

"Between 2005 and 2009, the 14 oil and gas service companies used more than 2,500 hydraulic fracturing products containing 750 chemicals and other components. Overall, these companies used 780 million gallons of hydraulic fracturing products – not including water added at the well site – between 2005 and 2009." [Waxman 2011]

Among these 750 chemicals were several hazardous air pollutants and human carcinogens that were used in large quantities. Table 15 lists the eight most relevant European Directives concerning the use of chemicals including legislation to prevent accidents.

Table 15: Relevant EU Directives on Chemicals and associated accidents

	Directive	Title
30.	Regulation 1907/2006	Regulation concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (**REACH**), establishing a European Chemicals Agency
-	ECE/TRANS/215[8]	United Nations Economic Commission for Europe (ECE): European Agreement Concerning the International Carriage of Dangerous Goods by Road. **ADR** applicable as from 1 January 2011.
31.	1996/82/EC	on the control of major-accident hazards involving dangerous substances **Seveso II Directive**
32.	2003/105/EC	Directive amending Council Directive 96/82/EC (Seveso II Directive) on the control of major-accident hazards involving dangerous substances (this Directive is currently under review) [The most important extensions of the scope of that Directive are to cover risks arising from storage and processing activities in mining, from pyrotechnic and explosive substances and from the storage of ammonium nitrate and ammonium nitrate based fertilizers.]
33.	1991/689/EEC	Directive on hazardous waste
34.	1967/548/EEC	Directive on the approximation of laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous substances
35.	1999/45/EC	Directive concerning the approximation of the laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous preparations
36.	1998/8/EC	Directive concerning the placing of biocidal products on the market.

[8] All members of the European Union are also members of UNECE (United Nations Economic Commission for Europe). The ADR is listed here, as it is of great importance in this context.

4.3. Gaps and open issues

The multitude of legal perspectives from which mining projects are affected already indicates that the current legislation is not necessarily adequate to the specific requirements of the extractive industries. Especially the exploration and exploitation of shale gas and tight oil create new challenges.

Gap 1 - Investment security for extractive industries

Currently, extractive industries are facing problems due to insufficient legislation, as put by Tomas Chmal, Partner at White & Case, at the conference *Shale Gas Eastern Europe 2011* in Warsaw, Poland:

"Poland is traditionally a gas country, but the Geologic and Mining Law does not say anything about hydraulic fracking or horizontal drilling. The new law being discussed doesn't cover these either." [NGE 2011]

As mentioned at the beginning of chapter 4.1, national laws are often based on historical needs and there is no European mining framework Directive. As the quotation shows, this does pose a problem. Thus, further investigation should evaluate the need and possible scope of a Mining Framework Directive.

Gap 2 - Protection of the environment and human health

Directive 97/11/EC amending the EIA Directive in Annex I, defines a threshold of 500,000 m^3 daily extraction rate for natural gas wells above which an Environmental Impact Assessment is compulsory. [EIA cod][9] Exploitation of shale gas does not reach this threshold by far, and therefore EIAs are not carried out [Teßmer 2011]. As the EIA Directive is under consideration for revision, projects including hydraulic fracturing should be added to Annex I independently of a production threshold or the threshold value should be lowered (e.g. to 5,000 or 10,000 m^3 per day of initial extraction volume) in order to close this gap.

Gap 3 - Declaration of hazardous materials

A first US study provides a nearly comprehensive list of hydraulic fracturing chemicals. [Waxman 2011] Experiences from the USA show that the extraction companies themselves do not necessarily know which chemicals they are actually using. The chemical industry offers a variety of additives but does not in all cases declare the constituent parts in a sufficient way due to alleged trade secrets. The current legislation on the duty of declaration and the associated permitted limit values for the fracturing chemicals should be assessed in this respect.

At least for the following three, and possible further, Directives this topic is relevant:

- REACH: In 2012, the Commission is required to conduct an evaluation of the REACH regulation which gives the opportunity to adjust the current legislation.
- Water quality: The same aspects are relevant for Directive 98/83/EC on the quality of water intended for human consumption. An initiative to work on this Directive is planned for 2011.
- Seveso II is currently under review. It should be considered to revise the Directive in view of specific new risks related to hydraulic fracturing, and to require the detailed declaration of substances that might be involved in accidents.

[9] This is an unofficial codified version of the EIA Directive provided by the European Union.

Gap 4 - Approval of chemicals remaining in the ground

When hydraulic fracturing is completed, a mixture of hazardous materials remains in the ground. These chemicals are distributed over time and space in a neither controllable nor predictable fashion. [Teßmer 2011] suggests that an introduction of chemicals that will partially remain in the ground should require an approval under consideration of possible long-term effects.

Gap 5 - No BREF (Best Available Technique Reference) on hydraulic fracturing yet

The European IPPC Bureau publishes reference documents on the best available techniques (BAT). "Each document generally gives information on a specific industrial/agricultural sector in the EU, techniques and processes used in this sector, current emission and consumption levels, techniques to consider in the determination of BAT, the best available techniques (BAT) and emerging techniques." [EC BREF] Legislative authorities at national and international level can refer to these and incorporate them in laws and provisions. There is no such document yet on hydraulic fracturing. Due to the risks imposed by hydraulic fracturing on the environment and human health, consideration should be given as to whether to define harmonised requirements for this intricate process in a BREF on hydraulic fracturing.

Gap 6 - Capacity of water processing facilities

In the US, problems were reported with the water processing capabilities of sewage treatment plants that discharged water to rivers. In October 2008, the level of total dissolved solids ("TDS") in the Monongahela River exceeded water quality standards and therefore the volume of gas drilling wastewater they were allowed to accept, was reduced from 20% to 1% of their daily flow. [NYC Riverkeeper]

As a precaution, the prior examination of the capacity of waste water facilities should be required.[10]

Gap 7 - Public participation in decision-making at regional level

There is a general tendency of citizens to claim more participation rights in decision making for industrial projects with an impact on the environment and possibly human health. As part of the review of the Seveso II Directive, one of the main changes proposed is:

"To strengthen the provisions relating to public access to safety information, participation in decision-making and access to justice, and improve the way information is collected, managed, made available and shared" [EC 2011 S]

Industrial projects such as exploitation of shale gas or tight oil with a potentially significant effect on the environment and residents should require public consultation as part of the authorization procedure.

Gap 8 - Legal effectiveness of the Water Framework Directive and associated legislation

The Water Framework Directive entered into force in the year 2000. As hydraulic fracturing was not a prominent topic at that time, hydraulic fracturing and the related risks were not considered. The list of priority substances is reviewed every four years; the next review is due in 2011. The Directive should reassessed in view of its capacity to effectively protect water from accidents and regular operations accompanying hydraulic fracturing.

[10] The Directive on the management of waste from the extractive industries will be adapted as the regulations on insurance coverage will be modified.

Gap 9 – Life Cycle Analysis (LCA) mandatory

Life Cycle Analyses are actively promoted by the European Commission stating on its Life Cycle website:

"The key aim of Life Cycle Thinking is to avoid burden shifting. This means minimising impacts at one stage of the life cycle, or in a geographic region, or in a particular impact category, while helping to avoid increases elsewhere." [EC LA]

This holds especially for hydraulic fracturing, where strong impacts in specific geographic regions will occur, not the least due to the number of wells per km² and the required infrastructure. Consideration should be given to including a cost/benefit analysis as compulsory, based on an extensive LCA (including greenhouse gas emission and resource consumption) for each individual project in order to demonstrate the overall benefits for the society.

5. AVAILABILITY AND ROLE IN A LOW-CARBON ECONOMY

KEY FINDINGS

- Many European countries have shale gas resources, butonly a small amount of the gas in place might be converted into reserves and ultimately be produced.
- Gas shales are extended over large areas with low specific gas content. Therefore, the extraction rate per well is much lower than in conventional natural gas extraction. The development of shale gas requires many wells with corresponding impacts on landscape, water consumption and the environment in general.
- The decline rate of shale gas wells is up to 85% in the first year. A typical regional production profile rises fast but soon slows down. After several years all new wells are used to compensate for the decline of elder wells. As soon as the development of new wells stops, the overall production immediately declines.
- Even an aggressive development of gas shales in Europe could only contribute to the European gas supplies at one-digit percentage share at best. It will not reverse the continuing trend of declining domestic production and rising import dependency. Its influence on the European greenhouse gas emissions will remain small if not negligible, or could even be negative if other more promising projects are skipped due to wrong incentives and signals.
- At regional level shale gas might play a more significant role, e.g. in Poland which has large shale resources and a very small gas demand (~14 bcm/yr) of which 30% are already produced domestically.
- The oil shale in the Paris basin also contains large quantities of tight oil. Since more than 50 years oil has been produced from this formation. Since the easy to produce volume is consumed, further extraction would require many horizontal wells (up to 6 or more wells per km²) with hydraulic fracturing.

5.1. Introduction

This chapter assesses the potential shale gas and shale oil and tight oil resources and describes their probable role in the European gas sector. As experiences with European shale gas developments are still missing, these forward looking statements are speculative to a certain extent.

In order to minimize the uncertainties, the experiences in the USA are described and analysed in order to understand the typical characteristics of shale gas developments. Based on this experience, a hypothetical production profile is sketched and adjusted to the European situation. Though quantitative details might differ, the qualitative behaviour might help to better understand the possible role of shale gas.

The first subchapter summarizes the latest available resource assessment of European shale gas deposits. This assessment was performed by the US Energy Information administration [US-EIA 2011]. It includes the specification of some key parameters of US shales. This subchapter also gives a survey of shale oil deposits in Europe and the historical world production of shale oil with some links to tight oil, as these two are often mixed. A short overview of the tight oil development in the Paris basin in France is provided.

Since the understanding of the typical production profiles of shale gas fields is essential, the analysis of major US developments is summarised in an own subchapter which concludes with the modelling of a hypothetical shale development, exhibiting the typical characteristics with the fast decline of the individual wells. This is combined with a more detailed analysis of European shales. Finally, some conclusions concerning the possible role of shale gas production in reducing CO_2 emissions are drawn.

5.2. Size and location of shale gas and oil deposits compared to conventional deposits

5.2.1. Shale gas

Resource assessments of European Gas shales

Hydrocarbon assets are classified into resources, and reserves. Further classification takes care of the degree of geological certainty of the formation (speculative, possible, indicated, inferred, measured, proved), of technological and of economic aspects. A resource estimate is generally of much lower quality than a reserve estimate as it is based on a much weaker geological data analysis. Though not mandatory, resources are usually measured in terms of gas-in-place (GIP), while reserves already include assumptions on their recovery under common technical and economic conditions. Typically, 80 per cent of the gas-in-place (GIP) of conventional gas fields are extracted, though – depending on geological complexity – this range may vary from 20 up to more than 90 per cent. The extraction rate of unconventional gas fields is much smaller. Therefore, shale gas resources are not to be mistaken for gas reserves. Based on existing experience there is a probability of only 5-30 per cent that the evaluated gas-in-place might be converted into recoverable gas reserves over the next several decades.

Table 16 shows the conventional gas production ("Production 2009") and reserves ("Proven conventional gas reserves"). These numbers are compared with the assumed shale gas resources. The resource data are taken from a recent assessment by the US Energy Information Agency. [US-EIA 2011] According to definition, proven gas reserves should be producible with existing or planned wells under present economic and technical conditions. In-place resources of shale gas are estimates based on rough geological parameters such as extension and thickness of area, porosity and gas per volume, etc. In parts, these data are experimentally verified, but in most cases these are rough estimates at a large scale. These data for the gas in place resources are presented in the fourth column ("Shale-Gas GIP").

Technically recoverable shale gas resources are those quantities which according to the estimate might be producible with existing technology if the field is extensively developed. The assumed technically recoverable shale gas resources divided by the gas in place resources give the recovery factor, or yield. These data are in the last column ("Assumed Recovery Factor"). On average, US-EIA assumed a recovery factor or yield of 25% between gas in place and technically recoverable resources. The original US-units are converted into SI units.[11]

[11] A table with conversion factors is provided in the annex.

Table 16: Assessment of conventional gas production and reserves compared to shale gas resources (Gas-in-Place as well as technically recoverable shale gas resources); GIP = gas in place; bcm = billion m³ (the original data are converted into m³ by 1000 Scf= 28.3 m³)

Country	Production 2009 (1) [bcm] 2009 (1) [bcm]	Proven conventional Gas reserves [bcm] (1)	Shale-Gas GIP [bcm] (2)	Technically Recoverable Shale-Gas Resources [bcm] (2)	Assumed Recovery Factor (2)
France	0.85	5.7	20,376	5,094	25 %
Germany (data for 2010)	15.6 (13.6)	92.4 (81.5)	934	226	24.2 %
Netherlands	73.3	1,390	1,868	481	25.7 %
Norway	103.5	2,215	9,424	2,349	24.9 %
UK	59.6	256	2,745	566	20.6 %
Denmark	8.4	79	2,604	651	25 %
Sweden	0	0	4,641	1,160	25 %
Poland	4.1	164	22,414	5,292	23.6 %
Lithuania	0.85	0	481	113	23.5 %
Total EU 27 +Norway	**266**	**4202**	**65,487**	**16,470**	**~25 %**

Source: (2) US-EIA (2011), (1) BP (2010)

In order to judge the relevance of such resource estimates, the analysis of some major US gas shales is useful as European experience with shale gas developments is still in its infancy. Only a certain share of the technically recoverable shale gas resource will be converted into reserves and produced over time, since further restrictions limit the access to the whole shale. For instance, surface geography, protected areas (e.g. drinking water reservoirs, wild life refuges, national parks) or simply densely populated areas will restrict access to the shales. For that reason a short comparison with US experience is provided in the following in order to understand how big the share of the recoverable resource is which might ultimately be produced. In parts, one can learn from historical trends and their extrapolation here, even if the activities are not terminated yet. Based on US experience it is not unlikely that significantly less than 10 per cent of the gas in place might ultimately be produced within the next several decades.

Resource assessments of major US gas shales and some key parameters

The USA has a long experience from more than 50.000 wells over more than 20 years. Table 17 shows some key parameters of major US gas shales. Covered area, depth and thickness of the shale and the total organic carbon content (TOC) are such parameters. The TOC together with the rock porosity is a measure of the gas content of the shale. From these data, the gas in place and the recoverable resources in Europe are estimated by ALL consulting. These data together with the estimated production rate per well are taken from [ALL consulting 2008]. They are compared with recent developments such as the cumulative production until 2011, and the production rate per well in 2010.

The production rate per well in 2010 (see Table 17, last line) closely matches the forecast for projects in the Barnett shale and in the Fayetteville shale. The earlier developed Antrim shale exhibits a much smaller production rate per well as forecasted while the latest developed Haynesville Shale so far still shows a larger rate. These aspects are discussed in more depth later on.

Table 17: Assessment of major gas shale developments in the USA (the original data are converted by 1000 Scf= 28.3 m³ and 1 m = 3 ft)

Gas Shale Basin	Units	Antrim	Barnett	Fayetteville	Haynesville
Estimated Area	km²	30000	13.000	23.000	23.000
Depth	km	0.2-0.7	2.1-2.8	0.3-2.3	3.5-4.5
Net thickness	m	4-25	30-200	7-70	70-100
TOC	%	1-20	4.5	4-9.8	0.5-4
Total Porosity	%	9	4-5	2-8	8-9
Gas in Place	Mio m³/km²	70	720	65	880
Gas in Place	Tm³	2.2	9.3	1.5	20.3
Recoverable Resources	Tm³	0.57	1.2	1.2	7.1
Yield	%	26%	13%	80%	35%
Cum production (Jan 2011)	Tm³	0.08	0.244	0.05	0.05
Estimated production rate (2008)	1000 m³/day/well	3.5-5.7	9.6	15	18-51
Real gas production rate 2010	1000 m³/day/well	~1	9.5	21.8	~90

Source: Arthur (2008)

The cumulative production of these shales and their historical trends provide an indication of whether it is realistic to assume that their extrapolation will come close to the estimated recoverable resources or not. At first glance, after almost 30 years of development of the Antrim shale, only 14% of the recoverable resource or 3.5% of the gas in place are produced, though the field passed its production maximum already in 1998. Obviously, only marginal additions can still be expected as the production has declined for 10 years by 4-5% annually. Even the Barnett shale passed its production maximum early in 2010 [Laherrere 2011], when 20% of the recoverable resource or 2.5% of the gas in place were produced. The Fayetteville shale seems to have reached its maximum in December 2010 (see Figure 9), when about 4% of its recoverable resource or 3% of the gas in place are produced. Only Haynesville, the latest shale under development is still in steep production rise after 2 years of development. At present, less than 0.1% of the recoverable resource or 0.02% of the gas in place have been extracted from this shale.

From these considerations it seems that less than 5% of the gas-in-place will be produced in the Antrim shale and about 5-6% in the Barnett Shale and in the Fayetteville Shale, respectively. Only the Haynesville shale might still see a further rise of production, pushing the extraction rate possibly somewhat higher – here, it is too early for final conclusions.

5.2.2. Shale oil and tight oil

The above given geological history of shale gas deposits holds also for the origins of shale oil with the difference that hydrocarbons from oil shale are in a premature status of oil formation called kerogen. In order to transform kerogen into oil, it must be heated up to 350-450°C. Geologists call this temperature range the "oil window". The state of maturity of a source rock determines the composition of the organic material and the share of kerogen or even of crude oil which finally results from the heating process. Therefore, any shale oil deposit might have individual characteristics which influence its production properties. In most cases the immaturity of the shale requires huge energetic, economic and technological efforts with corresponding environmental side effects in order to transform the immature kerogen to crude oil by heating.

Generally, oil shale resources are huge, at world level probably exceeding conventional oil reserves. A resource estimate for Europe is shown in Table 18. Oil shales have been produced since decades and sometimes since centuries. But due to their poor performance these deposits never played a major role and their development was stopped when better alternatives were available. Therefore, these resource estimates are only a rough measure of their occurrences. At present, only Estonia produces oil from oil shales at a rate of 350 kt per year. [WEC 2010]

Table 18: Estimates of shale oil resources in Europe (in Mt)

Country	Resource in place (WEC 2010) [Gb]	Resource in place (WEC 2010) [Mt]
Austria	0.008	1
Bulgaria	0.125	18
Estonia	16.286	2,494
France	7	1,002
Germany	2	286
Hungary	0.056	8
Italy	73	10,446
Luxembourg	0.675	97
Poland	0.048	7
Spain	0.28	40
Sweden	6.114	875
UK	3.5	501
EU	109.1	15,775

Source: [WEC 2010]

Resource data on tight oil are very uncertain and often do not exist as these are integrated in the conventional oil statistics. Also, kerogen-rich oilshales are mixed with crude oil in pores and layers in between with low permeability. The mixture depends on whether part of the kerogen in the source rock has passed the oil window or not in its geological history. The extraction of this oil falls in the category of tight oil production, though it takes place in between oil shales. For instance, the Paris Basin contains a huge oil shale.

However, the presently relevant projects focus on the extraction of the tight oil in this shale. [Leteurtrois et al. 2011]

The Paris basin is located below and around Paris, France, with roughly an oval shape, 500 km east-west axis and 300 km north-south axis. Its total size covers about 140.000 km². [Raestadt 2004] East of Paris oil, bearing layers come closer to the surface. [Leteurtrois et al. 2011] A first well was drilled in 1923. During the 1950ies und 1960ies interest of oil companies grew and many exploration wells were drilled, some smaller fields were discovered, but only about 3 percent of these early wells became commercial. [Kohl 2009] A second boom phase took place during the 1980ies in the aftermath of the two oil price shocks when seismic trucks even came along the Champs Elyseés assessing the geological structure also below Paris. Several larger conventional oil fields were discovered at that time. In total, since 1950 about 240 Mb of oil have been extracted from the Basin from more than 800 wells. All of these developments were conventional oil extraction without hydraulic fracturing.

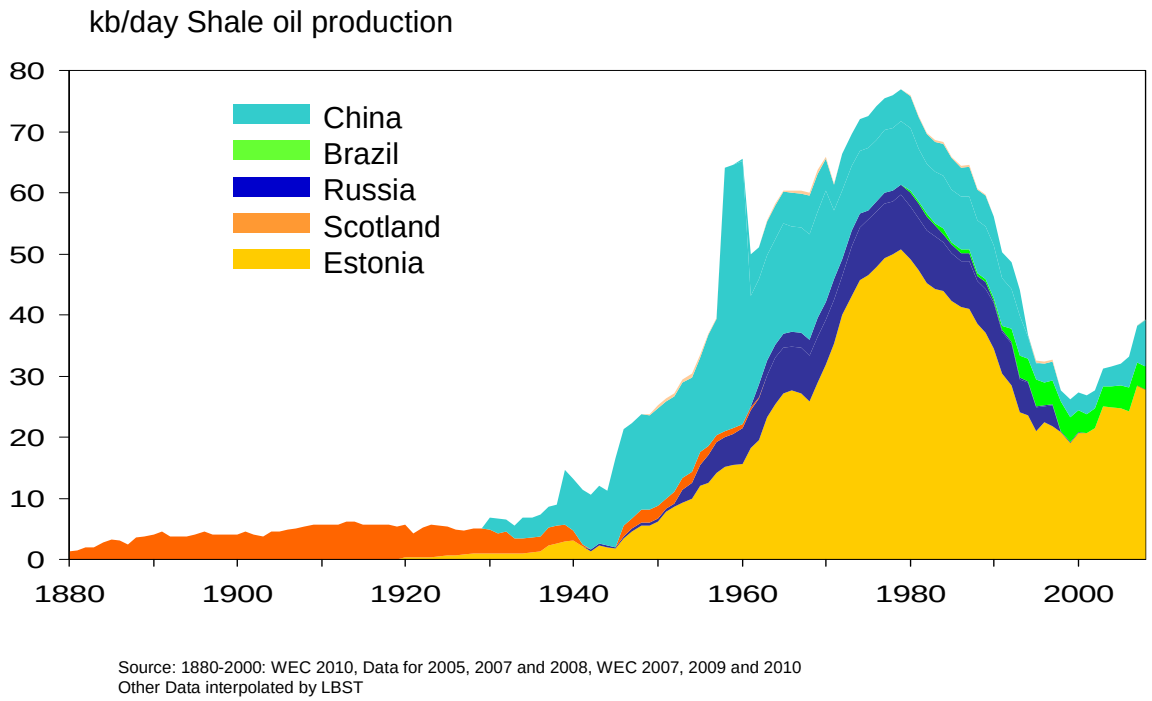
Recent interest grew when a small company, Toreador, after the analysis of old exploration protocols announced first estimates about the possible oil rich basin stretching from below Paris to the vine rich Champagne. Toreador has focussed its commercial activities on France, and has partnered with Hess Corp. for the development of the shale. [Schaefer 2010] Hydraulic fracturing is planned to play a major role in developing the basin and extracting the oil. Up to 65 Gigabarrels (Gb) oil or even more are said to be contained in the formation. [Kohl 2009] However, these figures are not confirmed independently, and should thus be taken with caution.

It should be noted that there are always commercial interests behind major development planswith huge possible resource numbers, which should thus be judged very cautiously. Often, these numbers are crude estimates on the high side not reflecting any problems which might hamper the possible extraction. At present, it is almost impossible to gather enough information in order to judge the actual size and production opportunity of this shale, as both enthusiastic [Schaefer 2010] as well as sceptical [Kohl 2009] comments are available in the literature. A novelty might be the use of horizontal wells with hydraulic fracturing in the basin at a large scale. It is estimated that there are about 5 Mb oil in place per km² which might be developed with horizontal wells. The typical production rate per well is optimistically believed to achieve 400 barrel/day first month production, followed by a decline of 50% per year. [Schaefer 2010]

A slightly similar though in some aspects different formation is the Bakken shale in the USA, where tight oil within an oil shale formation is produced.

Figure 6 shows the historical development of worldwide shale oil production since 1880. Even since 1830 shale oil was produced in France. It stopped in 1959. [Laherrere 2011] However, the extracted oil volume is too small to be visible in the graph. For the figure, the oil shale is converted into shale oil by assuming an oil content of 100 l or 0.09 tons of oil per ton of shale.

Figure 8: World production of shale oil; original units are converted with 1 ton of oil shale equals 100 l of shale oil



Source: [WEC 2007, 2009, 2010], Some data for 2001-2005 and 2007 are LBST estimates

5.3. Analysis of producing shale gas plays in the United States of America

5.3.1. First month production rate

Common characteristics of any shale gas deposit are:

- the low permeability (hundred thousand to million times less than in conventional fields [Total 2011]),
- the low specific gas content per volume, and
- the huge area covered by the shale.

Wells are drilled into the gas containing shale. In order to increase the contact surface between the gas containing pores and the well, various cracks are created by means of hydraulic fracturing. But nevertheless, the total accessible volume is small compared to that of conventional wells.

Therefore, the initial production rate is very small compared to wells in conventional gas fields. In addition, the companies aim to develop the most promising areas within a shale first. For instance, early vertical wells in the Barnett shale typically produced 700,000 m³ (25 MMcf) per month during the first full month operation. This flow declined to about 400,000 m³ (15 MMcf) per month for the latest developed wells. [Charpentier 2010]

A recent survey by the USGS confirms that the first full month production of vertical wells on average of all investigated wells is below 700.000 m³ per month. The only exception is the Bossier shale which showed a fourfold initial production rate (2.8 million m³ per month). However, its development started already 40 years ago confirming the early development of the most producible fields.

Horizontal wells on average show a larger initial production rate. In the Barnett shale or the Fayetteville shale it amounts to 1.4 million m³ per month (50 MMcf). Only the latest developed Haynesville shale exhibits an unusually high initial production rate of 7-8 million m³/month (~260 MMcf). This higher initial production rate, however, was already expected before, due to the geological parameters of this shale (see Table 17).

5.3.2. Typical production profiles

The initial pressure after fracturing is far above the natural deposit pressure. After fracturing the pressure is released. This results in a fast backflow of wastewater (frac-water) which contains all mobile ingredients and contaminations of the deposit including the natural gas itself. Due to the large flow rate compared to the deposit size, the deposit pressure drops very fast. This results in a steeply declining production profile. While conventional gas fields show decline rates in the order of several per cent per year, the production from gas shales declines with several per cent per month. A historical analysis of some US shales exhibits that the initial production rate is much smaller and the following decline rate much steeper than in conventional fields. Typically, the production drops at a decline rate of 50, 60 or even more per cent within the first year. [Cook 2010] Experience shows that the latest developed shale, Haynesville, has decline rates of 85 per cent in the first and 40 per cent in the second year. Even after nine years the decline rate is still 9 per cent. [Goodrich 2010] It seems that companies in Haynesville try to optimize production in a way to extract the gas as fast as possible.

5.3.3. Estimated ultimate recovery (EUR) per well

The statistical analysis of the production profiles allows to calculate the estimated ultimate recovery per well comparing various shales. Early vertical wells in the Barnett shale contain an EUR of about 30 million m³. This doubled for new wells to 60 million m³ for both, vertical and horizontal wells. Most other shale formations (Fayetteville, Nancos, Woodford, Arkoma Basin) exhibit much smaller gas quantities close to or below 30 million m³. Only in the early developed Bossier shale ultimate gas production from single wells was up to 90 million m³. The Haynesville shale exhibits estimated cumulative production volumes in between with an average around 75 million m³ per well. [Cook 2010]

5.3.4. Some examples in the USA

The Antrim shale in Michigan is only several hundred meters below the surface. Therefore, its development started early and the addition of new wells was fast. In 1998 it reached its maximum production. This was followed by a field decline of 4-4.5% per year though still today new wells are developed.

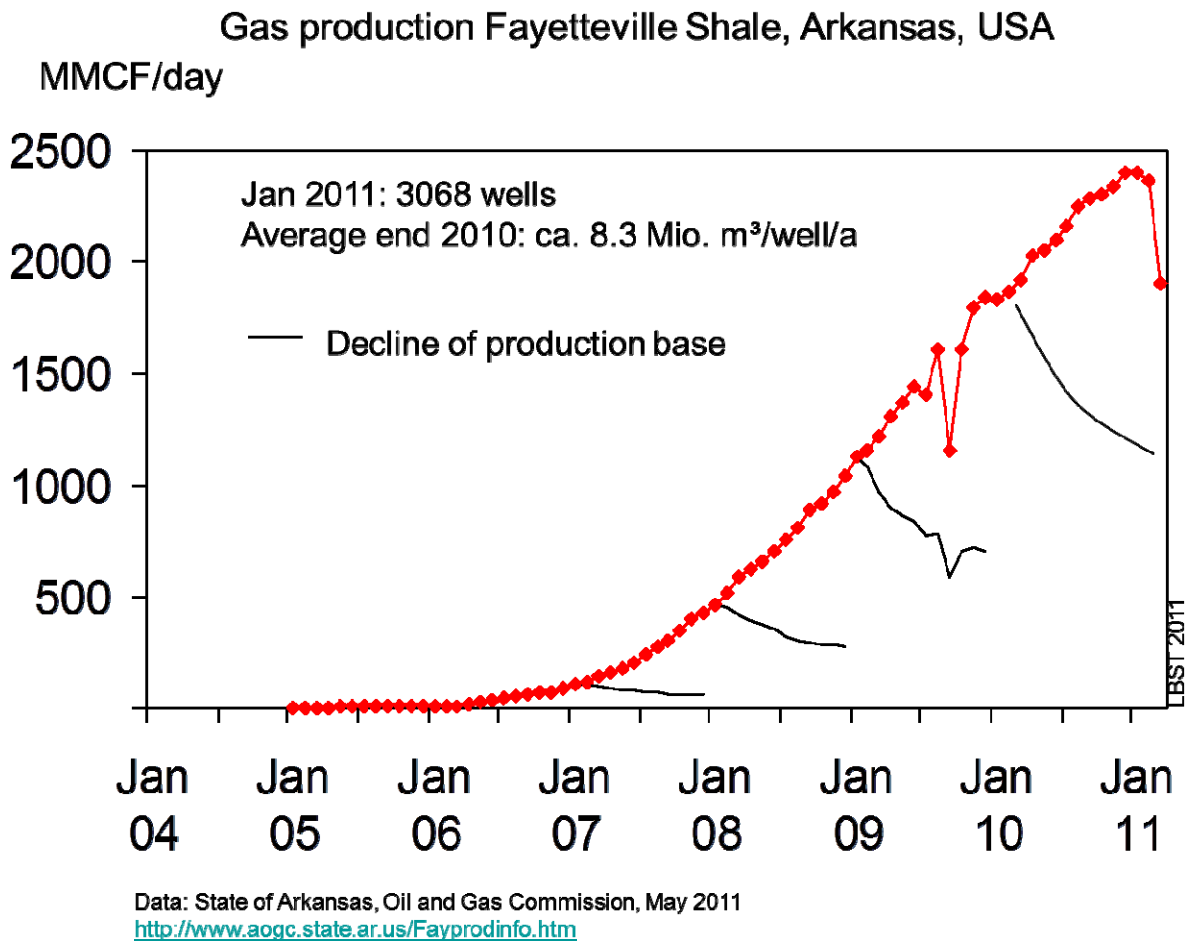
In parallel to the adoption of the Clean Energy Act by the US Parliament in 2005 which exempted hydrocarbon drilling from restrictions of the Save Drinking Water Act of 1974, the development of the Barnett shale increased. Within a few years, its production rose to 51 billion m³ in 2010 from almost 15.000 wells. On average, the 13,000 km² field is developed with 1 well per km², though at prospective areas more than 5 wells are drilled per km². Due to the fast development, the field reached its maximum production in 2010.

The further addition of more than 2,000 wells in 2010 was not able not prevent the onset of a production decline. At the end of 2010, the typical production rate per well was 3.4 million m³ per year.

Also the Fayetteville shale was developed from 2005 onward. Though smaller in size and yield, it exhibits a typical production profile which is shown in Figure 9. Black lines show the declining base production if no new wells would have been developed over the years.

The cumulative decline of the base production reflects the high decline rate which in Fayetteville is 5 per cent per month. The dips in September 2009 and March 2011 are due to the shut down of the wells in one part of the field because of severe weather restrictions. Analysing the individual well profiles, it is very likely that Fayetteville has already reached peak production in December 2010. The average production rate at the end of 2010 was about 8 million m³/yr per well.

Figure 9: Gas production from the Fayetteville shale in Arkansas



Source: own source based on [Arkansas 2009]

In 1993, Chesapeake, a small company with a turnover of 13 million $, grew predominantly with the development of the Fayetteville Shale. [Chespeake 2010] Due to the shale gas boom its turnover had increased to more than 5 billion $ by 2009. Last year it sold its entire assets in the Fayetteville shale for 5 billion $ to the company BHP Billiton. [Chon 2011]

The latest field under development is Haynesville. In 2010, it became the largest producing shale gas field in the USA, surpassing the Barnett shale. The fast production rise is predominantly due to higher initial production rates up to 7-8 million m³ per well in the first month. The higher production rate was already expected due to the different geological parameters of that field combined with the strategy to extract the gas as fast as possible. As already mentioned, this is followed by an unprecedented decline rate of 85 per cent in the first year.

5.3.5. Key parameters of major European gas shales

Table 19 specifies some key parameters of the major European gas shales. The investigated prospective area is much smaller than the total shale area as some exclusion criteria are already applied. This must be kept in mind when the specific gas in place per area is compared with the data in Table 17 where the whole shale extension was used for comparison. The gas in place (GIP) per km² gives a measure of how much gas might be produced from a single well.

The total organic carbon content (TOC) is a measure of the gas content of the shale, relevant for the resource estimate. Together with the layer thickness it also defines the preference of vertical or horizontal wells, their extension and the optimum well density.

Based on these considerations Eastern European shales in Poland seem to be the most promising European shales exhibiting the largest gas in place volumes. Other shales are much less producible, though their extension is much larger.This implies that the specific effort to produce that gas increases considerably with corresponding impacts on land use, water demand, etc.

Keeping these aspects in mind, it is very likely that almost all European shales except in Poland and maybe in Scandinavia might exhibit extraction rates and reserves comparable or even smaller to the Fayetteville or the Barnett shale in the USA.

Table 19: Assessment of key parameters of major European Gas shales (the original data are converted into SI units and rounded)

Region	Basin / Shale	Prospective Area (km²)	Net-Thickness (m)	TOC (%)	GIP (Mio m³/km²) (2)
Poland	Baltic	8846	95	4	1600
Poland	Lublin	11660	70	1.5	900
Poland	Podlasie	1325	90	6	1600
France	Paris	17940	35	4	300
France	South East	16900	30	3.5	300
France	South East	17800	47	2.5	630
Central Europe	Posidonia	2650	30	5.7	365
Central Europe	Namurian	3969	37	3.5	600
Central Europe	Wealden	1810	23	4.5	290
Scandinavia	Alum	38221	50	10	850
UK	Bowland	9822	45	5.8	530
UK	Liassic	160	38	2.4	500

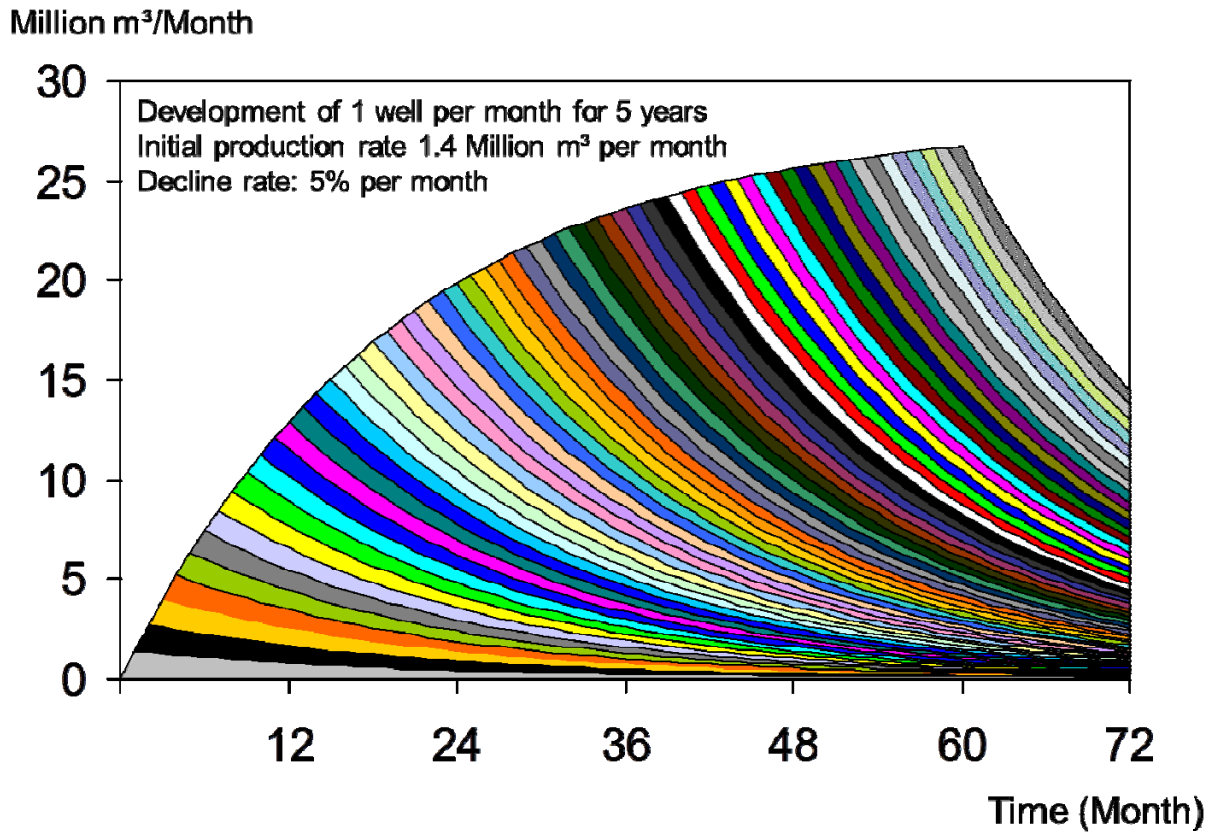
Source: US-EIA (2011)

5.3.6. Hypothetical field development

A major characteristic which distinguishes shale gas production from conventional gas production is the steep decline rate of individual wells. A hypothetical shale development may be constructed by adding many identical production profiles. Figure 10 shows the results of such a scenario calculation by summing up the production profiles within a shale with a new well being connected each month. The data are taken to be similar to those in the Barnett shale with typical first month production of 1.4 million m^3 and 5% per month decline rate. After 5 years 60 wells are connected which produce about 27 million m^3/month or 325 million m^3/year. Due to the steep decline of producing wells the average production rate per well decreases to 5 million m^3 per well per year after 5 years.

This development scenario is used in the following to estimate the impact of shale gas production on the European gas market.

Figure 10: Typical shale development by adding new wells at a constant development rate of one well per month



Source: own source

5.4. Role of shale gas extraction in the transition to a low-carbon economy and the long-term reduction of CO_2 emissions

5.4.1. Conventional gas production in Europe

The Natural gas production in the EU already passed peak production in 1996 at a production rate of 235 bcm per year. In 2009, production was already down by 27 per cent to 171 bcm/yr. In parallel, consumption rose from 409 bcm in 1996 to 460 bcm in 2009, an increase of 12%. Therefore, the share of domestic production declined from 57% to 37%.

Including Norway, peak production was in 2004 at 306 bcm/yr and declined to 275 bcm/yr in 2009 (-11%). The imports from outside EU or Norway rose from 37% in 2004 to 40% in 2009. [BP 2010]

The latest World Energy Outlook by the International Energy Agency expects a further production decline to below 90 bcm/yr in 2035 or, including Norway, to 127 bcm/yr.

Natural gas demand is still expected to rise by 0.7% annually, resulting in 667 bcm/yr in 2035. [WEO 2011] Unavoidably, the gap between demand and declining domestic supply rises further, forcing the EU to increase imports to more than 400 bcm/yr in 2035, equivalent to an import share of 60%.

5.4.2. Probable relevance of unconventional gas production on European gas supply

The IEA World Energy Outlook 2011, special edition, focuses on the possible role of unconventional natural gas. The development of unconventional natural gas resources in Europe will probably be led by Poland which is believed to possess 1.4 – 5.3 Tcm of shale gas [WEO 2011], predominantly in the north. By mid-2011, Poland has already granted 86 licences for exploration of unconventional gas.

However, WEO 2011 sees a number of hurdles which must be overcome: “Because of the relatively large number of wells needed to be drilled, obtaining approval from local authorities and communities may not be straightforward. The treatment and disposal of large quantities of waste-water may also complicate projects. In addition, third party access to pipeline infrastructure will require domestic policy reform.” But nevertheless, the potential is seen to be large: “Notwithstanding the technical, environmental and regulatory barriers, shale gas has the potential to radically change the Polish energy landscape.” [WEO 2011]

Despite these remarks, the report sees only a marginal influence of shale gas production for Europe. The average decline of domestic gas production including conventional and unconventional gas is seen at 1.4% per year.

The following basic scenario calculation based on the discussed production profiles sketches the size of the effort needed to transform possible shale gas resources into production. It also sketches the maximum influence of drillings which might be performed in gas shales. This underlines the statement that unconventional gas probably will not have the potential to reverse the declining European gas production.

In Europe about 100 rigs are available [Thornhäuser 2010]. An assumed average drilling time of 3 months per well would allow to drill 400 wells per year in Europe at maximum. This would imply that all rigs are used only for drilling in gas shales though not all rigs are adequate for that purpose and other wells are still developed. Further assuming a first month production rate of 1.4 million m^3, after 5 years, 2000 wells would have been drilled with a combined output of 900 million m^3/month or 11 billion m^3/yr. The production profile would look similar to the one in Figure 10,but scaled to the larger number of wells. These wells would contribute less than 5 per cent to the European gas production over the next decades, or 2-3 per cent of the gas demand. Even continuing the development rate at that speed (400 additional wells per year) would only marginally increase the production further, as the steep decline rate reduces the production by almost 50 per cent within one year if the development of new wells were be stopped.

5.4.3. Role of shale gas production for long-term reduction of CO_2 emissions

The combination of all technical, geological as well as environmental aspects discussed above makes it almost impossible that even an aggressive development of gas shales could have a relevant influence on future CO_2-Emissions of Europe.

As already mentioned before, the success of shale gas production in the USA was partly made possible by lowering the environmental restrictions within the Clean Energy Act in 2005. Even that aggressive and cheap development resulted in a share of only 10% contribution to the US natural gas production from several ten thousand wells.

In the meantime hydraulic fracturing is controversially discussed in the USA. Environmental restrictions might reduce further shale gas developments very fast, as described in an industry study performed by Ernst&Young: "The main factor that is likely to inhibit the projected growth in shale gas production is new environmental legislation", and further-on: "A comprehensive study is currently being undertaken by the US Environmental Protection Agency into the impact of hydraulic fracturing on water quality and public health. Investment in shale gas developments may dry up if hydraulic fracturing were to be outlawed or significantly limited as a result of the findings of the study." [Ernst&Young 2010]

An aggressive development of shale gas production in Europe could result in a contribution up to a few per cent to the European gas production. Due to the long lead times it is very probable that over the next 5-10 years the production remains almost negligible.

However, these statements do not exclude that a certain relevant amount of gas could be produced at regional level.

Assuming environmental restrictions to increase costs and to reduce the speed of developments, shale gas production in Europe will remain almost marginal.

The European gas production has been in decline for several years. This decline will not be stopped by unconventional gas developments. Even industry studies see the contribution of shale gas production to the European gas supply growing very slowly and not exceeding more than a few per cent of the demand. [Korn 2010]

Therefore, unconventional gas production inside Europe will not have the potential to reduce European import needs of natural gas. This does not necessarily hold for Poland. Here, it might have a visible impact as the low present production of 4.1 bcm covers about 30% of the low domestic demand of 13.7 bcm. [BP 2010]

Due to rising gas demand from other world regions and declining base production in Russia it cannot be ruled out – to say the least – that natural gas imports to Europe cannot be increased over the next two decades in the way European demand forecasts would require. In that case the European policy to increase gas demand would be counterproductive. Adequate adaptation measures would be to continuously reduce the total gas demand by appropriate incentives. Investments in shale gas projects could very likely become counterproductive as these could have a short but limited influence on the domestic gas supply and as these would give wrong signals to consumers and markets, namely to continue a resource dependence at a level which would not be justified by an ensured supply. The unavoidable faster decline would worsen the situation as it would reduce the available lead-time for substitutions and as huge investments would have been spent into these projects and into this dependence which should have been better used for transition technologies.

6. CONCLUSIONS AND RECOMMENDATIONS

Existing mining laws in Europe and related regulations affecting mining activities do not take care of the specific aspects of hydraulic fracturing. There are major differences between mining related regulations in European Member States. In many cases, mining rights are privileged over citizens' rights, and local political authorities ofen do not have an influence on possible projects or mining sites as these are granted by national or state governments and their authorities.

In a changing social and technical environment where climate change issues and the transition to a sustainable energy system are top priorities and where public participation at regional and local levels is being strengthened, national interests for mining activities and interests of regional and local governments as well as of the affected population need to be re-assessed.

A prerequisite of such an assessment should be a mandatory Life Cycle Analysis of new projects including an environmental impact analysis. Only a full cost/benefit analysis provides a proper base for a judgement about the relevance of individual projects and their justification.

The technology of hydraulic fracturing has a significant impact in the USA, which at present is the only country with several decades of experience and long-term statistical records.

The technology for shale gas development has characteristics which partly show unavoidable environmental impacts, partly have a high risk if the technology is not used adequately and partly have a possible high risk for environmental damages and hazards to human health even when applied properly.

One of the unavoidable impacts is huge land consumption and major landscape changes as the well density must be very high in order to fracture the source rocks at large scale for access to the stored gas. The individual well pads – in the USA up to 6 well pads per km^2 or even more are reported – must be prepared, developed and connected by roads which are accessible for heavy duty transport. Producing wells must be connected by gathering lines with low throughput, but also with purging units to separate waste water and chemicals, heavy metals or radioactive ingredients from the produced gas before it is pumped into the existing gas grid.

Possible risks due to inconvenient handling include accidents, e.g. blow out with frac-water spills, leakages from wastewater or from fracture fluid ponds or pipes, groundwater contamination due to improper handling or unprofessional cementing of the well casing. These risks can be reduced and probably avoided with adequate technical directives, cautious handling practise and supervision by public authorities. However, all these safety measures increase the project costs and slow down the development speed. Therefore, the risks of accidents increases with increasing economic pressure and the need for speeding up development. More wells per time need higher efforts for supervision and monitoring.

Finally, some risk is inherent to uncontrolled fracturing which results in uncontrolled mobilization of fracture liquids or even of the natural gas itself. For instance, it is well known that small earthquakes can be induced by hydraulic fracturing which might mobilize gas or fluids through "naturally" created fractures.

Experience from the USA shows that in practise many accidents happen. Too often, companies are fined from official authorities for violations. These accidents are partly caused by leaky or malfunctioning equipment, partly caused by bad practises in order to save costs and time, partly due to unprofessional casing of the wells and partly due to groundwater contamination through undetected leaks.

At a time when sustainability is key to future operations it can be questioned whether the injection of toxic chemicals in the underground should be allowed, or whether it should be banned as such a practice would restrict or exclude any later use of the contaminated layer (e.g. for geothermal purposes) and as long-term effects are not investigated. In an active shale gas extraction area, about 0.1-0.5 litres of chemicals are injected per square meter.

Greenhouse gas emissions from natural gas are usually lower than from other fossil fuels at about 200 g CO_2-equivalent per kWh. Due to the low gas recovery per well and fugitive methane losses, the higher efforts for development, and the low throughput of gathering lines and compressors the specific emissions of shale gas use are higher than from conventional gas fields. Nonetheless, assessments from US practice cannot simply be transferred to the European situation. A realistic assessment based on project data is still missing. The assessment performed in this study might be seen as a first step towards such an analysis.

The present EU-legislative framework requires an environmental impact assessment only when the production rate of the well in question exceeds 500.000 m^3 per day. This limit is far too high and ignoring the reality of shale gas wells which typically produce in the order of several ten thousand m^3 per day in the beginning. An environmental impact assessment with public participation should be mandatory for each well.

Regional authorities should possess the right to exclude sensitive areas (e.g. potable water protection zones, villages, arable land, etc.) from possible hydraulic fracturing activities. Moreover, regional authorities should be strengthened in their autonomy to decide about the banning or licencing of hydraulic fracturing in their territory.

The present privileges of oil and gas exploration and production must be reassessed in view of the following facts that

- European gas production has been in steep decline for several years and is expected to decline by another 30 per cent or more until 2035,
- European demand is expected to rise further until 2035,
- imports of natural gas will unavoidably increase further if these trends become reality,
- it is by no means guaranteed that additional imports in the order of 100 billion m^3 per year or more can be realised.

The resources for unconventional gas in Europe are too small to have any substantial influence on these trends. This holds even more as the typical production profiles will allow extracting only a limited share of these resources. Environmental obligations will also increase project costs and delay their development. This will reduce the potential contribution further.

Whatever reasons for allowing hydraulic fracturing exist, the justification that it helps to reduce greenhouse gas emissions are rarely among them. On the contrary, it is very likely that investments in shale gas projects – if at all – might have a short-living impact on gas supply which could be counterproductive , as it would provide the impression of an ensured gas supply at a time when the signal to consumers should be to reduce this dependency by savings, efficiency measures and substitution.

RECOMMENDATIONS

- There is no comprehensive directive providing for a European mining law. A publicly available, comprehensive and detailed analysis of the European regulatory framework concerning shale gas and tight oil extraction is not available and should be developed.
- The current EU regulatory framework concerning hydraulic fracturing, which is the core element in shale gas and tight oil extraction, has a number of gaps. Most importantly, the threshold for Environmental Impact Assessments to be carried out on hydraulic fracturing activities in hydrocarbon extraction is set far above any potential industrial activities of this kind, and thus should be lowered substantially.
- The coverage of the water framework Directive should be re-assessed with special focus on fracturing activities and their possible impacts on surface water.
- In the framework of a Life Cycle Analysis (LCA), a thorough cost/benefit analysis could be a tool to assess the overall benefits for society and its citizens. A harmonized approach to be applied throughout EU27 should be developed, based on which responsible authorities can perform their LCA assessments and discuss them with the public.
- It should be assessed whether the use of toxic chemicals for injection should be banned in general. At least, all chemicals to be used should be disclosed publicly, the number of allowed chemicals should be restricted and its use should be monitored. Statistics about the injected quantities and number of projects should be collected at European level.
- Regional authorities should be strengthened to take decisions on the permission of projects which involve hydraulic fracturing. Public participation and LCA-assessments should be mandatory in finding these decisions.
- Where project permits are granted, the monitoring of surface water flows and air emissions should be mandatory.
- Statistics on accidents and complaints should be collected and analysed at European level. Where projects are permitted, an independent authority should collect and review complaints.
- Because of the complex nature of possible impacts and risks to the environment and to human health of hydraulic fracturing consideration should be given to developing a new directive at European level regulating all issues in this area comprehensively.

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ANNEX: CONVERSION FACTORS

Table: United States customary units

Unit	SI Equivalent
1 inch (in)	2.54 cm
1 foot (ft)	0.3048 m
1 yard (yd)	0.9144 m
1 mile (mi)	1.609344 km
1 square survey foot (sq ft) or (ft^2)	0.09290341 m^2
1 acre	4046.873 m^2
1 cubic foot (cu ft) or (ft3)	28.31685 L
1 cubic yard (cu yd) or (yd3)	0.7645549 m^3
1 acre-foot (acre ft)	1233.482 m^3
1 US gallon (gal)	3.785412 L
1 oil barrel (bbl)	158.9873 L
1 bushel (bu)	35.23907 L
1 pound (lb)	453.59237 g
1 (short) ton	907.18474 kg
Fahrenheit (F)	(5/9) * (F – 32)° C
1 British thermal unit (BTU) or (Btu)	1055.056 J

Source: http://en.wikipedia.org/wiki/US_units_of_measurement

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