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International Developments in the Field of Unconventional Gas and Oil Extraction

Update 2017

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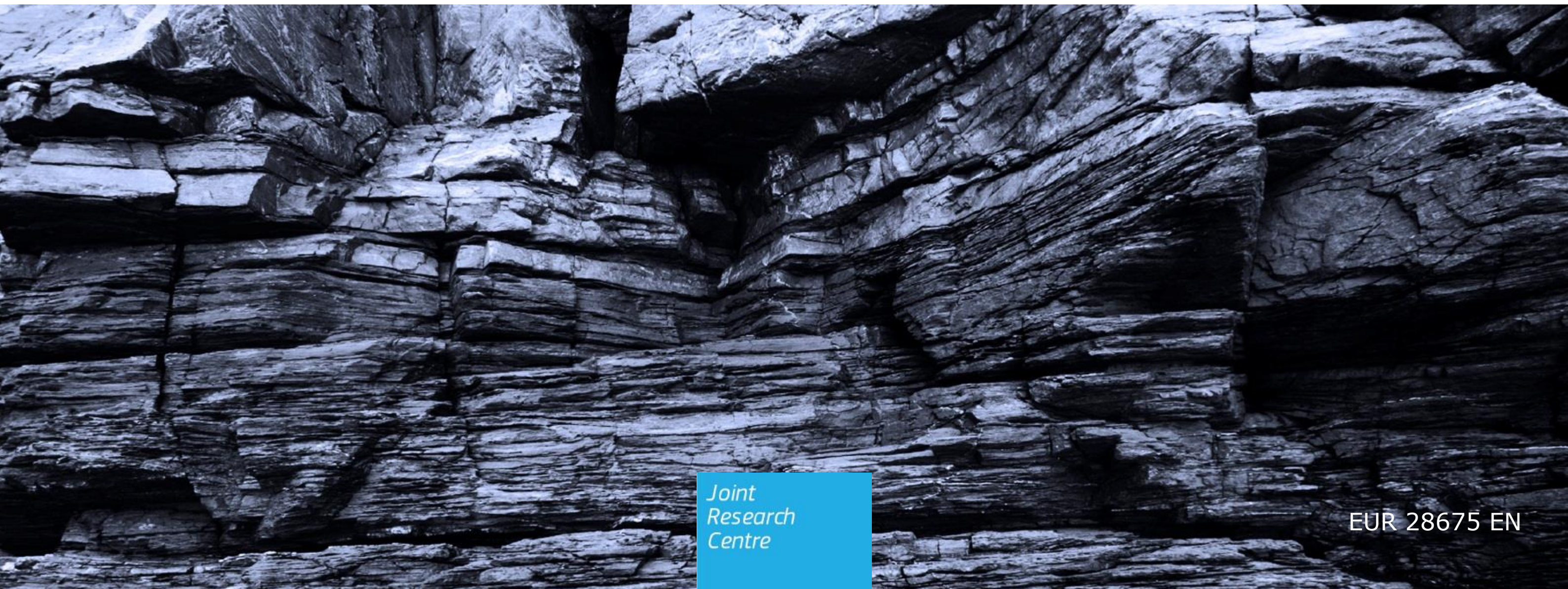

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Abstract

The last few years have witnessed a wealth of studies, reports and assessments being published in many EU member states, by national and international organisations and in the research community on economic, environmental and human health related aspects of unconventional oil and gas exploration and production. Many R&D initiatives are also underway.

This report attempts to provide a survey of several of such studies and initiatives, with a focus on the years 2015, 2016 and early 2017. Principally, reports and studies from public bodies and scientific institutes were covered. Additionally, several papers published in peer-reviewed journals were included.

A review of the quality of the studies covered, the accuracy of their claims and their possible limitations was not carried out. This report is therefore only meant to provide a compilation of their summaries, without any endorsement of the findings reported in any of the studies and assessments covered in the report.

1 Introduction

Unconventional hydrocarbon extraction has been subject to significant debates at national, European and international level. Apart from political aspects a considerable amount of research has been performed or is underway in areas such as technology, environment, geology and social issues. In 2014, the European Commission concluded that *"it is also necessary to continue increasing our knowledge on unconventional hydrocarbon extraction technologies and practices also in order to further reduce potential health and environmental impacts and risks. In this context, it is also essential that information is open and transparent to the public". (COM(2014)23 final)*

With regard to the exploration and exploitation of shale gas, the EU is undoubtedly still in an early exploration phase. Shale gas drilling activity in the EU remains very low, whilst tight gas and coal bed methane are already produced, although on a different scale of reservoirs and predominantly with low-volume stimulation. In addition, there is also a number of site scale research activities now underway or about to be undertaken.These can provide useful information particularly for understanding the baseline environmental conditions.

According to Council conclusions of 26.04.1994 (J.O. C 126 of 7.05.1994) on the role of the DG Joint Research Centre, the JRC activities include institutional support activities such as scientific and technical support activities necessary for the formulation and implementation of Community policies and of the tasks allotted to the Commission pursuant to the Treaties, which necessitate the neutrality of the JRC. Within this framework, the Joint Research Centre (DG JRC), provided other services of the European Commission (such as DG-RTD, DG-ENER and DG-ENV) through an Administrative arrangment with "Energy Policy support on unconventional gas and oil", as provided for in the HORIZON 2020 work programme 2014-2015, part 10. Secure, clean and efficient energy, item B.2.9, (European Commission Decision C (2013)8631 of 10 December 2013). The priority issues to be addressed as a part of the the Arrangement were identified as:

A. Assessment of European unconventional gas and oil resources;

B. Unconventional hydrocarbons and energy markets;

C. Communication and dissemination, international knowledge sharing.

The assessment of European unconventional gas and oil resources was undertaken in the EUOGA project, and its findings are discussed in Section 3.1.

Unconventional hydrocarbons and energy markets were investaigated in a series of activities summarised in Chapter 2 . In particular, a modelling analysis of the economic impacts on global energy markets and implication for Europe was carried out (Section 2.2.2). Case studies of Germany and Poland regarding economic impacts and framework conditions for potential unconventional gas and oil extraction in the EU were perfomed (Section 2.2.3). A techno-economic assessment of the conditions for the development of a potential unconventional gas and oil industry was also performed by looking at experiences outside Europe and analysing the European potential (Section 2.2.4).

International knowledge sharing was fostered by compiling reports on international developments in the field of unconventional gas and oil (the present report, and for instance (Gandossi 2015) and by organising a transatlantic Conference on unconventional hydrocarbons where resources, risks, impact and research needs were discussed by an interdisciplinary and intercontinental (EU, USA, Canada) audience of scientists, engineers, social scientists geologists and representatives from the civil society. The outcome of this conference, that took place in Amsterdam (The Netherlands) on 20-21 June 2017, is described in Chapter 8.

The last few years have witnessed a wealth of studies, reports and assessments being published in many EU member states, as well as by national and international organisations and in the research community, covering economic, environmental and public health aspects related to the exploitation of unconventional hydrocarbons. Many R&D initiatives are also currently underway. This report attempts to provide a survey of several of such studies and initiatives, with a focus on shale gas and mainly covering the years, 2015, 2016 and early 2017. Some relevant, earlier reports (not older than 2011) are covered as well. Principally, reports and studies from public bodies and scientific institutes were covered. Additionally, relevant papers published in peer-reviewed journals were included.

Each study or report is briefly described and a selection of its conclusions and/or recommendations is extracted and reproduced herein, but a review of the quality of the studies covered, the accuracy of their claims and their possible limitations was beyond the scope of this report. Therefore, this report is only meant to provide a compilation of such studies and their summaries, without any endorsement of the findings reported.

Globally, fossil fuels supply more than 80% of primary energy (IEA 2015). Conventional and unconventional fossil fuels differ in their geologic locations and accessibility. While conventional fuels are normally found in discrete, easily accessible reservoirs, unconventional fuels may be found within pore spaces throughout a wide geologic formation and require advanced technologies to extract. If unconventional oil resources (e.g. shale oil, oil shale, oil sands-based extra heavy oil and natural bitumen) are taken into account, the global oil technically recoverable reserves quadruple current conventional reserves (World Energy Council 2013).

The following section has been adapted from the factsheet developed by the (Center for Sustainable Systems - University of Michigan 2015). Table 1summarises the various resources types.

Unconventional natural gas and oil are primarily sourced in three forms: shale gas/oil found in low-permeability shale formations, tight gas/oil found in low-permeability sandstone and carbonate reservoirs, and coalbed methane found in coal seams (NETL 2013).

Although several countries have begun producing unconventional gas, many global resources have yet to be assessed. According to current estimates, China has the largest technically recoverable shale gas resource with 1,115 trillion cubic feet (Tcf), followed by Argentina (802 Tcf) and Algeria (707Tcf) (U.S. Energy Information Administration 2013). Global tight gas resources are estimated at 2,684 Tcf, with the largest in Asia/Pacific and Latin America (International Energy Agency 2012). Resources of coalbed methane are estimated at 1,660 Tcf, with more than 75% in Eastern Europe/Eurasia and Asia/Pacific (International Energy Agency 2012).

Oil sands, i.e., "tar sands" or "natural bitumen," are a combination of sand (83%), bitumen (10%), water (4%), and clay (3%). Bitumen is a semisolid, tar-like mixture of hydrocarbons. Known oil sands deposits exist in 23 countries (World Energy Council 2013). Canada has 73% of global estimated technically recoverable oil sands, approximately 2.4 trillion barrels (bbls) of oil in place.

Deposits less than 75 metres below the surface are mined and processed to separate the bitumen (Ramseur, Lattanzio et al. 2014). Bitumen must be upgraded to synthetic crude oil before refining into petroleum products; non-upgraded bitumen must be diluted or mixed with synthetic crude oil before transport. Deeper deposits employ in situ (underground) methods, including steam or solvent injection, or oxygen injection with a portion of oil sands burned for heat. Cyclic steam stimulation and steam-assisted gravity drainage are common in situ methods.

Oil shales are sedimentary rocks containing deposits of organic compounds (kerogen) which have not undergone enough geologic pressure, heat, and time to become conventional oil. Oil shale contains enough oil to burn without additional processing, but can be heated (retorted) to generate petroleum-like liquids (RAND Corporation 2005). Known oil shale deposits exist in 40 countries. The U.S. has the largest oil shale technically recoverable resource in the world, approximately 3.7 trillion barrels of oil in place (77% of world supply), of which the Green River formation in the Western U.S. accounts for 83% (U.S. Energy Information Administration 2015).

Oil shale can be processed in two ways. In the first method, the oil shale is mined and brought to the surface to be retorted to temperatures around 500°C.The second method, in situ conversion process, involves placing electric heaters throughout the shale for up to three years until the rock is heated up to 340-370°C, at which point oil is released (Andrews 2008). Oil retorted above-ground must be further processed before refining and the spent shale disposed. Oil extracted through in situ conversion can be sent directly to the refinery.

Methane hydrates are ice-like combinations of gas and water that form naturally and in great quantities. Water molecules, which make up approximately 85 per cent of a gas hydrate, form a crystalline lattice. The lattice is stabilized by other molecules, usually methane. Methane gas hydrates form naturally where adequate supplies of methane and water can combine in a location with both high pressure and relatively low temperature, typically in the Arctic (where cold air temperatures create thick zones of permanently frozen soils) and at the bottom of oceans or deep inland lakes. The methane itself is created by the decomposition of organic carbon, which generally migrates upward through water-laden sediment. In the right conditions, this triggers the formation of gas hydrates (Beaudoin 2015).

<table>
<tr><th></th><th>Resources type</th><th>Description</th><th>Resource sub-category</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">Unconventional Natural Gas/Oil</td><td rowspan="3">Natural gas or oil trapped in unconventional reservoir rocks (tight sands, shales, coal beds, etc.)</td><td>Shale gas/oil from low-permeability shale formations</td></tr>
<tr><td>Tight gas/oil from low-permeability sandstone and carbonate reservoirs</td></tr>
<tr><td>Coal bed methane from coal seams</td></tr>
<tr><td>2</td><td>Tar Sands (also Oil Sands or Natural Bitumen)</td><td>Combination of sand, bitumen, water and clay. Bitumen is a semisolid, tar-like mixture of hydrocarbons.</td><td>Tar Sands</td></tr>
<tr><td>3</td><td>Oil Shales</td><td>Sedimentary rock that holds deposits of organic compounds (kerogen) that have not undergone enough geologic pressure, heat, and time to become conventional oil. Not to be confused with shale oil.</td><td>Oil Shales</td></tr>
<tr><td>4</td><td>Methane Hydrates (also Methane Clathrates)</td><td>Solid compounds where a large amount of methane is trapped within a crystal structure of water, forming solids similar to ice.</td><td>Methane Hydrates</td></tr>
</table>

Table 1 Identification of resources types and sub-categories

Most marine gas hydrate deposits found so far have been in continental margin and slope sediments. The global inventory of gas hydrates appears to be very large. Recent technically recoverable estimates of the total amount of methane contained in the world’s gas hydrates range from 1500 to 15,000 gigatonnes of carbon. At standard temperature and pressure, this represents 3000 to 30,000 trillion cubic meters (Beaudoin 2015).

Experimental programmes have shown that gas hydrates can be produced in the short term using conventional hydrocarbon recovery methods, but it is still too early to conclude whether large-scale methane production from gas hydrates can be carried out economically. (Beaudoin 2015) conclude that meaningful production of methane from gas hydrates is probably still a decade or more away in the future.

2 General reports and studies

2.1 Studies on Hydraulic Fracturing

2.1.1 Royal Society of Edinburgh (2015)

The Royal Society of Edinburgh (RSE) published in 2015 a report that looks into options for Scotland's gas future. The report followed a Scottish Government announcement in January 2015 of a temporary moratorium on unconventional gas development, including the use of fracking, to allow for a national debate (The Royal Society of Edinburgh 2015). The report provided an overview of the options available to Scotland in order to meet its demand for gas over the coming decades. Scotland is heavily reliant on gas in both the residential and commercial sectors for heating, and natural gas plays a significant role in electricity generation as well. A significant quantity would still be required not only for heating, but also as a chemical feedstock for the petrochemical industry even considering an unprecedented decrease in UK gas consumption. Two main conclusions were drawn. The first conclusion related to the large degree of uncertainty surrounding much of the debate. A reduction in this uncertainty, particularly in relation to onshore and offshore resources and reserves, would enable the decision-making process to be better informed. The Scottish Government was hence urged to consider investing funds to reduce the areas of larger uncertainty, notably health impacts and potential reserves. The second conclusion related to the involvement of civil society. The reports noted that the importance of giving the public a genuine opportunity to contribute to the decision-making process regarding decisions over Scotland's gas future. The proposed way forward must be addressed at a societal level with meaningful public involvement. The choice should not be imposed on the public from above, nor should it be left to communities to decide whether they wish to host onshore developments on a case by case basis.

2.1.2 German Academy of Science and Engineering (2015)

The German Academy of Science and Engineering published a study that looked at the technology of hydraulic fracturing and its potential, opportunities and risks, intended for both decision-makers and the interested public (ACATECH – Deutsche Akademie der Technikwissenschaften 2015). The most notable conclusion from this report was that a general prohibition of hydraulic fracturing cannot be justified on the basis of scientific and technical facts, provided that the development of unconventional gas (and geothermal energy) follows strict safety standards, is clearly regulated and comprehensively monitored.

2.1.3 Basque Institute of Competitiveness (2016)

The Basque Institute of Competitiveness published in 2016 a book (in Spanish) with a review of issues related to shale gas and hydraulic fracturing (Álvarez Pelegry and Suárez Diez 2016). The book discussed the role of natural gas in the global context, by examining gas demands and production. It examined global resources and reserves but focused on the situation in Spain and in particular in the Basque country. It presented an overview of hydraulic fracturing and related technologies for exploiting shale gas (including topics such as well integrity, horizontal drilling, well completion, circulating and fracturing fluids, etc.). It discussed environmental issues related to fracturing, in particular looking at the water cycle and induced seismicity, and, finally, it reviewed regulatory and licensing issues.

2.2 European Commission studies

2.2.1 Study on the application of Recommendation 2014/70/EU (2016)

In January 2014, the European Commission adopted a Recommendation setting out minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing (HVHF)[1] (European Commission 2014). The European Commission funded a study, produced by external consultants, to support such review (Ricardo Energy & Environment and Milieu - Law and Policy Consulting 2015).

The effectiveness of the Recommendation was set for review by the Commission 18 months after its publication, and this was done in December 2016 (European Commission 2016). This study assessed the first two and a half years of application of the Recommendation in a limited number of projects in a few Member States. It found that the Recommendation had been applied unevenly across Member States and unsatisfactorily in some. On the basis of the findings of the review, it was considered impossible to confirm the effectiveness of the Recommendation in preventing, managing and reducing environmental impacts and risks. The report argued that the variety of ways in which the Member States have followed the Recommendation was also a result of its legally non-binding status. The Commission therefore encouraged Member States to take greater account of the principles of the Recommendation when planning to develop hydrocarbons requiring hydraulic fracturing. The report concluded that more progress is necessary, both in the application of the Recommendation in the relevant Member States and in the correct and uniform application of the EU environmental legislation. To this end, the Commission plans to focus on increasing transparency and monitoring, encouraging a more uniform application of relevant provisions across Member States, addressing the environmental impacts and risks of hydrocarbon exploration and extraction; and filling research gaps on health impacts and risks of hydrocarbon extraction (European Commission 2016).

2.2.2 Unconventional oil and gas resources in future energy markets: a modelling analysis of the economic impacts on global energy markets and implication for Europe

The key objectives of this analysis (Chiodi, Gargiulo et al. 2016)were to quantitatively explore the medium and long-term potential (up to 2040) development of unconventional hydrocarbons and their by-products at global scale and to assess its possible impacts on the European market.

The sharp development of unconventional oil and gas in the United States during the last few years has radically changed perspectives about its import dependency outlooks and created new oil and gas markets dynamics. On another hand, due to growing worldwide concerns regarding anthropogenic interference with the climate system, 188 countries have, since December 2015, committed to the Paris Agreement that stated that deep cuts in global greenhouse gas (GHG) emissions are required so as to hold the increase in the global average temperature to well below 2 °C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C. In this respect, the European Union (EU) has committed to achieve a 40% reduction in GHG emissions by 2030 relative to 1990 levels and aim to a long-term emissions reduction to between 80% and 95% by the year 2050, relative to 1990 levels. Under these transition perspectives, this study aimed to investigate the potential role of unconventional oil and gas in the future worldwide energy systems, and their implications for the European markets. This report extended the scope of the previous JRC analysis published in (Pearson, Zeniewski et al. 2012) by analysing both unconventional oil and gas (previously only shale gas) and both global and EU regional dynamics (previously only global focus).

[1] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014H0070

During the past few years a number of studies have discussed the potential impact of unconventional oil and gas on global energy markets. However, only few studies are underpinned by a model-based analysis and had a specific focus on implications for Europe. This report uses the global energy system model JRC Energy Trade Model (JRC ETM) to explore the medium and long-term implications of the worldwide increased development of unconventional gas and oil and their by-products on global and European markets. The analysis was developed in two phases. First a detailed analysis of the current and past oil and gas markets dynamics identifies the key drivers which underpin the development of unconventional hydrocarbons globally and ultimately in the EU. Secondly a scenario analysis assesses the role of the following key variables in the current and future energy markets: a) regional distribution of unconventional hydrocarbon production and its exploitation costs; b) infrastructure; c) interregional trades; and d) global policies (post-COP climate policies). The study explained how the reciprocal effects of substitutions on both the supply and demand-side play an important role in constraining or enabling the penetration of unconventional resources, by illustrating the chain of actions and feedbacks induced by different economics of unconventional fuels, their magnitude, their relative importance, and the necessary conditions for the global potential to be realized.

The following conclusions were highlighted (Chiodi, Gargiulo et al. 2016):

- The natural gas market will expand in the future years and will contribute –replacing other more carbon intensive fossil fuels – to the decarbonisation of energy sectors.
- Under scenarios with favourable unconventional gas development, natural gas has the potential of capturing 30% of the world’s total primary energy supply by 2040. This would make it surpass oil as the world’s foremost source of energy.
- Natural gas in Europe can be considered as transition fuel towards a low carbon economy.
- Unconventional gas is relatively evenly dispersed around the world and many regions will likely witness at least some level of production in the future. In scenarios with favourable unconventional gas development, the USA, China and Other Developing Asia are well placed to become the top producers of unconventional gas. In EU-28, the exploitation of unconventional gas resources is driven by emissions targets. Stricter mitigation policies drive to low extraction activity. UK and, with a lesser extent, Germany are the regions where most of these extractions take place.
- Significant unconventional gas production has the potential to lower the natural gas prices.
- The global trade in natural gas will increase in any scenario. Unconventional gas development, however, has the potential to moderate the growth of pipeline trades, while increasing interregional LNG flows.
- Global oil market will expand in the medium term in all scenarios, then from 2040 tighter mitigation policies may drive to a decline. In these scenarios, oil reduces to 16-17% of the world’s total primary energy supply. Unconventional oil production will be only slightly impacted by mitigation policies, i.e. the relative share grows to 60-62% of total oil production by 2040.
- Unconventional oil production will grow in the future years, but has limited potential on lowering oil prices. Canada and Latin America are well placed to become the top producers of unconventional oil. The EU-28 exploitation of unconventional oil will be very limited.
- The global trade in crude oil will increase in any scenario at least in the medium term (till 2030). Climate policies have the potential of reducing the growth of trades from 2040 on.

2.2.3 Economic impacts and framework conditions for potential unconventional gas and oil extraction in the EU: Case studies of Germany and Poland

The purpose of this study was to assess the potential benefits associated with the possible development of new unconventional hydrocarbon resources in Poland and Germany (Godec and Spisto 2016). A number of important factors for characterizing these potential benefits were considered. Cost and resource deployment estimates were specifically tied to the resource characteristics in Poland and Germany, as best those are known at the time of writing. New unconventional hydrocarbon resource productivity and economics account for increased resource understanding, technology evolution, and improvements in efficiency that takes place over time and as development in a play evolves. Benefits characterizations were performed at two points in the maturity of an unconventional hydrocarbon resource play: when exploration, development, and production initiates and as development in the play matures. Finally, best environmental practices based on the U.S. experience, and the corresponding costs, were assumed.

A crucial aspect regarding the outlook for new unconventional hydrocarbon resources in Europe is the pace and ability to find the most productive areas of a play (the so-call sweet spots, often representing a small portion of the total area of a play). For both Poland and Germany, a potential future "sweet spot" with modest productivity was posited in a potential "yet be discovered" region as a result of future exploration drilling. Estimated ultimate recovery (EURs) values for fractured horizontal oil and/or gas wells for a Base Case (most likely), Low and High Case were developed.

The economic assessment concluded that, in both countries, commercial viability would likely not be achievable under the Low or Base Case EUR. Only if EURs approach the High Case or higher, or resource development costs and/or government royalties are significantly reduced, can economic viability be achieved. Thus, the estimated benefits will only be fully realizable if per well productivity exceeds that associated with the Most Likely Case EURs, and only in areas defined as the sweet spots. Given the recent experience in these two countries, this may be a challenge, at least in the near term.

Given these caveats, economic and employment benefits for unconventional hydrocarbon resource development and production were estimated for two phases of activity: (1) a site evaluation and initial exploration phase, and (2) (if pursued) a development and production phase. Under the most aggressive development scenario considered, the following benefits for Germany or Poland were estimated to result during the site evaluation and initial exploration phase:

- 110 direct jobs and 330 indirect jobs (440 total) associated with drilling, of which 193 are local jobs, and 247 are expat or home office jobs.
- 125 jobs, of which 94 are local jobs, associated with site construction.
- Expenditures on drilling and site construction peak at € 67.5 million per year.
- Payment of € 37.6 million in salaries for the 369 local jobs created.
- Collection of € 10.8 million in income taxes from salaried workers in Poland, and € 14.2 million in income taxes from workers in Germany.
- During the development and production phase, assuming that the basin/play proceeds to this phase, employment and economic benefits associated with a most aggressive, large-scale development scenario in Poland are:
- At full development, 1,800 wells are producing, with a peak production of 5.8 billion cubic meters per year
- Annual capital expenditures peak at nearly € 2 billion. As many as 9,700 local personnel are employed in development activities.
- Operating expenditures grow to over € 340 million annually; as many as 32,400 local personnel are employed in oil and gas operations.

- € 3.5 billion annually are earned in salaries by these personnel; for which, they eventually pay over € 1.1 billion annually in income taxes.
- Industry can earn as much as € 1.9 billion to € 2.9 billion annually; the government could earn as much as € 26 to € 44 million annually in royalties.

Similarly, highlights of the employment and economic benefit associated with a large-scale development scenario in Germany were:

- At full development, 600 wells are producing, with a peak production of over 1.5 billion cubic meters per year
- Annual capital expenditures for development drilling and facility construction peak at nearly € 325 million. As many as 3,300 local personnel are employed in these activities.
- Annual operating expenditures grow to nearly € 115 million; as many as 10,800 local personnel are employed in oil and gas field operations.
- € 1.2 billion annually are earned in salaries by these personnel; for which, they eventually pay nearly € 490 million annually in income taxes.
- Industry can earn as much as € 500 to € 800 million annually; the government could earn as much as € 150 to € 240 million annually in royalties.

Regarding the policy context, two categories of potential challenges were identified with the potential to impact new unconventional hydrocarbon resource exploration and development. These can add to development and production costs, and adversely affect commercial viability: (1) concession terms and the sharing of the proceeds of unconventional hydrocarbon resource development and production with the government; and (2) issues, and associated costs, related to addressing environmental concerns. In Poland, the oil and gas tax regime has been modified for unconventional hydrocarbon resource development to encourage investment, with the government gaining most of its financial benefits when projects are sufficient profitable. Poland's Special Hydrocarbons Tax is structured such that its applies at its maximum rate only when revenues sufficiently exceed expenses, and income taxes only apply if an operator is in fact generating positive cash flow. Germany, on the other hand, imposes high royalties, such that the government takes its share "off the top" regardless of whether or not positive cash flow is being realized by the operator. This could stifle potential investment.

2.2.4 Techno-economic assessment of the conditions for the development of a potential unconventional gas and oil industry: Review of experiences outside Europe and analysis of the European potential

In this study (D'amato, Shastri et al. 2017), the authors provided an introductory overview based on existing literature and on industry knowledge on the key factors that have influenced the development of the unconventional hydrocarbon industry in selected countries, namely US, China, Australia and Canada.

The analytical framework used in this work connects the facts and variables that have shaped each country's experience to relevant segments of the supply chain. The same approach was then used to understand the potential of an industrial development of the unconventional hydrocarbon sector in Europe, by analysing the existing technology, know how, and the features of correlated sectors that could support the emergence of this type of industry in Europe.

As it emerged from the analysis of the experiences in countries outside Europe, drivers and barriers to the industrial development change according to the economic culture in each region, the infrastructure endowment of the gas and oil sector, the availability of related industries and services in support of the unconventional resources exploitation, and the financial support or constraints from the public and private sectors.

The analysis for Europe aimed at assessing the conditions for the potential development of an unconventional hydrocarbon industry by analysing the features of the sector, not only in those European countries with an estimated resource potential but also in other countries, which, for example, may have an advantage in the provision of correlated services in specialized sectors.

A number of open issues were identified in relation to the development of an unconventional hydrocarbon industry in Europe, such as the skill building strategy for EU member states, the development of institutions for imparting education in this thematic area, the availability of deeper resource knowledge, the features of existing value chains, etc.

The assessment of the unconventional hydrocarbon value chain elements, of the cost and economic structure and of the required skills to develop an industrial base suggested that the areas in which more knowledge is still needed include, amongst others:

- A more detailed study aimed at understanding the success of EU players in the US Unconventional Industry and at exploring potential models for engagement.
- A synthesis study of the assessments made by member states geological surveys to assess the unconventional hydrocarbon potential.
- A cross functional study to determine the potential role that the unconventional hydrocarbon industry, if launched, could be expected to play in an evolving EU energy system.

2.2.5 JRC study on the "Use of nanomaterials in fluids, proppants, and downhole tools for hydraulic fracturing of unconventional hydrocarbon reservoirs"

In this study (Gottardo, Mech et al. 2016) a literature and Internet search was carried out, aimed at collecting and reviewing available information on the use of nanotechnology in fluids, proppants, and downhole tools for hydraulic fracturing of unconventional hydrocarbon reservoirs. Different sources were consulted to cover both potential nanotechnology applications as proposed in peer reviewed scientific literature and patents and commercially available applications.

Twenty-five different types of nanotechnology applications were identified and a large variety of different nanomaterials were encountered, ranging from inorganic and organic nanoparticles to more complex core-shells and nanocomposites. The study found that most of the nanomaterials used in applications for hydraulic fracturing are of inorganic nature. About half of the application types are specific for unconventional reservoirs including tight and ultra-tight gas, shale gas, and coal-bed methane. Although more than two thirds of the application types are still at the research and development stage, 31 commercial products claiming to use nanotechnology were identified. Only few of them are available in the European market, according to producers' claims.

The study also found that, according to the consulted sources, the use of nanotechnology in fluids, proppants, and downhole tools for hydraulic fracturing of unconventional hydrocarbon reservoirs is considered a success. No disadvantage or additional cost from the use of nanomaterials was reported.

3 Resource assessments

3.1 European Union: EUOGA project

As of 2016, shale gas resources in Europe were still uncertain to a large degree, since there had been very limited exploration and no production. The European Commission, via the Joint Research Centre, funded a project, called EUOGA and carried out by EuroGeoSurveys (EGS), with the aim to develop a consistent pan-EU data sets and uniform estimation principles. EUOGA (an acronym standing for "**E**uropean **U**nconventional **o**il and **g**as **a**ssessment") is an inventory of existing published knowledge on shale oil and gas resources in Europe. The project compiled data from European countries, with the work organised in several subsequent tasks, such as (a) define and setup a common resource assessment methodology, (b) overview the current status of the exploration and development of shale gas and shale oil in Europe; (c) analyse the geological resources and compile geological maps of prospective European oil and gas bearing shale formations; (d) carry out a quantitative resource estimation of prospective shale gas and shale oil resources in Europe based on the common assessment methodology; and (e) present data and results in a web-interactive database and map application. The report outcome is summarised in various reports, see for instance (Nelskamp and Zijp 2016; Nelskamp 2017; Schovsbo, Anthonsen et al. 2017; Zijp, Nelskamp et al. 2017)

The resource assessment was performed using basins and plays as main Units of Assessments. The novel methodology allowed resource calculation on aggregated (geographical regions, trans-boundary basins) or disaggregated scales (country specific). The resource for all EUOGA Units of Assessments was formulated as theoretical resource while for some individual Units of Assessments total recoverable resource (TRR) is forwarded depending on the availability of detailed information. In the resource assessment the following Units of Assessment were used:

- Basins. 38 sedimentary basins were identified within Europe showing potential shale gas and shale oil resources (see Figure 1)
- Formations or layers. From the identified basins, 82 formations were appraised that could contain relevant shale gas and shale oil formations.
- Plays. Within the formations, 49 plays were identified for which stochastic volumetric probabilistic resource assessment was conducted.

The total resource potential found for all EUOGA formations is 89.2 tcm of gas initially in place (GIIP, P50) and 31.4 billion barrels of oil initially in place (OIIP, P50). The resource is distributed between 15 formations holding both oil and gas, 26 gas bearing formations and 8 oil bearing formations.

The volumetric assessment was performed using the following input and preparatory steps (see also Figure 2):

1) Characterization of each shale formation by 20 geological assessment parameters, as provided by the National Geological Surveys and processed by GEUS. In case no value for a parameter could be provided for a certain assessment unit, an average value has been used based on the combination of available parameters for all shale formations included in EUOGA.
2) Determination of the probability and uncertainties regarding the presence of gas and oil in each shale formation.
3) Subdivision of each shale formation into regional assessment units using GIS data, parameter values and common agreed cut-off values.
4) Implementation of a ranking system based on TOC, depth, thickness and maturity of the shale formation leading to three uncertainty classes that are represented in the final numbers.

Based on the outcomes of these preparatory steps and input data the GIIP/OIIP values per formation and basin were estimated by applying a stochastic probability (Monte

Carlo) method. For gas-bearing shale formations the amount of free gas as well as the amount of adsorbed gas has been estimated. For oil-bearing shale formations the amount of free oil has been estimated. Note that if a formation is classified as either gas or oil only this type of hydrocarbon is calculated although in reality it is very likely that both are present. No recoverable volumes are calculated due to the lack of successful shale operations in the EU which inhibits realistic estimates of recovery factors.

Figure 1 European Unconventional Oil and Gas basins as identified in the EUOGA assessment.

The main results of this study are the collection and standardisation of geological data for potential shale gas/oil formations from the participating European countries as well as the identification of gaps in this dataset. During this study it became evident, that a lot of relevant data is missing from the current inventory (for various reasons). Accordingly, this study should be regarded as a basis for future extensions and improvements of the database. The unified method that is adopted for data gathering and resource estimates makes it easier to implement new or modified data into the present calculations.

	Total gas in place estimates (bcm)			Total oil in place estimates (billion bbl)		
	P90	**P50**	P10	P90	**P50**	P10
Austria*	898	**2237**	4863	0.06	**0.35**	1.97
Belgium	368	**852**	1842			
Bulgaria	2646	**7177**	16786	1.01	**6.54**	39.38
Croatia**	1	**2**	5			
Czech Republic*	169	**514**	1269	0.03	**0.18**	1.04
Denmark	1317	**2533**	4488			
France				0.44	**2.61**	14.68
Hungary	287	**813**	1885	0.22	**1.28**	7.09
Italy				0.26	**1.46**	8.46
Lithuania	187	**256**	391	0.90	**2.03**	3.88
Netherlands	1254	**2710**	5872	0.25	**1.38**	7.36
Poland	6221	**13243**	26206	2.93	**6.64**	12.24
Portugal	412	**1079**	2480	0.32	**1.77**	9.94
Romania**	3324	**9714**	26972			
Slovenia	83	**195**	411	0.04	**0.21**	1.13
Spain	798	**2049**	4700			
Sweden	257	**482**	823	0.02	**0.06**	0.16
UK	11844	**35432**	84984	0.67	**4.16**	24.44
Ukraine	3846	**9949**	23080	0.41	**2.78**	17.17
Total EU EUOGA		**89235** bcm			**31.4** billion bbl	

Table 2 **Overview of total GIIP and OIIP for all 49 EUOGA assessed formations presented as breakdown per country, gas or oil, and P10, P50 or P90.**

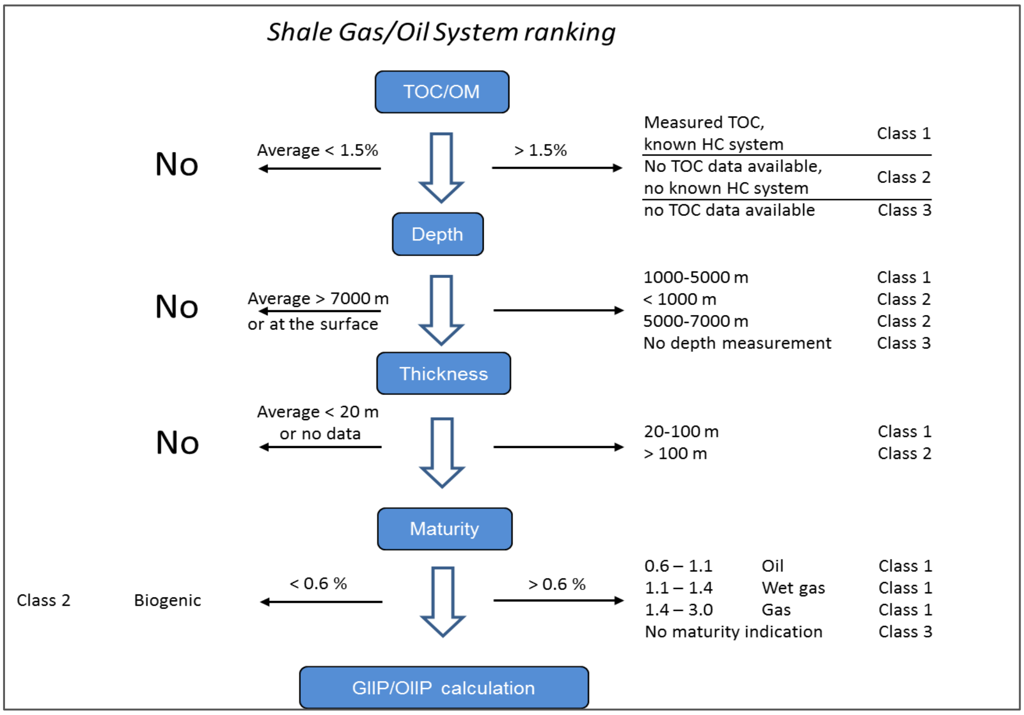

Figure 2 **Shale ranking/pre-screening criteria developed and mentioned in step 4 from above.**

3.2 EIA: World Shale Resource Assessments

The U.S. Energy Information Administration (EIA) maintains and regularly updates a series of assessments on the world's shale resources[2]. The first edition of the series was released in 2011 and updates are released on an on-going basis. Four countries were added in 2014: Chad, Kazakhstan, Oman and the United Arab Emirates (UAE). A round of updates was published in September 2015.

3.3 Canada

The Canadian Society for Unconventional Resources[3] (CSUR), published in 2015 the 4th edition of the Unconventional Resource Guidebook, including information related to shale gas, tight oil and other unconventional resources in Canada (CSUR 2015). The Canadian Association of Petroleum Producers[4] (CAPP) and the Canadian Energy Research Institute (CERI) frequently publish[5] relevant report on oil and gas developments, often including unconventional sources.

3.4 Poland's assessment of undiscovered tight gas resources

The Polish Geological Survey carried out in 2014 an assessment of undiscovered tight gas resources in selected tight reservoirs of Poland. Tight gas is produced using similar technologies as in the case of shale gas but present in other types of reservoir rocks (mainly tight impermeable sandstones). The report (Wojcicki; A., Kiersnowski; H. et al. 2014) did not cover tight gas fields recently discovered in reservoir traps in Poland (e.g., Siekierki- Trzek and Pniewy gas fields) but focused on yet unexplored tight gas reservoirs in hydrocarbon basin centers of likely higher potential. The most probable value of the undiscovered (risked) GIP in the selected reservoirs was assessed to be in the range of 53.94 to 70.42 Tcf. The estimation of technically recoverable resources was also calculated assuming a recovery ratio of 5-15% of the GIP.

3.5 UNEP report on Methane Hydrates

The United Nations Environment Programme (UNEP) published in 2014 a report on methane hydrates, covering all relevant issues in current global gas hydrate research and development (Beaudoin 2015). The report is a two-part review that covers the role of gas hydrates in natural systems (Volume 1) and the potential impact of gas hydrates as a possible new and global energy resource (Volume 2).

Volume 1 is divided into three chapters. As a basis for understanding how gas hydrates occur and evolve in nature, Chapter 1 describes the crystal structures of gas hydrates, their stability requirements, and the environmental settings in which gas hydrates commonly occur. It also gives estimates of the global quantity and distribution of gas hydrates. Chapter 2 summarizes how methane is generated, moved into and out of gas hydrates, and gets consumed. Chapter 2 also discusses the link between gas hydrates and deep marine ecosystems. Chapter 3 considers models of past climate change and future climate conditions and how those models might be affected by potential feedbacks from gas hydrates.

Volume 2 presents the central message that gas hydrates may represent both an enormous potential energy resource and a source of greenhouse gas emissions for a world with ever-increasing energy demands and rising carbon emissions. Even if no more than a small subset of the global resource is accessible through existing technologies, that portion still represents a very large quantity of gas. To date, a few short-term, pilot-scale methane production tests have been conducted in research wells. The results

[2] https://www.eia.gov/analysis/studies/worldshalegas
[3] http://www.csur.com
[4] http://www.capp.ca
[5] http://www.ceri.ca

suggest that larger-scale exploitation may be feasible, but no commercial gas hydrate production has yet occurred. Several nations, however, are currently researching the energy potential of gas hydrates. Recent detailed assessments of the energy potential of methane-gas hydrates concluded that there are no anticipated technical roadblocks to producing gas from hydrate deposits. Ultimately, a combination of technological advances and favourable global/regional market conditions could make gas hydrate production economically viable. Therefore, the second part of the assessment provides a summary of gas-hydrate-based, energy-related information useful in evaluating future energy resource options. Topics addressed include a review of likely future trends in energy supply, a characterization of prospective gas hydrate resources, technologies for exploration and development, and the potential environmental, economic, and social implications of gas hydrate production.

The report mentions that "*science has yet to understand fully the socio-ecological impacts of extracting gas hydrates*". Among the environmental topics requiring further study are featured notably the "*potential ground subsidence associated with production [as gas hydrates are generally located at shallower depths than most currently producing gas reservoirs] and the "disposal of produced water*". Further "*each proposed development must also consider disruption of sensitive ecosystems and the cumulative impact of development on the global climate system*".

4 Environmental Assessments

4.1 General Reports

4.1.1 Polish Geological Institute (2015)

A site specific environmental assessment was commissioned by the Polish ministry of the environment and carried out by a consortium led by the Polish Geological Institute and including the University of Science and Technology in Cracow and Gdańsk University of Technology. The aim of the project was to determine the environmental impact of works related to the exploration and appraisal of unconventional hydrocarbon accumulations at 7 test sites, including a detailed analysis of the potential and actual impacts on particular environmental topics, including the following: air, ground surface, soil, surface water and the groundwater. The final report was published in 2015 (Konieczyńska, Adamczak et al. 2015), along with several reports from the research activities at the different individual test sites. The work was also accompanied by a study on seismic monitoring (see Section 4.4.1) and followed a previous environmental study carried out in 2011 at the Łebień site (Polish Geological Institute – National Research Institute 2011).

Initially 5 test sites around the following exploratory wells were chosen: Lubocino-2H, Stare Miasto-1K, Wysin-1, Syczyn OU-2K and Zwierzyniec-1. During the project, the research was expanded to include the test site around Gapowo B-1A exploratory well, as well as research included in the long-term monitoring in the following test sites: Stare Miasto, Syczyn and Zawada, and around Łebień LE-2H exploratory well. In total, a diverse range of works was delivered under the project in the area of 7 test sites, located in the Pomeranian Voivodeship and Lubelskie Voivodeship.

The research covered the following elements: (1) identification of the local conditions and field studies planning, (2) examination of the baseline status of the environment prior to the commencement of exploration, (3) monitoring while drilling vertical/directional wells, (4) monitoring during hydraulic fracture stimulation and gas flow testing, (5) monitoring of the status of the environment on completion of drill site operations, (6) occasional monitoring of the status of the environment at certain times after the completion of downhole operations. It must be noted that for two sites only (out of the seven) it was possible to carry out the assessment of the status of the environment prior to drilling activities and in one case only it was possible to assess the status of the environment after well abandonment. The maximum duration of the monitoring carried out at one site was two and a half years.

The study reports fourteen main conclusions. In particular, it concluded that in Poland, unconventional gas-bearing formations occur at great depths and are surmounted by deposits that provide excellent sealing capability with regard to potential upward migration of fluids or gas to the main commercial aquifers. Hydraulic fracture stimulation of individual wells did not induce seismic vibrations that are noticeable on the ground surface and recorded vibrations did not exceed the permitted vibration limit values for the stability of structures under Polish law. The noise levels in immediate vicinity of drill sites occasionally exceeded the permitted daytime values for inhabited areas. These exceedances were connected with the operation high-output pumps at some stages of hydraulic fracture stimulation jobs. The operation of some high-power combustion devices can cause a temporary increase in the concentration of gases (fuel combustion products) in the air. Elevated radon concentrations in drilling areas were not observed.

Water usage under relevant water permits at all test sites had no effect on the status of groundwater resources and did not cause a lowering of the groundwater level. The study showed no negative impact of exploration on the ground and surface water chemistry in the observed period of time. There was no contamination of the groundwater as a result of well stimulation, but the obtained results indicate that operations made improperly on the drill site may potentially result in penetration of certain substances from the surface to the top aquifer. However, the reported cases were limited to small areas only.

Drill site operations had no adverse effects on soil quality for farming, but the study concluded that a prolonged load may affect the degree of subsoil compaction, adversely affecting agricultural production until the initial conditions are restored. Drilling operations had a relatively short-term effect on the landscape and should not leave any significant imprint on the landscape upon completion of operations.

In conclusion, the study concluded that operations at the drilling sites may have a potential direct, although limited and short-term, adverse impact on the environment, while stressing the need for "*an adequate control of operations and the establishment of uniform monitoring of the environment (topmost and commercial aquifers, as well as soil gas in immediate drill site vicinity)*". Further, the study stressed that "*Such monitoring must be strictly adapted to the local geological and hydrogeological conditions, should be independent and guarantee reliability and comparability of results*".

4.1.2 New York State Department of Environmental Conservation (2015)

In the state of New York, most projects or activities proposed by a state agency or local government require an environmental impact assessment. Such assessment is prescribed by a State Environmental Quality Review act (SEQR), which requires the governmental body to identify and mitigate the significant environmental impacts of the activity it is proposing or permitting.

The New York State Department of Environmental Conservation released in 2015 the results of the SEQR for high-volume hydraulic fracturing. The review lasted seven years and aimed at evaluating "*the environmental impacts of this activity, determin[ing] the measures and controls that would minimize such impacts, review and understand the science and experiences observed in other parts of the country, and understand the risks and uncertainties arising from the activity.*" It concluded that "*there are no feasible or prudent alternatives that would adequately avoid or minimize adverse environmental impacts and that address the scientific uncertainties and risks to public health from this activity*". Consequently it was decided to officially prohibit high-volume hydraulic fracturing in the state of New York "*based on the balance between protection of the environment and public health and economic and social considerations*".

The study is published in two volumes (New York State Department of Environmental Conservation 2015a; New York State Department of Environmental Conservation 2015b) and the main findings are summarised in a shorted document (New York State Department of Environmental Conservation 2015c).

The assessment's webpage (link in the footnote[6]) include the full suits of accompanying documents and appendixes.

4.1.3 Environmental Protection Agency of Ireland (2016)

In 2011 the Environmental Protection Agency of Ireland was requested by the Irish government to commission and coordinate the management of research in relation to the environmental impacts of unconventional gas exploration and extraction. The EPA established a Steering Committee of relevant stakeholders and held a detailed public consultation in 2013 to inform the terms of reference for such a Research Programme. Funding for the research programme was committed by various governmental departments. In August 2014, the contract to carry out the research was awarded to a

[6] http://www.dec.ny.gov/energy/75370.html

consortium led by CDM Smith Ireland Limited. See the link provided in the footnote for more details regarding this project[7].

The research programme was designed to produce outputs that will assist regulators to fulfil their statutory roles regarding impact assessment and regulation of any potential unconventional hydrocarbons operations in Ireland. The two key questions posed for the research programme were

1. Can unconventional projects and operations be carried out in the island of Ireland whilst also protecting the environment and human health?
2. What is the best environmental practice in relation to unconventional projects and operations?

The research, intended to be completed in two overlapping phases, involves extensive desk-based work (literature review and assessment) by technical experts (Phase 1) as well as baseline-monitoring of seismicity and water resources (Phase 2). At the time of writing, Phase 1 was substantially completed. In January 2016, the EPA was requested by the Department of Communications, Energy and Natural Resources to pause the next Phase of the research to allow time to review the multiple outputs of Phase 1. Following consideration of this request by the project Steering Committee, the Steering Committee has agreed to complete Phase 1 of the study before any decision is made about future work. A set of 11 reports summarising the conclusions from the project were issued in November 2016[8].

4.1.4 US EPA (2015) assessment of the potential impacts of hydraulic fracturing for oil and gas on drinking water resources (External review draft)

The United States Environmental Protection Agency (US EPA) released in 2015 a draft assessment of the potential impacts to drinking water resources from hydraulic fracturing for public comment and peer review. The assessment is meant to provide a review and synthesis of available scientific literature and data to assess the potential for hydraulic fracturing for oil and gas to impact the quality or quantity of drinking water resources. Further, it identifies factors affecting the frequency or severity of any potential impacts (US EPA 2015).

The scope of the assessment was defined by the hydraulic fracturing water cycle and includes five main activities:

- *Water acquisition*, i.e. the withdrawal of ground or surface water needed for hydraulic fracturing fluids;
- *Chemical mixing*, i.e. the mixing of water, chemicals, and proppant on the well pad to create the hydraulic fracturing fluid;
- *Well injection*, i.e. the injection of hydraulic fracturing fluids into the well to fracture the geologic formation;
- *Flowback and produced water*, i.e. the return of injected fluid and water produced from the formation to the surface, and subsequent transport for reuse, treatment, or disposal; and
- *Wastewater treatment and waste disposal*, i.e. the reuse, treatment and release, or disposal of wastewater generated at the well pad, including produced water.

The external review draft identified potential mechanisms by which hydraulic fracturing could affect drinking water resources. Above ground mechanisms affecting surface and ground water resources included (1) water withdrawals at times or in locations of low water availability, (2) spills of hydraulic fracturing fluid and chemicals or produced water,

[7] http://www.epa.ie/researchandeducation/research/researchpillars/water/ugee%20research
[8] http://www.epa.ie/pubs/reports/research/ugeejointresearchprogramme/

and (3) inadequate treatment and discharge of hydraulic fracturing wastewater. Below ground mechanisms included (1) movement of liquids and gases via the production well into underground drinking water resources and (2) movement of liquids and gases from the fracture zone to these resources via pathways in subsurface rock formations.

The external review draft did not find evidence that the mechanisms above have led to widespread, systemic impacts on drinking water resources in the United States. Specific instances were found where one or more of these mechanisms led to impacts on drinking water resources, including contamination of drinking water wells. Such cases occurred during both routine activities and accidents and resulted in impacts to surface or ground water. Spills of hydraulic fracturing fluid and produced water in certain cases reached drinking water resources, both surface and ground water. Discharge of treated hydraulic fracturing waste water were found to have increased contaminant concentrations in receiving surface waters. Below ground movement of fluids were found in some instances to have contaminated drinking water resources. In some cases, hydraulic fracturing fluids were also directly injected into drinking water resources.

Overall, the number of identified cases where drinking water resources were impacted was small relative to the number of hydraulically fractured wells, but the report could not draw a definite explanation. This could reflect a rarity of effects on drinking water resources or may be an underestimate as a result of several factors. The study concluded that "*There is insufficient pre- and post-hydraulic fracturing data on the quality of drinking water resources. This inhibits a determination of the frequency of impacts. Other limiting factors include the presence of other causes of contamination, the short duration of existing studies, and inaccessible information related to hydraulic fracturing activities*".

4.1.5 Peer-reviewed journal articles

(Jackson, Lowry et al. 2015) is a study the goal of which was to quantify the depths of recent hydraulic fracturing in the Unites States and to analyze the water used for hydraulic fracturing. Using ~44 000 observations of hydraulic fracturing depths reported to FracFocus between 2008 and 2013, the authors addressed three questions: (1) the range of depths and water use for hydraulic fracturing across the United States; (2) in which states and at what locations the shallowest high-volume hydraulic fracturing occurred; and (3) what policy protections were or might have been put in place to minimize the risk of direct contamination of drinking water from hydraulic fracturing. The study found that some 5% of the wells drilled shallower than one mile (1600m) and about 1% of wells drilled shallower than 3000 ft (914m) were hydraulically fractured in several US states. The analysis suggests that "*additional safeguards would be beneficial if shallow hydraulic fracturing continues in the future", considering that "fractures can propagate 2000 ft (609 m) upward*".

(Kondash and Vengosh 2015) evaluated the overall water footprint of hydraulic fracturing of unconventional shale gas and oil throughout the United States based on integrated data from multiple database sources. It showed that between 2005 and 2014, unconventional shale gas and oil extraction used 708 billion liters and 232 billion liters of water, respectively. From 2012 to 2014, the annual water use rates were 116 billion liters per year for shale gas and 66 billion liters per year for unconventional oil. The authors concluded that while the hydraulic fracturing revolution has increased water use and generated new sources of highly saline and toxic wastewater production in the United States, its water use and produced water intensity, when normalised to the energy production, is not higher than conventional oil or coal mining and represents only a fraction of total industrial water use nationwide.

We additionally mention the following papers published on the topic of water quality and use, although this is not meant to be an exhaustive list:

- "*Impact to Underground Sources of Drinking Water and Domestic Wells from Production Well Stimulation and Completion Practices in the Pavillion, Wyoming, Field* " (DiGiulio and Jackson 2016).

- *Overview of Chronic Oral Toxicity Values for Chemicals Present in Hydraulic Fracturing Fluids*" (Yost, Stanek et al. 2016)
- "*Brine Spills Associated with Unconventional Oil Development in North Dakota*" (Lauer, Harkness et al. 2016).
- "*Water Use and Management in the Bakken Shale Oil Play in North Dakota*" (Horner, Harto et al. 2016).

4.2 Emissions of methane and other greenhouse gasses

4.2.1 ReFINE study on fugitive methane emissions (2016)

ReFINE (Researching Fracking IN Europe) is an independent research consortium on fracking, led jointly by Newcastle University and Durham University (see Section 7.3.2 for more information). The consortium published in 2016 a study that investigated fugitive emissions of methane from former oil and gas exploration and production wells drilled to exploit hydrocarbon reservoirs onshore in the UK (Boothroy, Almond et al. 2016).

This study selected 102 wells which appeared to be properly decommissioned (with ages between 8 and 79 years), located in four different basins. The soil gas above each well was analysed and assessed relative to nearby control sites of similar land use and soil type. The results showed that of the wells considered, 30% had soil gas methane at the soil surface that was significantly greater than their respective control. Conversely, 39% of well sites had significant lower surface soil gas methane concentrations than their respective control. The authors interpret the elevated methane concentrations to be the result of well integrity failure, but could not explain the source of the gas nor the route to the surface. Where elevated methane was detected, it appeared to have occurred within a decade of the well being drilled. The authors also noted that the measured methane fluxes at the wells were actually low relative to the activity commonly used on decommissioned well sites (such as sheep grazing).

4.2.2 University of Austin study on methane emissions (2015)

A team of researchers from the Cockrell School of Engineering at The University of Texas at Austin carried out a study[9] on methane emission, looking at two major sources of methane emissions, liquid unloadings (Allen, Sullivan et al. 2015) and pneumatic controller equipment (Allen, Pacsi et al. 2015), at well pad sites across the United States.

The study found that 19% of the pneumatic devices accounted for 95% of the emissions from pneumatic devices, and 20% of the wells with unloading emissions that vent to the atmosphere accounted for 65% to 83% of those emissions.

4.2.3 Peer-reviewed journal articles

We mention the following papers on emissions, although this is not meant to be an exhaustive list:

- "*Aerial Surveys of Elevated Hydrocarbon Emissions from Oil and Gas Production Sites*" (Lyon, Alvarez et al. 2016). The authors performed helicopter-based infrared camera surveys of more than 8000 oil and gas well pads in seven U.S. basins to assess the prevalence and distribution of high-emitting hydrocarbon sources. It concluded that "*the proportion of sites with high-emitting sources was 4% nationally but ranged from 1% in Wyoming to 14% in North Dakota. (…) Over 90% of almost 500 detected sources were from tank vents and hatches*"

[9] http://dept.ceer.utexas.edu/methane2/study/index.cfm

- "*Reconciling divergent estimates of oil and gas methane emissions*" (Zavala-Araiza, Lyon et al. 2015). In the study the authors tried to reconcile estimates of methane emissions from atmospheric data (top-down approaches) from source-based inventories (bottom-up approaches) based on data from the Barnett Shale. They concluded inter alia that "*two percent of oil and gas facilities in the Barnett accounts for half of methane emissions at any given time, and high-emitting facilities appear to be spatiotemporally variable. Measured oil and gas methane emissions are 90% larger than estimates based on the US Environmental Protection Agency's Greenhouse Gas Inventory and correspond to 1.5% of natural gas production. This rate of methane loss increases the 20-y climate impacts of natural gas consumed in the region by roughly 50%*".
- "*Influence of oil and gas field operations on spatial and temporal distributions of atmospheric non-methane hydrocarbons and their effect on ozone formation in winter*" (Field, Soltis et al. 2015). It found, inter alia, that "*fugitive emissions of natural gas and of condensate were the two principal emission source types for non methane hydrocarbons*".

4.3 Public Health/Environment

4.3.1 The Center for Rural Pennsylvania's study (2015)

The Center for Rural Pennsylvania commissioned an impact study that looked at health and health care as a consequence of shale gas developments in the Marcellus shale (The Center for Rural Pennsylvania 2015).

The motivation behind the study was the uncertainty related to the potential human health effects of Marcellus Shale drilling and related development activities. It was considered likely that different phases of drilling and development may affect human health differently, with some aspects of drilling impacting health directly and others indirectly. The research examined changes in healthcare services, the use of healthcare services, reported injuries, and emergency medical service complaints in four counties in Pennsylvania before and after the start of shale gas developments. The objective was to determine if incidences of certain health status indicators and demand for healthcare services changed in the study counties during the years that Marcellus drilling activity increased. Results indicated that:

- Inpatient hospitalizations in the four counties and the two regions increased slightly in the northern tier and decreased slightly in the southwest, but it was not possible to directly connect this to Marcellus Shale drilling.
- There were no overall trends for injuries in the four study counties. There were noticeable increases in injuries associated with falls and motor vehicle accidents, but these types of injuries could be related to any type of large-scale construction activity and not necessarily to Marcellus Shale drilling.
- There was a substantial increase in the number of emergency medical services complaints, however data was not available on the exact nature of the injuries and complaints could not be tied directly to drilling activity. A likely relationship was inferred given the time frame in which the data were reported.
- Data should be collected in a more consistent and systematic way to allow for more meaningful analyses.

4.3.2 Pennsylvania Department of Environmental Protection study on TENORMs (2015)

In 2013, the Pennsylvania Department of Environmental Protection initiated a study to collect data relating to technologically enhanced naturally occurring radioactive materials (TENORMs) associated with oil and gas operations in Pennsylvania. This study included the assessment of potential worker and public radiation exposure, TENORM disposal, and other possible environmental impacts. The study encompassed radiological surveys at well sites, wastewater treatment plants, landfills, gas distribution and end use, and O&G brine-treated roads. The media sampled included solids, liquids, natural gas, ambient air, and surface radioactivity. The final report was published in 2015 (Pennsylvania Department of Environmental Protection 2015).

The following conclusions were drawn:

1. There is little potential for additional radon exposure to the public due to the use of natural gas extracted from geologic formations located in Pennsylvania.
2. There is little or limited potential for radiation exposure to workers and the public from the development, completion, production, transmission, processing, storage, and end use of natural gas. There are, however, potential radiological environmental impacts from fluids if spilled.
3. There is little potential for radiation exposure to workers and the public at facilities that treat wastes. However, there are potential radiological environmental impacts that should be studied at all facilities treating wastes to determine if any areas require remediation.
4. There is little potential for radiation exposure to workers and the public from landfills receiving waste from the oil and gas industry. However, filter cake from facilities treating oil and gas wastes are a potential radiological environmental impact if spilled, and there is also a potential long-term disposal issue.
5. While limited potential was found for radiation exposure to recreationists using roads treated with brine from conventional natural gas wells, further study of radiological environmental impacts from the use of brine from the oil and gas industry for dust suppression and road stabilization should be conducted.

4.3.3 British Columbia's Ministry of Health study (2015)

The Ministry of Health (MoH) funded an assessment of the human health risks associated with oil and gas activities in northeastern British Columbia. The study was carried out by a consortium of companies led by Intrinsik (Intrinsik Environmental Sciences Inc. 2014).

The objectives of this study were to provide a comprehensive and focused assessment of potential health risks that may exist for people living in proximity to oil and gas activities.

The literature review conducted concluded inter alia that "*there is an apparent need for additional studies with case control or cohort study designs to evaluate the potential association between cancer incidence and oil and gas activity", and that "there is an overall lack of published research regarding respiratory health effects and oil and gas activities*" and "t*he majority of the studies evaluated lacked information regarding exposure pathways of interest, exposure concentrations, or chemicals of potential concern*".

The risk assessment (which had a regional focus) found that, in general, the predicted short-term air concentrations of chemicals of potential concern were less than their health based exposure limits. Also, the potential combined risks of these chemicals were not predicted to result in adverse health effects in people living or visiting the study area. However, the predicted exposures at some locations were found to exceed exposure limits for certain individual chemicals (such as acrolein, formaldehyde, NO_2 and SO_2). The exceedances for formaldehyde, NO_2 and SO_2 were found to be attributable to oil and gas emission sources, with some contributions from other sources in the area. Overall, long-term inhalation exposures to the chemicals of potential concern were predicted to be associated with a low potential for adverse health effects. The overall findings of the detailed assessment suggested that, while there is some possibility for elevated chemical concentrations to occur at some sites, the probability that adverse health impacts would occur in association with these exposures is considered to be low. It is to be noted that "aerial deposition onto regional water bodies, direct releases to water (groundwater or surface water) were not included in the detailed human health risk assessment".

The report makes a range of recommendations including inter alia the need to update land-use and setback provisions, to implement baseline, pre-drilling ground water testing requirements (with results to be made publically available), to refine its fracturing fluid disclosure process, to pursue air monitoring and to expand the aquifer mapping.

4.3.4 Quebec National Public Health Institute (2015)

As part of Québec's Strategic Environmental Assessment (SEA), and more specifically contributing to the work carried out under the Human Health and Safety component of the SEA working group on health and societal impacts, the Institut National de Santé Publique du Québec (Quebec National Public Health Institute) was given the mandate to document the issues and potential effects on public health related to the exploration and production of gas and oil hydrocarbons.

The following objectives were specified: (1) draw up a knowledge profile on potential risks for human health (both in the general population and the workers) related to gas and oil hydrocarbon exploration and production; (2) determine the additional knowledge required on public health and hydrocarbon exploration and production activities; and (3) propose prevention and management options regarding the health risks that the public might be exposed to in relation to hydrocarbon exploration and production in Quebec.

The study was published in 2015 (Quebec National Public Health Institute 2015).

4.4 Seismicity

4.4.1 Central Mining Institute of Katowice (2015)

A seismic monitoring study of Polish drilling sites was commissioned by the Polish ministry of the environment and carried out by the Central Mining Institute in Katowice.

The aim of the project was to design and installed networks of seismic probes to measure the seismic vibrations in three areas where hydraulic fracturing treatments were carried out. These were the Syczyn-OU2K well in Syczyn and the Zwierzyniec-1 well in Zawada (both in the Lubelskie Voivodeship) and the Gapowo-1 well in Stężyca (in the Pomorskie Voivodeship). The final report was published in 2015 (Lurka, Mutke et al. 2015).

The purpose of the seismic networks was to carry out continuous digital recording of seismic background and seismic events in designated areas around the wells. Specifically, the task of seismometers was to register vibrations caused by work carried out in the wells. Seismic monitoring included the following works: preparation: determination of the installation sites, installation of equipment, seismic background measurement before hydraulic fracturing, measurement during hydraulic fracturing, and measurement after hydraulic fracturing.

The study concluded that registered vibrations did not exceed the permissible vibration levels according to the Polish standard (PN-88 / B-02171) and had no impact on people in buildings.

4.4.2 Peer-reviewed journal articles

We mention the following papers on induced seismicity, with a particular focus on the European situation, although this is not meant to be an exhaustive list:

- From the ReFine Project: "*Anthropogenic earthquakes in the UK: A national baseline prior to shale exploitation*" (Wilson, Davies et al. 2015). In this study the authors reviewed the distribution, timing and probable causes of ~8000 onshore UK seismic events between the years 1970-2012.
- From the U.S. Geological Survey and the Geological Survey of Canada: "*Myths and Facts on Wastewater Injection, Hydraulic Fracturing, Enhanced Oil Recovery, and Induced Seismicity*" (Rubinstein and Mahani 2015). In this paper, induced seismicity associated with wastewater injection and hydraulic fracturing is discussed.
- "*Hydraulic Fracturing and Seismicity in the Western Canada Sedimentary Basin*" (Atkinson, Eaton et al. 2016). The authors notably concluded that whilst in the central United States, most induced seismicity is linked to deep disposal of produced waste water from oil and gas extraction, in western Canada most recent cases of induced seismicity are highly correlated in time and space with hydraulic fracturing.
- *"Human-induced seismicity and large-scale hydrocarbon production in the USA* and Canada" (van der Baan and Calixto 2017) compared current and historic seismicity rates in six States in the USA and three Provinces in Canada to past and present hydrocarbon production. The study found that increased seismicity in Oklahoma, likely due to salt-water disposal, has an 85% correlation with oil production. Yet, the other areas do not display State/Province-wide correlations between increased seismicity and production, despite 8-16 fold increases in production in some States. However in various cases seismicity locally increased.

4.5 Chemical additives usage

(Elsner and Hoelzer 2016) attempted to bridge the gap between existing alphabetical disclosures by function and emerging scientific contributions on fate and toxicity of hydraulic fracturing additives. Published in early 2016, the study quantitatively reviewed the structural properties of additives, using voluntary U.S. disclosures from the FracFocus registry and from a House of Representatives database, the so-called "Waxman" list (Waxman, Markey et al. 2011).

The authors noted that out of more than a thousand reported substances, classification by chemistry yielded only small sets where it was possible to illustrate the rationale of their use and properly identify physical and chemical properties relevant for determining environmental fate and toxicity. Whilst many substances were nontoxic, frequent disclosures also included notorious groundwater contaminants such as petroleum hydrocarbons (solvents), precursors of endocrine disruptors, toxic propargyl alcohol, biocides and strong oxidants. Application of highly oxidizing chemicals suggested to the authors the possibility that relevant transformation products may be formed and advocated full disclosure of hydraulic fracturing additives in order to adequately investigate such reactions.

JRC published a study on the Use of nanomaterials in fluids, proppants, and downhole tools for hydraulic fracturing of unconventional hydrocarbon reservoirs (Gottardo, Mech et al. 2016). This is described in more detail in Section 2.2.5.

4.6 Surface impacts

ReFINE (Researching Fracking IN Europe) is an independent research consortium on fracking, led jointly by Newcastle University and Durham University (see Section 7.3.2 for more information). The consortium published in 2016 a study that presented an environmental assessment of traffic impacts for individual and groups of hypothetical fracking sites (Goodman, Galatioto et al. 2016). In this study, a model was developed to produce estimates of the traffic-related impacts of fracking on greenhouse gas emissions, local air quality emissions, noise and road pavement wear, using a range of hypothetical scenarios to quantify changes in impacts against baseline levels.

Results suggested that the local impacts of a single well pad may be of short duration but of large magnitude. For instance, the model showed that whilst small percentage increases in emissions of CO_2, NO_x and particulate matter were estimated for the period from start of construction to pad completion, excess emissions of NO_x on individual days of peak activity could reach 30% over the baseline values. Similarly, excess noise emissions appeared negligible when normalised over the completion period, but could be considerable in particular hours, especially in night-time periods. The use of the model to explore hypothetical future technology timelines over a range of well development scenarios covering several decades showed that the overall impact to a region, or a country as a whole, appeared "*somewhat negligible compared to general traffic or industrial activities, though it is recognised that the methodology used may underestimate emissions associated with network congestion*".

5 Hydraulic fracturing in the social sciences

There has been a growth in social science research on fracking recently, especially since 2010 (Williams, Macnaghten et al. 2015).This growing body of work has largely focused on three areas: policy research (Rinfret, Cook et al. 2014), attitude surveys (Boudet, Clarke et al. 2014) and fracking in the media (Jaspal and Nerlich 2014).

ReFINE (Researching Fracking IN Europe) is an independent research consortium on fracking, led jointly by Newcastle University and Durham University (see Section 7.3.2 for more information). The consortium published in 2015 a study on the public perceptions of hydraulic fracturing. This paper was motivated by an analysis by (Jaspal, Turner et al. 2014), claiming that there is both a lack of research on the public perceptions of hydraulic fracturing and consideration from the point of view of science and technology studies.

The ReFINE study (Williams, Macnaghten et al. 2015) was aimed at addressing both these gaps. In particular, it explored the factors that are shaping the public controversy through qualitative research on public perceptions in the United Kingdom. The UK institutional framing of hydraulic fracturing policy and the understanding of fracking articulated by lay participants, derived from six in-depth qualitative focus groups held in early 2013, were explored.

The authors argued that the problem associated with fracking is not simply about the existence of objective risks, nor just about the ability of the public to understand them, but also about the institutional ability and willingness to recognise and accommodate diverse public views. Four key lessons for policymakers emerged from this research. First, it is important that policymakers avoid adopting the position of salesperson for fracking because salespeople are not likely to be viewed as legitimate arbiters. Second, it is important to submit the possible benefits of fracking to the same level of scrutiny as the risks. Third, policymakers should avoid giving the disingenuous impression that there is no choice on whether to go ahead or not with the exploitation of shale gas. Finally, engagement with the public must be a real dialogue, not a monologue.

The interesting discussion that took place during the Transatlantic Knowledge Sharing Conference on Unconventional Hydrocarbons: Resources, Risks, Impact and Research Needs on the subject of multi-actor and public engagement in research and innovation is described in Section 8.4.

6 Risk and safety assessments

6.1 TNO study (2015)

In 2013, a study commissioned by the Dutch government was carried out carry into the possible risks and consequences of the exploration for and extraction of shale and coal gas in the Netherlands (Witteveen+Bos, Arcadis et al. 2013). The following conclusions emerged from this assessment:

- Compared with conventional gas extraction, shale gas extraction has a bigger footprint and there are more industrial activities on each drilling site.
- Methane may be released during various phases of exploration and extraction and due to the intensive logistics, longer drilling and fracking more CO_2 is emitted compared with conventional gas extraction.
- Due to the high pressure injection of fracking fluid in or near an active fault zone, earthquakes may possibly occur during shale gas extraction.
- The fracking fluid consists mainly of water containing proppants and additives (approx. 2%). A number of these additives may be harmful in high concentrations.
- One possible risk of shale gas extraction is the contamination of the groundwater due to the failure of well integrity, migration of fluid or methane directly from the shale or coal stratum either via the well or due to spillages and leaks on the drilling site.

The Witteveen+Bos study concluded that the potential risks for nature, people and the environment are manageable and that the current Dutch legal frameworks offer sufficient options for addressing them. It also recommended the execution of site-specific research with the aim of evaluating for each potential extraction site the effects of shale gas extraction on people, nature and the environment.

Because the Witteveen+Bos mainly looked at the subsurface aspects and only to a lesser extent to the surface effects, a further study was commissioned to TNO, to evaluate the existence and development of new technologies that may reduce the risks of shale gas extraction for people and environment with a focus on ground- and drinking water, emissions, induced seismicity and surface footprint. The central research question that was posed was the following: are there developments and technologies with which the (residual) risks of the extraction of shale gas (drilling, fracking, production of gas, water and drilling muds) can be reduced?

TNO published the findings of such study in 2015 in a report titled "*Inventory of technologies and developments for reducing (residual) risks in shale gas extraction*" (Heege, Griffioen et al. 2014). The work included firstly a study of relevant literature, available expert reports and identification of gaps. These gaps were then filled in by interviews with experts and additional literature research. A second phase followed with a process of knowledge integration to answer the research questions posed and to indicate any existing relationship between them.

7 R&D initiatives

Several research projects on unconventional fossil fuels are currently under way both in Europe and worldwide. Four EU-funded projects within the Horizon2020 framework have kicked off and are described in Section 7.1 below. Other EU initiatives are described in Section 7.2. Relevant projects in EU member states are described in Section 7.3. Finally, Section 7.4 reviews several projects taking place in non-EU countries.

The near totality of the projects reviewed is concerned with assessing the environmental risks associated with shale gas exploration and exploitation. The following broad topic areas of research can be identified: (1). Scale and nature of unconventional oil and gas resources in a given region; (2). Water quality and availability; (3). Air quality and greenhouse gas emissions; (4). Effects on human health; (5) Ecological effects; (6) Induced Seismicity.

7.1 EU-funded projects

7.1.1 M4ShaleGas

The M4ShaleGas[10] (Measuring, monitoring, mitigating managing the environmental impact of shale gas) program focuses on reviewing and improving existing best practices and innovative technologies for measuring, monitoring, mitigating and managing the environmental impact of shale gas exploration and exploitation in Europe. The technical and social research activities intend to deliver scientific recommendations on (1) how to minimize environmental risks to the subsurface, surface and atmosphere; (2) how to reduce and mitigate the risk and 3) how to address the public attitude towards shale gas development. Knowledge and experience on best practices will be informed by direct collaboration with US and Canadian research partners and input from representatives from the industry.

7.1.2 SHEER

The objective of SHEER[11] (SHale gas Exploration and Exploitation induced Risks) is to develop best practices for assessing and mitigating the environmental footprint of shale gas exploration and exploitation. The consortium includes partners from Italy, United Kingdom, Poland, Germany, the Netherlands and USA. It intends to develop a probabilistic procedure for assessing short and long-term risks associated with groundwater contamination, air pollution and induced seismicity. The consortium intends to approach the issue from a multi-hazard, multi parameter perspective, by developing methodologies and procedures to track and model fracture evolution around shale gas exploitation sites and a robust statistically based, multi-parameter methodology to assess environmental impacts and risks across the operational lifecycle of shale gas. The developed methodologies will be applied and tested on a comprehensive database consisting of seismicity, changes of the quality of ground-waters and air, ground deformations, and operational data collected from past case studies. Additionally, they will be improved by the high quality data SHEER will collect monitoring micro-seismicity, air and groundwater quality and ground deformation in a planned hydraulic fracturing to be carried out by the Polish Oil and Gas Company in Pomerania.

[10] http://cordis.europa.eu/project/rcn/193743_de.html
[11] http://www.sheerproject.eu/objective.html

7.1.3 ShaleXenvironmenT

The primary objective of this project[12] is to assess the environmental footprint of shale gas exploitation in Europe in terms of water usage and contamination, induced seismicity, and fugitive emissions. Using both experiments and modeling, this project intend to achieve a much improved understanding of rock-fluid interactions, fluid transport, and fracture initiation and propagation, via technological innovations obtained in collaboration with industry, and via improvements on characterization tools. ShaleXenvironmenT will maintain a transparent discussion with all stakeholders, including the public, and will suggest ideas for approaches on managing shale gas exploitation, impacts and risks in Europe, and eventually worldwide.

7.1.4 FracRisk

The objective of FracRisk[13] is to develop knowledge for understanding, preventing and mitigating the potential impact of the exploration and exploitation through hydraulic fracturing (fracking) of shale gas reserves found throughout Europe, and to develop a decision support tool for risk quantification of the environmental impacts of the technology. The aim is to provide key scientific-based recommendations aimed at minimising the environmental footprint of shale gas extraction through effective planning and regulation, whilst at the same time addressing public concerns.

7.1.5 ShaleSafe

The objective of ShaleSafe is to develop a monitoring system embedded in a sonic drilling pipe for inspection of soil and aquifer contamination by shale gas and hydraulic fracturing chemicals. This project was selected in 2015 for funding under the Fast track to innovation H2020 call.

7.2 EU initiatives

7.2.1 EERA Joint Program on Shale Gas

The European Educational Research Association[14] (EERA) Joint Program on Shale Gas is meant to establish a common knowledge platform for research on the potential, impact and safety of shale gas development in Europe. Existing technologies and methodologies are to be evaluated and improved to establish an independent knowledge basis which is based on research by twenty four independent research institutes from 15 European member states.

7.2.2 UH Network

The European Science and Technology Network on Unconventional Hydrocarbon Extraction[15] (UH Network) was officially established by the 2014 Communication from the Commission on the exploration and production of hydrocarbons (COM/2014/023 final/2). The main objective of the Network, managed by the Joint Research Centre in close cooperation with DG Environment, DG Energy, DG Research & Innovation, DG Climate Action and DG Internal Market, Industry, Entrepreneurship and SMEs, was to collect, analyse and review results from exploration projects as well as to assess the development of technologies used in unconventional gas and oil projects. The objectives

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[12] https://shalexenvironment.wordpress.com
[13] http://www.fracrisk.eu
[14] http://eera-shalegas.eu
[15] https://ec.europa.eu/jrc/uh-network

of the Network were (1) to structure the dialogue among the stakeholders, fostering open information and knowledge sharing; (2) to present and discuss research activities and their results; (3) to identify research gaps and innovation needs; (4) to examine knowledge gained from exploration and production projects; and (5) to identify and assess emerging technologies including their economic, environment and climate impacts.

Work was organised in two Working Groups. Working group 1 (Exploration, demonstration and production projects in the EU) was tasked with collecting data obtained from exploration and possible demonstration and production projects as well as related research projects carried out in the EU, with the aim to carry out a comparative assessment. Working group 2 (Emerging technologies for well simulation) was tasked to complement and update the JRC document of 2013 providing "an overview of hydraulic fracturing and other formation stimulation technologies for shale gas production" (Gandossi 2013), based on practical experience with these technologies in exploration, possible demonstration and production projects in and outside the EU. The Working Groups carried out their activities in 2015 and were closed at the beginning of 2016. The Network's activities were paused at the Annual conference held in February 2016.

7.3 National Projects and Initiatives in EU Member States

7.3.1 Poland

Blue Gas– Polish Shale Gas

This national programme[16] is a joint undertaking of National Centre for Research and Development (NCBR) and Industrial Development Agency (ARP S.A.). It is focused on supporting integrated large R&D projects, testing results in pilot scale and commercialization of innovative technologies in the area of shale gas extraction. The main aim is the development of technologies related to shale gas extraction in Poland and their implementation by companies operating in Poland.

7.3.2 United Kingdom

Scottish Government

The Scottish Government is conducting a program of research and public consultation for onshore unconventional oil and gas. The detailed evidence-gathering phase will take place between 2015 and 2016 and a consultation phase, covering engagement, public consultation and analysis, is due to conclude in spring 2017. For more information, please refer to the link provided in the footnote[17].

Energy Security and Innovation Observing System for the Subsurface (ESIOS)

This is a programme[18] coordinated by the British Geological Survey (BGS) with the aim of establishing the Energy Security and Innovation Observing System for the Subsurface (ESIOS). ESIOS intends to be a group of science research facilities where subsurface activities such as fracking for shale gas can be tested and monitored under controlled conditions. The scientific data will be published freely online to encourage transparency in the industry and to provide science for regulation. Research will address many of the environmental issues that need to be answered for the development of secure energy solutions, including carbon capture and storage, geothermal energy, nuclear waste

[16] http://www.ncbir.pl/en/domestic-programmes/blue-gas-polish-shale-gas
[17] http://www.sepa.org.uk/environment/energy/non-renewable/shale-gas-and-coal-bed-methane
[18] http://www.bgs.ac.uk/research/energy/shaleGas/esios.html

disposal, underground coal gasification and underground gas storage. The first ESIOS facility will be based in Thornton, Cheshire and a second site will be located in a suitable area in the UK covering a different range of geological and energy conditions. The new facilities will complement and build on those already at the disposal of the BGS and the wider academic community.

British Geological Survey: Shale gas environmental monitoring

The British Geological Survey (BGS) is monitoring environmental baseline conditions in relation to potential shale gas development in the UK[19]. Monitoring addresses quality of groundwater and surface water, seismicity, atmospheric composition assessment, ground motion (subsidence and uplift). In particular, environmental baseline monitoring is to be undertaken in the Vale of Pickering and in Lancashire by a consortium of universities.

ReFINE

ReFINE[20] (Researching Fracking IN Europe) is an independent research consortium on fracking, led jointly by Newcastle University and Durham University. Launched in 2013, ReFINE was formed after trans-European discussions between scientists, policy-makers and the petroleum industry identified the need for unbiased research into shale gas exploitation. The consortium has recently published several studies related to various aspects of hydraulic fracturing, see for instance Sections 4.2.1, 4.4.2, **Error! Reference source not found.** and **Error! Reference source not found.**.

Task Force on Shale Gas

The Task Force on Shale Gas[21] was launched in September 2014 to provide an impartial, transparent and evidence-based assessment of the potential benefits and risks of shale gas extraction to the United Kingdom. The Task Force's funding comes from businesses involved in the shale gas industry. However, the Task Force operates independently from its funders and the funders have no influence over its research, recommendations or publications.

Recognising that the issue of shale gas extraction and its potential benefits and risks is a polarising topic in the UK, the Task Force intended to create a platform to provide reasoned and evidence-based conclusions and recommendations to both industry and Government about the potential of shale gas extraction in the UK, to inform the general public and to promote reasonable discussion about these findings.

A first interim report, published in March 2015, examined the existing planning and regulatory system for shale gas and the public consultation process and made a series of recommendations to address the concerns raised by the public around potential shale gas extraction (Task Force on Shale Gas 2015a).

A second interim report, published in July 2015, looked at the impacts of shale gas associated with the local environment. Specifically it looked at seismic activity, at potential impacts on air and water and on public health impacts. The report made a series of recommendations that would provide a framework under which it would be possible to minimise the risk associated with shale gas to acceptable levels (Task Force on Shale Gas 2015b).

A third interim report, published in September 2015, examined evidence related to the potential climate change impacts associated with shale gas. This report concludes that, provided it is firmly regulated, shale gas can contribute to the decarbonisation of the British economy (Task Force on Shale Gas 2015c).

[19] http://www.bgs.ac.uk/research/groundwater/shalegas/faq.html
[20] http://www.refine.org.uk/
[21] https://www.taskforceonshalegas.uk

A fourth report, published at the end of 2015, examined the economics of a shale gas industry in the UK, including community benefits and compensation (Task Force on Shale Gas 2015d).

7.3.3 Germany

Nicht-konventionelle Kohlenwasserstoffe (NiKo)

This project[22] aims at evaluating of the shale gas potential in Germany, conducted by the German Federal Institute for Geosciences and Natural Resources (BGR).

7.3.4 Ireland

As described in greater detail in Section 4.1.3, the Environmental Protection Agency of Ireland is funding a research effort in relation to the environmental impacts of unconventional gas exploration and extraction. A set of 11 reports summarising the conclusions from the project was issued in November 2016.

7.3.5 The Netherlands

In reaction to the public debate on shale, the Dutch Ministry of Economic Affairs set out a study in 2011, on the possible risks and effects of exploration and exploitation of shale gas, which was carried out by Witteveen and Bos, Arcadis and Fugro (Witteveen+Bos, Arcadis et al. 2013). This was described in greater detail in Section 6.1. The resulting advice was that more research is needed to determine the local effects on people and nature, and that environment location-specific investigations are needed, for instance in the form of an environmental impact assessment.

In reaction to this study, the Ministry of Economic Affairs and Infrastructure and Environment decided to develop a "Structural Vision" on shale gas that will give the government information on whether shale gas in the Netherlands could be developed and how and in what areas on national level this could take place. In July 2015 three studies that are part of this initiative were published[23]:

- PlanMER (Environmental impact assessment),
- Inventory of innovative technologies to minimize environmental impact of shale gas development and
- Exploration of societal effects.

Based on the studies above, the Minister announced that no commercial shale gas development will take place in the Netherlands in the next 5 years.

7.4 Important Projects of Major Non-EU Countries.

The USA has developed a federal multiagency strategy for coordinating on-going and future research associated with the safe development of onshore shale gas, tight gas, shale oil, and tight oil resources (U.S. DEPARTMENT OF ENERGY, U.S. DEPARTMENT OF THE INTERIOR et al. 2014). This identifies key questions the agencies involved, the Department of Energy (DOE); Department of the Interior (DOI) and the Environmental Protection Agency (EPA) use to guide on-going research[24]. The following describes more in detail some of the initiatives.

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22 https://www.bgr.bund.de/DE/Themen/Energie/Projekte/laufend/NIKO

23 http://www.rijksoverheid.nl/documenten-en-publicaties/kamerstukken/2015/07/10/kamerbrief-schaliegas.html

24 http://unconventional.energy.gov

Marcellus Shale Energy and Environmental Laboratory (MSEEL)

The Department of Energy's National Energy Technology Laboratory (NETL) and several partners conduct this project[25] to monitor the process and progress of unconventional gas production at a Marcellus Shale well near Morgantown, WV. MSEEL will enable continuous monitoring of produced water and air quality. The project also gives researchers access to a dedicated science well for subsurface geophysical observation while NNE deploys a range of next-generation well-completion technologies designed to increase operational efficiency and reduce environmental impact.

EPA's Study of Hydraulic Fracturing for Oil and Gas and Its Potential Impact on Drinking Water Resources

The overall purpose of this study[26], conducted by the U.S. Environmental Protection Agency (EPA), is to investigate how hydraulic fracturing may have an effect on drinking water resources. An external review draft was published in June 2015 for public comments and peer review.

AirWaterGas

The mission of this Sustainability Research Network[27], funded by the National Science Foundation, is to provide a logical, science- based framework for evaluating the environmental, economic, and social trade-offs between development of natural gas resources and protection of water and air resources and to convey the results of these evaluations to the public in a way that improves the development of policies and regulations governing natural gas and oil development.

USGS - Produced Waters

Researchers of the U.S. Geological Survey (USGS) Energy Resources Program (ERP) are engaged in examining several aspects related to characterization, use, and impact of produced waters[28]. Currently research is focused in three areas: (1) the assessment of the impact of coalbed methane produced waters; (2) chemical characterization and sources of Appalachian Basin produced waters; and (3) water balances for energy resource production (water budget methods for understanding water inputs and outputs).

USGS - Hydraulic Fracturing

Research on hydraulic fracturing is underway by a number of USGS offices including the Energy Resources Program, Water Resources, Natural Hazards and Environmental Health[29]. This includes the major environmental study conducted by the U.S. Environmental Protection Agency, mentioned above.

[25] http://mseel.org
[26] http://www2.epa.gov/hfstudy
[27] http://airwatergas.org
[28] http://energy.usgs.gov/EnvironmentalAspects
[29] http://energy.usgs.gov/OilGas/UnconventionalOilGas

8 Transatlantic Knowledge Sharing Conference on Unconventional Hydrocarbons: Resources, Risks, Impact and Research Needs

The *Transatlantic Knowledge Sharing Conference on Unconventional Hydrocarbons: Resources, Risks, Impact and Research Needs* was organised by JRC and took place in Amsterdam on 20-21 June 2017. This interdisciplinary and intercontinental (EU, USA, Canada) conference aimed to attract scientists, engineers, social scientists, geologists and represenatitives from the civil society to contribute with their research on unconventional hydrocarbon extraction and to share their knowledge.

The topics discussed at the conference were organised under five sessions:

1. Induced seismicity resulting from hydraulic fracturing and water waste management.
2. Risk assessment and environmental impact assessment.
3. Modelling bench-marking using experimental data.
4. Multi-actor and public engagement in research and innovation.
5. Innovative measurement methods for environmental parameters.

The conference was opened by Jeroen Schuppers (EC - DG RTD) Marcelo Masera (EC - DG JRC). The conference program and the presentations delivered can be found online at this link. The content of this chapter is based on the presentations given by the speakers during the conference as well as on the abstracts that were submitted prior to the conference. Verifying the claims made and the results reported was beyond the scope of this report.

A keynote presentation was given by Alan Krupnick (RFF - Resources for the future) on "Community Impacts of Shale Gas Developments: Myths and Realities". He argued that rapid shale gas development in the U.S. has been lauded by its supporters for economic gains, while detractors focus on the evils of fracking. In reality, according to the speaker, both groups are exaggerating. He highlighted the state of knowledge about community impacts, spanning the positive effects on wages and economic development and the negative on health, traffic accidents, induced seismicity and others. He argued that from an economics points of view, benefits are gained at national and state level, at least during a boom. Regarding externalities, he argued that a lot of uncertainty still exisit. There are definitely reasons for real concern and perception may have a notable influence, for instance by strongly affecting housing markets. The speaker concluded by arguing that best practice is not enough, and that comprehensive regulations and real (but costly) community engagement are needed.

8.1 Induced seismicity resulting from hydraulic fracturing and water waste management.

Torsten Dahm (GFZ German Research Centre for Geosciences) presented a study entitled "*advances in microseismic monitoring and understanding of hydraulic fracturing: the contribution of the SHEER EU project*". Large data volumes currently recorded by dense microseismic networks provide lots of information on weak seismicity and microseismicity induced by human geomechanical operation, including hydraulic fracturing. New seismological methods and algorithms need to be developed to tackle the big data challenges and extract from large datasets a broad information on weak ongoing rupture processes. The first step in a microseismicity study concerns the detection of seismic activity and the subsequent creation of a seismic catalog, which should be as accurate and complete as possible. The signal detection is then accompanied by first seismological analysis, devoted to the determination of source locations and magnitudes. New tools need to be automatized and the user interaction minimized or in the optimal case removed, so that large datasets can be handled and the data mined. In addition, a seismic detector needs to be performant, so that massive datasets can be processes in a reasonable time, whereas a seismic locator needs to be accurate, so that the small-scale patterns and migration of rupture processes can be resolved. The author presented recently developed seismological tools, designed to detect coincident arrivals of seismic energy in different frequency bands at seismic stations in a local network and locate their seismic source. He illustrated the functionality of these methods by showing two different applications to hydraulic fracturing experiments. The first case concerned a small-scale experiment in a Swedish mine, where thousands of microfractures (acoustic emissions) were detected and geo-located during an hydraulic fracturing and re-fracturing experiment. The second case concerned a recently exploited hydraulic fracturing site in north-east Poland, monitored in the framework of the EU project SHEER (see Section 7.1.2). There, the techniques presented were used both with realistic synthetic data and real data to analyse one of the first hydraulically fractured well in Europe. An independent seismic monitoring of hydraulic fracturing operations was also performed.

Megan Zecevic (University of Calgary, Canada) discussed the *dynamics of fault activation by hydraulic fracturing in western Canada.* Fluid-injection processes such as disposal of saltwater or hydraulic fracturing can induce earthquakes by increasing pore pressure and/or shear stress on faults. In western Canada, hydraulic fracturing has been inferred as the dominant triggering mechanism for most injection-induced earthquakes. This is in contrast with the Midwestern United States where massive saltwater disposal is the predominant trigger. The speaker presented two examples from western Canada where earthquakes induced by hydraulic fracturing are strongly clustered within areas characterized by pore-pressure gradient in excess of 15 kPa/m. Contrarily, induced earthquakes are virtually absent elsewhere in the same formations, despite extensive hydraulic-fracturing activity associated with resource development. Monte Carlo analysis indicated that there is negligible probability that this spatial correlation developed by chance. A detailed analysis was undertaken within a 400 km^2 region in Alberta, Canada where uniquely comprehensive data characterize dynamic interactions between well completions at 6 drilling pads. Seismicity was strongly clustered in space and time, exhibiting spatially varying persistence and activation threshold. The largest event (ML 4.4) was reconciled with a previously postulated upper bound on magnitude, only if considering the cumulative effect of multiple treatment stages. Induced seismicity from hydraulic fracturing reveals contrasting signatures of fault activation by stress effects and fluid diffusion. Patterns of seismicity indicated that stress changes during operations can activate fault slip to an offset distance of more than one km, whereas pressurization by hydraulic fracturing into a fault yields episodic seismicity that can persist for months.

Brecht Wassing (TNO, The Netherlands) presented her work on *Key controlling factors of induced seismicity cause by shale gas operations*. The key questions, according to this speaker, are (1) the identification of the key controlling factors (site-specific and operational); (2) the capability to assess the potential for inducing felt earthquakes during shale gas operations; and (3) whether induced seismicity can be mitigated. A proposed way forward would be to further the understanding of the underlying mechanics of injection-induced seismicity, by for instance coupling experiments with models and data gathered from monitoring activities. Mitigation can be achived by several means, for instance mapping of faults and fractures, avoiding injection into or nearby critically stressed (basement) faults, reducing injection volumes, baseline monitoring of background seismicity and establishing operational protocols for injection sites, such as an advanced traffic light system.

Kris Nygaard (ExxonMobil, USA) discussed *averaging cross-disciplinary science for induced seismicity risk management*. In this presentation, a risk assessment framework was discussed that considers a range of technical elements that may affect the risk level and that could be used on a qualitative basis to estimate relative risk levels for a proposed project. The framework is based on multiple factors that may affect the probability and consequences associated with a potential induced seismic event. Potential probability elements include volume of injected fluid, formation characteristics, tectonic/faulting environment and operating experience. Potential consequence elements include physical damage, environmental impact, economic disruption, social or community impact and public disturbance. Given the uncertainty that exists in characterizing various subsurface data, approaches considering probabilistic based risk assessment methodologies to characterize the "fault slip potential" were then discussed. Generally, is it not possible to determine a priori whether a fault is at or near critical-stress and prone to slip. As such, probabilistic based risk assessment methods can provide key insights on subsurface and operational parameters that can affect risk level. These quantitative methods are based on cross-disciplinary technical integration of reservoir modeling of reservoir pressures and geomechanical modeling of subsurface stress fields that influence the potential for fault re-activation. This presentation further described the actions that may be appropriate to take for evaluation of causation, including assessment of all potential natural and anthropogenic factors that induce subsurface stress perturbations in area; and the type of data acquisition, analysis, and modeling that could be required for science-based assessment of causation. This could enable stakeholders to better consider the type of data collection and analysis that may be considered if anomalous seismicity occurs. Finally, the speaker discussed several key research areas that, if pursued, could help facilitate improved understanding and risk mitigation of seismicity.

Mark Petersen (USGS, USA) presented a model for the "*2017 One-Year Seismic Hazard Forecast for the Central and Eastern United States from Induced and Natural Earthquakes*". The speaker discussed how he and his co-workers produced a one- year 2017 seismic-hazard forecast for the central and eastern United States from induced and natural earthquakes updating the 2016 one-year forecast. The foreceast is represented by a map, intended to provide information to the public and to facilitate the development of induced seismicity forecasting models, methods, and data. The 2017 hazard model applied the same methodology and input logic tree as the forecast from the previous year, but with an updated earthquake catalogue. The 2016 forecast indicated high seismic hazard (greater than 1% probability of potentially damaging ground shaking in one year) in five focus areas: Oklahoma–Kansas, the Raton basin (Colorado/New Mexico border), north Texas, north Arkansas, and the New Madrid Seismic Zone. During 2016, several damaging induced earthquakes occurred in Oklahoma within the highest hazard region of the 2016 forecast; all of the 21 moment magnitude (M) ≥4 and 3 M≥5 earthquakes occurred within the highest hazard area in the 2016 forecast. The 2017 forecasted seismic rates were estimated as lower in regions of induced activity due to lower rates of earthquakes in 2016 compared with 2015, which may be related to decreased wastewater injection caused by regulatory actions or by a decrease in unconventional oil and gas production. The speaker concluded by noting that, nevertheless, the 2017 forecasted hazard is still significantly elevated in Oklahoma compared to the hazard calculated from seismicity before 2009.

8.2 Risk assessment and environmental impact assessment.

Olga Lipińska (PGI, Poland) discussed *soil hazards related to shale gas activities.* She argued that when environmental impact of shale gas activities is considered soil hazards should be comprehensively tested. Due to high population density in Europe and land use patterns some local conflicts might be expected between agricultural and gas extraction activities. In Poland many exploration drilling sites were located in rural areas, particularly on arable lands. Moreover shale gas prospective zones in Poland are mostly located beyond traditional industrial and mining areas, which poses additional social concerns related to environmental quality during and after gas exploration and production. The speaker argued that there are many ways in which negative impact might be put on soil, among others: accidental spills, fugitive emission, overburden from infrastructure and topsoil temporary storage heaps. These diverse risks impose the need of tests variety as different impact may affect different soil characteristic, e.g. productivity, contamination, compaction, erosion etc. A wide array of possible tests can be applied for soil monitoring, such as atmogeochemical methods, especially for methane and others light hydrocarbons concentration determination, but also concentration of radon, physical and chemical analyses of soil content, including agricultural productivity parameters, and geoengineering measures, in particular for soil and subsoil compaction assessment. A proper monitoring strategy should ensure early warning for many different sources of contamination and disturbances.Baseline is an essential part of monitoring strategy related to shale gas activities, because it is important to indicate initial state, in terms of soils properties in particular. In contrast to groundwater and surface water monitoring which is based on Water Framework Directive), there is no pan-European common basis for planning and executing (so called 'soil directive' is suspended). Experiences and results which have been obtained so far on exploratory sites in Poland present factual risks and the importance of advanced planning of monitoring, with sufficient knowledge of hazards that can be posed by technology itself.

Ma Lanting (UPM/Ciemat, Spain) discussed *organic compounds concentration change in flowback water and environmental risks associated*. The speaker argued that in order to achieve the goal of an environmentally friendly hydraulic fracturing technology, a mathematical model is needed for predictive assessment of organic compounds behavior along the water transportation process as well as concentration change within time throughout the whole hydraulic fracturing operation life cycle. A comprehensive model, which fits the experimental data, combining an Organic Matter Transport Dynamic Model with a Two-Compartment First-order Rate Constant Model was presented to quantify the organic compounds concentration. This model is composed of two transportation rates, fast and slow respectively. For the fast part, the curve fitting technique is used to assess transport coefficients using flowback water data derived from the Marcellus Shale gas fracturing site. The coefficients of determination of all analyzed compounds demonstrate a high experimental feasibility of this inverse adjustment method. This technique has not been yet used to obtain the parameters associated with slow rate transport due to the lack of experimental data. Instead, it has been used studies conducted along a decade of drilling to allow a first approximation to these values. Concentration ratio curves have been estimated in the slow part of this model. The results show the relationship between the value of the organic carbon partition coefficient in chemicals and the reach of the maximum concentration in water as well as the maximum concentration percentage of the initial concentration of the various compounds in the shale formation which is expected to reach in a sufficient time-frame. The predictive evolution of the pollutant concentration in flowback and produced water allows assessing the distribution of a potential spill in the atmosphere, surface water and groundwater. The main objective of the work discussed above is to incorporate this predictive knowledge into the various criteria to be considered in the shale gas project decision-making process to prevent negative environmental impact as far as possible.

Christopher McDermott (University of Edinburgh, UK) presented *FracRisk*, an international EU H2020 project with the objective of identifying ways of reducing the environmental footprint of shale gas development (see also Section 7.1.4). The project employs the source pathway receptor concept for looking at potential subsurface contamination transport, coupled with the features events and processes (FEP) approach, state of the data collection (geomechanical facies approach), multiphysics numerical simulation, risk based corrective action software development and development of monitoring strategies. The speaker discussed how so far the project has established the first features events and processes database specifically for hydraulic fracturing. The FEPs are ranked, and key generic conceptual models are created addressing the most relevant problems. To simulate and predict potential outcomes of events, capabilities of open-source numerical simulators have been expanded. Linking complex modelling outcomes to risk based corrective action assessments requires a new framework based on a geomechanical facies approach for scenario characterisation and a polynomial chaos fitting to provide a response surface within the framework of the variables defined for scenario characterisation. Results include the development of a computationally efficient data-assimilation and uncertainty quantification framework, keyed to the characterization of dynamically evolving plumes of dissolved chemicals in heterogeneous aquifers. Prediction of possible outcomes facilitates the determination of best suited monitoring technologies. FracRisk provides an overview of current state of the art geophysical monitoring in hydrocarbon reservoirs, and has developed fully nonlinear imaging methods for near-surface resistivity imaging extending significantly deeper into the Earth than previously possible. According to the speaker, the results obtained so far by the FracRisk research indicate clearly that risks arising from fracking operation can be handled according to already existing law and potentially minimized to such an extent that impacts on nature and society are minimal.

Paolo Capuano (University of Salerno, Department of Physics, Italy) discussed the *SHEER approach to the evaluation of risks connected to shale gas exploration and exploitation*. He argued that, *w*ithout exception, the exploitation of any energy resource produces impacts and intrinsically bears risks. To make sound decisions about future energy resource exploitation, it is important to clearly understand the potential environmental impacts in the full life-cycle of an energy development project. Shale gas operations may affect the quality of air, water and landscapes; furthermore, it can induce seismic activity, with the possible impacts on the surrounding infrastructure. The H2020 SHEER (SHale gas Exploration and Exploitation Risks, see also Section 7.1.2) project aims at setting up a probabilistic methodology to assess and mitigate the short and the long term environmental risks connected to the exploration and exploitation of shale gas. A shale gas test site located in Poland (Wysin) was monitored before, during and after fracturing operations with the aim of assessing environmental risks connected with groundwater contamination, air pollution and earthquakes induced by fracking and injection of waste water. Data analysis methodologies were developed and applied to test site and past case data. SHEER is performing a multi-hazard risk assessment to evaluate the likelihood of occurrence of incidents and the relative potential impacts on surrounding environment, considering different aforementioned hazards and interactions. A multi-hazard risk assessment applied to the development of shale gas poses a number of challenges, making of this one a particularly complex problem. First, a number of external hazards might be considered as potential triggering mechanisms. Such hazards can be either of natural origin or anthropogenic events caused by the same industrial activities. Second, failures might propagate through the industrial elements, leading to complex scenarios according to the layout of the industrial site. Third, there is a number of potential risk receptors, ranging from environmental elements (as the air, soil, surface water, or groundwater) to local communities and ecosystems. The multi-hazard risk approach for this problem is set by considering multiple hazards (and their possible interactions) as possible sources of system's perturbation that might drive to the development of an incidental event. A multi-level approach will be adopted to perform a qualitative analysis oriented to the identification of a wide range of possible scenarios.

Jan ter Heege (TNO, The Netherlands) discussed a c*omparison of current practices for measuring, monitoring, mitigating and managing the environmental impact of shale gas in the US and conventional gas in the Netherlands*. In this study, a summary of hazards, risks and best practices of shale gas operations was given based on current practices in the USA and Canada. Hazards and risks associated with operations in the subsurface and on the surface were reviewed. Available data on the occurrence and potential effects of hazards were also summarized to give a rough indication of the relative importance of hazards and risks. Risks were defined as the combination of the likelihood of an incident or hazardous event (e.g., loss of zonal isolation) and the effects the incident might have on human health, safety and natural environment (e.g., the contamination of a shallow aquifer). The speaker noted that identified hazards do not necessarily lead to significant risks, i.e. high risks require frequent occurrence of incidents and significant effects on human health, safety or natural environment. The most prominent risks associated with shale gas operations in the USA and Canada are linked with (1) incidents related to well site construction, storage and traffic that may reduce general safety, (2) air emissions that may lead to a reduction of air quality and/or elevated greenhouse gas emissions, (3) issues with drilling, completion operation and abandonment of wells that may allow subsurface migration of hazardous substances, (4) spills and leaks of potentially hazardous substances, (5) landscape disturbance that may impact wildlife, biotopes or local communities, (6) extensive water use that may reduce water quality or availability, and (7) the occurrence of problematic seismicity during hydraulic fracturing or waste water disposal. A qualitative comparison between the different risks was performed on the basis of a risk assessment matrix. The speaker also argued that it is also important to evaluate the impacts for unconventional gas production in comparison to other large scale energy technologies, such as conventional gas production that is most common in Europe. Therefore, a comparison was made with similar risks for conventional gas operations in the Netherlands. The difference in scale of drilling and hydraulic fracturing operations required for unconventional gas extraction compared to conventional gas extraction plays an important role in evaluating the impact of shale gas operations.

Ann-Helene Faber (University of Utrecht, The Netherlands) discussed the *chemical and biological assessment of unconventional tight sand gas related waters*. The speaker's research focuses on relatively polar organics present in hydraulic fracturing related waters from a tight sand gas development in the Netherlands. Fracturing fluid, flowback water samples and surrounding aquifers before and after the actual fracturing were analysed by means of HR LC-MS/MS, the Ames test and several CALUX bioassays. A suspect list (candidate compounds) containing 881 chemicals was based on US and EU used and produced chemicals related to hydraulic fracturing. Less than half of these global candidate compounds are currently registered under European legislation. Considering that hydraulic fracturing in Europe only can make use of authorized chemicals, the amount of possible chemicals is restricted compared to the US. In the fracturing fluid samples, 1009 different compounds were detected, including 11 that matched with the suspect list. 714 of these occur in concentrations – semi-quantitatively expressed as internal standard equivalent - exceeding groundwater thresholds based on the Threshold of Toxicological Concern (TTC) of 0.1 µg/L. 348 of these compounds were also found in the flowback samples although at lower concentrations. In the flowback samples a total of 980 peaks were detected, of which 631 originate from the subsurface and 20 could be matched with the candidate list. Between the first and eighth day of flowback, the number of compounds exceeding the TTC value drops from 291 to 189. In the groundwater samples there is no significant change in composition between the samples taken before and after the actual fracturing possibly related to earlier activities at the site, however there is a relation with distance from the well. 50 peaks were detected with 12 exceeding TTC values. Results point to the importance of handling, transport and treatment of hydraulic fracturing related waters to avoid adverse environmental and human health impacts.

Yannick Kremer (University of Strathclyde, UK) discussed a study which concluded that *faults do not provide a realistic pathway for fracking to pollute freshwater aquifers.* Pollution of potable groundwater by hydraulic fracturing fluids or reservoir brines is an issue of public and regulatory concern. Faults are often cited as possible pathways for such contamination. In the hydrocarbon industry faults can act as structural traps or as baffles to production, or form migration pathways, promoting vertical flow and bypassing top seals over geological timescales. Faults can also be important in groundwater hydrology, are spatially associated with springs, but are also known barriers to flow in shallow aquifers. It has been suggested that under the right driving pressure conditions, a permeable fault could form a pathway connecting deep shale reservoirs to shallow aquifers. However counter-arguments have stated that those conditions are vanishingly rare. While the hydraulic properties of faults in hydrocarbon reservoir rocks are well characterised, much less is known about faults in shale-rich sequences; partly because of the historically low economic importance of shale and partly because of typically poor quality exposures formed by shales. In the presentation the speaker pooled disparate datasets of the hydraulic properties of faults in shale-rich sequences to investigate the full range of fault permeability values in shale gas reservoirs. The analysis showed that fault rock permeability in shale-rich sequences is highly variable, ranging from 10-9 mD to 104 mD. Based on these data, the authors simulated fluid flow through a faulted shale-rich sequence from a hydraulically fractured shale reservoir. They modelled a worst-case scenario of fracking within a reservoir that is cut by a fault that cuts the entire sequence of rocks all the way to the shallowest aquifer. An absolute worst-case scenario was investigated, where the well is abandoned immediately after fracking, leaving the high fracking pressure in the reservoir for years rather than the typical 3-5 hours under normal operational conditions. It was assumed that fracking fluids are less saline than the formation water in the reservoir and would therefore move through a combination of pressure drive and buoyancy. Even in the worst possible scenario fracking fluids only migrated upwards along the fault to a maximum of 200m above the reservoir, as the fluids disperse laterally out of the fault and are diluted to such a point that buoyancy drive is lost. Leakage only occurs if the modelled fault acts as a continuous high permeability conduit from the reservoir level to the near-surface. Considering the heterogeneity of fault zones and the control of stratigraphy on fault zone properties, the existence of such faults is highly unlikely. Even in this case the leaked fluids remain trapped in the deep saline aquifers, where they will be further diluted to well below detection limits. This finding is regardless of the timescales considered. The speaker argued that the study demonstrates that even in the worst case scenario hydraulic fracturing fluids cannot be driven upwards along faults a sufficient distance to reach near surface aquifers.

Mara Hauck (TNO, The Netherlands) presented a research on the subject of *carbon footprint of potential future shale gas exploitation and use in Europe*. Such footprint is an important indicator for the suitability of natural gas and shale gaso act as a lower-carbon transition fuel. To estimate the carbon footprint of potential shale gas pro-duction and use in Europe, the authrs of the study modified and extended an existing tool: GHGenius, originally developed for Canada. GHGenius quantifies the life cycle greenhouse gas emissions of a range of fuels, feedstock extraction pathways and applications (transportation, electricity and heat generation). For Europe, carbon footprints of natural gas and oil from various producing regions were calculated in four different regions: central, northern, southeast and south-western Europe. Emissions for shale gas production in 8 European plays were included, based on literature values for leakage rates and combustion needs, such as fugitives from hydraulic fracturing or combustion emissions from horizontal drilling. Per MJoule delivered, total GHG emissions excluding combustion of the gas ranged from 8 to 29 g CO_2-equ/MJoule, in line with ranges reported in the literature. Emissions were generally higher than average emissions from conventional gas delivered to Europe. The estimated total leakage rate related to production ranged from 1% to 1.8%. That is lower than the 3% often cited as being the maximum for natural gas to certainly have a lower carbon footprint than other fossil sources, especially coal. In the study the authors assumed shale gas produced in Europe to be used for electricity generation. For a kWh of electricity produced, the combustion of the fuel is the largest contributor to overall greenhouse gas emissions. For a comparison between fossil fuels, the combustion phase was therefore also included. On a per kWh basis the default calculations showed negligible differences between carbon footprints of conventional and shale gas, both lower than those of oil and coal. The effects of using shale gas for power generation (possibly replacing existing power plants) on carbon footprints at country level was also assessed in different scenarios. Most shale specific data used in this research was derived from expert estimations and proxies from other regions, mostly North America. All footprint estimations are therefore accompanied by uncertainties and subject to further improvement. A first sensitivity analysis indicated the key importance of good estimations of the fugitive emissions from hydraulic fracturing flowback and the impact of large variation in data on production emissions.

Paula Costa (LNEG, Portugal) presented an investigation on the *Baseline concentration and raw gas composition. Relevance for Shale Gas operations.* The speaker argued that besides the identification of emissions to air associated with the shale gas exploration and exploitation, it is important to discuss the relevance of atmospheric concentration baselines. The raw shale gas composition was investigated as part of the shale gas components that may be used to identify gas leakages. Concentration baselines of methane and other components in shale gas can provide a standard of the pre-shale gas development state of the environment. The important objective of baselines is that upon implementation of shale gas activities there is clear and transparent information about the atmospheric composition before and after the activities started. The speaker argued that there is evidence that shale gas extraction has proceeded, in most cases, without adequate environmental baseline data being collected. This makes it difficult to properly identify, quantify and characterize environmental impacts that may be associated with shale gas development. Minimising these impacts on the atmosphere requires the monitoring of ambient air quality prior to and during operations, and the prevention and minimization of greenhouse gases and toxic chemicals emissions. Anothe main concern addressed in the project M4ShaleGas, when considering the global climate impact of a potential European Shale gas industry, is the leakage of methane.

Zoe Shipton (University of Strathclyde, UK) discussed *the cumulative effect of unconventional exploitation on water stress and demand on local water resources.* One of the most discussed aspects of unconventional gas extraction is the effect on water resources, yet recent research focuses on water contamination (water quality) and has not considered water stress (water quantity). Unconventional gas extraction is a water intensive industry; water consumption of 3 million gallons per shale gas well have been reported as typical in the USA. Such water needs may challenge supplies and infrastructure: a similar unconventional gas extraction water demand for the UK shale resource could be as much as three times the annual Scottish whisky industry water requirement (~16 billion gal total water; both cooling water and whisky product). Thus a nation-wide programme of UGE is likely to place extra demands on existing water resources. UK shale resource areas all lie within, or close to, regions that are either prone to drought now, or are drought forecast in 50-70 year projections. If a water demand model similar to the situation in the US were employed in the UK, the growth of unconventional gas extraction could place additional stress on existing water resources. A significant challenge is securing a sustainable water supply while protecting existing water resources. Use of potable water places stress on domestic supplies and water use by other industries already in place. This is particularly relevant to cumulative effects of an up-scaled, nation-wide industry. The trade-offs and interdependencies between treatment requirem ents, environmental impacts, and social/economic impacts of different water supplies must be considered to get the most benefit from UGE. This investigation used the Scottish shale gas resource as a case study to assesses the potential for water stress associated with unconventional gas extraction and examines the longer-term environmental sustainability of cumulative water demands with existing and future water resources. Combining recent water resource planning with UK climate change projection scenarios (UKCP09) and rainfall data for Scotland, an appraisal using GIS-based mapping and analysis was made of likely water demands and available resources for specific zones in Scotland and assessed to determine potential water stress. Initial results showed that while unconventional gas extraction is unlikely to have a significant impact on the long-term availability of water in Scotland. If 10% of the total wells required were to be fractured within one three month summer period around 2080, then the water demands of UGE would account for 4% of the total potable water available. The study highlighted the need for appropriate measures ensuring that to protect regional water resources and ensure future water supply availability a UGE schedule must be managed and exploited. The lessons learned from this study can be further developed for the rest of the UK and European contexts.

8.3 Modelling bench-marking using experimental data.

Hans Custers (DOE Alberta, Canada) discussed *modelling, benchmarking and validation*. Empirical models, over the course of human history, have had an important role in improving understanding of key natural and industrial processes and phenomena. However, in today's world there are considerable pitfalls in the use of empirical models ("lifecycle models") to assess and predict the performance of major industrial processes, such as oil and gas extraction and processing. These processes are complex, highly variable and are constantly evolving at a rapid pace. Simplifications and assumptions inherent in such lifecycle models can result in a model that may only be applicable to a small section of the industry, at a specific point in time. The use of or reliance on such models, by regulators and/or decision makers, requires extra caution and due diligence.

In such cases careful examination of the assumptions used in the models and assessment of the current practices employed in the target industry operating in the area of interest, supplemented by measurements and validation are warranted. Increasingly, decision makers are instead opting to rely on actual measurements, monitoring and verification in order to assure objectivity.

Jop Klaver (MaP GmbH Aachen, Germany) presented a study on *storage capacity and transport properties assessment of unconventional reservoir rocks using nanotechnology imaging.* He argued that understanding processes related to storage capacity and transport properties in rocks is crucial for modeling scenarios. However, measuring porosity and permeability from fine-grained rocks like unconventional reservoir rocks or seals is challenging for several reasons. Firstly, measuring these properties from experiments is complicated because of their small pore throats and variable pore sizes. Secondly, these measurements can be highly effected by micro-fractures which might be artefacts due to core damage or drying. Moreover, in bulk measurements, heterogeneity in organic matter, mineralogy and fabric complicates understanding the controlling factors on these properties. In this respect, nanotechnology imaging like Scanning Electron Microscopy (SEM) can help as it resolves a large spectrum of pore sizes and mineralogy within these kinds of rocks. Combining SEM with Broad Ion Beam (BIB) milling enables quantification of pore sizes and microstructures in a representative way and allows comparison to bulk measurements. Results showed that number of pores increase with increasing resolution, following a power law distribution from the micrometer size pores down to 50 nm in equivalent pore diameter. Combining the pore image maps with the mineral image maps enables to draw pore-mineral associations. It follows that the occurrence of significant organic matter porosity depends on the type of organic matter and maturity. Selective Focused Ion Beam SEM tomography of regions of interest enables investigation of the 3D microstructure, pore morphology and pore throats. It shows very complex pore networks in organic matter but still most of the pore throats remain unresolved. Moreover, investigated volumes are relatively small and might not be representative. Complementary Liquid Metal Injection followed by BIB-SEM, however, shows the connected porosity at relatively large sample area of up to 1 cm^2 in size at nanometer scale resolution. It shows connected porosity, depending on the sample investigated, in the various mineral phases like calcite fossils, organic matter clay and micro-fractures, improving understanding of to the associated transport processes. This contribution will show exemplary imaging studies of the Posidonia Shale and Haynesville Shale formations and other fine grained or tight rocks. These findings add knowledge to existing modeling scenarios like for example porosity prediction. Moreover, since the sample size can be very small, analyses of cuttings enables validation of existing models relatively easy.

Dave Risk (St Francis Xavier University, Canada) talked about *fugitive and vented emissions from energy developments in Alberta, Canada: Lessons from extensive measurement campaigns*. The speaker presented his research work at St. Francis Xavier University, where he leads a 30-strong group on gases and emissions measurement technology. The work carried out is multi-scale, ranging from satellite to soil gas monitoring, with an industry focus. The techniques used enable to monitor various analytes such as H_2S, CH_4, CO_2 and SO_2. Some of the research issies addressed are baseline monitornig in Canada, accuracy of inventories and identificaton of potenital super-emitters. The speaker presented some of their field work and discussed the lessons learnt. For instance, they found that in some cases vents and fugitives occur with high incidence. Infrastructure of all classes have shown to emit to some degree, including abandoned wells and facilities. Tank batteries were found to be a common emission source. Some industrial developments are more emission-prone than others, and volumes reflected in bottom-up inventories seem underestimated when measured from top. A positive result was the fact that sites with historic odour or H_2S issues seem to have improved, indicating that regulators and industry can solve problems when working together.

8.4 Multi-actor and public engagement in research and innovation.

Michael Bradshaw (University of Warwick, UK) discussed *public understanding of the environmental and social impacts of shale gas development*. Both the EERA Shale Gas joint programme (see Section 7.2.1) and the M4 Shale Gas Horizon 2020 research programme (see Section 7.1.1) have a sub-programme on the social science dimensions of public understanding of the environmental and social impacts of shale gas development. In the case of M4 Shale Gas, this is the only H2020 shale gas research programme with a significant social science element. The speaker aruged that commercial shale gas development is not going to become a reality in Europe unless there is public acceptance of its environmental and social impacts. Thus, a consideration of these issues is an essential element of any discussion of unconventional hydrocarbon resources, risks and impacts. The presentation reported on the findings of this research activity, divided into four sections. The first section introduced the research programme, its aims and objectives and the participants. The second section reported the findings of the first stage of the research where the status of public understanding based on published research in North America and Europe was reviewed, along with the lessons that can be learnt from attitudes towards other large-scale energy infrastructure (CCS, nuclear and onshore wind energy). The third section presented a critical analysis of the concept of the *social licence to operate* and considered its applicability to the issue of shale gas development. Finally, the fourth section presented some best practice recommendations for public engagement, regulation and decision making in relation to shale gas exploration and development in a European context.

Karen Turner (University of Strathclyde, UK) presented a talk entitled "*Seven questions about fracking in Scotland*". In January 2015, the Scottish Government placed a moratorium on the "*granting of planning consents for unconventional oil and gas developments, including fracking*" and, in October 2015, announced a timetable for a programme of research and public consultation. In February 2017 a 4-month period of public consultation begun, followed by a period of analysis. Results of a research process have been published to allow consultation participants to have the opportunity to study the evidence before contributing to the consultation. The authored stated that she and co-authors have published a policy brief that is intended as a comment on what we view as the urgent need to improve on the quality of the so-called "fracking debate" that has been conducted in the public domain in Scotland over the past year. Their argument is that not only has the debate been somewhat polarised, but the questions raised and debated have been very narrowly focussed and lacking a wider contextual view. The seven questions that were identified in order for the process of consultation to come to a well-informed conclusion were:

1. What do we need gas for and how much will Scotland need in the future?
2. Have the potential health impacts of fracking been considered in sufficient breadth and depth?
3. What is the Scottish context for assessing the potential economic benefits of fracking?
4. What is the likely distribution of risks and rewards from fracking in Scotland?
5. Just what is covered by Scottish regulation of fracking?
6. Are the potential risks and benefits of fracking being set in proportion and in context?
7. Has the Scottish government’s moratorium on fracking been placed on the right thing?

The speaker discussed how three further stages are planned in the analysis of the Scottish debate. The first is to assess the extent to which the research commissioned by Scottish Government answers the questions identified in the brief. The second is to consider how the issues raised are reflected in the consultation document. The third stage involves inviting actors from different industry, regulatory, NGO and other stakeholder groups to consider each of the seven questions in the context of the research findings. The results are intended to be drawn together in a second policy briefing.

Alwyn Hart (Environment Agency, UK) discussed *talking to the public about (their) public sector research on onshore oil and gas*. In recent years, the concept of involving a wide range of actors in the design and orientation of research has gained significant interest captured in the concepts of *responsible research*. As a public body with duties to protect the environment and enforce relevant legislation, the Environment Agency (EA) has many research needs which must be met either by in-house work or by acquiring external research knowledge. This often means working with partners in academe and industry but those very contacts can then lead to suspicion and distrust from third parties. Yet working more broadly with "the public" brings many problems, not least defining initially who are "the public" and how to understand potentially millions of people with often competing desires. The presentation explored the EA's public outreach on onshore oil and gas (including shale gas) and detailed a case study of public consultation. What did members of the public think of the EA work and what else would they want the EA do? An internet based conference was used to explore in detail the existing knowledge and the concerns or interests of an invited panel of residents from three potential onshore gas fields. The discussions were led by a third party though government funded organisation "Sciencewise" whose remit is to enable public policy discourse. The results were discussed in the context of the EA's terms of employment as scientists in a government agency and the operational engagements of "Meet the regulator" events where EA staff attend public events about how they work now rather than what research is needed.

Dirk Scheer (ITAS KIT, Germany) presented a study called "*Enriching geoscience research with participatory modelling approaches: A case study on brine migration due to CO2 injection*. Public acceptance and a profound understanding of risks, hazards, and benefits have become key issues for researching and implementing earth system technologies. Therefore, it is good practice to involve stakeholders at an early stage when corresponding technologies are considered. Any effort in investigating and developing the Carbon Dioxide Capture and Storage technology (CCS) unavoidably touches the social and political spheres, and needs to take into account the broader societal debate. Within this research on brine migration, the author and co-workers applied a participatory modelling approach from the very beginning, involving expert and stakeholder knowledge in simulating the impacts of injecting CO_2. As a starting point, guideline-based interviews were carried out by social scientists to elicit expert and stakeholder knowledge and assessments on geological structures and mechanisms affecting CO_2 injection-induced brine migration. The second step consisted of a stakeholder workshop, including the world café format, which was carried out in order to elicit evaluations and judgments on the modeling approach, on the scenario selection, as well as on the preliminary simulation results. The author concluded that involving external experts and stakeholders in the evaluation of brine migration models by means of participatory modelling techniques proved to be a helpful approach, leading to valuable recommendations for the modelers' research and enabling knowledge transfer back to stakeholders.

Aleksandra Lis (Adam Mickiewicz University, Poland) discussed *knowledge, uncertainty and the future: negotiating shale gas exploration locally in Poland.* This presentation examined shale gas development as a situation of resource exploration loaded with multiple uncertainties stemming not only from technology-generated unknowns but mainly from the unknowns about the volume of exploitable resource and about the ways in which industry will exist locally. By examining first information meetings organized by NGOs, companies and local authorities in Poland: Przywidz, Mikołajki Pomorskie and Żurawlów, the author showed that uncertainty is built around three things that are to be shared by communities and companies if exploration takes place: knowledge, space and time. Discussions around these three issues revealed knowledge deficits on all sides, contributing to the emergence of new areas of uncertainty and making any agreement difficult. By referring to the concept of *hybrid forums*, the analysis also showed how a meeting that is initially framed by the organizers as an "information meeting" changes into a "hybrid forum" where new facts and values emerge.

Meri-Katriina Pyhäranta (UEF Law School, Finland) discussed *protecting landowners in sustainable shale gas production*. *She argued that* state ownership of shale gas resources is considered to be one of the factors preventing rapid shale gas development in Europe. Due to the state ownership model, landowners do not have right to royalties or other direct financial benefits from shale gas production, and their possibilities to control the shale gas activities taking place on their land is limited. Thus, landowners are in a weaker position, both financially and legally, as their American counterparts. Not surprisingly then, landowners in Europe are less willing to allow shale gas development on private land. As landowners are a key stakeholder group in shale gas development, protecting landowners' rights and interests is essential in promoting sustainable shale gas development in Europe. The speaker looked at regulatory models adopted in selected countries to protect landowners in unconventional energy production (especially the land access code in Queensland, Australia, and surface landowners' protection in some states in the USA. She discussed whether these models could provide examples for the protection of landowners in the EU and whether such protection would enhance sustainable shale gas development in the EU.

Patricia Faasse (Rathenau Instituut, The Netherlands) presented a *pilot training course practice of informing policy through evidence for shale gas*.

On 1 and 2 February 2017, the Rathenau Instituut and JRC staff from Health, Consumers & Reference Materials partecipated in a pilot training course, called "Practice of Informing Policy Through Evidence". This event took place at the JRC site in Geel Belgium). Part of this course was a role-playing game. The purpose of the game was to simulate a situation in which (diverging) public values, evidence of various kinds, expertise, experience, and stakeholder interests became part of the decision-making process. This allowed the participants to experience the complexities of making informed decisions within the policy process and to understand the different standpoints involved. The speaker shared with the audience some important lessons learned during the exercise. The game was played in two rounds. In Round 1 ("selection of evidence"), all the participants assumed a role as an expert. They gathered to help the Minister make an informed decision on an application made by Drilling & Co for concessions to start exploratory drillings near Boxing Town and Flat City. In Round 2 ("evidence contested"), six months had passed since Round 1. The Minister had granted Drilling & Co concessions to start exploratory drillings. But quickly after this news broke, local authorities and concerned citizens had started to stir. Several municipalities had followed suit and had signed a shale gas free declaration, calling for a ban on shale gas development in their regions. At this stage, discussion on shale gas included a variety of actors: government actors on two levels (national and municipal), industry, independent research organisations and engaged (local) citizens. Some of the evidence used to asses risks and uncertainties in Round 1 was now highly contested. The participants were invited to a meeting in Flat City town hall. The meeting was organised by the Ministry of Energy to manage the unrest within the municipality. At the end of the meeting, the Minister needed to reconsider his or her decision to grant the concessions. Moreover, he/she needed to have a clear idea of how to proceed with this complicated dossier. The following lessons where learnt:

- When policy objectives are controversial evidence and experience might become contested too.
- Local contexts do matter, also for the quality of the evidence.
- More evidence may increase complexity instead of solve the issue.
- Citizen concerns are not just emotions, they are as real as policy issues and can be addressed properly.
- During controversies, knowledge brokers have more impact than scientists.

- Policy makers and stakeholders do not necessarily share concerns that fit into your evidence framework.
- Accept that your evidence is not always convincing.
- Accept that policy makers and stakeholders have concerns that do not fit in your evidence framework.
- Make efforts to understand what the issues are for the policy maker and other stakeholders.

Michiel Köhne (Wageningen University Research, The Netherlands) discussed a case study in the Noordoostpolder (the Netherlands), entitled "*Practices and Imaginations of Energy Justice in Transition*", based on two and a half years of ethnographic fieldwork. According to this speaker, renewable energy technologies are often idealized as environmentally innocent alternatives to fossil fuels. Fossil fuel extraction is often considered as "unjust" and renewable energy as the "just" alternative. At the same time renewable energy projects, such as wind parks, are often resisted because of the uneven impacts of the required infrastructure to be installed. The presentation analysed such ambiguous meanings of energy justice (i.e. social justice issues related to energy) along the lines of its three tenets: distributional, procedural and recognition justice, aiming to understand how energy justice is constructed from below. It did so on the basis of a case study in the Noordoostpolder, a small region in the Netherlands where plans for extracting shale gas go together with both large-scale and small-scale renewable energy practices. The speaker discussed how energy justice is constructed by the way people engage with energy in daily life practices and as such produce new imaginations and normativities of energy justice. According to the speaker, such an ethnographic approach helps to understand energy justice as a process of co-construction of activists, policy makers and scholars and as such responds to recent calls for a human-centred approach to the study of energy transitions.

8.5 Innovative measurement methods for environmental parameters.

Alberto Striolo (University College London, UK) discussed "*Cutting Edge Measurements to Assess the Environmental Implications of Shale Gas – The ShaleXenvironmenT Approach*". In his presentation, the multi-disciplinary efforts implemented within the ShaleXenvironmenT consortium to assess the potential impacts of shale gas exploration and production in Europe were discussed. Emphasis was given to the innovative instrumentation developed within the consortium, and on the insights we achieve using an arsenal of techniques, including new modelling efforts. The scientific activities implemented within the consortium included the characterisation of shale core samples, the quantification of the fluids contained in them, the study of the fluid behaviour in nano- and meso-pores, the design of fracturing fluids, the optimisation of the water (both flowback and production) reclamation strategies. It also included life-cycle assessment as well as an analysis of socio-economical aspects related to the development of a shale gas industry in Europe.

Samuel Grainger (University of Strathclyde, UK) presented work on *development and evaluation of methods to assess air pollution exposure at unconventional natural gas extraction sites*. He first presented the background and aim of this investigation. Unconventional gas extraction activities have considerable potential to affect air quality, however there are very limited quantitative observations of the magnitude of such impacts. To provide context, the authors compared exposures to diesel engine exhaust from industrial fracking equipment at an experimental site in Łowicz, Poland to pedestrian exposures to traffic-related air pollution in the city centre of Glasgow, UK. They also described the further development of portable monitoring systems for versatile measurements at fracking sites. The methods used were based on mobile and static measurements at varying distances from sources at both the above mentioned locations with portable real-time micro-aethalometers and Aeroqual series-500 monitors for NO_2 and O_3 carried by researchers. Results indicated that duplicate BC instruments provided very similar real-time measurements, which in turn were relatively highly correlated with NO_2 observations at 5-minute temporal resolution at the HF experimental site. Average BC and NO_2 concentrations measured approximately 10 m downwind of diesel powered fracking pumps were 14 and 292 µg/m³ respectively. These concentrations were approximately 20 times and 4 times higher than the upwind background BC and NO_2 concentrations at the site, and approximately 4 and 2 times higher than average BC and NO_2 concentrations measured in traffic influenced areas in Glasgow city centre. In conclusions, marked levations of BC and NO2 concentrations were observed in downwind proximity to industrial fracking equipment and traffic sources. Exposure to diesel engine exhaust emissions from fracking equipment may present a significant risk to people working on HF sites over extended time periods. The short time resolution of the portable instruments used enabled identification of sources of occupational and environmental exposure to combustion-related air pollutants.

Dominic DiGiulio (Stanford University, US) discussed *quality assurance and control procedures to improve soil-gas sampling methods in stray gas investigations*. Soil-gas sampling has been used as a reconnaissance tool for natural gas exploration for over 50 years. Since the 1980s, soil-gas sampling has been used to screen locations for soil and groundwater sampling to assess contamination by volatile organic compounds. Since approximately the year 2000, soil-gas sampling has been used to evaluate risk (stipulated concentrations trigger action) posed by vapor migration from groundwater and soil to indoor air (vapor intrusion). The use of soil-gas sampling for risk assessment has prompted use of minimum quality assurance and control requirements in many states in the U.S. and most Canadian provinces. However, these requirements are highly variable and often lack a scientific basis, and often are largely absent in the European Union and elsewhere (e.g., Australia and New Zealand). Most recently, soil-gas sampling has been used to evaluate migration of stray gas (carbon dioxide and methane) to the surface at test sites for geologic sequestration and during unconventional oil and gas extraction. One state, Colorado, now mandates the use of soil-gas sampling to evaluate stray gas migration during coal-bed methane production. However, there are little or no requirements for soil-gas sampling to evaluate stray gas migration – even in Colorado where investigations to support this activity are required. Emissions at the surface remain an unquantified contribution in the life-cycle analysis of greenhouse gas emissions from unconventional oil and gas extraction. To support work in this area, the authors conducted research on procedures to improve quality assurance methods during soil-gas sampling. They investigated four aspects of soil-gas sampling: (1) calibration and flow testing of portable gas analyzers; (2) leak testing of above ground components of a soil-gas sampling train, leak testing of boreholes containing one to three dedicated soil-gas probes including communication between probes, and leak testing of direct-push soil-gas sampling systems; (3) selection of vapor probe construction materials and equations suitable for gas permeability testing; and (4) purge testing, including gas flow modeling, to evaluate stabilization of fixed gases and hydrocarbon concentrations prior to collection of a soil-gas sample for fixed-laboratory analysis. Findings from this investigation should be useful to regulatory agencies seeking to improve quality assurance and control procedures to improve soil-gas sampling, especially to support stray gas investigations related to unconventional oil and gas production.

Antoon Visschedijk (TNO, Netherlands) presented an investigation on *monitoring fugitive methane from large scale shale gas operations in europe* as a part of the M4ShaleGas research program. The speaker argued that one of the main concerns surrounding shale gas exploitation is the leakage of methane, a strong greenhouse gas. Measurements in the US have reported total fugitive methane emission from shale gas operations ranging from 0.2% to 10% of the total produced amount of gas. Since natural gas is less carbon intensive than coal by approximately half, extra gas sources, such as unconven-tional gas, could have an important role transition to future low carbon sustainable energy systems. However, this potential of unconventional gas resources to contribute to a transition from carbon-intensive energy systems to a low-carbon systems is highly dependent on the actual leakage rates of the entire gas production chain; with high leakage rates of 3% and higher the advantage over other fuels may well be lost . High leakage should therefore be detected and identified as early as possible after which immediate action can be taken. To support policy makers and environmental protection, the author of this study investigated how atmospheric monitoring could be used to detect and identify significant leakages from a potential future shale gas industry in Europe. Future European shale gas production will occur in a complex landscape with many different sources of methane present such as animal husbandry or wetlands. This complicates the monitoring and timely recognition of potential high methane leakage rates during shale gas production. The speaker argued that this problem can be solved by using unique tracers such as isotopes or coemitted species. The authors identified suitable tracers in shale gas based on a European gas composition database and attempted to predict tracer content based on thermal maturity data for a selection of the most promising shale gas plays in Europe. They selected ethane to be the most suitable tracer. By assuming three different production scenarios in addition to a range of possible gas leakage rates, they estimate potential tracer release and location, resulting in gridded emission data for atmospheric composition modelling. The LOTOS-EUROS atmospheric chemistry and transport model was successfully modified to track released ethane concentrations over Europe. Preliminary results were presented showing that high release rates from large scale future unconventional gas exploration would be detectable through atmospheric composition monitoring.

9 Conclusion

The last few years have witnessed a wealth of studies, reports and assessments being published in many EU member states, by national and international organisations and in the research community, covering many aspects related to the exploitation of unconventional hydrocarbons, most notably shale gas. Many R&D initiatives are also underway.

This report has attempted to provide a survey of several of such studies and initiatives, with a focus on shale gas and mainly covering the years 2015, 2016 and early 2017. Principally, reports and studies from public bodies and scientific institutes were included, as well as several relevant papers published in peer-reviewed journals.

Each study or report was briefly described and a selection of its conclusions and/or recommendations, when relevant, was extracted and reproduced herein, but a review of the quality of the studies covered, the accuracy of their claims and their possible limitations was beyond the scope of this report. Therefore, this report is only meant to provide a compilation of such studies and their summaries, without any endorsement of the findings reported.

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