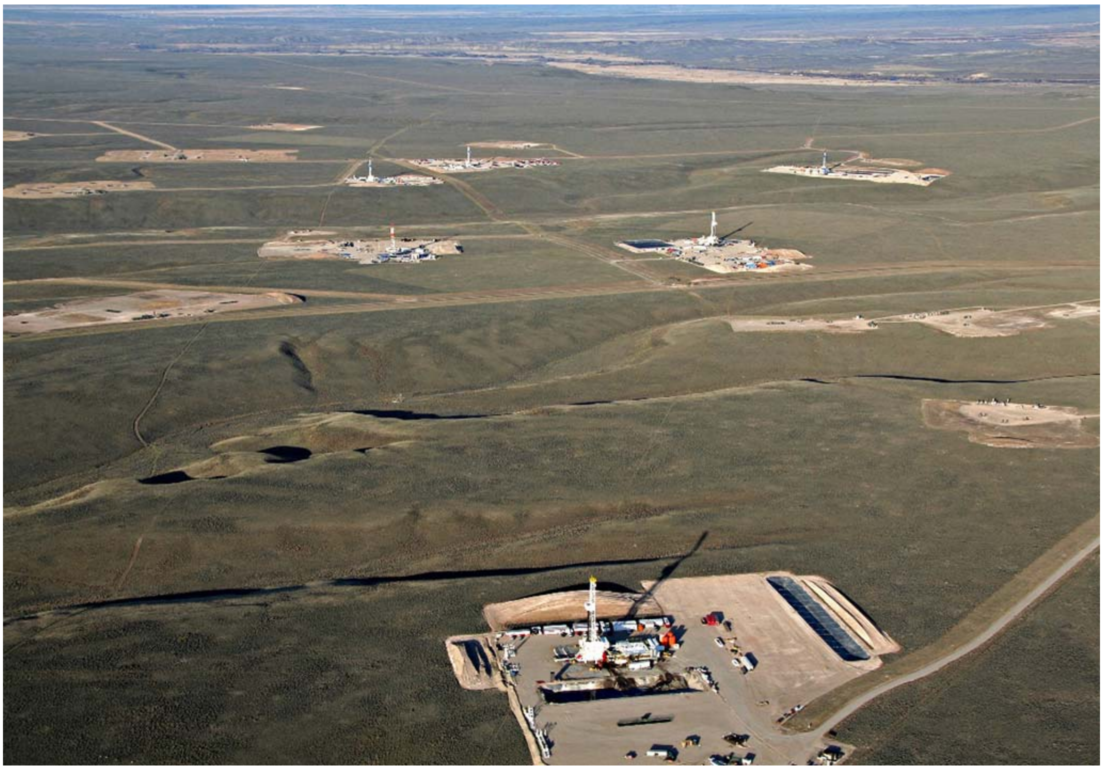
Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Department of Soil and Environment

Fracking
– Is it worth the risk?

Jonte From



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Fracking – Is it worth the risk?

Jonte From

Supervisor: Torbjörn Nilsson, Department of Soil and Environment, SLU
Examiner: Lars Lundin, Department of Soil and Environment, SLU

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Abstract

This review aims to summarize the current knowledge about the environmental impacts and risks about fracking and to answer the question if, on the whole, it is worth it? Peer-reviewed articles mainly from the database “Web of Science” were used.

The world’s fossil fuels are rapidly running out and new sources of energy are required. Vast resources of natural gas trapped within tight shale formations have been found and can be acquired by using a combination of horizontal drilling and hydraulic fracturing (fracking). This unconventional gas development is most broadly used in the USA, where the industry has expanded very quickly and left much of the research based science lagging behind. The process is not without its risks, however, and poses a threat to both the environment and public health in the form of contamination through air, soil, surface and groundwater. Lacking regulations, leakages, large numbers of well sites and low transparency have given the industry a low public acceptance. Even though economical wealth is often sure to be gained, many countries in Europe have temporarily banned the practices, awaiting further research before making any final conclusions. With the risk that near-zero emission systems may be delayed due to investing in further fossil fuels it may not be such a step towards clean energy as was first thought. With the evidence at hand, it is highly uncertain that the short-term gains are worth the long-term risks.

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1 Introduction

As the world's fossil fuel resources are in decline and the world is striving to keep ever higher living standards, search for new sources of fossil energy has been vital to uphold energy requirements. It has been found that many countries have vast resources of fossil fuel in the form of natural gas trapped within tight shale formations deep underground and thanks to the recent technological advances over the last decade these are no longer economically unviable to pursue (Council of Canadian Academies, 2014). In order to acquire these resources of natural gas within the shale formations, horizontal drilling is being used in combination with high-volume hydraulic fracturing, also known as "fracking" (Vengosh *et al.*, 2014).

These advances together with very accommodating political policies have led to a very quickly expanding industry, especially in the USA. There are certain hazardous risks involved with hydraulic fracturing for both the environment and public health, but this fast-growing industry has left the evidence-based research with little possibility to keep up with properly determining these (Werner *et al.*, 2015).

This review aims to summarize the current knowledge about the impacts and risks of hydraulic fracturing with a main focus on the environment, but also the possible effects to public health and if, on the whole, it is worth it?

2 Methods

This review has been made mainly using the database Web of Science, where only peer-reviewed articles are featured. It was accessed from the library at the Swedish University of Agricultural Sciences (SLU). Where reasonable, the sources have been traced back to the original authors. Others rely upon the peer-review system to provide a scientific security. Photos and illustrations have been acquired by contacting and gaining permission from the relevant artists and photographers. Or used with permission from the sources themselves, such as public material from the Energy Information Administration (EIA).

When using the Web of Science the search terms of "((fracking OR "shale gas" OR skiffergas OR "hydraulic fracturing" OR "hydraulisk spräckning") AND (hazard OR risk OR environment OR skador OR miljö OR environmental))" were used. It was further refined to "Environmental Sciences Ecology" and publication years of 2013-2016.

3 Shale

Shale is the most common sedimentary rock and was formed by the compaction of silt and clay-sized mineral particles over great periods of time. Some shales have specific properties which can make them an important and useful resource.
The presence of oil or gas in some shale formations is wholly dependent upon the amount of organic materials within it. Shales which contains more than one percent organic carbon (2 – 10 % is a common range) have, due to the content of organic matter, a dark colour and are therefore usually called black shale. These shales usually also contain elevated concentrations of pyrite, uranium and other heavy metals. The flora of the

geological time period it was created is of especially great importance as it determines how much organic material was available and thusly trapped within (Nordling *et al.*, 2015).

Usually, organic materials in sediments are decomposed by microorganisms with the presence of oxygen. However, in tight, fine-grained shale formations where there is a very limited amount of oxygen available the organic material is not fully decomposed, but creates a form of organic sludge. This sludge creates an organic substance called kerogen. When a kerogen-rich rock lies deep beneath the surface where the temperature and pressure is adequate a process begins which creates oil and gas (Erlström, 2014).

As the fine grain and tightness of the shale allows for no structural gaps and also disallows the oil or natural gas to migrate it becomes trapped where it was created in tiny pores within the rock. Because of this and that these formations of shale, containing the most common unconventional natural gas resource, shale gas, are in most cases thick, regionally extended and at depths varying from 600 – 4000 m below the surface, it is necessary to use horizontal drilling and hydraulic fracturing at these depths in the process of acquiring these natural resources (Erlström, 2014; Macuda & Konieczynska, 2015; Prpich *et al.*, 2016).

4 Fracking and unconventional gas extraction

Hydraulic fracturing, or “fracking”, is a process in which horizontal drilling combined with high volumes of water mixed with proppants (usually suspended sand) and chemical additives are pumped down into a borehole to fracture the surrounding rock in order to gain access to the desired natural resources. It is used to acquire oil, shale gas or uranium and was first used for natural gas extraction in the USA already 1947 (Michalski & Ficek, 2016). When hydraulic fracturing is used to acquire natural gas it is called unconventional gas extraction, or shale gas extraction. It is called unconventional because the gas remains trapped within the source rock and has not migrated from the source (Barcelo & Bennett, 2016). This compared to conventional gas extraction where the gas has moved over long periods of time and gathered in structural gaps, thus no hydraulic fracturing is required to reach it.

4.1 Why fracking

The reasons as to why shale gas development has grown so quickly over the last decade are multiple. For countries which already use natural gas as an energy source and thus have the required infrastructure to distribute it, but currently imports, have much to gain by establishing independent unconventional gas development (Nordling *et al.*, 2015). By doing so, the country may reduce the dependency of natural gas imports and thus strengthen both its economy and energy security (Arthur & Cole, 2014).

There are also other incentives which may play a significant role. A study assessing the energy situation in China found that shale gas is of great practical and strategic value as it is found in great abundance within its borders and the country is struggling to meet energy demands within the growing population and rising living standards. Much of the energy produced in China is today from coal, and many areas suffer issues such as acid rain and smog. As natural gas is cleaner than oil and coal, it may help to lessen these issues (Li *et al.*, 2016). Also in Poland, where approximately 90 % of the energy is derived from hard and brown coal, unconventional gas development is very promising. Poland are currently struggling to meet the requirements of the EU environmental policies, but have readily available resources of shale gas which may help in this endeavor (Michalski & Ficek, 2016).

Even though many countries find the prospect of fracking promising, relatively few have actually begun the process of developing the industry. The country where the shale gas industry has grown the most is the USA, where the U.S. congress even exempted hydrocarbon development from a number of federal environmental and public safety laws (Centner & Petetin, 2015). There are many areas in the USA where unconventional gas development is possible (Fig. 1). This rapid expansion has significantly boosted the USA in terms of energy independence and given them a strong position in the global energy market (Arthur & Cole, 2014). Because of this it has often been described as a “game changer” and it is of no wonder as it is found in abundance, already close to major markets and is also within reasonable production costs (Council of Canadian Academies, 2014).

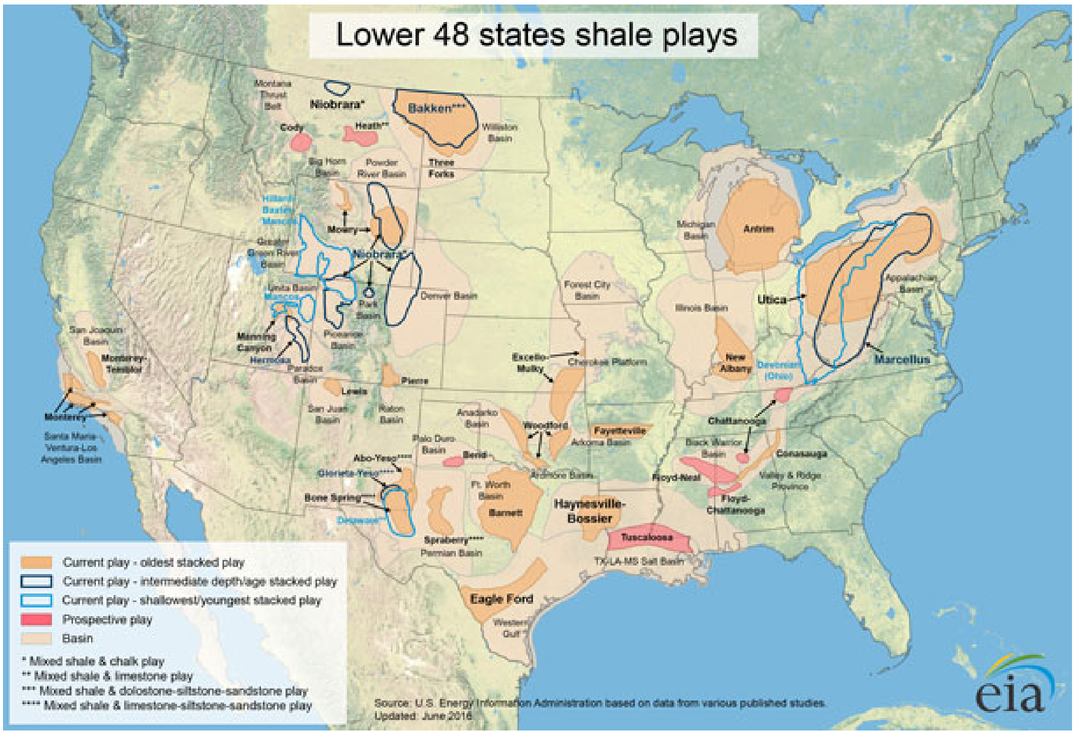

Figure 1. *The major shale plays in the USA where shale gas can be found. Used with permission from the EIA.*

4.2 The fracking procedure

After an area suitable for shale gas development has been found the process of setting up the necessary infrastructure begins (Fig. 2). The well pad including its ancillary construction of connections for pipelines, transportation and production waste materials requires an area ranging from 15000 - 30000 m^2 (Annevelink *et al.*, 2016). A borehole is then drilled straight downward and proceeds with horizontal drilling as it reaches the desired depth within the shale formation. In order to protect the surrounding soil and groundwater, a cement casing is cast around the hole to an adequate depth.

When the borehole is complete the hydraulic fracturing can begin; a mixture of water, chemicals and proppants (most usually suspended sand) is pumped into the borehole under high pressure to form, enlarge and maintain fractures in the rock. The amount of water as well as the composition of the fracturing fluids varies from site to site as the geology, technology and design of the borehole can be very different (Macuda & Konieczynska, 2015). Due to this, assumptions and generalizations in regards to water usage should be made with caution (Gallegos *et al.*, 2015). The amounts required are substantial however, approximately 10 000 – 70 000 m^3 water is required for each borehole (Erlström, 2014). In addition to the water, the fracking fluids also contain approximately 9 % proppants and 0,5 – 2 % chemicals (Macuda & Konieczynska, 2015; Werner *et al.*, 2015). The proppants are used to keep the fractures open and give the gas a way to reach the borehole instead of getting trapped within the newly created openings. The different chemicals are numerous and serve many different purposes; to prevent scale formation, corrosion and bacterial development on the equipment, lower friction and surface tension in the fluid, form gel to easier carry the gas, stabilize clayey particle concentration and adjust the pH (Macuda & Konieczynska, 2015).

To then proceed with the gas extraction the fluids are removed through pressure reduction. This is called the flowback phase. Only 10 – 50 % of the fluids return to the surface however, whereas the rest remain underground (Council of Canadian Academies, 2014; Vengosh *et al.*, 2014). These flowback fluids can then later be reused in other fracking operations or be removed as industrial waste (Michalski & Ficek, 2016). The practice to reuse flowback fluids is becoming more widely used as it is more efficient

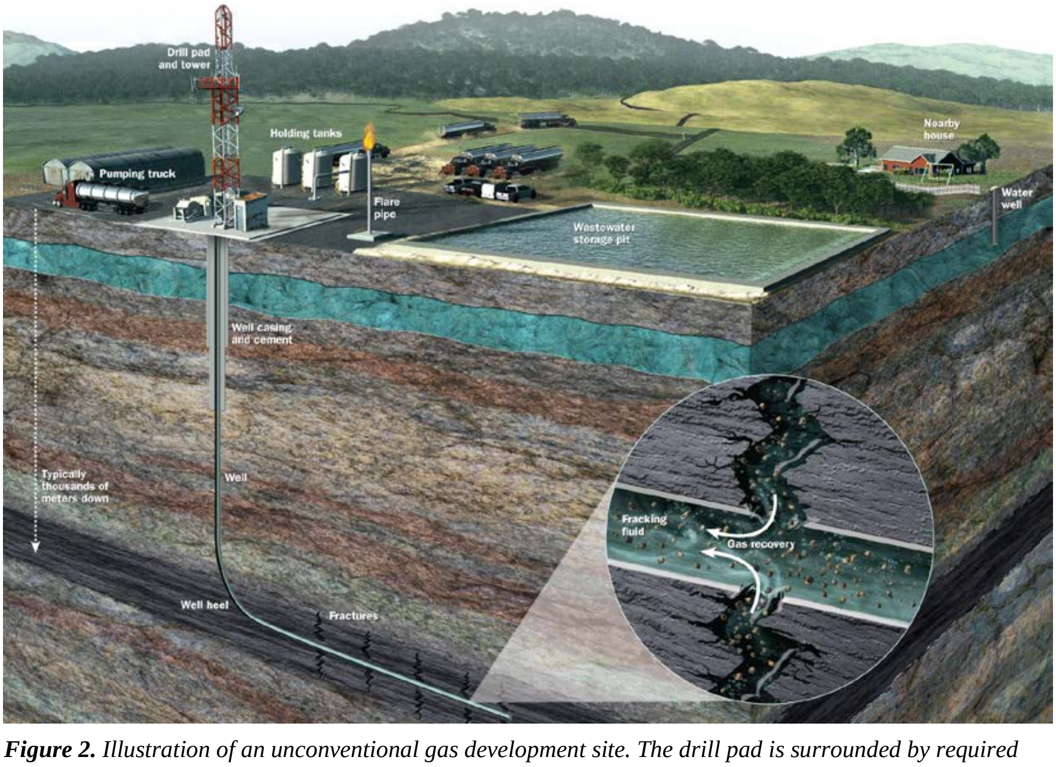

Figure 2. *Illustration of an unconventional gas development site. The drill pad is surrounded by required infrastructure such as flowback water storage pit, holding tanks, flare pipe as well as an area for trucks to deliver the fracking fluids. The drill hole extends horizontally in order to allow for the hydraulic fracturing to fracture the shale formation as much as possible. Image used with permission from Nicolle Fuller, Sayo Art. LLC.*

than to add new chemicals and collect the vast amount of water required for each fracking operation. Especially since experience from the USA shows that the production from an unconventional gas well decreases relatively rapidly and new boreholes must be drilled within 3 – 5 years. This also means that shale gas extraction requires more boreholes than in conventional gas extraction (Erlström, 2014).

When the well is no longer profitable it is plugged with cement to protect from contamination to groundwater, as well as emissions to the atmosphere (Michalski & Ficek, 2016).

4.2.1 Well integrity

As there are many similarities in the operational procedures between conventional oil and gas extraction and unconventional gas extraction, much of the findings and knowledge from these can be applied.

A well-known yet unresolved problem that has persisted for many years within the oil and gas extraction industry, is leakages due to improperly formed or placed, damaged or deteriorated cement seals (Council of Canadian Academies, 2014). A leakage of either natural gas or especially, the flowback fluids, pose a great risk for contamination of groundwater resources but also the increase of greenhouse gas emissions; as methane is approximately 25 times as effective a greenhouse gas as carbon dioxide over a 100 year time-period (Council of Canadian Academies, 2014).

A study made in the UK of decommissioned oil and gas wells showed that 30 % of these had methane in the soil around the well of significantly higher levels than the control sites of similar soil type. In contrast however, 27 % of the wells were considered a net sink of methane as these had lower levels of methane in the soil than the control sites. The study believes that leaks develop early in the post-production life of decommissioned wells as 40 % of recently decommissioned wells showed leakage (Boothroyd *et al.*, 2016). Another study where 15 000 production oil wells in the Gulf of Mexico were tested, it was found that 30 % of the wells had reported cement damage over the first 5 years after drilling, and after 20 years this had increased to 50 % (Vengosh *et al.*, 2014). A review which has studied papers from both independent and oil and gas industry suggests that between 6 – 75 % of all the wells suffer from integrity failures (Hays *et al.*, 2015). Leakage through the cement casing is not the only concern as far as well integrity goes. There is also a concern that the fractures created by the hydraulic fracturing may connect to other, preexisting, cracks within the rocks, or even connect to old, abandoned wells. A study from the USA however, found that the reservoirs are unlikely to act as a continuing source of migrating gas and that incidents of gas escaping due to a linkage to old abandoned wells or preexisting fractures are likely to be limited in both scope and duration (Reagan *et al.*, 2015). It should be noted that this was a numerical simulation in a hydrostatic environment and did not take into account any type of failure-scenario. But in order to prevent that a contamination occurs due to the unlikely event that a technical failure in combination with unfavorable geological conditions it is of great importance that there is a thorough well-seal 300 m below any superficial groundwater aquifer (Schwartz, 2015). This is because the combination of methane with the fracturing and flowback fluids may cause them to travel up to 300 m vertically through the ground.

Even though the issues with well integrity is a problem for all oil and gas extraction it is an even greater issue with unconventional gas extraction since it requires a larger number of wells.

4.2.2 Flowback water

The water which returns as flowback water is toxic to most living organisms, this is partly because of the chemical additives which was put into the water, but mostly due to what was previously trapped within the shale and now brought up (Macuda & Konieczynska, 2015). The flowback fluids typically contain components such as potentially hazardous salts, metals, metalloids, natural radioactive constituents, hydrocarbons which includes various amounts of benzene as well as other aromatics, and the fracturing chemicals that were added beforehand (Council of Canadian Academies, 2014).

Because of its hazardous nature, this wastewater cannot just be disposed into the environment but also poses technical challenges for treating it. In some cases, where available, deep wastewater injection wells are used to dispose of the flowback fluids. These are decommissioned oil and gas wells where wastewater is injected and then sealed up. In areas where this is not possible however, very efficient technologies for treating the fluids are required (Macuda & Konieczynska, 2015).

5 Impacts and risks

As with all industrial operations, there are always risks to be assessed with the benefits. If properly run and regulated, unconventional gas development presents a low risk to the public health, but there is little validation of this from experience (Hays *et al.*, 2015).

Since unconventional gas extraction has expanded so quickly over the last decade the scientific community has had a hard time to keep up with monitoring and controlling the effects of the industry. During 2009 and 2010 only a total of 12 peer-reviewed papers were published assessing the impacts of unconventional gas development. This has steadily risen and during 2015 alone 226 papers were published, making a total of 685 published peer-reviewed papers from the years 2009 – 2015 (Hays & Shonkoff, 2016). One study examining the papers published about unconventional gas development and the possible detrimental neural effects it may have, found that out of 106 matching papers, only 8 contained detailed examination of the link between brain and/or mental health and unconventional gas development. Whereas the others only conducted a superficial exploration of the relationship between these effects and made little to no mentions of the ethical implications the industry might have (Cabrera *et al.*, 2016).

5.1 Environment and public health

The environmental impacts of shale gas development will vary depending on where the sites are located, the geological composition of the ground and what the land area is currently used for.

The large number of well sites (Fig. 3) in combination with the extensive infrastructure required for each, such as roads, well pads, compressor stations, pipelines and staging areas, will create a cumulative effect on communities and ecosystems (Council of Canadian Academies, 2014). The use of multi-well pads may reduce the environmental impact somewhat in comparison to individual wells, but the impact will still be significant. This will lead to habitat loss and fragmentation, deforestation as well as risks towards local biodiversity, agroecosystems, agriculture and tourism (Council of Canadian Academies, 2014; Hays *et al.*, 2015).

Drilling an unconventional gas well ordinarily takes four to five weeks with a 24 hours a day working schedule as well as almost 2000 one-way truck deliveries for all the supplies (Michalski & Ficek, 2016). This means that there will also be a lot of noise as well as bright lights. There have been reports of psychosocial impacts related to physical stressors, such as noise, and a perceived lack of trustworthiness of the industry and government (Council of Canadian Academies, 2014).

There are concerns that cracks and vibrations may damage groundwater aquifers and infrastructure during the drilling or fracturing process. The risks for contaminations through leaks or spills to soil, surface- and groundwater may cause significant damage to both environment and public health (Erlström, 2014). It has been found that health concerns including nosebleeds, gastro-intestinal effects, asthma and respiratory complaints, have been connected to contaminations through air and water from shale gas development (Cabrera *et al.*, 2016).

Figure 3. *An aerial photograph of unconventional gas well pads in Wyoming, USA. Image from the Institute for Policy Studies, used within the Creative Commons license.*

After the extraction operations are complete it takes about five years to restore a well-site, which includes the required remediation, phytoremediation and phytostabilization (Michalski & Ficek, 2016). Phytoremediation and pyhtostabilization describes the process of using different plants to aid the cleaning of an area from heavy metals or toxic components. In many cases, however, full restoration may never be possible if the previous land use had very high agricultural or natural value. Due to the leakages through faulty well integrity and the impacts of possible spills there may be permanent changes to the local ecosystems in much bigger areas than just the mining areas themselves (Michalski & Ficek, 2016).

5.1.1 Water resources

The large amounts of water required in hydraulic fracturing may cause the groundwater levels to change (Erlström, 2014). A water footprint-study found that unconventional gas and oil development in USA only accounted for 0,87 % of the industrial water usage over the years 2012 – 2014 and does not generate more wastewater than conventional oil or coal mining (Kondash & Vengosh, 2015). But even so, there is still a risk that it may create water shortage in drier areas or decrease water quality. This in turn may lead to giving it a higher water footprint (Vengosh *et al.*, 2014). Shale gas development could pose problems in areas where the fracking industry would compete against other, already established industries for the water resources, such as in the Sichuan Basin in China, where one of China's most promising shale gas findings has been made. This may cause high to very high water stress in the area (Yu *et al.*, 2016).

Due to the large quantities of water used in hydraulic fracturing it is seldom readily available from the local area and such a large momentary consumption might negatively affect both surface and groundwater resources (Macuda & Konieczynska, 2015). It is therefore important that the gathering of water used for hydraulic fracturing is done over sufficiently long periods of time. It could also be eased by not only using fresh water, but also rain water, treated flowback fluids as well as sewage and brines combined with consistently monitoring the water infiltration and local hydrology for effects caused by new infrastructure, over-usage or leakages (Council of Canadian Academies, 2014; Macuda & Konieczynska, 2015).

5.1.1.1 Chemicals used

The chemical substances in the fracturing fluids are numerous and over 1000 different chemicals are being used in hydraulic fracturing (Nordling *et al.*, 2015). They are used to improve the gas-yield as well as to protect equipment and smooth operations. For this additives to adjust for viscosity, viscosity reducers, friction reducers, scale inhibitors, biocides, oxygen scavengers, iron precipitation controls, corrosion inhibitors, acids and proppants such as sand, metabasalt or synthetic chemicals, are added to the water (Vengosh *et al.*, 2014). Many of these; such as methanol, ethylene glycol and hydrochloric acid are acutely toxic, whereas others are linked to geno-, neuro- and immunotoxicity as well as endocrine disruptive effects which are especially harmful at specific stages of human development (Hays *et al.*, 2015). Endocrine disruptive effects can include malformations during development and disrupted reproductive, neurological and immune systems. The majority of the chemicals used are completely dissolvable in water and few evaporate which mean that large quantities of chemicals will remain in the water (Nordling *et al.*, 2015).

If the hydraulic fracturing is performed correctly and carefully the fracturing fluids should not have any contact with the environment before the depth of fracturing (Macuda & Konieczynska, 2015). There are however recorded cases where fractures even at that depth, have transported gas and fracturing fluids through an old well to drinking water aquifers. Groundwater samples of areas with unconventional gas development shows significantly higher levels of endocrine disruptive chemicals (Hays *et al.*, 2015; Nordling *et al.*, 2015).

5.1.1.2 Flowback water

As stated earlier, the returning flowback water from hydraulic fracturing is more hazardous than the water which is pumped down to fracture the rocks as it contains not only the chemical additives and proppants, but also the waters from the formations themselves, also called formation waters. These waters are hypersaline and can also contain bitumen, oil, hydrocarbon condensates such as benzene and toluene, and naturally occurring radioactive materials (NORM). The higher the salinity of the water is, the greater the concentration of toxic elements such as barium, strontium and radioactive radium will be, thus the salinity increases over time the more it is reused in hydraulic fracturing (Vengosh *et al.*, 2014). Salinity is measured in total dissolved salts (TDS), and in the flowback waters these are found up to thousands times the background levels. In Pennsylvania, USA, for example, the TDS of flowback water was 120 000 mg/l with bromide and chlorine concentrations of 12000-fold and 6000-fold respectively compared to the background levels and a study from West Virginia, USA, found similar levels (Vengosh *et al.*, 2014; Ziemkiewicz & He, 2015). The typical critical limit of what an ecosystem may sustain is 1000 mg/l, whereas acceptable drinking water is at 500 mg/l. There is also the risk that the upbringing of potentially harmful elements due to anthropogenic activities over the course of such a short time period has important implications for elemental cycling and will increase weathering as well as the release of trace elements to the environment which in turn will affect environmental and human health (Perkins & Mason, 2015).

The flowback waters are usually stored in tanks, impoundments and pits awaiting reuse or transport to the treatment facilities. When the NORM becomes concentrated, they can become what is called technologically enhanced NORM (TENORM), which poses a greater hazard. Especially to those working with removing solids from tanks or pits, handling drill cuttings and repairing and handling the equipment used in those operations (Werner *et al.*, 2015).

Due to its hazardous nature, treatment of flowback water is of great importance even though it is allowed in some states in the USA to use flowback wastewater to be spread on roads for dust suppression or de-icing (Vengosh *et al.*, 2014). Previous methods included treatment at brine and sewage treatment plants, which would remove some constituents. The high salinity was more difficult to handle, which leads to discharge waters with significantly higher TDS concentrations than the waters it is released into (Wilson & VanBriesen, 2012). Recent changes in the treatment process include dilution which lowers the TDS concentrations but they are generally still higher than the levels before the unconventional gas development began. Most of the tests from waters where treated water has been discharged has found elevated levels of TDS, metals, organic and inorganic compounds where the highest exceedance were between 1000 – 10000 times higher the allowed levels (Annevelink *et al.*, 2016). In the example from Pennsylvania, USA, previously mentioned, the bromide levels approximately 2 km downstream from the discharge site were still 16 times higher after dilution at the treatment plant. This also led to significant problems for the drinking water treatment plants due to increased levels of carcinogenic trihalomethanes in the municipal drinking water (Wilson & VanBriesen, 2012; Vengosh *et al.*, 2014).

A study evaluating the structural integrity and safety of impoundments and pits which contained flowback liquids and freshwater in the biggest black shale region, the Marcellus shale, USA, found risks with especially surface erosion, which was observed at every site, but also found issues with slope movement, seepage and wet zones at the vast majority of the impoundments and pits (Darnell *et al.*, 2016). This could lead to a leakage of untreated flowback waters into the surrounding natural area. The increased number of static surface waters could also lead to an increased number of potential breeding habitats for mosquitoes as well as other waterborne pests (Werner *et al.*, 2015).

A leakage, spill or poorly treated flowback water may have detrimental impacts upon the surrounding environment. This was deemed to be true as in 2007, in Acorn Fork Creek, Kentucky, USA where a widespread death and distress of aquatic beings was caused by untreated flowback water which was released directly into the river (Vengosh *et al.*, 2014). The frequency of leaks or spills correlates to the density of the unconventional gas development and while only 0,5 % of the wells may experience a spill, since there are more than one million oil and gas wells in the USA, there may be 5000 spills every year (Vengosh *et al.*, 2014; Centner & Petetin, 2015). In just Colorado, USA, 600 spills were reported during 2013 (Barcelo & Bennett, 2016).

Flowback waters pose a great threat to the environment due to the fracturing water and its interaction with the brine, minerals and organic compounds within the formations, and although the chemical additives contribute, their part is most likely a minor one. Thus, poorly treated flowback water or a minor spill or leakage may have significant impacts upon the environment (Vengosh *et al.*, 2014; Werner *et al.*, 2015; Ziemkiewicz & He, 2015; Annevelink *et al.*, 2016).

5.1.1.3 Groundwater quality

It is not uncommon for methane to be naturally present in ground- and surface-water and a study from Quebec, Canada, found that it is even possible for methane to reach such concentrations that exceed solubility within the groundwater wells (Moritz *et al.*, 2015). However, contamination caused by faulty well integrity from active and abandoned oil and gas wells, or faults and fractures caused by hydraulic fracturing combined with the upward migration of natural gas and saline waters may pose a long-time hazardous risk to shallow groundwater aquifers (Council of Canadian Academies, 2014; Vengosh *et al.*, 2014; Werner *et al.*, 2015). Due to failed structural integrity the wells may continue to leak, even though plugged, for many years. A study of the groundwater after surface spills in Colorado, USA, found elevated levels of benzene, toluene, ethylbenzene and xylene components. These levels were reduced by 84 % after remediation (Vengosh *et al.*, 2014). In Pennsylvania, USA, there have been 284 confirmed water contaminations since 2010, due to unconventional and conventional oil and gas operations. The most common fault is failed casings and barriers for the wastewater fluids which contains naturally radioactive materials which are brought up with the flowback water (Hays *et al.*, 2015; Pennsylvania Department of Environmental Protection, 2016).

Normally, the fractures caused by hydraulic fracturing extends less than 600 m above the horizontal borehole according to micro-seismic studies, which in most cases would not reach up to shallow groundwater aquifers (Vengosh *et al.*, 2014). Combined with the low permeability of overlying rock formations, high density of fluids and low upward hydraulic gradients it is unlikely for the contaminants to reach such levels. However, there are cases where deep saline waters and gas travel through natural faults and fractures in the bedrock up to the shallow aquifers and there is a risk that this could occur over the relatively short time period of six years. An occurrence of this was recorded in the Marcellus shale region in Pennsylvania, USA before unconventional gas development began (Vengosh *et al.*, 2014). Another study from a deformed basin in British Columbia in Canada found that the area had natural water circulation to depths of at least 3,8 km. Even though it might be possible, it was deemed unlikely that sedimentary basins which are not deformed to have connections between the deep shale gas resources and surface or ground-waters as well (Grasby *et al.*, 2016).

The distance between the unconventional gas wells and the faults within the bedrock is also of importance as it has been found that there is a correlation between methane concentration and the distance to the faults. This is of importance as it could lead to much greater contamination of groundwater than in other areas (Moritz *et al.*, 2015). Groundwater samples also have shown to contain significantly higher concentrations of methane when the wells are in close proximity to unconventional gas wells than groundwater wells lying further away. There were however, no traces of flowback waters or fracturing fluids (Werner *et al.*, 2015). By studying isotopic fingerprints the origin of the methane can be determined. In cases when they are tracked back to unconventional gas development sites the test site usually lies within 1 km of the fracturing site (Vengosh *et al.*, 2014). The contaminations are most likely caused by failed well integrity and even though the risks for other mishaps will likely be minimal if proper precautions and management practices are followed, the existing best practices cannot assure long-term prevention of leakages through faulty well integrity (Council of Canadian Academies, 2014; Vengosh *et al.*, 2014; Werner *et al.*, 2015). Studies have, so far, failed to explain why there are differences in methane and ethane concentrations in consideration to the distance of unconventional gas wells, but have found that the gas may migrate into shallow aquifers due to geochemical reasons and that topography is, in some cases, statistically significant (Vengosh *et al.*, 2014).

Quantifying contamination risks may pose a difficulty due to many unknown factors and since the potential impacts are not being systematically monitored. Thus the predictions will remain unreliable until an effective monitoring system is developed (Council of Canadian Academies, 2014; Vengosh *et al.*, 2014). However, since distance seems to be a viable factor, companies should respect a safe distance from major natural faults within the intermediate superficial bedrock as well as enforce a safe zone of 1 km from any drinking water wells when setting up new unconventional gas wells (Vengosh *et al.*, 2014; Moritz *et al.*, 2015).

5.1.1.4 Surface water

Surface waters are mainly at risk due to spills, leaks and unauthorized discharge, or insufficiently treated flowback water. Several studies have found effects from the unconventional gas development industry in aquatic systems and wild life which depends upon it.

After a spill in Kentucky, USA, it was found that fish which were exposed to the fluids had more gill lesions and signs of stress due to the exposure of heavy metals, as well a drop in the pH value in comparison to unexposed fish. Elevated levels of metals were also found to affect the growth, fecundity and survival of brook trout (Werner *et al.*, 2015). In Pennsylvania, USA, a study found elevated levels of both halides and ammonium after treated water had been discharged into the stream compared to upstream. This affects both the aquatic ecosystems as well as drinking waters due to its possibility to create toxic and cancerous brominated and iodinated disinfectant by-products (Harkness *et al.*, 2015). Another study, also in Pennsylvania, found that streams where hydraulic fracturing had occurred had lower water pH, higher amounts of dissolved organic compounds and higher dissolved mercury concentrations. This was observed to decrease biodiversity and increase the mercury concentrations across several trophic levels, but not at the top one (Grant *et al.*, 2015). Whether top predators will remain unaffected will hopefully be seen from further studies in the area. In other areas however, top predators are most definitely affected. The riparian songbird, Louisiana Waterthrush, were found in the Marcellus and Fayetteville shale regions to have significantly elevated levels of the metals barium and strontium in areas where hydraulic fracturing occurs. The study further concludes that hydraulic fracturing may be contaminating surface water and calls for additional monitoring and further studies (Latta *et al.*, 2015).

The radioactive constituents in the discharged waters may also cause issues in the aquatic ecosystems as it was found that even with current standards for treatment, a build-up of radioactive isotopes of radium as well as other metals can be observed downstream of treatment facilities (Vengosh *et al.*, 2014). The radioactive isotope of Radium-226 was found in a concentration approximately 200 times greater downstream than upstream or in the background sediments. Due to its long decay rate with a half-life of 1600 years, it will remain in the environment for a very long time, generating radiation strong enough to pose both environmental and health risks (Warner *et al.*, 2013; Vengosh *et al.*, 2014).

As mentioned before, having methane occurring naturally in water and soil is not uncommon and organisms in a methane-rich lake usually consume 10 – 90 % of all the methane before it reaches the atmosphere (Grasby *et al.*, 2016). Leakages which increase the amount of methane may, however, lead to more methane going through the lake without being consumed and may disrupt the lake's ecosystem as it adapts to the higher methane concentrations. One study suggests establishing monitoring of streams prior to shale gas development as well as using a method of stream methane monitoring, which is cost- and time efficient and can also be done with the help of local citizens with very basic training (Heilweil *et al.*, 2015). This in order to much better monitor and keep track of changes in the local environment as well as get a better understanding of the environmental effects of unconventional gas development.

5.1.2 Air

There is a risk that unconventional gas development will increase the concentration of chemical pollutants such as methane and other greenhouse gases, carbon monoxide, hydrogen sulfide, sulphur dioxide, volatile organic compounds (VOC's) like benzene and formaldehyde as well as NOx-components on the ground and in the atmosphere (Werner *et al.*, 2015; Annevelink *et al.*, 2016). The contaminants will be released throughout the entirety of the active years of the well pad, as well as through leakage after decommissioning (Hays *et al.*, 2015). When the NOx-components and VOC's are struck by sunlight they react and cause ground level ozone to be released. This mostly affects those working in the development area and may affect respiratory mucus membranes and respiratory functions. Even short-term exposure to ground level ozone has been found to, among other inflictions; increase mortality and changes in heart rate whereas chronic exposure has been found to cause reduced lung function in adolescents (Werner *et al.*, 2015).

Air pollutants from the traffic while constructing the well pad and preforming hydraulic fracturing should also be taken into consideration. When looking at a longer perspective the emissions from traffic may only contribute a minor addition, but its releases are large over short periods of time (Goodman *et al.*, 2016).

Just how the ecotoxic effects will affect the environment cannot be predicted as the lack of field data hampers any attempt of validation, thus more research is required (Annevelink *et al.*, 2016). When comparing the emissions of air contaminants to conventional gas extraction, it was found that they are similar, however due to the greater effort required to retrieve the unconventional gas it is deemed that unconventional gas development has a higher emission rate per unit gas produced (Council of Canadian Academies, 2014).

5.1.3 Soil and land use

The main risks for soil are from the ground usage from infrastructure and roads in the unconventional gas development as well as the risks for spills and leaks of contaminated water. These could occur during operations, storage, transport and disposal (Werner *et al.*, 2015).

When the environmental protection agency (EPA) of the USA did a study of some of the chemicals used in hydraulic fracturing they found that the majority of the 453 studied chemicals combined strongly with soil and organic materials. This could pose a long-lasting threat to the local area if a spill or leak should occur (Nordling *et al.*, 2015). Other constituents, of flowback water for instance, may leach with rain and/or snowmelt which may later affect ground- or surface waters. They can also be inhaled from dust, adsorbed through skin or ingested. Especially younger children are at a risk from the latter (Werner *et al.*, 2015). If a spill should occur however, it is possible by using specific grass and plant nutrients to create a diluting effect to decrease the soil salinity to levels where plants can grow (Wolf *et al.*, 2015).

The rapid increase of unconventional gas development in the USA also lead to other industries expanding to provide resources. For instance, the proppants most commonly used in hydraulic fracturing is a type of sand with 98 % quartz content, round grains and with similar size range. This type of sand being mined in the USA increased tremendously and if this were to occur in Europe it would mean large extractions from quarries of near-shore or coastal areas (Michalski & Ficek, 2016). A study which modelled different scenarios of potential shale gas development in northern Poland suggested that use of a restrictive and lower development rate would result in the lowest environmental impact.

There should also be restrictions as to how much the natural areas and forests may be fragmented and strict protections for natural parks and other protected areas. Increasing the number of wells per well pad would lower requirements for infrastructure and reduce costs, both during operations as well as restorative. It is however likely that this will increase the impact on a very local scale. They also found that it will most likely also be a conflict of interest between shale gas development and agricultural land usage (Baranzelli *et al.*, 2015).

To test the harmfulness to the environment of a potential leakage or spill, untreated flowback waters were released into a forest in an experiment. This caused severe mortality to ground vegetation in only 10 days, and after two years about half of the trees had died and the sodium and chloride concentration had increased by 50 times in the soil (Adams, 2011). In an uncontrolled area, such a leakage or spill would possibly have large environmental implications to soil, surface and shallow groundwater (Vengosh *et al.*, 2014; Werner *et al.*, 2015).

As with much else of unconventional gas development, there is little to no data on soil and soil quality before shale gas development has begun and thus to fully understand the effects and impacts more studies are necessary (Werner *et al.*, 2015).

5.1.4 Urban areas and public health

Living in close proximity to a shale gas development area may prove troublesome and can affect the health of the residents (Fig. 4). A large study in Colorado, USA, which examined the associations between maternal proximity to unconventional gas development sites and birth outcomes studied 124 842 births between 1996 and 2009. They found that babies born to mothers living in close proximity or surrounded by wells were twice as likely to have neural tube defects as those who didn't have any wells within 16 km of their residence (Cabrera *et al.*, 2016). When sampling air in residential areas in close proximity to shale gas development, it was found that the samples contained high levels of benzene which is carcinogenic and even in minor concentrations increases the risk for birth defects, causes headache, eye, skin and respiratory tract infections and chronic exposure increases the risk for leukaemia and may cause blood disorders and reproductive effects. The same study found that the air pollutants of greatest concern to public health were benzene, formaldehyde and hydrogen sulfide (Macey *et al.*, 2014; Werner *et al.*, 2015). Formaldehyde is a suspected carcinogen which can affect human tissue leading to acute health effects such as dermal allergies and chronic health effects such as asthma, neuro-, reproductive, genetic and cellular damage. Hydrogen sulfide is a broad toxicant which may affect most organ systems as well as contribute to a number of short- and long-term neurological, upper respiratory and blood related symptoms.

As was stated before, the shale gas development area is a 24 hours operation and the bright lights and noise will continue throughout the nights. The increased traffic which goes close to, or through, residential areas may result in lowered air quality, increased noise pollution and increased risk of motor vehicle crashes (Werner *et al.*, 2015). No evidence has been found of a direct cause and effect between residents reporting numerous health effects which they believe is related to unconventional gas development and the industry. However, a pattern has been found in the USA where the closer in proximity to shale gas development areas residents live, the more people are reporting health issues. And a similar pattern, which was not quantified and thoroughly studied, was found in Australia. The health symptoms which were reported from residents included weakness, extreme drowsiness, fatigue, nose, eye and throat irritation, nausea, nosebleeds, rash, sleep disturbances, respiratory symptoms, headaches, ringing in ears, and abdominal pain or cramping (Werner *et al.*, 2015).

5.1.5 Agriculture

As has been discussed earlier, the shale gas industry may compete with the agricultural industry over land usage. As well as the potential hazards for those living and being around the well pads. In the USA, hydraulic fracturing wells and grazing ground for livestock and other farm animals are many times situated in close proximity which may lead to undesired consequences (Fig. 5). In a case study in the USA it was found that after hydraulic fracturing began in proximity to the residents and their agricultural land their children had to be acutely hospitalized for, amongst other things, arsenic poisoning after the continued usage of their private drinking water well. Farm animals and pets suffered from breeding issues with stillborn and many also got so sick that they had to be euthanized. The families also suffered from nosebleeds, headaches and rashes. When tested they all had high concentrations of benzene in their urine samples. There were however, no conclusive evidence that the shale gas drillings were the cause of these health effects (Bamberger & Oswald, 2012).

Another study found that in all the areas where livestock had been exposed to contaminants from unconventional gas development, there had been only one case where they had been quarantined and not slaughtered and sent to food processing as per normal procedure. As very few random tests are made for food quality in the USA, how these contaminants will have affected the food supply is difficult to answer as the current data is insufficient. But with the multitude of potential hazardous contaminants which can be found in flowback water or in proximity of the well pads, consistent monitoring of agricultural areas are required to assess potential impacts on the food supply (Bamberger & Oswald, 2014). There have also been other studies which suggests that unconventional gas development has led to a decline in both milk production for each individual cow and, eventually, the number of cows.

The lack of evidence for direct links between unconventional gas development and health effects is an outcome of the rapid expansion of the industry and does not necessarily mean that it is viable to dismiss the claims of possible health effects. There is very seldom any data before hydraulic fracturing began, which means that it is nigh impossible to assess water or soil quality comparisons. It is also possible that there are many health impacts with longer latency and thus have not been discovered yet (Werner *et al.*, 2015).

Figure 5. *A fracking well pad in close proximity to rural houses and cattle farms. Photo taken in Washington County, Pennsylvania, USA, 2010. Used with permission from Mark Schmerling.*

5.1.6 Social acceptance

Most data and information has been gathered from the USA where the unconventional gas development has expanded the most and the quickest. The reason for the quick expansion and also low social acceptance of the shale gas industry has much to do with the U.S. Congress' exempt for hydrocarbon development, i.e. oil and gas, from a number of federal public safety and environmental laws (Centner & Petetin, 2015). This made it possible for the shale gas industry to begin extracting gas before proper regulatory safeguards and procedures were developed. The individual states were also forbidden to implement any laws or rules which might go against the expansion of the industry. State legislatures also did not always allocate sufficient funding to the regulatory agencies to allow for enough personnel to develop these necessary regulations and perform well inspection and further budgetary constraints resulted in governments lacking the personnel to meaningfully enforce the regulations that actually were in place. This meant that there were no consequences for those firms which failed to follow the regulatory proscriptions and gave the possibility for companies to cut corners concerning public and environmental safety (Centner & Petetin, 2015). Regulatory changes are effective however, as environmental violations decreased 45 % after a single policy-implementation (Rahm *et al.*, 2015).

Even though the shale gas industry has resulted in an expanding industry with benefits to employment rates, economy and greenhouse gas emissions, it has not been popular among many groups of people. The chemicals used in hydraulic fracturing are many times disclosed as “confidential business information” and thus remains unknown (Centner & Petetin, 2015; Werner *et al.*, 2015). This is especially troublesome for people who have been exposed to spills or live in areas close to unconventional gas development whom are becoming ill as doctors have little to no idea what chemicals they may have been exposed to. The volume of chemicals are also of a concern as an hydraulic fracture may require up to 70 000 m^3 fluids and 0,5 – 2 % consist of chemicals, which amounts to tons of chemicals being used for each fracture (Werner *et al.*, 2015).

To put things into a European perspective, the population density will be a large factor when comparing studied areas today and potential shale gas development areas in Europe. The average population density in Europe averages from just below 100 up to 600 people/km^2. This compared to 3 people/km^2 in Canada and Australia and 32 in the USA it is inevitable that hydraulic fracturing operations will cause issues and compete with other interests (Michalski & Ficek, 2016). Hydraulic fracturing is nothing new to Europe however, and no serious incidents have been connected with fracking so far, even though there are over 1000 horizontal wells and thousands of hydraulic fracturings has been performed in the recent decades (Michalski & Ficek, 2016). Some European countries also have the precautionary principle which will most likely provide more meaningful policies to the environment and public health. This will not mean a stop to the unconventional gas development, instead it means dealing with uncertainties and the vulnerability of the natural system to avoid irrevocable damage (Centner & Eberhart, 2016).

To increase the social acceptance of the unconventional gas industry it is of great importance that proper sophisticated policies are worked out and that the industry lends itself to process and continued research, societal learning and risk assessment so that risks and benefits can be assessed properly at relevant community and governmental levels (Wheeler *et al.*, 2015). It should also use best management practices to protect the public and environmental health from hazards, manage impacts in context of local concerns and values and allow residents to be engaged in decisions concerning the shale gas development (Council of Canadian Academies, 2014; Centner & Eberhart, 2016). As the Council of Canadian Academies (2014) puts it in their report about environmental impacts of shale gas in Canada;
"*Public acceptance of large-scale shale gas development will not be gained through industry claims of technological prowess or through government assurances that environmental effects are acceptable. It will be gained by transparent and credible monitoring of the environmental impacts*".

5.1.7 Disposal wells and earthquakes

Disposal wells, or wastewater injection wells are, as been stated previously, decommissioned oil and gas wells where flowback fluids are injected for disposal. And even though injecting these hazardous waters deep underground will, hopefully, reduce the impacts they could possibly make for health and environment above ground, what they may cause below ground is largely unknown.

The geological factors are most likely important but as there has been little monitoring of formation pressures and very few attempts to track the injected fluids in the subsurface it is difficult to dismiss concerns about the environmental impacts of injection (Ferguson, 2015). There are also concerns about contamination to ground and groundwater around these injection sites as they usually have storage ponds which may leak due to improper lining and management, but also that the decommissioned wells have faulty well integrity

(Vengosh *et al.*, 2014). It was also found from a study in southern Texas, USA, that disposal wells were predominately permitted in poorer areas and with residents of colour, which is a phenomenon also known as “environmental injustice” (Johnston *et al.*, 2016).

The risk of seismic activities and earthquakes caused by hydraulic fracturing are low according to the majority of experts, but wastewater injection may trigger these events (Council of Canadian Academies, 2014). Studies have found that the injection of disposal water may induce fault slippage and between 2014 and 2015 Oklahoma, USA, experienced 5991 induced earthquakes at a magnitude of over 2.7. This is a significant increase compared to the average of 21 per year from 1980 – 2010. One earthquake at the magnitude of 5.7 was found to be caused by disposal wells in Oklahoma (Hays *et al.*, 2015; Petersen *et al.*, 2016). And the UK’s suspension of hydraulic fracturing activities was due to two seismic events after hydraulic fracturing, where the largest had a Richter magnitude of 2.3, caused by the injection of fluids into an adjacent fault zone by Preese Hall 2011 (Prpich *et al.*, 2016).

6 Step towards clean energy?

An argument commonly used in favour of unconventional gas development is that our society is so dependent upon fossil fuels that it will be too big a leap to go straight to renewable energy sources as, amongst other things, our infrastructure is not ready for it. In that sense the unconventional and conventional natural gas would be a step towards clean energy by working as a “bridge fuel”. The argument is compelling when compared to coal, which is what both Swedish gas energy companies Svensk Energi and Energigas Sverige as well as the largest oil and gas company in the world, ExxonMobil, have done. The Swedish companies found that carbon dioxide emissions of natural gas is 40 % less than coal and 25 % less than oil (Nordling *et al.,* 2015). Whereas ExxonMobil found that their production of natural gas from shale in Pennsylvania, USA, had a 53 % lower carbon footprint than coal-produced energy over a 100 year time period and 47 % lower at a 20 year time period (Laurenzi & Jersey, 2013). Other life cycle assessments find that shale gas emits 20 – 50 % less carbon dioxide per energy produced than coal, but still 11 % more than conventional natural gas extraction and electricity production (Nordling *et al.*, 2015).

If unconventional gas development were to displace only coal and oil energy production it would lower the emissions of greenhouse gases. Coal production also emits hazardous pollutants such as particulate matter, mercury and sulfur dioxide which shale gas development emits lesser quantities of. Coal production has been studied far longer however, and its environmental and health effects are well known. There have so far not been any health assessments comparing coal production and unconventional gas development (Hays *et al.*, 2015). If it also displaces other energy alternatives such as nuclear and renewables, the impacts would be different and some even conclude that methane leakages from decommissioned wells would offset the benefits from shale gas development. There is also the risk that it promotes the use of high carbon infrastructure and undercuts the market for lower carbon alternatives (Council of Canadian Academies, 2014).

A study using five integrated assessment models examined the effects if a direct switch from coal to natural gas was possible. They found that it would be unlikely to reach the lower emissions required to slow down climate change. If issues with leaking methane caused by, mainly, faulty well integrity would be addressed by the industry, this might change however (Hays *et al.*, 2015). With the current heavy substitutions, large abundance and, in some parts of the world, relaxed regulatory environment it creates a very difficult field for other energy alternatives to compete in. A further investment in natural gas as a bridge fuel may delay the expansion of near-zero emission systems with more than 24 additional years (Hays *et al.*, 2015; Zhang *et al.*, 2016).

7 Discussion

Assessing the use of hydraulic fracturing and unconventional gas development is highly dependent on which viewpoint is taken. A study monitoring five Canadian newspapers for five years found that the articles written could be placed into two categories; economical and environmental. The economic potential of unconventional gas development were rarely discussed against its environmental risks however, which may lead to a divide in the public opinion. Also, the papers did not include any clear voices of environmentally concerned scientists (Olive, 2016). Without assessing these two viewpoints against each other, a conclusive picture may be missed and even though the gas industry has led to some communities in the USA growing extensionally, so called “energy boomtowns”. This is not the first time this has occurred, and they usually transform from the initial economic boom into a steady long-term economic decline. Especially as even unconventional fossil fuel reserves are rapidly decreasing and new sources are required constantly (Hays *et al.*, 2015).

It is an enticing source of energy, however, primarily, as has been discussed earlier, for those countries which wish to reduce the dependence upon foreign energy sources and/or boost their own economy (Centner & Petetin, 2015; Nordling *et al.*, 2015). These short term gains must be weighed against the long-term sustainability and economic concerns such as indirect costs of healthcare, or if well pads are placed in “beauty spots” or in natural parks, which is possible in, for instance, the UK, it may lower the income generated by tourism not to mention the environmental impacts on the flora and fauna in those areas (Hays *et al.*, 2015). Many countries that are considering unconventional gas development do not yet have laws in place to protect water sources which are used both for agriculture and human uses (Esterhuyse *et al.*, 2016). This must be in place as the experience from USA has shown that without the proper supervision, regulations, policies and laws for operations and management of flowback water, waste, emissions and operational disturbances, companies release excessive amounts of pollutants which may harm both the environment and public health. Also full disclosure of the chemicals and chemical components of flowback water is necessary as well as proper studies before the unconventional gas development is started (Council of Canadian Academies, 2014; Centner & Petetin, 2015; Hays *et al.*, 2015; Esterhuyse *et al.*, 2016; Prpich *et al.*, 2016).

At the moment, many questions about the impacts of unconventional gas development remain unanswered and the large consensus is that more research is required before any conclusive decisions can be reached. There may also be impacts which cannot be seen in the immediate future, but may become apparent through contaminations migrating to groundwater over long periods of time.

If any form of conclusions were to be drawn with the evidence at hand it would be that; if sufficient regulations and management practices to avoid spills and contaminations as well as release clean waste and waste water cannot be provided by the industry the long-term risks of contaminations, public health and environmental damage is too great to allow for the practice. Unconventional gas development is already banned, or on moratorium (temporarily banned), in five European countries and multiple local regions (*List of Bans Worldwide*, 2012). Adhering the precautionary principle may in this case be the wisest cause of action as it will give the science-based studies time to properly assess the effects before possible long-lasting damage could be inflicted.

It also raises the question if it is environmentally viable to invest in a finite energy source instead of renewable alternatives. As has been discussed earlier, it is merely postponing the switch to renewable energy sources and may actually lead to a setback in renewable research. New reports from climate scientists say that climate change may occur even faster than had been earlier anticipated and with recent political development in USA, climate and environmental issues may become more pressing (Friedrich *et al.*, 2016). It is therefore of great importance to limit the impacts of climate change as much as possible. One way which will aid in these efforts is by switching to renewable energy resources as quickly as possible and making sure that the research is allowed for unimpeded.

The main question which those creating policies and laws need to consider is if the short term benefits of this industry will be worth the long term risks for environment and public health.

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