Can Fracking Be Environmentally Acceptable?

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Abstract: The hydraulic fracturing or fracking and extraction of shale gas is vital to the continued success of the human race to provide a relatively clean energy source. However, there are several environmental issues that must be solved in order to make fracking environmentally acceptable. Once these issues are resolved, it could lead to a brighter future by allowing shale gas to act as a bridge to clean energy, while providing energy independence for the United States. To achieve these goals, there is a need to find suitable solutions to the following problems: methane gas leaks while fracking and during production, trigger of earthquakes due to fracking, and the disposal of the wastewater (largely comprised of fracking fluid) after the completion of fracking. To investigate the aforementioned environmental impacts, comprehensive research was performed using data for the Marcella formation. Although it is clear that additional research must be performed to fully deal with all the issues, the following strategies have been found to solve or mitigate the problems. To prevent the impact of methane gas leaks, well workers must be properly trained and supervised. As another precaution to prevent the methane from contaminating groundwater, groundwater wells must be a minimum of 1 km away from the vertical section of fracking wells. To lessen the intensity and frequency of earthquakes caused by fracking, a regulation should be set in place that prevents disposal of wastewater by groundwater injection wells. In addition, the site should be checked for possible active and inactive faults before the approval of fracking. Finally, fracking companies must be required to withdraw most fluids from wells and to treat them according to state regulations and reuse or surface disposal as treated water. If all of these suggestions are implemented, fracking can be made much more environmentally viable and safe. **DOI: 10.1061/(ASCE)HZ.2153-5515.0000330.**

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Introduction

Fracking is the process of drilling into the earth before a high-pressure water mixture is directed at the rock to fracture and subsequently release the shale gas trapped inside. The components of the water mixture are primary: water, sand, and chemicals are injected into the rock at high pressure, which allows the gas to flow out to the head of the well. In the United States, it has significantly boosted domestic oil production and driven down energy prices. A published review (Petroleum Resources Branch 2011), fracking is estimated to have offered gas security to the United States and Canada for the next 100 years, and has presented an opportunity to generate electricity at half the CO_2 emissions from coal (Nature 2009).

The U.S. Energy Information Administration (EIA) estimated that as of January 1, 2012 there were about 6.42×10^{13} cubic meter [2,266 trillion cubic feet (tcf)] of technically recoverable resources of dry natural gas including 2.08×10^{13} cubic meter (736 tcf) of shale gas (EIA 2015) in the United States. According to the EIA database, a remarkable boom of shale gas occurred during the past decade. Fig. 1 shows the annual natural gas production and future projection in the United States and Fig. 2 shows the percentage of all sources of natural gas in total production. Before 2000, the shale gas accounted for only about 1% in total natural gas production. Thereafter, rapid and considerable growth in production numbers was observed. In 2013, about 2.43×10^{11} cubic meter (8.6 tcf) of dry natural gas was produced from shale gas, amounting to almost 35% of total natural gas production in the United States. The seed for the shale gas boom was planted in the late 1970s when the U.S. government decided to fund government research and development programs and provided tax credits for developing unconventional natural gas in response to the severe natural gas shortage at the time (Wang and Krupnick 2013). Some key technologies such as horizontal drilling and three-dimensional exploration resulted from that program. During the 1970s, hydraulic fracturing started to extract shale gas. In 1997, Mitchell Energy took the fracturing technique used in east Texas by Union Pacific Resources and applied it to the Barnett Shale formation of north Texas (Robbins 2013), and found that this technology can be used to exploit gas in a cost-effective manner.

Hydraulic fracturing is presently the primary extraction technique for oil and gas production in low or tight permeability, unconventional reservoirs (Gallegos and Varela 2014). As of the year 2013, at least 2 million wells have been hydraulically fractured, and in addition up to 95% of new wells drilled currently are hydraulically fractured (U.S. DOE 2013). During hydraulic fracturing, water containing chemical additives and propping agents are injected into a low-permeability petroleum reservoir under high pressure, fracturing the formation (Tanya et al. 2015). A single shale gas well requires approximately 9,000 to 29,000 m^3 (2.0 to 6.4 million gal.) of water (U.S. DOE 2009). Over 82,000 wells were fracked since 2005, using approximately 9.5×10^8 m^3 (250 billion gal.) of water in addition to adding 7.6×10^6 m^3 (2 billion gal.) of chemicals to fracking wells (Ridlington and Rumpler 2013) and subsequently generating large quantity of wastewater.

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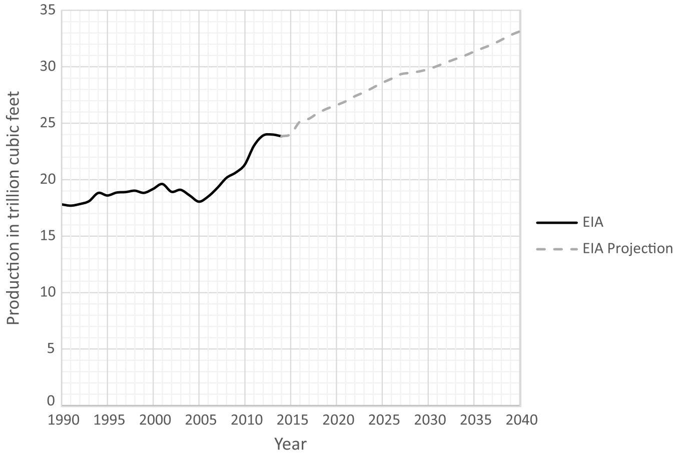

Fig. 1. Total U.S. natural gas production and projection production

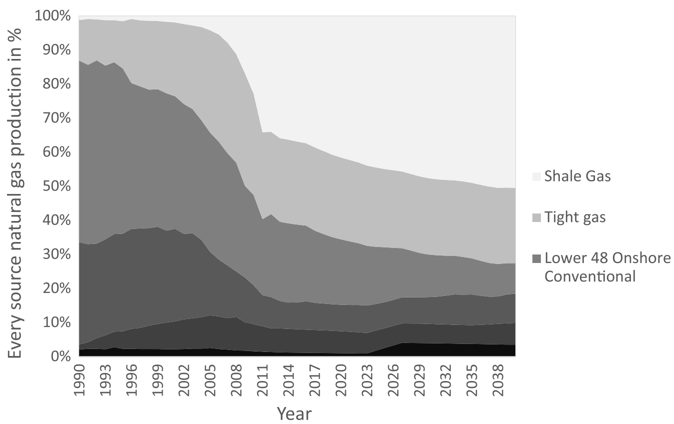

Fig. 2. Natural gas production by source

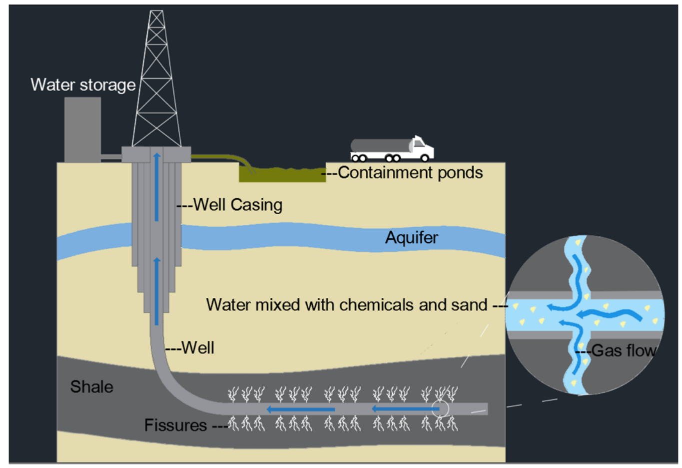

Fig. 3. Shale gas extraction

Hydraulic fracturing, more commonly referred to as fracking, is older than most people presume it to be. The inspiration for the earliest version of fracking came when Civil War veteran Colonel Edward Roberts witnessed, "Exploding artillery rounds plunging into the narrow millrace canal" during a battle. Roberts later patented an "exploding torpedo" device to carry the process that Roberts referred to as fluid tamping, which become the earliest form of hydraulic fracturing (AOGHS 2014). The next big leap towards modern fracking did not occur until the 1930s, when nitroglycerin was replaced with a nonexplosive fluid substitute termed acid, increasing the productivity of wells by making them less likely to close. The first research into modern fracking was performed in the late 1940s and during the remainder of the century, both the popularity and the technology (such as drilling techniques and extraction methods) of fracking expanded (Cahoy et al. 2012). George Mitchell, who combined fracking with horizontal drilling (Zuckerman 2013), developed the final technological leap of fracking in the 1990s. As shown in Fig. 3, the horizontal drilling can be performed for several hundred to thousand meters inside the shale layer and extract shale gas over larger area. This vastly increased the efficiency while reducing the deleterious environmental impacts.

Fracking includes several steps as shown in Fig. 4. Before the start of vertical drilling, a well casing made of cement must be installed deeper than the groundwater to protect the aquifer. Drilling mud is used to lubricate the drill and protect the borehole. After the desired depth is reached, horizontal drilling into the gas shale layer is accomplished by gradually tilting the drill and drilling horizontally. The horizontal drilling will continue for several thousand feet inside the shale layer. After drilling, a production casing surrounded with cement will be installed in the borehole. Then plugs are added to prepare the separate fracturing stages. A perforating gun is sent to the horizontal borehole to blast small holes into the shale. Then, the high-pressure fracking fluid is pumped into the borehole to create fissures in the shale. These fissures provide free paths for the gas to flows to the surface. One well can be fractured at multiple locations, and when the fracking is completed, the fracking fluid is stored in a wastewater pond once it is pumped out to the surface. As stated before, fracking fluid contains water, sand, and chemicals. The function of the sand in the fracking fluid is to prevent the closing of created fissures. Approximately 10 to 20 chemicals are added to the fracking fluid, with each having a specific purpose such as polyacrylamide to reduce the friction between fluid and pipe and ethylene glycol to prevent scale deposit in the pipe (U.S. EPA 2015).

Fracking allows countries such as the United States great economic benefits. The current low gas prices can be in part attributed to fracking. For example, Brookings Institute has reported an average decrease of $13 billion per year in consumer gas bills due to fracking from 2007 to 2013 (Hausman and Kellogg 2015). Not only is fracking saving money for American citizens, but it is also providing a wealth of employment opportunities in America. In addition to the economic benefits, fracking provides political advantages to the United States. One of the main foreign policy issues of America is its dependence on foreign oil for energy. The widespread popularity of fracking could vastly reduce this dependency, giving other countries less control over the United States.

The recent push to develop unconventional sources of oil and gas both in the United States and abroad via hydraulic fracturing (fracking) has generated a great deal of controversy (Boudet et al. 2014). Concerns about possible risks associated with public health and water quality arising from the migration of chemicals in the fracking fluid and methane gas into local groundwater aquifers. Methane gas can also escape into the atmosphere, adding to the greenhouse effect. The quantity of water required for the hydraulic fracturing process is also of concern especially in the arid and semiarid regions (Davis 2012). These concerns are heightened largely by the unwillingness of fracking companies to divulge the content of the fracking fluid to the public and their unwillingness to be subjected to regulatory policies, thereby creating the perception of possible deception and cover-up. This have mainly created a fertile ground for speculation among the public. This atmosphere has also

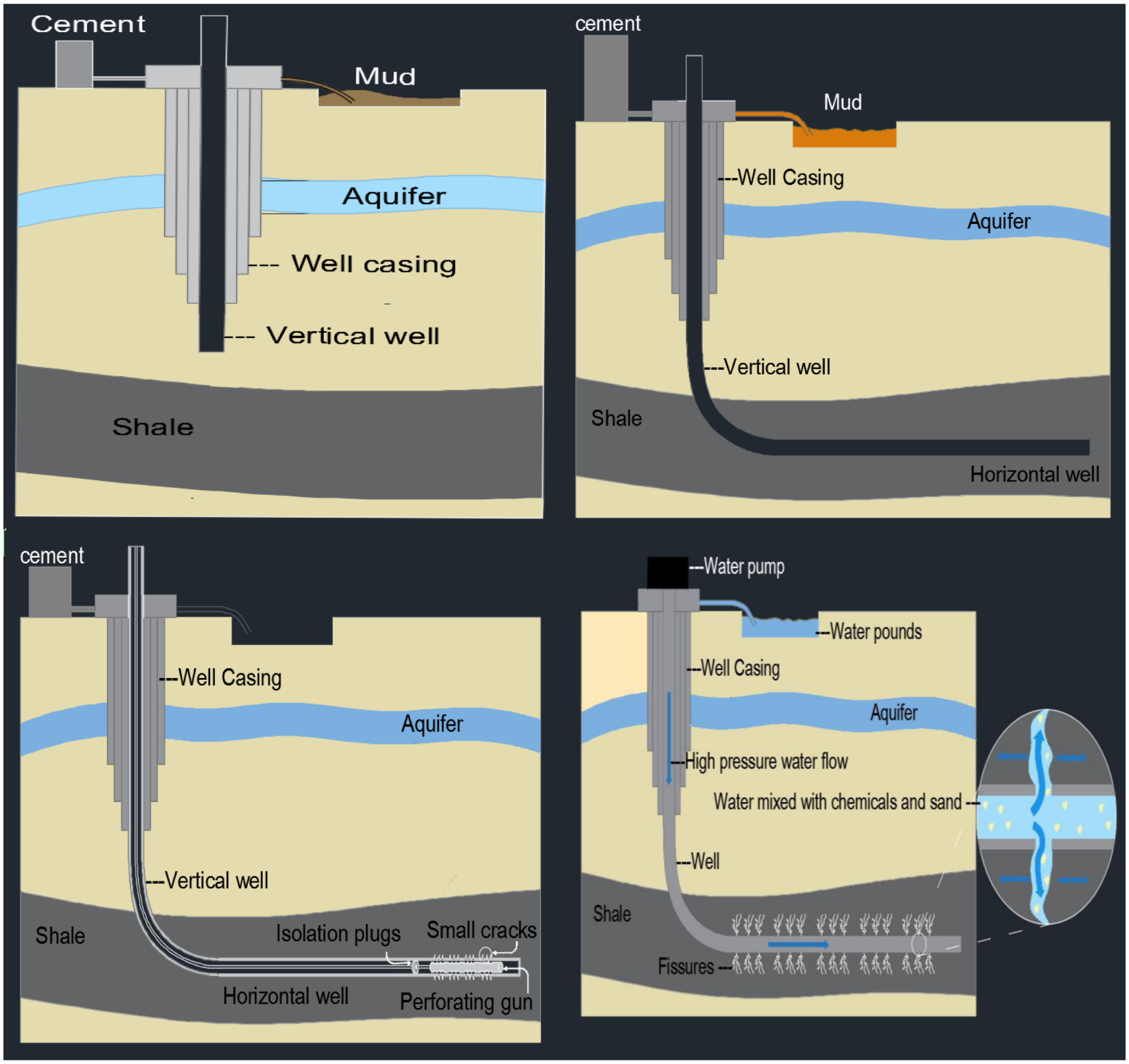

Fig. 4. How the fracking is performed

made it difficult for researchers and scientists to undertake factual studies evaluating potential environmental impacts of the process, which will help to decipher and different between the legitimate and perceived concerns of the public, thereby putting the technology on the path to eventual public acceptance. Effectively engaging stakeholders and setting appropriate policies requires insights into current public perceptions of this issue (Boudet et al. 2014). The current main issues of public concerns are described in the following sections.

Groundwater Contamination

The most likely cause for methane and fracking fluid contamination of groundwater is "poorly built wells- inadequate steel casing and poor cement construction" (North Carolina Health News 2014). Proper sealing of annular spaces with cement creates a hydraulic barrier to both vertical and horizontal fluid migration (FracFocus .org 2015a, b, c). In some situations, a buildup of localized pressure occurs because of inadequately seal pipes, which results in the release of gas and drilling fluids into the natural environment (Lustgarten 2009). Therefore, human error is most likely liable for contamination of groundwater around fracking wells. Avoidance of this requires strict regulatory monitory in construction and verification methods using geophysical logs such as cement bond logs (CBL) and variable density logs (VDL) to evaluate the sealing quality of the cement in the annulus (FracFocus.org 2015a, b, c). Another source of contamination of groundwater typical of methane is from other naturally occurring shallow pockets that are drilled through to assess the deep shale formations.

Air Pollution

Gas wells are connected to many valves and joints, and those may release pressure by venting gas. Recently, the amount of methane in the atmosphere has been increasing due to leaks from shale gas wells and loose pipefittings (Zeller 2011). Methane venting and leakage can be decreased by upgrading old pipelines and storage systems, and by applying better technology for capturing gas in the 2-week flow back period after fracking (Howarth et al. 2011a, b). Though shale gas contributes to greenhouse effects through leakage during gas extraction and carbon dioxide release during burning, it is less damaging than coal. The carbon footprint of shale gas estimated to be about 53% lower than coal (Laurenzi and Jersey 2013). In addition, burning of coal also emits metals such as mercury into the atmosphere that eventually settle back into our soils and waters (Brantley and Meyendorff 2013).

Large Volume Water Use in Water-Deficient Regions

Shale gas production on the average require approximately 15,000 m^3 (4 million gal.) of water per well. These varies from well to well in the range of 9,000 to 29,000 m^3 (2 to 6.4 million gal.) (U.S. DOE 2009). As reduction in water use is been advocated by promotion of fluid recycling whenever possible, the quantity of water demand for fracking has become a big issue for officials in water-scarce states concerned about balancing energy-related demands with those related to municipal consumption and irrigated agriculture (Davis 2012). The location of the fracking operation is also very important (Davis 2012). Conflicts resulting from competing demands for energy and water are of increasing global concern, especially in expanding urban areas (Fry et al. 2012). This conflicts of opposing demand of water will become more pronounced, especially in areas of scarce water resources, as shale gas extraction technologies gets rooted throughout the world.

Effect on Drinking Water Resources

According to the U.S. Environmental Protection Agency (EPA), the impact of hydraulic fracturing activities on drinking water resources depends on a couple of factors such as proximity to drinking water resources. Residents and drinking water resources in areas that experience hydraulic fracturing activities are most likely to be affected by any potential impacts. However, hydraulic fracturing can also affect drinking water resources outside the immediate vicinity of a hydraulically fractured well, as trucks carrying wastewater could spill or a release inadequately treated wastewater that could have downstream effects. Some other activities associated with hydraulic fracturing activities also have the potential to impact drinking water resources. These include water withdrawals in times of, or in areas with, low water availability, spills of hydraulic fracturing fluids and produced water, fracturing directly into underground drinking water resources, belowground migration of liquids and gases, and inadequate treatment and discharge of wastewater. They, however, did not find any evidence that these mechanisms have led to widespread, systemic impacts on drinking water resources.

Blowouts due to Gas Explosion

Methane gas can escape into the environment out of any gas well, creating the real, though remote, possibility of dangerous explosions. However, unlike with oil exploration, for shale gas exploration this is a concern only during initial installation.

Due to the blowouts due to gas explosings and recent occurrence of earthquakes, hydraulic fracturing has recently experienced great opposition due to environmental issues commonly associated with it. Hence, all issues can be lumped into three major concerns: (1) the occurrence of methane contamination of groundwater and surface water herein referred to as "leaking methane gas," (2) the occurrence of earthquakes, and (3) the improper treatment methods and disposal of fracking fluid. This manuscript provides a detailed discussion of these three environmental issues to find an acceptable common ground to proceed with fracking for economic prosperity and energy security.

Leaking Methane Gas

As stated before, fracking is a process by which shale gas is extracted from thousands of feet below the earth. Methane gas is a major component of the shale gas and methane has been detected in groundwater reserves near extraction wells of shale gas. Since the primary purpose of fracking is to extract the methane gas, fracking has been accused of contaminating the groundwater reserves with methane gas.

Methane (CH_4) is considered the second damaging greenhouse gas, and has a global warming potential of 25 over a 100-year period and 12 years of life in the atmosphere. In other words, methane can trap 25 times more heat than carbon dioxide in 100 years and can exist in the atmosphere for over a decade. Atmospheric CH_4 has increased by about 1,000 parts per billion since the beginning of the industrial era of the late 1700s, representing the fastest changes in this gas over at least the last 80,000 years (U.S. EPA 2010d, a). Methane emission occurs not only due to the human activities, but also due to natural causes such as wetlands and agricultural activities. However, over 60% of total methane emissions are due to human activities such as leakage form natural gas systems and from waste/landfills (U.S. EPA 2010a). In the atmosphere, methane will react with airborne particles called aerosols. Aerosols can affect climate directly by the scatter of solar radiation and indirectly by clouds (IPCC 2001). Emissions of methane have substantial impacts on aerosols by altering the abundance of oxidants, especially hydroxyl, which convert SO_2 into sulfate (Shindell et al. 2009). Global burdens of hydroxyl and sulfate change by −26 and −11% for methane (Shindell et al. 2009). When methane uses up hydroxyl, a lower sulfate aerosols concentration will be present in the atmosphere and less incoming light will be scattered, causing a warmer climate (IPCC 2001).

Fugitive emissions during the production and distribution of shale gas exploration are an inevitable and serious environmental issue. Emissions from natural gas production accounted for approximately 66% of CH_4 emissions and about 25% of nonenergy CO_2 emissions from the natural gas industry in 2006 (U.S. EPA 2010d, a). Emission during well completion; leakage from the equipment; and losses during distribution, processing, and transport are three main processes causing methane emission.

During the production process, methane emissions can occur due to two reasons. The first is emission from the well. During the construction, methane emission occurs when the plugs are drilled out and when the fracking fluid is recovered back to the ground surface. The U.S. EPA (2007) estimated drill-out emissions at 142×10^3 to 425×10^3 m^3 per well. After the fracking is completed, a significant amount of fluid returns to the surface as flow back within the first few days to weeks and is accompanied by large quantities of methane (Bol et al. 1991). With the development of the cracks, a large amount of gas is released and is dissolved in the fluid, exceeding the methane solubility in the fluid. Hence, when the fluid flows back it will contain a large amount of methane. With careful process designs, this methane can be recovered.

The second cause for methane emission is from the gaps between the casing, cement, and formation. There are already several protective measures to prevent methane leakage from the fracking wells and subsequent operation. The primary defense against methane gas leaking is the pipe that transports the methane gas from the shale layer, on the average of 2,133 m (7,000 ft) underground, to the surface where the gas is collected. Fracking companies have included several precautions to prevent methane gas leaks (Fig. 5). The specifics vary slightly based on the fracking company, but in general, the pipe that transports the methane has up to seven protective layers, with extra layers of cement when the

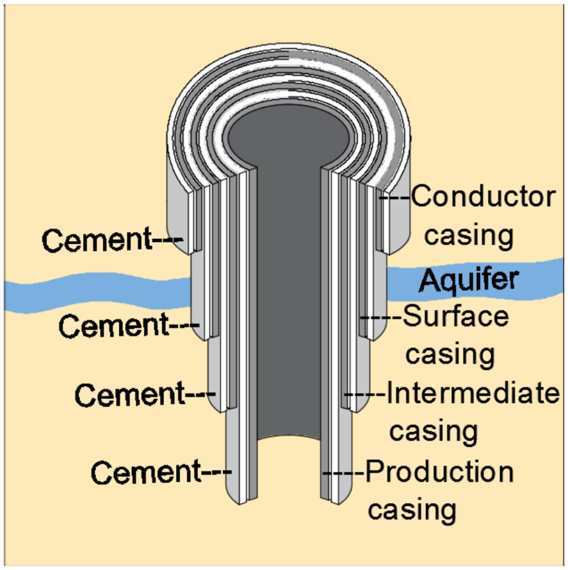

Fig. 5. Schematic of a section of vertical well

pipe approaches the surface level. Typically, the seven layers include four casing layers and three cement layers between the casings. The objectives of these layers are to protect the groundwater, protect the well bore, and let the gas flows to the surface. Actually, the casing and cement are also set to isolate the water and subsurface formation. The number and size of the layer depend on each well's subsurface characteristics, such as depth of groundwater table, groundwater bearing, and rock formation. Normally, the four casing layers include conductor casing, surface casing, intermediate casing, and production casing. Conductor casing has two primary purposes: to hold back any unconsolidated surface sediments and to isolate shallow groundwater from the content in the well (Encana 2015). It has varied size and length from 24 to 46 m (80 to 150 ft). After the conductor casing is installed, the drilling will begin. To control the well and provide blowout protection, second layer, called the surface casing, is installed and cemented. The size of this layer depends on the depth of the deepest groundwater table, usually up to 610 m (2,000 ft). The third layer is called intermediate casing and it is used to protect the well bore and to avoid the instability caused by abnormally pressured subsurface formation. This layer casing a cement top must isolate any hydrocarbon zones (Petrowiki 2015). The final layer is the production casing, which carries the fracking fluid and the path for the gas to flow to the surface after fracking. Casing and cement play an important role in groundwater protection.

Due to aforementioned measures, it is highly unlikely that the methane would leak from the well, in the absence of a poorly built well due to human error. However, when the integrity of the well bore is compromised, gas migration or stray gas can become an issue (Harrison 1983). The emission may occur when the cement and the casing are not properly set and cause a gap between the casing and the cement. Such emissions can also occur between the formation and the cement. The well is drilled into a deep formation with high-pressure gas, and this high-pressure gas can have deleterious effects on the integrity of the outer cement annulus, such as the creation of microchannels (Bol et al. 1991). Due to the high working pressures, the design of the cement is important. If the hydrostatic pressure of the cement column is not higher than the gas-bearing formation pressure, the gas can fracture the cement before it sets and a loss of cement slurry can occur (Vidic et al. 2013). Fractures of the cement and gaps between the cement and the formation can occur due to these reasons. Hence, the integrity of the vertical well should be carefully checked before horizontal drilling.

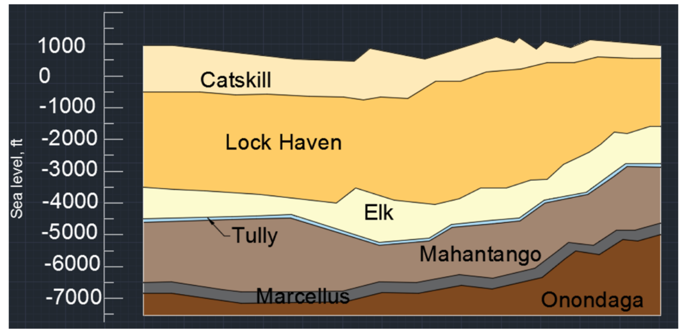

Fig. 6. Cross section of Marcella formation

In addition to the reasons mentioned earlier, emissions from pneumatic pumps and dehydrators comprise major parts of the leakage (GAO 2010). A typical well has 55 to 150 connections to equipment such as heaters, meters, dehydrators, compressors, and the vapor-recovery apparatus (Howarth et al. 2011a, b). During the production, the well is connected through many different valves and those may release pressure by venting gas. Aging equipment and improper sealing of the pipe or equipment will allow methane to be released from the system. The GAO (2010) concluded that 0.3–1.9% of the lifetime production of a well is lost due to routine venting and equipment leaks. Other emissions occur during processing, transport, and distribution. The default EPA facility-level fugitive emission factor for gas processing indicates a loss of 0.19% during production (Shires et al. 2009). Due to the difficulty in measuring the losses during the transport and distribution, there is no proper direct quantification from these two losses. However, there are methane monitors in the market that could trigger alarms and locate such leaks.

A high level of protection does not safeguard against methane gas that migrates to the groundwater from the shale layer (without ever passing through the pipe). This situation is thought to occur in horizontally drilled wells. Horizontal drilling is a more efficient version of fracking than the original vertical drilling. In horizontal drilling, once the well has reached a desired depth, the trajectory of the drill slowly changes continually until the drill creates a horizontal well. This allows a larger area to be fracked with less disturbance to the surface within a shorter period. However, it is assumed that horizontal drilling has a fatal drawback; it causes methane at the shale layer to migrate through the thousands of feet of rock, to the groundwater. This is thought to occur when the well is fractured (explosions are detonated in order to create cracks in the shale layer and the retrieval of the shale gas) and the shale gas is redisturbed.

Fig. 6 shows a cross-section of Marcella shale; Table 1 shows its hydraulic properties. The following computation is performed to estimate the time (t) of arrival of shale gas to the surface. Vertical hydraulic conductivity, K_v, is given as

$$K_v = \frac{\sum_{i=1}^{n} H_i}{\sum_{i=1}^{n} \frac{H_i}{K_{v_i}}} \tag{1}$$

where H_i = average thickness of each rock type in the Marcella formation and K_{v_i} = hydraulic conductivity of each rock type.

Therefore, from Eq. (1), the vertical hydraulic conductivity (K_v) of the Marcella formation is estimated as

$$K_v = \frac{305\text{ m} + 792\text{ m} + 152\text{ m} + 30\text{ m} + 610\text{ m}\,(1{,}000\text{ ft} + 2{,}600\text{ ft} + 500\text{ ft} + 100\text{ ft} + 2{,}000\text{ ft})}{\frac{305\text{ m}\,(1{,}000\text{ ft})}{1.52\times10^{-6}\text{ m/day}\,(5\times10^{-6}\text{ ft/day})} + \frac{792\text{ m}\,(2{,}600\text{ ft})}{1.52\times10^{-6}\text{ m/day}\,(5\times10^{-6}\text{ ft/day})} + \frac{152\text{ m}\,(500\text{ ft})}{1.52\times10^{-3}\text{ m/day}\,(5\times10^{-3}\text{ ft/day})} + \frac{30\text{ m}\,(100\text{ ft})}{1.52\times10^{-3}\text{ m/day}\,(5\times10^{-3}\text{ ft/day})} + \frac{610\text{ m}\,(2{,}000\text{ ft})}{3.05\times10^{-9}\text{ m/day}\,(10^{-8}\text{ ft/day})}}$$
$$= 9.45\times10^{-9}\text{ m/day}\,(3.1\times10^{-8}\text{ ft/day})$$

The hydraulic gradient i is defined as

$$i = \frac{P}{L \times \gamma w} \tag{2}$$

where P = reservoir pressure [$P = 27.6$ MPa (4,000 psi = 576,000 psf)]; L = average depth of the shale formation to the ground water table [$L = 1,890$ m (6,200 ft)]; and γw = unit weight of water [$\gamma w = 9.8$ kN/m^3(62.4 pcf)].

Substituting the values into Eq. (2) gives the hydraulic gradient as

$$i = \frac{27,579\text{ kPa}}{1,890\text{ m}\times 9.8\text{ N/m}^3}\left(\frac{576,000\text{ ps}f}{6,200\text{ ft}\times 62.4\text{ pcf}}\right) = 1.32$$

The Darcy velocity (Vd) is expressed as

$$Vd = K_v \times i \tag{3}$$

Hence, from Eq. (3), the Darcy velocity can be written $Vd = 9.45\times10^{-9}$ m/day $(3.1\times10^{-8}$ ft/day$)\times 1.32 = 1.25\times 10^{-8}$ m/day $(4.092\times10^{-8}$ ft/day).

Average linear seepage velocity, Vs, is given as

$$Vs = \frac{Vd}{n} \tag{4}$$

Assuming an average porosity (n) of 8.0%, then from Eq. (4)

$$Vs = \frac{1.25\times10^{-8}\text{ m/day}}{0.08}\left(\frac{4.092\times10^{-8}\text{ ft/day}}{0.08}\right)$$
$$= 1.56\times10^{-7}\text{ m/day}\ (5.115\times10^{-7}\text{ ft/day})$$

Hence, the time (t) of arrival of the shale gas to the groundwater is estimated below as 33 million years

$$t = \frac{L}{Vs} = 1,890\text{ m}\,(6{,}200\text{ ft})/[1.56\times10^{-7}\text{ m/day}\,(5.115 \times 10^{-7}\text{ ft/day})]/(365\text{ day/year}) = 33\text{ million years}$$

Please note that methane diffusion could also occur due to the methane concentration gradient, but the time for methane to reach the surface is much longer than 33 million years. Fick's second law was used to estimate the time it takes to increase the atmospheric concentration of methane by 10% due methane gas migration by diffusion. The resulting time was computed as 470 million years. The diffusion coefficient was assumed to be 0.022 m^2/day (0.24 ft^2/day) (Chen et al. 1977). Hence, it is virtually impossible for methane to contaminate the groundwater due to horizontal drilling and can be considered as a perceived environmental concern.

While it has been proven that most of the accusations against fracking causing methane contamination are false, there is still undeniably a presence of methane in the groundwater around some fracking locations. The most likely culprit for this methane contamination is "poorly built wells- inadequate steel casing and poor cement construction (North Carolina Health News 2014)." In other words, human error is most likely responsible for any contamination of groundwater around fracking wells. This is because there is high pressure in the pipe during fracking. Specifically, when the fracking fluid is pumped into the well and when the methane gas is pumped out of the well. Even a small irregularity in the casing due to poor installation or cementation could produce a leak, such as a full water balloon pricked with a tiny hole (Ewen et al. 2012). From that leak, it is feasible that the methane gas could slip past the cement and contaminate the groundwater.

As with horizontal drilling, this situation is not the case. Studies have shown that there is a negligible amount of contamination if the groundwater is more than 1 km away from fracking wells (Mason et al. 2015). Hence, it is proposed that any residential or commercial activities should be at least 1 km away from the vertical well. While this would be inconvenient for fracking companies as there is groundwater above many of the places that contain shale gas, it is definitely possible to work around. This is especially true when horizontal fracking is considered (which has already shown not to be the cause of methane contamination). Horizontal fracking could be used to circumvent the 1-km restriction by drilling down vertically more than 1 km away from the groundwater and then drilling horizontally underneath the groundwater. As it is now, horizontal wells extend several miles, so the 1-km constraint would not be overly detrimental to the productiveness of fracking.

There is another possible explanation for methane contamination. Groundwater naturally contains methane in low quantities. However, it is possible that some groundwater has a larger concentration of methane. The preceding time of arrival calculation showed that it would take approximately 33 million years for methane to seep from the shale layer up to the groundwater reserves. Yet, most of the shale formations that are fracked are far older than that of the Marcellus shale (the second largest fracking field in the world), which is 385 million years old. With such a long time, it is possible that the shale migrated into the groundwater long before fracking was even conceived and that it was only noticed once fracking became popular and controversial. This explanation is corroborated by reports (Lustgarten 2009) of people being able to set their water aflame (due to the high methane concentration) long before fracking began in their area.

Between human error and natural methane migration into groundwater, the presence of methane in groundwater around fracking wells can be explained. It is also evident that fracking does not inherently cause contamination of groundwater, provided that

Table 1. Hydraulic Properties of Rock in Marcella Formation

Formation[a]	Rock type[b]	Thickness[a] [m (ft)]	Hydraulic conductivity[c] [m/day (ft/day)]
Catskill	Sandstone	305 (1,000)	1.52×10^{-6} (5×10^{-6})
Lock haven	Siltstone, shale, sandstone	792 (2,600)	1.52×10^{-6} (5×10^{-6})
Elk	Dolomite, shale	152 (500)	1.52×10^{-3} (5×10^{-3})
Tully	Limestone	30 (100)	1.52×10^{-3} (5×10^{-3})
Mahantango	Shale	610 (2,000)	$3.05\times10^{-9}(10^{-8})$

[a]Data from Molofsky et al. (2011).
[b]Data from Harper (1999).
[c]Data from Domenico and Schwartz (1990).

the vertical well is at least 1 km away from any groundwater well. Therefore, with sufficient training and supervision to avoid most human error, along with the proper regulation preventing fracking companies from drilling vertically within 1.6 km (1 mi) of groundwater, the process of fracking can be made safe, and prevent methane from contaminating groundwater reserves.

Earthquakes

Another environmental concern due to fracking is the occurrence of earthquakes near fracking sites. Although the direct link between earthquakes has not been definitively proven, there are viable theories for how fracking could directly cause earthquakes and the level of correlation between fracking and earthquakes makes a cause and effect relationship between the two undeniable. The earthquakes tend to occur mainly during two steps of the fracking: (1) during the injection of the fracking fluid into the well and (2) after the fracking is completed, when the fracking companies inject waste fluid into deep underground formations. The vast majority of the earthquakes attributable to fracking are not powerful enough to be detected by humans without the aid of a sensor; however, a larger earthquake could occur infrequently with the potential to cause damage.

Currently, there are only a few preventative measures employed by fracking companies to prevent earthquakes (partially due to the ambiguous cause and nature of the earthquakes). One such protective measure utilized by Cabot Oil and Gas Corporation (along with other fracking companies) is to perform a detailed sonar analysis of the ground before fracking (Fetzer 2012). Unfortunately, this technique has proven insufficient in preventing earthquakes.

The most likely cause of the earthquakes is either fracking fluid or waste fluid seeping into undetected faults deep underground when they the fluids are injected into their respective wells. The fluids are injected with high pressure underground and this great pressure may cause them to move through the fractures that are created during fracking, causing leakage from the fractures in the shale layer to fault lines. The fluid could then provide lubrication and cause the fault to slip, creating earthquakes around the area.

A precaution that should be taken (in addition to screening the ground before beginning to frack) is to ensure that disposal wells are not overloaded, because overloading a well could increase the pressure and make earthquakes more frequent. It would not be feasible to lessen the pressure exerted by the fracking fluid because high pressure is needed in order for the fluid to create the fractures, keep them open, and extract the shale gas. Another proposed solution is to not frack within a certain range of a population due to the perception that earthquakes only occur in areas close to the well. This, however, has recently been disproved. A Cornell University research team measured earthquakes that were most likely attributed to fracking approximately 50 km (31 mi) away from the fracking wells (Keranen et al. 2014). The cause of these earthquakes has not yet been conclusively determined but it is suspected to be due to fracking. Katie Keranen, professor of geophysics at Cornell University, stated, "Existing criteria for an induced earthquake do not allow earthquakes associated with the well activity to occur this far away from the wellbore," implying that the current explanation for earthquakes is not due to fracking, or a given explanation is incomplete.

In a study on the impact of fracking on earthquakes, an investigation of the Marcella formation in the state of Pennsylvania was conducted. There are 301 fracking wells in Pennsylvania (FracFocus 2015a, b, c). Based on U.S. Geological Survey (USGS 2015) data, there were only six earthquakes of magnitude 4 or higher that occurred within the last 30 years. Earthquakes of magnitude 4 or less are considered a minor earthquake of minimal disruption. Upon further analysis of those six earthquakes, it was found that all occurred prior to fracking starting in Pennsylvania. Furthermore, the epicenter of those earthquakes was much deeper than the Marcella formation, indicating minimal or no contribution due to fracking in Pennsylvania, one of the major shale gas producers.

Despite the research performed, earthquakes remain one of the most mysterious issues associated with fracking. However, it is important to note that the issue of earthquakes is not as pressing as other environmental concerns surrounding fracking due to the infrequent occurrence of earthquakes and the far less likely chance that an earthquake occurs that could cause any damage. With the current research, the best solution would be to prohibit underground injection of waste fluid or at least prevent overfilling of disposal wells. In addition, it is important to check as thoroughly as possible for any fault or abnormality in the ground before drilling begins. If these preventative measures are followed, the likelihood of earthquakes, especially severe ones, should decrease.

Fracking Fluid

Handling of flow back and produced waters is another issue that arises from fracking operations. Currently, this wastewater can be recycled for subsequent fracking, reinjected underground, or treated and released into rivers. Other environmental issues are the impacts on land use, noise, and air quality. The exploration process in general generates a lot of activities and associated traffic, noise, and air pollution (Davis 2012). Despite the fact that the industry is adapting where possible to more benign fracking chemicals, information on the exposure to natural and added chemicals and the fate and ecotoxicity of the generated wastewater is not available (Batley and Kookana 2012).

High concentrations of natural contaminants such as metals, radionuclides, total petroleum hydrocarbons (TPHs), and phenols have also been observed in return wastewaters and formation waters (Cheung et al. 2009; Wood and Patterson 2011). Even though these chemicals are naturally occurring, there are risks of possible modification and release processes associated with the introduction of oxygenated waters, as ythe oxidation of reduced iron may lead to iron oxyhydroxide precipitation and a lowering of water pH (Batley and Kookana 2012). Elevated iron and manganese concentrations have been observed in flow-back waters (Wood and Patterson 2011). Acids in the fracking fluids will cause metal dissolution, aided by chelating agents. Surfactants and solvents may assist in the dissolution of organic compounds (Batley and Kookana 2012).

Therefore, a third major environmental issue is the disposal of waste products (mostly fracking fluid) after a well is fully formed for gas production. Different chemicals perform different functions in a hydraulic fracturing. Although there are dozens to hundreds of chemicals that could be used as additives, there are a limited number that are routinely used in fracking. Table 2 shows a list of the most frequently used chemicals.

Fracking fluid is pumped down into the well at high pressure and used to create, expand, and keep open the fissures created in the shale layer in order to allow the shale gas to be withdrawn from the well. Once the factures are initiated, the fracking fluid is retrieved. The proper disposal of fracking fluid remains an important environmental issue.

There are three processes that fracking wastewater can undergo. The most environmentally friendly is the first option, reusing the

Table 2. Typical Composition of Fracking Fluid

Product function[a]	Chemical purpose[a]	Typical example[a]	Technology to remove
Acids	Helps dissolve minerals and initiate cracks in the rock	Hydrochloric Acid	pH control
Biocide	Eliminates bacteria in the water that produces corrosive by-products	Glutaraldehyde	Biodegradation
Breaker	Allows a delayed break down of the gel	Ammonium persulfate	Neutralization
Clay stabilizer	Prevents clays from swelling or shifting	Tetramethyl ammonium chloride	Oxidation
Corrosion inhibitor	Prevents the corrosion of the pipe	Acetaldehyde	Biodegradation
Cross-linker	Maintains fluid viscosity as temperature increases	Potassium metaborate	pH control
Friction reducer	Carrier fluid for polyacrylamide friction reducer	Petroleum distillate	Coagulation
Gelling agent	Product stabilizer and/or winterizing agent	Ethylene glycol	Biodegradation/Microfiltration
Iron control	Prevents precipitation of metal oxides	Thioglycolic acid	Biological activated carbon
Nonemulsifier	Prevent the formation of emulsions in the fracture fluid	Lauryl sulfate	Activated carbon
pH adjusting agent	Adjusts the pH of fluid to maintains the effectiveness of other components, such as cross-linkers	Sodium hydroxide	pH control
Scale inhibitor	Prevents scale deposits in the pipe	Copolymer of acrylamide and sodium acrylate	Microorganisms
Surfactant	Product stabilizer	2-Butoxyethanol	Activated carbon
Granular	Keep the factures open	Sand	Filtration

[a]Data from FracFocus.org (2015c).

fracking fluid and treating the waste in a private treatment plant. As seen in Table 2, there are existing technologies to effectively treat or neutralize each component of fracking fluid. Waste still needs to be properly disposed even with this option. "The process cleans most of the water, but at least some smaller amount of fluid, or solid 'cake,' still needs to be disposed" (NPR 2014). This injection back into the ground is simiar to the second option: putting wastewater into a disposal well. This option involves injecting waste into a Class II disposal well (the type of well for fracking waste) and leaving it thousands of meters underground, commonly surrounded by sandstone or limestone. This option can have detrimental effects on the environment, and fracking fluid must be disposed of properly.

The treatment and renewal of fracking liquid waste are more important because some of these compounds are hazardous substances and known carcinogens, which can enter and pollute drinking water supplies from the well, well pad, or in the wastewater disposal process. Some of the listed additives are listed in Table 2 (FracFocus 2015a, b, c). Their adverse effects and removal strategies are discussed in the following.

Acetaldehyde, which is use as corrosion inhibitor, is considered a probable human carcinogen (Group B2) and has been shown to cause nasal tumors in rats and laryngeal tumors in hamsters (U.S. EPA 1997). Additionally, acetaldehyde cannot be effectively treated by traditional water-treatment processes, but was reported to be effectively removed by microbial degradation using biological activated carbon (BAC) filters (Chun-Lei et al. 2013).

Ethylene glycol is an organic solvent, and is a major constituent of antifreeze and coolant. It functions as a product stabilizer and/or winterizing agent in a fracking fluid mixture. Chronic exposure effects include kidney toxicity and liver damage. Several oral or inhalation exposure studies on rodents also showed that ethylene glycol is toxic to fetuses (U.S. EPA 1999). The EPA has not listed ethylene glycol as a controlled or priority substance, however. Ethylene glycol is reported to undergo aerobic and anaerobic biodegradation in water (Dwyer and Tiedje 1983); thus, ethylene glycol can be removed from the waste fracking fluid by biodegradation.

Another compound of interest is 2-Butoxyethanol, which functions as a product stabilizer in fracking. The EPA currently does not classify 2-Butoxyethanol for human carcinogenicity, but rather cautions against effects of acute and chronic exposures such as severe liver and kidney damage, testicular damage, reduced fertility, maternal toxicity, early embryonic death, birth defects, delayed development, and hematological disorders from inhalation and oral exposure (U.S. EPA 1984). Removal of 2-Butoxyethanol can be achieved with techniques like activated carbon filtration and ozone reaction.

Glutaraldehyde is a biocide with wide industrial applications. In fracking operations, it is used to eliminate bacteria in the water that produce corrosive by-products. Glutaraldehyde is acutely toxic to both aquatic and terrestrial organisms. Results from environmental partitioning indicated that glutaraldehyde is hydrophilic and tends to remain in the aquatic partition and is nonbioaccumulative (IPCS INCHEM 2005). Aqueous solutions of glutaraldehyde are stable at room temperature under acidic to neutral conditions, and stable in sunlight, but unstable at elevated temperatures and under alkaline conditions. Glutaraldehyde is biodegradable under both aerobic and anaerobic conditions (Leung 2001).

Ammonium persulfate is an inorganic salt that is highly soluble in water. It is a strong oxidizing agent, which is used in fracking liquid as a polymerization inhibitor to aid delayed break down of the gel. Ammonium persulfate is harmful to aquatic organisms (ILO-ICSC 2001). In human beings, it is reported to cause asthmatic effects (De Vooght et al. 2010). The substance can be absorbed into the body by inhalation in its aerosol form and by ingestion (ILO-ICSC 2001). Ammonium persulfate can be removed by neutralizing it with a base.

Tetramethyl ammonium chloride is used in fracking fluid as a clay stabilizer to prevent clays from swelling or shifting. Tetramethyl ammonium chloride is a nonvolatile quaternary ammonium salt, which exists in the cation form in the environment and generally adsorbs strongly to soils containing organic carbon and clay. It is reported to be toxic to microorganisms an also has a low bioaccumulative potential (TOXNET-HSDB 2012). It can be absorbed into the body by inhalation and by ingestion (CDC 2003). Above 300°C, tetramethyl ammonium chloride decomposes to produces ammonia, carbon monoxide, hydrogen chloride, and nitrogen oxides. It can also react with oxidants (ILO-ICSC 2003) and thus can be treated by oxidation.

Regulations need to be implemented that require companies to extract as much fracking fluid from the well bore as they reasonably can and dispose of it in an environmentally acceptable manner. The ideal solution would be to treat as much of the fluid as possible, but this is more expensive. One final consideration to consider when disposing of fracking fluid is to create a regulation that prevents overloading of disposal wells as this can cause other problems, primarily earthquakes and leaks.

The proper disposal of fracking fluid could lead to both environmental and economic benefits. If a technique for cheaply treating the wastewater is created, then only a minimal amount of fracking fluid will need to be disposed of and the rest can be reused in other fracking wells, leaving a smaller environmental footprint and allowing fracking companies to not have to acquire new fracking fluid. Additionally, with proper regulation and enforcement, most of the issues associated with disposal wells should be mitigated.

To make fracking safe, both for the environment and any citizens in the area, the issue of proper disposal of waste products must be solved. All of the remaining fracking fluid should be treated or disposed of in a manner in accordance with regulations that should be put in place to prevent issues with disposal. This should diminish the issues related to the correct disposal of wastewater.

Several studies have revealed the use of toxic fracking fluids such as diesel and benzene (Davis 2012). In the Energy Policy Act of 2005 the Halliburton loophole was added to the EPA's Resource Conservation and Recovery Act (RCRA), which regulates hazardous and solid waste, exempting from oversight the waste from oil and gas exploration, development, and production.

Cost and Benefit Analysis

A cost and benefits analysis of hydraulic fracking and production of shale gas is required to complete the evaluation. This is essential as studies addressing total lifecycle costs are rare and previous reports have come to different conclusions on the cost and environmental benefits of shale gas compared to other alternatives. Stamford and Azapagic (2014) demonstrated that shale gas has a wide range of lifecycle environmental impacts (favorable and unfavorable) depending on the potential variation of different parameters. Laurenzi and Jersey (2013) reported that the carbon footprint of Marcellus gas 53% lower than coal, and the freshwater consumption is about 50% less than coal. Weber and Clavin (2012) also reported that the most likely upstream carbon footprints are largely similar for both shale and conventional gas production, with overlapping 95% uncertainty ranges of 11.0–21.0 g CO_2e/MJ_{LHV} and 12.4–19.5 g CO_2e/MJ_{LHV} for shale and conventional gas, respectively. However, a complete cost benefit analysis of fracking considering environmental costs and benefits of issues discussed in this manuscript requires an in-depth analysis and is thus beyond the scope of the present work. A detailed study of the topic has been initiated for a future manuscript.

Regulations

The biggest issue with fracking is the lack of or minimal regulation. The federal government is unable to regulate the industry because of the Halliburton loophole in the Energy Policy Act of 2005; this clause excludes "underground injections of fluids or propping agents, other than diesel fuels, in hydraulic fracturing activities." Hence, regulatory oversight falls to the state, but states have competing monetary interests. The result of these conflicts of interest is to reduce the motivation or incentive to regulate the industry. Regulatory bodies are urgently needed to control the fracking fluids used. Furthermore, regulatory procedures should be put in place to ensure safety, prevent contamination, and make the involved parties responsible for violations (Ince et al. 2013). In the Energy Policy Act of 2005, the "Halliburton loophole" exempts fracking from the Safe Drinking Water Act because it was believed that fracking posed no risk to drinking water (Manuel 2010). The Clean Water Act and Clean Air Act encounter similar difficulties in enforcement. Therefore, the EPA has little to no actual authority over this booming industry. Other regulatory agencies that have a role in the fracking include the Underground Injection Control Program (UICP), which regulates the pumping of fluids into wells, and the National Pollutant Discharge Elimination System (NPDES), which regulates runoff from waste pits and surface spills (EPA). Both of these groups set standards for acceptable practices regarding aspects of the fracking process. However, UICP has very little control over the well injections under the 2005 Energy Policy Act; hence, UIP can only regulate the disposal of the fracking fluids in underground waste wells (Ince et al. 2013).

The current lack of regulations and oversight for the chemicals and wastewater of fracking is the main source of controversy and leads to a lack of confidence on the part of some stakeholders, hindering the wider public acceptance of the process. Regulation reform and proper oversight is urgently needed that should prioritize abatement of potential risks and to boost public confidence in the fracking process. The reform regulation should endeavor to embrace the concerns of all the stakeholders in an effort to provide social and economic benefits for the society.

Summary and Conclusions

Fracking, the process of drilling deep down and injecting high-pressure water mixture to fracture rock to release trapped shale gas, promises the potential of energy independence for the United States. It has presented an opportunity to generate electricity at half the CO_2 emissions from coal. There are three major environmental issues identified with fracking, namely, leaking methane gas while fracking and during production, triggering of earthquakes due to fracking, and the disposal of the wastewater. A comprehensive literature search and a detailed analysis were performed to address the question of whether fracking be environmentally acceptable. It can be concluded that if the following actions were taken, then fracking could indeed be made environmentally acceptable.

Earthquakes remain one of the most mysterious issues that has been associated with fracking, but there is no definitively proven direct link between earthquakes and hydraulic fracking. However, for the Marcella shale formation, earthquakes are not as pressing as other environmental concerns surrounding fracking due to the infrequent occurrence of earthquakes and the far less probability that such an earthquake occurs that could cause any damage. The vast majority of the earthquakes attributable to fracking are not powerful enough to be detected by humans without the aid of a sensor; however, a larger earthquake can occur infrequently with the potential to cause damage. With the current level of knowledge, the best precaution would be to prohibit underground injection of waste fluid. In addition, a complete geological investigation should be performed to locate any active or dormant faults or abnormality in the ground before drilling. Once it is confirmed that no such geological formations are found, the vertical wells should be located at least a mile away from any residential or commercial activities.

Based on shale gas seepage and diffusion calculations herein, it is virtually impossible for methane to contaminate the groundwater due to horizontal drilling. However, there is a possibility of shale gas release from a vertical well and it is proposed that any residential or commercial activities should be at least 1 km away from the vertical well. In addition, the vertical wells should be constructed with precautions to prevent methane gas leaks and a proper quality assurance and quality control procedure should be established during construction. Furthermore, the workers should be trained and properly supervised during construction. Methane monitors that could trigger alarms and locate leaks can be used in order to prevent losses during the transport and distribution.

To make fracking safe, the issue of proper disposal of waste products must be solved. Most fracking fluid should be extracted from the well bore and treated for reuse. The waste fracking fluid should be treated or disposed of in a manner in accordance with regulations that should be put in place. The proper disposal of waste fracking fluid could lead to both environmental and economic benefits. This should diminish the issues surrounding correct disposal of wastewater. Finally, regulation and openness are major issues limiting stakeholder acceptance of the process. Therefore, regulation reformation is vital to ensure that all shareholder concerns are addressed in an effort to provide social and economic benefits for society as a whole.

An in-depth cost-benefit analysis of fracking, considering environmental costs and benefits of issues discussed in this manuscript, is required. Then, new regulations can be put in place for locating new wells, construction of new wells, and recovery and proper disposal of fracking fluids. If the aforementioned suggestions are implemented, fracking can be made environmentally safe.

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