THE OPPORTUNITIES AND CHALLENGES OF SUSTAINABLE SHALE GAS DEVELOPMENT[1]

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Horizontal drilling and multistage hydraulic fracturing technologies have enabled the rapid expansion of natural gas production from organic-rich shale formations around the world. Abundant new supplies of natural gas have made possible large-scale fuel switching—from coal to natural gas—in electrical power generation in the United States. This fuel substitution has had beneficial effects on air pollution and greenhouse gas emissions, along with significant economic impacts as a fuel for consumers and industry. But fuel switching to natural gas will not be sufficient by itself to combat long-term climate change; further decarbonization by eventually switching to noncarbon energy sources will also be required. In this context, global shale gas resources represent a critically important transition fuel on the path to a decarbonized energy future.

For the benefits of natural gas to be realized, however, it is imperative that the resources are developed with effective environmental safeguards to reduce the impacts of development on water resources, air quality, ecosystems, and nearby communities. It is equally important that countries around the world implement energy policies that encourage the environmentally responsible development of shale gas resources while continuing to develop and deploy renewable energy sources.

Geologists have long known that large amounts of organic matter and natural gas are trapped (usually by clay and other fine-grained minerals) in low-permeability, organic-rich shale formations. Because of the shale's extremely low permeability (on average about 6 orders of magnitude lower than in conventional gas reservoirs), it is only through the use of horizontal drilling and multistage hydraulic fracturing that commercial quantities of natural gas can be produced.

As reviewed by King (2012), typical shale gas development operations proceed as follows: First, the operator drills a vertical wellbore to near the depth of the shale (Fig. 1), typically about 2–3 km. After drilling, steel casing is cemented into the well to stabilize the rocks surrounding the wellbore and prevent well fluids from contaminating the geologic formations drilled through. It is particularly important to protect shallow aquifers from contamination. Then, when the vertical well almost reaches the depth of the shale, the well is progressively deviated until its trajectory is near horizontal and lies within the layer of shale that contains the natural gas. The length of this horizontal section averages about 1.5 km, although this varies by region. After drilling, the horizontal section of the well is usually fully cased and cemented. Small explosive devices are used to sequentially shoot holes through the casing and cement to enable the well to be hydraulically fractured in stages, starting at the toe of the well (the most distant part) and working back toward the heel (closest to the vertical section). A wellbore that extends 1.5 km laterally may be hydraulically fractured in 10 to 20 stages, spaced more-or-less evenly along its length. During hydraulic fracturing, the formation is pressurized to extend fractures through the shale. Fracturing fluids used for shale gas formations are commonly 99 percent water and sand (the latter is used as a proppant to hold open the hydraulic fractures after the well goes into production.) The website Frac Focus (www.fracfocus.org) lists many of the commonly used hydraulic fracturing fluids and chemical additives.

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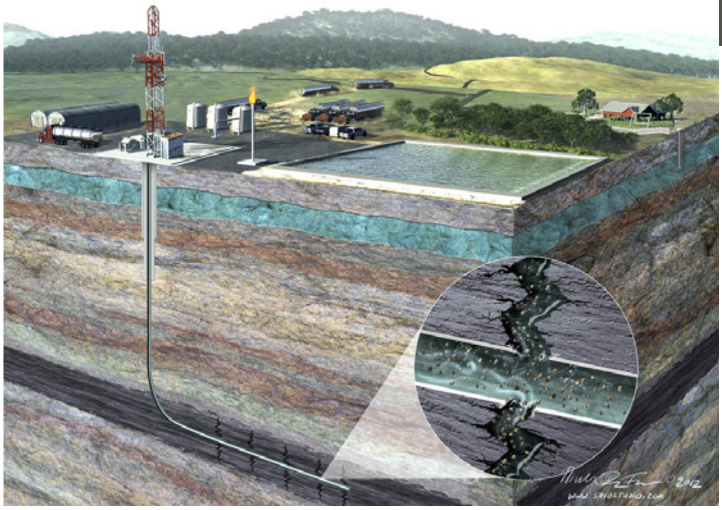

Figure 1 Artist's rendering of a horizontal well drilled for shale gas production (courtesy N. Fuller, SayoStudio.com). Typically, the vertical section of the well is drilled, cased, and cemented to a depth of 2–3 km and then the well is drilled horizontally through the shale for about 1.5 km.

Pad drilling is a common practice in which multiple wells (commonly 4 to 12, but as many as 75) are drilled at the same site to optimize the efficiency of drilling and hydraulic fracturing operations. At a given pad, the wells are drilled, cased, and cemented in sequence. After the drilling is completed and the drill rig and drilling equipment removed from the site, hydraulic fracturing equipment is brought to the site and operations commence. This type of operation, which is usually completed at a given site over a few months, dramatically reduces the amount of land needed for drilling, new road and pipeline construction, etc., and thus the overall impact of shale gas development on communities and ecosystems.

OPPORTUNITIES

A number of gains are already apparent from the widespread development of North American shale gas resources. These include the direct economic benefits of jobs created, taxes paid, the overall stimulus associated with development activities, and the royalty payments to the mineral interest owners. According to IHS (2014), unconventional gas development in the United States in 2015 is expected to be responsible for approximately 1.5 million jobs, $50 billion in federal, state, and local taxes, and an overall contribution to the US economy of $200 billion. Both the number of jobs and the economic benefits are expected to roughly double by 2020.

When natural gas is used for electrical power generation in place of coal, it has the potential to reduce postcombustion CO_2 emissions by about 50 percent. In the United States, the switch from coal to natural gas over the past six years, along with other factors such as the cumulative impacts of energy-efficiency measures and the increased use of renewable electricity, has resulted in a marked decrease in CO_2 emissions. A substantial shift from coal to natural gas, particularly given the enormous reserves in China, Australia, South Africa, Argentina, and countries in Europe, could result in a significant reduction in global CO_2 emissions. In China, coal-generated electricity currently produces about 7 billion tonnes of CO_2 each year (over 3 times the emissions in the United States). The anticipated growth in energy consumption in China over the next ~25 years could double these emissions without abatement action. Because using natural gas to generate electricity produces negligible NO_x, SO_x, Hg, and particulates, switching from

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coal to natural gas would lead to significant and immediate health and quality-of-life improvements, especially in large urban centers in countries like China and India.

LIMITING THE ENVIRONMENTAL IMPACTS OF SHALE GAS DEVELOPMENT

Production of large amounts of shale gas resources is a large-scale industrial process that, over time, will involve drilling tens of thousands of wells, carrying out hundreds of thousands of hydraulic fracturing operations, and building numerous roads and pipelines. Environmental issues generally fall into four main categories—air, land, water, and community (Fig. 2)—and shale gas development may affect them all. We briefly address three issues about which there has been widespread concern: potential contamination of groundwater by drilling and hydraulic fracturing operations, methane leakage, and earthquakes triggered by injection of wastewater following flowback of hydraulic fracturing fluids.

Numerous studies have addressed water issues surrounding shale gas development; these issues include the availability, quantity, transport, and treatment of produced water as well as the contamination of local aquifers via underground methane leakage (see recent review by Jackson et al. 2014). Detailed studies where groundwater contamination has occurred in areas of shale gas development have consistently shown that hydraulic fracturing itself is not the source of the contamination. Rather, the contamination appears to result from poor well construction or poor drilling practice. King (2012) and SEAB (2011) discuss the importance of preventing contamination of aquifers and/or methane leakage and identify many operational issues that require close attention to achieve proper construction. In a survey of experts from industry, academia, NGOs, and government regulators, Krupnick et al. (2013) also found well-construction issues to be of most importance.

Another water issue associated with shale gas development involves the disposal of wastewater flowing back from the shale formation after hydraulic fracturing. Flowback water typically contains large amounts of salt, various quantities of selenium, arsenic, and iron, and small amounts of naturally occurring radioactive materials, all of which come from the gas-producing shale formation. Practices related to water usage and treatment are rapidly evolving and improving. In Pennsylvania, for example, nearly all of the flowback water is reused for hydraulic fracturing in subsequent wells, thus returning the contaminants to the shale formations from which they originated. This reduces both the need for new sources of water and concerns associated with truck traffic and wastewater disposal. In other areas, brackish or saline water can be used for drilling and hydraulic fracturing, thus minimizing the use of freshwater.

Another environmental issue of appreciable concern (and debate) is the importance of methane emissions that occur during drilling, hydraulic fracturing, well production, and natural gas transmission and distribution (which, of course, are not unique to shale development). Because methane is a more potent greenhouse gas (GHG) than CO_2, if methane leakage, or so-called *fugitive* methane emissions, at well sites is appreciable, it could offset the inherent advantage of using natural gas over coal for producing electricity.

The scientific community must carry out comprehensive studies of the many issues surrounding methane leakage through detailed data collection and analysis. However, two recently published comprehensive studies indicate that methane leakage is not of sufficient magnitude to offset the appreciable advantages of switching from coal to natural gas for electrical power generation. First, a standardized comparison by Heath et al. (2014) shows through a life cycle assessment that the GHG intensity of natural gas–derived power is on average about 50 percent of that of coal-derived power, for natural gas produced from both conventional reservoirs and shale gas formations, but the authors caution that

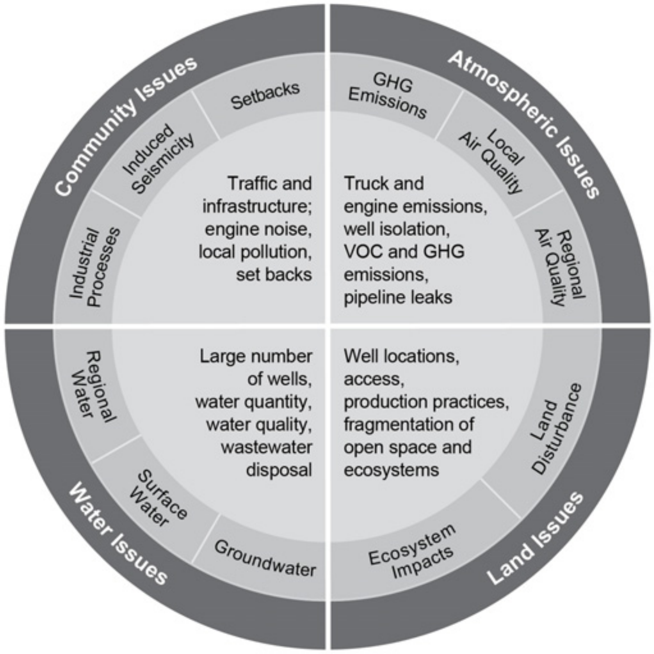

Figure 2 Risk factors associated with large-scale shale gas development. GHG = greenhouse gas; VOC = volatile organic compound.

much fundamental data are still needed to reduce uncertainties. In the second study, Brandt et al. (2014) point out that while the current level of atmospheric methane is generally higher than previously estimated, it is impossible to attribute this difference to shale gas development, and regardless of the sources of this additional methane, it does not offset the intrinsic advantage of fuel switching from coal to natural gas for electrical power generation. Another important finding of this study is that the majority of methane leakage results from relatively few, but large, leaks in the pipeline and distribution system—not from poorly constructed wells or the drilling and hydraulic fracturing process.

Finally, there is an apparent association between shale gas development and the marked increase in seismicity observed in recent years in the central and eastern United States. It has been known since the 1960s that the increase in pore pressure that results from fluid injection may cause seismicity by decreasing the normal stress on potentially active, preexisting faults. As the pore pressure changes at depth are usually quite small compared to the ambient stress, the pore pressure can be thought of as triggering the release of stored elastic strain energy resulting from natural geologic processes over time. In effect, the pore pressure increase from fluid injection advances the timing of an earthquake that would someday have occurred as a natural geologic process.

Hydraulic fracturing operations very rarely trigger earthquakes large enough to be felt by humans, principally because pressurization affects a relatively small volume of rock for a short period of time (a few hours) (NRC 2012). However, wastewater injection wells operate for years, sometimes injecting large volumes of wastewater that could affect large volumes of rock over large areas. Some straightforward steps can reduce the probability of triggering seismicity associated with wastewater disposal (Zoback 2012). Flowback water can be recycled by injecting it back into the shale during subsequent hydraulic fracturing operations. In addition, it is important to establish adequate seismic networks to detect and locate triggered seismicity, to improve the frequency and thoroughness of injection rates and pressures, and to establish protocols that define how operations might be modified in the event of triggered seismicity. Most important is to avoid injection near potentially active

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faults or into formations immediately above crystalline basement, in which case pressure changes in the injection zone might affect potentially active faults in basement.

Fundamentally, whether one is addressing the potential risks associated with earthquake triggering, contamination due to poor well construction, or methane leakage, the solutions come down to all of the stakeholders—oil and gas operators, regulatory authorities, utilities, and the public—being proactive about dealing with the associated environmental impacts. As we noted at the outset, switching from coal to natural gas for electrical power generation could have profound and far-reaching benefits; however, to realize these benefits, shale gas resources must be developed in an environmentally responsible manner.

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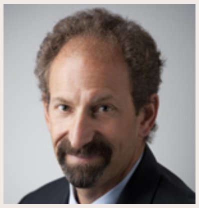

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process needs to be communicated. In these discussions, it is critical that stakeholders learn how they can obtain credible information.

What will the future of energy look like? This is a difficult question to answer. The growth in consumption is projected to be primarily in developing countries / emerging economies such as China and India. This is a critical point because significant steps toward reducing CO_2 emissions in the short term will require more conservation and increased efficiency as well as a faster transition from coal to natural gas in China and India. Ultimately, the high-growth energy consumers will have to transition rapidly to renewables for the largest potential reductions in greenhouse gas emissions and for a sustainable energy future. But it is difficult to say if this is a realistic expectation. As one looks to other energy opportunities, the role the nuclear option will have in supplying global energy is debatable.

From a global energy perspective, scientists and engineers generally agree that a technological breakthrough in renewable energy is necessary. The long-term goal is to reduce cost and increase efficiency such that a global-scale transformation from nonrenewable to renewable energy could occur. Such a breakthrough would give a truly sustainable energy future to us all. Still, impacts from renewable energy sources must be understood and managed.

It is poignant to consider a visionary statement by Thomas Edison that refers to nonrenewable versus renewable energy. During a discussion with Henry Ford and Harvey Firestone in 1931, Mr. Edison said, *"We are like tenant farmers chopping down the fence around our house for fuel when we should be using Nature's inexhaustible sources of energy—sun, wind and tide. I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that."* At the present time, we are unfortunately nowhere close to attaining this vision. In 2013, the United States used approximately 91% nonrenewable energy and 9% renewable energy, while world use was estimated at 89% nonrenewable and 11% renewable energy (EIA 2014).

The expansion of natural gas production is upon us. Geoscientists are uniquely positioned to lead the effort to create a balance between extracting this resource and managing impacts. As a college professor to hundreds of undergraduates each year and as a parent, I cannot overemphasize how important it is for the geoscience community to engage in the discussion about how to balance global energy needs with environmental and societal needs. To transform the black box of energy extraction into an informed process, stakeholders, politicians, and the public need geoscientists to communicate their interdisciplinary insights. If we don't initiate these discussions, who will?

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