The Technology and Policy of Hydraulic Fracturing and Potential Environmental Impacts of Shale Gas Development

Corrie E. Clark, Andrew J. Burnham, Christopher B. Harto, Robert M. Horner

The development of large-scale shale gas production has been described as a game-changer for the US energy market and has generated interest in expanding the use of natural gas in sectors such as electricity generation and transportation. This development has been made possible by improvements in drilling technologies—specifically utilizing hydraulic fracturing in conjunction with horizontal drilling—that have enabled the production of natural gas from unconventional formations. However, the environmental implications of natural gas production and its use have been called into question. Environmental impacts associated with shale gas development can occur at the global and local levels and include impacts to climate, local air quality, water availability, water quality, seismic events, and the local community. A variety of technologies and practices are available to operators to reduce these impacts. Policies are currently under development at the federal, state, and local level to mitigate environmental impacts. In this document, we discuss the technologies involved in shale gas production, the potential abiotic impacts of shale gas production with an emphasis on air and water issues, and the practices and policies currently being developed and implemented to mitigate these impacts.

Environmental Practice 14:249–261 (2012)

Introduction to Shale Gas Resource and Opportunity

The United States Energy Information Administration (US EIA, 2012) projects that natural gas from shale formations will be the primary driver of growth in domestic natural gas production through 2035, growing from 16% of supply in 2009 to 49% in 2035. While the US has significant shale resources, forecasts have a high degree of uncertainty. In 2011, the EIA estimated 23.4 trillion cubic meters (tcm) [827 trillion cubic feet (tcf)] of unproved technically recoverable resource but reduced the estimate in 2012 by approximately 40%, to 13.6 tcm (482 tcf) (US EIA, 2012). Important shale plays are shown in Figure 1 and include the Marcellus, Haynesville, Fayetteville, Barnett, Eagle Ford, and Bakken, among others.

Growth in shale gas production has led to rapid growth in domestic natural gas supplies and significant decreases in prices, creating an interest in expanding the use of natural gas for both electricity production and transportation. As natural gas power plants burn more cleanly than coal plants, it may assist utilities in meeting Clean Air Act National Ambient Air Quality Standards for ozone (proposed) [US Environmental Protection Agency (US EPA), 2012d] and for nitrogen and sulfur oxides (final) (US EPA, 2012e), as well as the EPA's Carbon Pollution Standard for New Power Plants (proposed) (US EPA, 2012c). Between 2004 and 2010, natural gas vehicles have accounted for nearly 50% of the petroleum savings from alternative fuel vehicles deployed by the US Department of Energy Clean Cities program, saving approximately 2.8 billion gasoline liter equivalents (GLEs) (Office of Energy Efficiency and Renewable Energy, 2012). With the increased supply, significant interest has developed in expanding natural gas use in many heavy-duty vehicles, especially in the regional-haul and vocational markets. In addition to natural gas, shale gas development has expanded the supply of propane and other natural gas liquids (NGLs). Over the next five years, US NGL production is expected to increase by more than 40%, which could lead fuel distributors to promote pro-

Affiliation of authors: Corrie E. Clark, Environmental Systems Engineer and Team Lead, Environmental Science Division, Argonne National Laboratory, Washington, DC. Andrew J. Burnham, Fuel and Vehicle Systems Analyst, Energy Systems Division, Argonne National Laboratory, Argonne, Illinois. Christopher B. Harto, Energy Systems Analyst, Environmental Science Division, Argonne National Laboratory, Washington, DC. Robert M. Horner, Energy Systems Analyst, Environmental Science Division, Argonne National Laboratory, Washington, DC.

Address correspondence to: Corrie E. Clark, 955 L'Enfant Plaza SW, Suite 6000, Washington, DC 20024; (phone) 202-488-2419; (fax) 202-488-2413; (e-mail) ceclark@anl.gov.

doi:10.1017/S1466046612000415

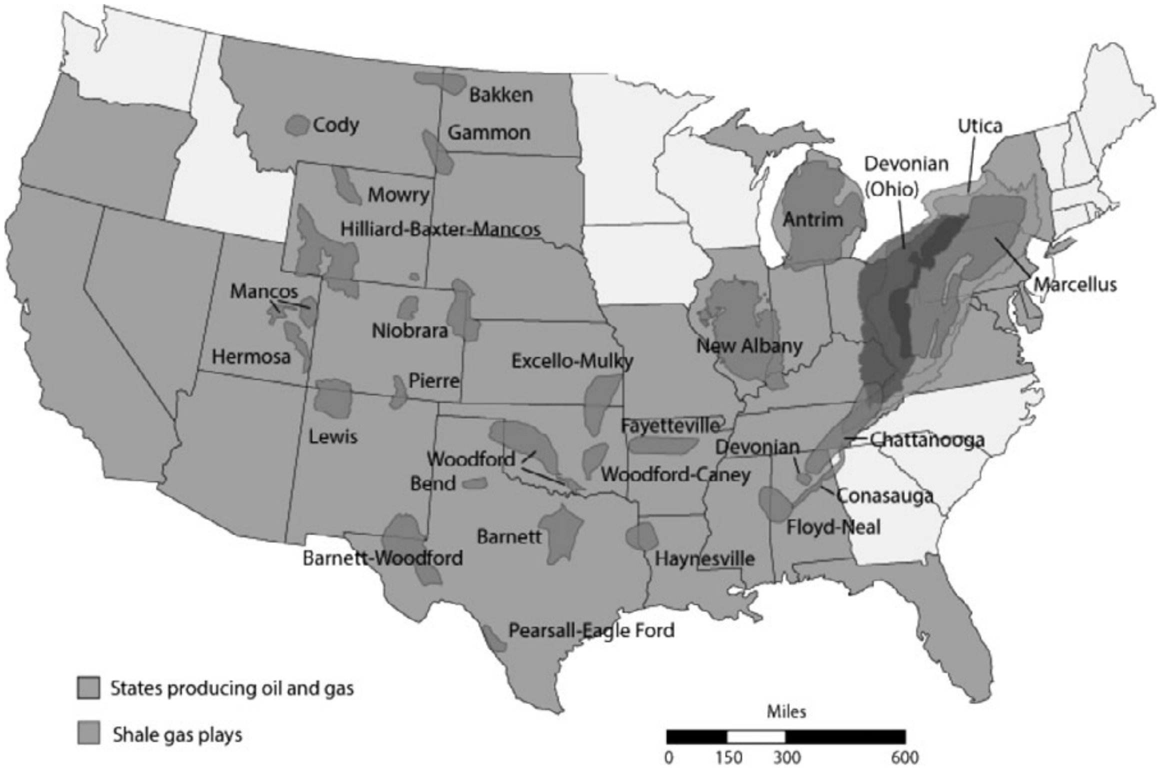

Figure 1. US shale gas plays (Veil, 2010).

pane more aggressively for vehicles and allow fleets to negotiate favorable long-term fuel prices (BENTEK Energy and Turner, Mason & Co., 2011; Rood Werpy, Burnham, and Bertram, 2010).

Hydraulic fracturing is a key technique that has enabled the economic production of natural gas from shale deposits, or plays. However, the environmental implications of rapid expansion of natural gas production from shale plays are uncertain. This article explains the technologies involved in shale gas production, the potential impacts of shale gas production, and the practices and policies currently being developed and implemented to mitigate these impacts. Although there are potential ecological impacts from the development of shale resources, such as terrestrial and aquatic habitat loss and fragmentation, this article focuses on the potential abiotic impacts to air and water from shale gas development and production.

Hydraulic Fracturing and Shale Gas Production

Unlike conventional mineral formations containing natural gas deposits, shale has low permeability. *Hydraulic fracturing* is a treatment performed on low-permeability reservoirs to increase communication with the formation and improve productivity. The process of producing natural gas from shale deposits involves many steps in addition to hydraulic fracturing, all of which involve potential environmental impacts. Hydraulic fracturing (commonly referred to as *fracking* or *fracing*) is often misused as an umbrella term to include all of the steps involved in shale gas production. These steps include road and well pad construction; drilling; well completion, which often includes hydraulic fracturing; production; abandonment; and reclamation.

Road and Well Pad Construction

Horizontal wells used to exploit gas and oil production from shale formations require a prepared area on the surface, called a *well pad*, that provides a stable base for a drilling rig, retention ponds, water-storage tanks, loading areas for water trucks, associated piping, and pumping and control trucks. After well completion, the pad serves as the location of the wellhead and other production equipment. Its size depends on the depth of the well and the number of wells to be drilled on the site. Typically, 4–6 wells (or more) may be drilled on a single pad to develop a 260-ha unit [Ground Water Protection Council and ALL Consulting (GWPC and ALL), 2009]. In addition to 1.5 to 3 ha of land disturbed for building the well pad (Entrekin et al., 2011), 1–2 ha are disturbed per pad for roads and utilities to service the pad. For comparison, developing a 260-ha unit by using vertical wells would require the use of 16 individual wells, each using up to 2 ha of land for pads and production facilities (GWPC and ALL, 2009).

Well Completion

Completion includes the steps to assemble the downhole casing, tubulars, and equipment to produce oil or gas efficiently from a well once it is drilled. This also includes the processes of perforating the production casing and hydraulic fracturing. The following sections describe the different stages of drilling a well and its completion.

Drilling

Most shale gas resources are located at depths of 1,800 meters (m) or more below ground level and can be relatively thin (for example, the Marcellus Shale formation is between 15 and 60 m thick, depending on the location) (GWPC and ALL, 2009). The efficient extraction of gas from such a thin layer of rock requires drilling horizontally through the shale as shown in Figure 2. This is accomplished by drilling vertically downward until the drill bit reaches a distance of around 275 m from the shale formation. At this point, a directional drill is used to create a gradual 90° curve, so that the *wellbore*, the drilled hole bounded by the rock face, becomes horizontal as it reaches optimal depth within the shale. The wellbore then follows the shale formation horizontally for 1,524 m or more (Rotman, 2009). Multiple horizontal wells accessing different parts of the shale formation can be drilled from a single pad, reducing the footprint of operations and enabling a large area of shale to be accessed from a single pad.

Casing and Perforating

At various stages in the drilling process, drilling is stopped and steel casing, pipe, is installed in the wellbore. After the wellbore reaches a depth below the deepest freshwater aquifer, casing and cement are installed to protect the water from contamination from the drilling process. Cement is pumped down the center of the casing and forced up the annulus between the casing and the borehole. One or more intermediate strings of casing may be needed in these deep wells, thus providing several layers of protection through the freshwater zones. After the well has reached its full horizontal length, production casing is run the entire length of the borehole and is cemented in place from the end of the horizontal borehole to at least a point beyond the curve where the well is vertical. This process is intended to prevent leakage of natural gas from the well to the rock separating the shale formation from the surface and to prevent the escape of natural gas to the surface through the annulus. The section of the well through the shale formation is then perforated by using a device called a perforating gun that selectively detonates small explosive charges, creating small holes in the well casing, which extend a short distance into the surround shale formation, to ultimately enable the pumping of hydraulic fracturing fluids into the shale and the eventual flow of natural gas, oil, and salt water out of the shale into the well.

Hydraulic Fracturing

After perforation, little gas will flow freely into the well. Fracture networks must be created in the shale to allow natural gas to flow. This is accomplished through hydraulic fracturing. In this process, typically 8,700–20,820 m^3 (2.3–5.5 million gal) of a fluid composed of 98%–99.5% water and proppant (usually sand) are pumped at high pressure into the well through the perforations (GWPC and ALL, 2009). The frac fluid itself (0.5%–2.0% by volume) is composed of a blend of chemicals that enhance the fluid's properties. These chemicals typically include acids to "clean" the perforations to improve gas flow, biocides to prevent organisms from growing and clogging the shale fractures, corrosion and scale inhibitors to protect the integrity of the well, gels, or gums that add viscosity to the fluid and suspend the proppant, and friction reducers that enhance fluid flow and, thus, the transmission of pressure from the pumps at the surface to the bottom of the wellbore and on to the deepest parts of the induced fractures (GWPC and ALL, 2009).

The hydraulic fracturing process in the shale usually creates a vertical fracture extending away from the perforated horizontal wellbore connecting pores and existing fractures that exist in the shale and creating a pathway for fluids to flow. The proppant lodges in the fracture to keep it open once the pressure is reduced and the fluid flows back out of the well. Approximately 300 m (1,000 ft) of wellbore is hydraulically fractured at a time, so each well must be hydraulically fractured in multiple stages, beginning at the furthest end of the wellbore. Plugs are used to isolate each hydraulic fracture stage and must be removed to enable the flow after all hydraulic fracturing is complete.

After the postfracture shut-in, the surface valves of the wellbore are opened to allow fluid (commonly referred to

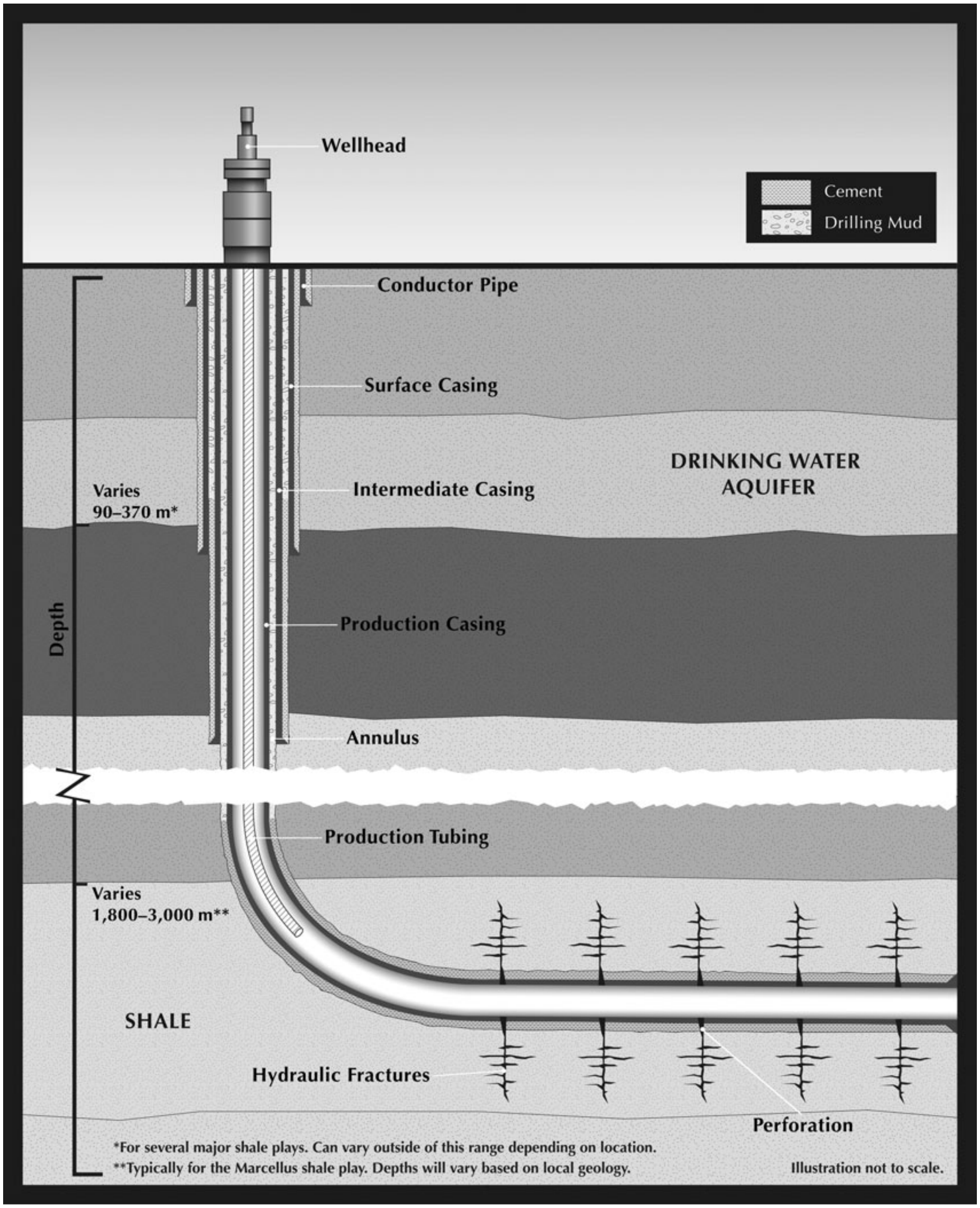

Figure 2. Typical configuration for a horizontally drilled, hydraulically fractured shale gas well.

as *flowback water*) to flow back out the top of the well. The fluid not only contains the proprietary blend of chemicals present in the hydraulic fracturing fluid but may also contain fluids and other components naturally present in the reservoir, including hydrocarbons, salts, minerals, and naturally occurring radioactive materials (NORMs). The chemical composition of the flowback water varies significantly according to the formation and the time after well completion, with early flowback water resembling the fracturing fluid but later converging on properties more closely resembling the fluids existing naturally in the formation.

In many cases, flowback water can be reused in subsequent operations, depending upon the quality of the flowback water and the economics of other management alternatives. Flowback water that is not reused is managed through disposal. While past disposal options sometimes involved dumping into surface waters or depositing at wastewater treatment plants, most disposal now occur at Class II injection wells as regulated by the US EPA's Underground Injection Control Program (Veil and Clark, 2011). These injection wells place the flowback water in deep, underground formations isolated from drinking-water sources.

Production

During production, gas that is recovered from the well is sent to small-diameter gathering pipelines that connect to larger pipelines that collect gas from a network of production wells; oil and brine are generally collected in large tanks on location and trucked off site. Because large-scale shale gas and oil production began relatively recently, the production lifetime of shale wells is not fully established. Although there is substantial debate on the issue, it is generally observed that shale gas wells experience more rapid production declines than do wells completed in conventional reservoir rock formations. In the Fayetteville play in north-central Arkansas, it is estimated that half of a well's lifetime production, or estimated ultimate recovery, occurs within its first five years (Mason, 2011). After the initial production period, the well may be *recompleted* (cleaned and hydraulically fractured) multiple times or shut in. Once a well no longer produces at an economic rate, the wellhead is eventually removed and the wellbore is filled with cement to prevent leakage of reservoir fluids into shallower formations or to the surface. The surface is then reclaimed, and the site is abandoned to the holder of the land's surface rights.

Potential Environmental Impacts Associated with Shale Gas Development

Environmental impacts associated with shale gas and oil development occur at the global and local levels. These may include impacts to climate change, local air quality, water availability, water quality, seismic events, and the local community.

Life-Cycle Greenhouse Gas Emissions

Natural gas has been referred to as a low-carbon fuel because its combustion produces significantly less carbon dioxide emissions than do coal and petroleum-based fuels. However, one must look at both the greenhouse gas (GHG) emissions from combustion and those from production activities. For natural gas, the primary concern is leakage and venting throughout the supply chain, as methane (CH_4), a potent GHG, is its primary constituent.

In 2011, the EPA doubled its estimates of CH_4 leakage for the US natural gas industry, in part to include emissions from shale gas production (US EPA, 2011a). Significant CH_4 emissions can be produced from shale gas well completions due to venting prior to the beginning of gas production. In practice, natural gas operators capture a portion of the gas that otherwise would be vented. The EPA's Natural Gas STAR Program, an industry and government partnership to reduce CH_4 emissions, has reported significant (approximately 50%) emission reduction through the use of flaring and reduced emissions completions (RECs), which capture gas that otherwise would have been vented to the atmosphere (Clark et al., 2011). An area of uncertainty is projecting future well productivity, which is an important factor in life-cycle calculations. Because shale gas production is relatively new, these projections range widely. If wells are less productive than the industry projects, then the emissions impacts of well completions will be of greater importance when evaluated per unit of energy (Burnham et al., 2012).

Taking this uncertainty into account, Burnham et al. (2012) estimated a base-case leakage rate for shale gas of 2.0% over the entire life cycle and 1.2% for drilling, completion, and production activities. The US EPA (2011a) does not explicitly examine shale gas leakage but rather examines the entire natural gas industry. Previous EPA estimates for natural gas leakage in 1992, which is prior to large-scale hydraulic fracturing and shale gas production, were 1.4% for the life cycle and 0.4% for drilling, completion, and production (Kirchgessner et al., 1997). While the estimated leakage rate has increased significantly from previous estimates for various activities associated with production, those for other stages such as transmission and distribution have declined due to replacement of older lines, thereby reducing the overall impact.

Using current leakage estimates from Burnham et al. (2012), it was found that natural gas CH_4 emissions account for approximately 15% by mass of the total life-cycle GHG emissions on a 100-year timescale and that the relative benefits of natural gas depend on how it is ultimately used. For example, natural gas power plants can provide approximately 30%–50% reduction in GHG emissions, depending on the plant's efficiency, as compared to a typical coal plant. For light-duty vehicles, compressed natural gas may provide nearly a 10% reduction in GHG emissions as compared to gasoline. However, for heavy-duty natural gas vehicles using spark-ignited engines, such as a transit bus, there may be no GHG benefit as compared to diesel vehicles, owing to the efficiency advantage of compression-ignition engines (Burnham et al., 2012).

Local Air Pollution

Production activities can produce significant amounts of air pollution that could impact local air quality in areas of concentrated development. In addition to GHGs, fugitive emissions of natural gas can release volatile organic compounds (VOCs) and hazardous air pollutants (HAPs), such as benzene. Nitrogen oxides (NOx) are another pollutant of concern, as drilling, hydraulic fracturing, and compression equipment—typically powered by large internal combustion engines—produce significant emissions.

Several state emission inventories have shown that oil and natural gas operations are significant sources of local air pollution and that shale gas operations may lead to increased levels of ozone and HAPs near these areas. For example, the 2008 Colorado emission inventory showed that they accounted for 48% of VOCs, 18% of NOx, and 15% of benzene emitted from anthropogenic sources (Colorado Department of Public Health and Environment, 2012). However, the impact of these emissions is uncertain, as air quality depends on local conditions; therefore, detailed modeling is required to examine these issues. For example, while elevated levels of benzene emissions have been found near production sites, concentrations have been below health-based screening levels (Alvarez, 2012).

Water Consumption over the Life Cycle

Although water is used in multiple stages of the shale gas life cycle, the majority of water is typically consumed during the drilling and completion stages. This is primarily due to the large volumes of water, 8,700–20,820 m^3 (2.3–5.5 million gal) required to fracture a well hydraulically (Clark et al., 2011). Water in amounts of 720–1,174 m^3 (190,000–310,000 gal) are also used to drill and cement a shale gas well during construction (Clark et al., 2011). After fracturing a well, anywhere from 5% to 20% of the original volume of the fluid will return to the surface within the first 10 days as flowback water; an additional volume of water, equivalent to anywhere from 10% to almost 300% of the injected volume, will return to the surface as produced water over the life of the well (Mantell, 2010). In the Marcellus play, operators reuse 95% of the flowback, whereas in the Barnett and Fayetteville plays, operators typically recycle 20% (Mantell, 2010). Water reuse often depends upon the quality and quantity of water and the availability and affordability of management options. When flowback water is not reused in hydraulic fracturing activities, it is most often disposed of in Class II injection wells, although other management options such as use as a roadway dust suppressant may be employed (Veil and Clark, 2011). Over a 30-year life cycle, assuming a well is hydraulically fractured three times during that period (US EPA, 2010), construction and production of shale gas would consume 27,000–64,000 m^3 (7,100,000–17,000,000 gal) of water per well. It should be noted that while refracturing is frequently discussed as a potential way to extend the economic life of shale wells that exhibit a steep decline curve, the exact number of times a well would be refractured, if at all, is highly uncertain because of the limited production history of most shale plays.

Once the gas is produced, it is processed, transported and distributed, and ultimately used. Water is consumed in each of these stages, with the most significant nonproduction consumption potentially occurring during end use. Although natural gas can be combusted directly with no additional water consumption, if the end use of the gas is a vehicle tank, it might be compressed via an electric compressor. The electricity for compression is associated with water consumption of 0.6–0.8 liter per GLE (King and Webber, 2008), making the total consumption for the vehicle life cycle 1.0–2.3 liters per GLE. For comparison, vehicle life-cycle water consumption associated with the use of conventional natural gas is between 0.9 and 1.1, conventional crude oil is between 2.8 and 6.6, and corn ethanol is between 26 and 359 liters per GLE (Wu et al., 2011). Although water vapor is created during the end-use combustion process, it does not become a useful resource again until it works its way back through the hydrological cycle.

Water Quality

Concerns over water quality focus on potential drinking-water contamination by methane or fluids from hydraulic fracturing activities. The possible pathways for this contamination include underground leakage from the wellbore to drinking-water aquifers and improper disposal or accidental leakage of hydraulic fracturing fluids to surface-water bodies. Owing to the depth of most shale plays, it is unlikely that a credible pathway (independent of the wellbore) exists for fluids to flow from the fractures within the shale through thousands of feet of overlaying rock into a drinking-water aquifer. However, shallower shale deposits may be vulnerable to this direct connection, as is suggested by the EPA's ongoing groundwater investigation in Pavillion, Wyoming, where as little as 128 m separated gas deposits from drinking-water resources (US EPA, 2011b).

For deep formations, contamination may occur due to defects in the wellbore. When the annulus is not adequately sealed with cement during well installation, methane can migrate from the shale resource up the outside of the wellbore to shallow aquifers where it could dissolve in the drinking water. Another possible pathway for contamination is a defect in the casing at a shallow depth, allowing gas to flow from inside the wellbore to the aquifer. Faulty well construction appears to have caused one of the largest documented instances of water contamination, which occurred in Bradford County, Pennsylvania, after wells had been drilled but before any hydraulic fracturing [Pennsylvania Department of Environmental Protection (PA DEP), 2011]. Having multiple strings of casing cemented through the freshwater zones should prevent this problem. In addition to faulty well construction, Osborn et al. (2011) suggest that uncased, abandoned wells may provide pathways for methane migration. Perhaps the most easily prevented pathway for contamination is intentional dumping or accidental spilling of flowback water on the surface. A common cause of accidental spillage is overflows from retention ponds during major rain events.

Contaminants in flowback water include those from the mineral formation, such as NORMs, and additives to the hydraulic fracturing fluid. These can be a health concern when present in significant concentrations. The EPA's investigation into possible groundwater contamination at Dimock, Pennsylvania, was launched out of concern over such toxic substances. While there are no federal drinking-water standard limits for methane, it is nevertheless a hazard in water because at sufficient concentrations it can volatilize and collect in houses, which can lead to suffocation or serve as a fuel for fire and explosions. It should be noted that methane may occur naturally in shallow formations including freshwater aquifers and may not be indicative of defective wells or connectivity to shale reservoirs through hydraulic fracturing.

Induced Seismicity

Disposal of flowback water from hydraulic fracturing depends upon the availability of suitable injection wells. For example, the limited availability of suitable geology in Pennsylvania has led to hauling flowback water to Ohio for disposal in Class II injection wells. The increased injection activity has been linked to seismic events or earthquakes, according to the Ohio Department of Natural Resources (ODNR, 2012). Additional studies have indicated that injection activities in Arkansas have been linked to nearby earthquakes (Horton, 2012). Injection activities have been halted in associated wells in Arkansas and Ohio.

According to the ODNR, a properly located injection well will not cause earthquakes. A number of factors must be present to induce seismic events at a disposal site. For earthquakes to occur, a fault must exist nearby and be in a near-failure state of stress. The injection well must have a path of communication to the fault, and the fluid flow rate in the well must be at a sufficient quantity and pressure for long enough to cause failure along the fault or system of faults.

Human Community Impacts

Shale development is an industrial process and, as such, is not immune to the types of local impacts that most industrial activities tend to share. The process requires heavy equipment, including hundreds to thousands of truck trips to deliver water and chemicals to perform hydraulic fracturing, and many more to remove the flowback water generated. This traffic places enormous stress on local roads, causing significant road degradation, and can lead to congestion, which can become a source of frustration for local citizens. The large equipment used to drill and hydraulically fracture a well can also be noisy and visually unattractive, potentially negatively impacting property values in close proximity to wells, owing to a combination of real and perceived risks and impacts (Ecology and Environment, Inc., 2011). However, some aspects of shale gas and oil development differ from those of other industrial processes. Intense trucking near well pads often occurs over a brief period on rural roads. This traffic is heavy enough to cause significant road degradation, but unlike a road to a stationary industrial facility that will support traffic over a long period, these roads are subject to heavy traffic for only a brief period, making road upgrades a difficult decision for local or state governments.

Addressing Impacts: Strategies and Practices

Some of the largest shale gas and oil deposits are located in states that do not have a recent history of oil and gas production. This leads to two potential challenges: regulatory and public acceptance. State agencies may not be well positioned to deal with rapid growth in oil and gas development from either a staffing and permitting perspective or a regulatory perspective. The experience of Pennsylvania from 2008 to 2012 can be a lesson to other states. State officials were caught somewhat off-guard by the rapid development of the Marcellus Shale. In the process, they identified outdated laws regulating the disposal of produced water and well construction standards, including laws that did not prevent surface disposal of untreated produced water (Warren, 2010) and regulations that allowed operators to drill all the way to gas sources prior to isolating fresh groundwater in certain circumstances (Pennsylvania Environmental Quality Board, 2011). Improved regulations were developed, which are expected to significantly reduce risks to drinking water. Other states with shale resources have learned from Pennsylvania's experience and are beginning to review and modernize their regulations to ensure that they properly consider and minimize the risks associated with unconventional gas development.

In areas without a recent history of oil and gas development, the public may be more skeptical of new development and the risks involved. This skepticism can manifest itself in public opposition that can be costly for operators to overcome. Others may be supportive of shale gas development for the economic growth opportunities it can bring to a region. To improve public trust, additional, credible scientific research is needed to improve quantification of the actual vs. perceived risks. Adequate communication, coordination, and planning involving operators, regulators, and stakeholders prior to development may also help address public concerns and ensure that best practices are being used to mitigate impacts and risks. Best practices that address air emissions and freshwater use are discussed below.

Greenhouse Gas Emissions and Local Air Pollution

Historically, methane emissions (typically for safety reasons) were reduced through *flaring*, which involves sending the flowback water to an open pit or tank where the gas is combusted. This practice achieves about a 90% reduction in GHG emissions as compared to venting, as carbon dioxide is produced from the flare (Mintz et al., 2010). With regard to air quality, VOCs and HAPs are significantly reduced through flaring; however NOx, carbon monoxide, and other combustion emissions are produced. While flaring does provide benefits, they are somewhat mitigated by these combustion emissions and the loss of valuable natural gas.

More recently, RECs, or *green completions*, have become a key technology to limit the amounts of methane, VOCs, and HAPs that can be vented during the flowback period. RECs use portable equipment that enables operators to capture natural gas from the flowback water. A sand trap is used because the water and sand return to the surface at a high pressure and can erode the equipment. After the mixture passes though the trap, a three-phase separator removes natural gas liquids and water from the gas, which is then sent to sales pipelines. Fortunately, REC operations have been found to be very cost-effective even with low natural gas prices (US EPA, 2011c).

Other cost-effective technologies have been developed to reduce natural gas leakage, such as plunger lift systems, dry-seal systems, and no-bleed pneumatic controllers. Through the use of these technologies and practices, with RECs having the highest priority, the Natural Resources Defense Council estimates that nearly 90% of the natural gas leakage could be addressed (Harvey, Gowrishankar, and Singer, 2012). In addition, to reduce the local air emissions further at well sites in densely populated areas, electric motors could be used instead of internal combustion engines.

Water Quantity and Quality

Increasingly, flowback water is being recycled by operators. This practice has two positive effects: the first is reducing the amount of freshwater demand, and the second is reducing the amount of wastewater that must be disposed of. In practice, the amount of recycling varies by play and depends on the availability of freshwater, the cost of disposing of wastewater, and the quality and quantity of wastewater. The amount of treatment required for reuse of wastewater varies from simple settling or filtration to the use of expensive reverse osmosis or thermal treatment processes that remove dissolved salts and minerals (Veil, 2010).

Industry is also exploring the possibility of creating fractures without using water. Fractures can be created by pumping a mixture of propane gel and sand into the shale formations (Goodman, 2012). The propane gel may originate from natural gas as NGL or from petroleum as liquefied petroleum gas (LPG). After fracturing, the gel becomes a vapor under pressure, returning to the surface with the natural gas, where it can be recaptured. This process may introduce other safety hazards, however, and has not been widely accepted by the oil-field service industry.

Human Community Impacts

Public engagement will be essential for managing the short-term and cumulative impacts of shale development operations. Although each community is unique and a simple prescription will not necessarily apply to every case, several practices can be used to mitigate local issues. The drilling of multiple wells from a single well pad can reduce the footprint of shale development operations. The use of sound barriers can reduce typical noise pollution of approximately 85 decibels to background levels of 65 decibels at distances of a few hundred feet (Behrens and Associates, 2006). In addition to the GHG and air-pollution benefits, RECs eliminate light pollution from flare stacks, which can produce flames approximately 6 m high (Crompton, 2012). Many shale gas developers have entered into agreements that require them to maintain roads so as to leave them in better shape than they were in previous to shale gas operations. Operational agreements with the local community can also be beneficial, such as limiting the times when heavy truck traffic can pass by schools or homes. It will be important for the petroleum industry to continue to follow and improve best practices to manage local community impacts from shale development and production activities.

Policy Issues and Studies of Hydraulic Fracturing

The Energy Policy Act of 2005, section 322, excludes hydraulic fracturing fluids from federal regulation under the Safe Drinking Water Act, limiting the EPA's authority on hydraulic fracturing issues. Several Congressional efforts are under way to end this exemption, including H.R. 1084 and S. 587 (Tiemann and Vann, 2012). Meanwhile, other regulatory efforts have been under way on the federal, state, and local levels.

Federal Requirements

The US Department of the Interior Bureau of Land Management (US BLM) has proposed draft rules for hydraulic fracturing, which would require disclosure of the chemical components used in hydraulic fracturing fluids, among other groundwater protections (Soraghan, 2012; US BLM, 2012). The proposed rule requires operators to submit an operation plan prior to hydraulic fracturing. With the operation plan, the BLM would be able to evaluate groundwater protection designs based on the local geology, review anticipated surface disturbance, and approve proposed management and disposal of recovered fluids. In addition, operators would provide to the BLM the information necessary to confirm wellbore integrity before, during, and at the conclusion of the stimulation operation. Before hydraulic fracturing begins, operators would have to self-certify that the fluids comply with all applicable federal, state, and local laws, rules, and regulations. After the conclusion of hydraulic fracturing, a follow-up report would summarize what actually occurred during fracturing activities, including the specific chemical makeup of the hydraulic fracturing fluid.

While the EPA has limited ability to regulate the fluids used for hydraulic fracturing, it does have authority under the Clean Air Act to regulate hazardous air emissions from hydraulic fracturing operations. On April 17, 2012, the EPA released new source performance standards and national emissions standards for hazardous air pollutants in the oil and natural gas sector. The final rules include the first federal air standards for hydraulically fractured gas wells, along with requirements for other sources of pollution in the oil and gas industry that currently are not regulated at the federal level. These standards require either flaring or green completions on all feasible natural gas wells developed prior to January 1, 2015, with only green completions allowed for wells developed on and after that date. These rules are expected to reduce VOC emissions from applicable hydraulically fractured wells by approximately 95% (US EPA, 2012b) while reducing the natural gas industry's total VOC, CH_4, and HAP emissions by approximately 10%.

State Requirements

As previously mentioned, the EPA lacks the authority to require shale gas and oil developers to disclose the chemical constituents of the fluids they use in hydraulic fracturing operations. However, individual states have encouraged or required this disclosure. In 2010, Wyoming became the first state to require companies to disclose the chemicals used in hydraulic fracturing fluids, but this requirement contained an exemption for confidential commercial information. Under this exemption, drilling companies have requested 150 different chemicals to be protected from disclosure (Zuckerman, 2012). Subsequent state laws have attempted to maintain trade-secret protection while increasing public disclosure. Texas's disclosure law, which went into effect on February 1, 2012, requires disclosures to be made public through the FracFocus.org website and requires the disclosure of fluid and water volumes used in addition to chemical additives (State of Texas, 2011). At least four other states require disclosure through FracFocus.org, and others encourage it, though the specifications for what is to be disclosed differ (Maykuth, 2012). Colorado appears to have the most stringent disclosure rules, requiring all chemical constituents and their concentrations to be listed. Trade secrets are protected by listing chemical constituents and concentrations separately from the descriptions of products in the hydraulic fracturing fluids, thereby not revealing the particular chemicals or the amounts of chemicals in each product (Jaffe, 2011).

Some states have issued rules in addition to fluid-disclosure standards. Pennsylvania promulgated regulations limiting total dissolved solids in discharged water to levels that effectively prevent the direct disposal of produced well water to surface-water bodies. Some states, such as Texas, rely on regulations in place for all oil and gas well construction (Interstate Oil and Gas Compact Commission, 2012). Others, such as Pennsylvania, have been prompted by hydraulic fracturing activities to subject drillers to more stringent well construction standards, requiring casing pressure tests, minimization of annular pressure, quarterly inspections, and annual reporting. Pennsylvania requirements include procedures to follow for reported gas-migration events. In addition, drilling companies are required to submit a plan ensuring adequate well casing and cementing (PA DEP, 2010).

Several states have resorted to establishing moratoria or outright bans on hydraulic fracturing. New York has had a moratorium in effect since 2010, although it plans to lift it after instituting strict regulations on shale gas development. Maryland instituted a de facto two-year moratorium in March 2011 designed to give the state time to complete a study on hydraulic fracturing. Vermont may become the first state to ban hydraulic fracturing outright, although this action is of limited significance since Vermont sits on no known shale gas reserves (Burns and Marsters, 2012; Sullivan, 2012).

Local Requirements

Municipal governments in New York, Pennsylvania, and elsewhere have banned or effectively banned hydraulic fracturing operations through zoning provisions. Outright bans have been upheld by the New York State Supreme Court on several occasions (Efstathiou and Dolmetsch, 2012). However, municipalities in Pennsylvania that have limited hydraulic fracturing through prohibitive noise standards and other rules are facing preemption by a new state law that went into effect on April 14, 2012. The law is being challenged in the courts but is expected to be upheld (Reed, 2012). Some cities do not attempt to limit development but require it to be less impactful on human health and the environment. For example, Fort Worth and Southlake, Texas, require green completions on all natural gas wells (US EPA, 2012b).

The US EPA Study

The EPA is undertaking a study of hydraulic fracturing to improve understanding of its potential impacts on drinking water and groundwater (US EPA, 2012a). The purpose is to understand the relationship between hydraulic fracturing and drinking-water resources. The study will assess the complete life cycle of water in hydraulic fracturing, including water acquisition, mixing of water with chemicals, hydraulic fracturing activities, and the management of flowback water. The EPA is evaluating several prospective and retrospective study sites to explore the potential impact on drinking water. A preliminary report is expected by the end of 2012, and a final report will be released in 2014.

Secretary of Energy Advisory Board Recommendations

In addition to efforts by the BLM and the EPA to understand potential impacts, the Shale Gas Production Subcommittee of the US Department of Energy's Secretary of Energy Advisory Board (SEAB) made a number of recommendations concerning shale gas production in its final report issued on November 18, 2011 (SEAB, 2011). Their recommendations for immediate implementation included calls for better communication and greater coordination between federal agencies for both data acquisition and regulation concerning environmental impacts of shale gas development. Data-acquisition priorities included collection of air emissions data, analysis of the GHG footprint of shale gas, and investigations of possible methane migration from shale gas wells to water reservoirs. The subcommittee also recommended steps to mitigate potential impacts from shale gas development, including the elimination of diesel use in hydraulic fracturing fluid, the disclosure of fracturing fluid composition, and the reduction of air emissions by using proven technologies and practices. The subcommittee also recommended the improvement of public information about shale gas and oil operations.

Conclusion

Shale gas and oil production represents a large, new potential source of natural gas and oil for the US. However, development of this resource is not without risks to other natural resources. Potential abiotic impacts include the following:

— GHG emissions during completion and production activities.

— Air emissions that affect local air quality during completion and production activities.

— Water withdrawals for hydraulic fracturing.

— Induced seismicity from improper management and disposal of flowback water.

— Water-quality impacts to surface water or aquifer from faulty well design or improper flowback water management.

— Additional community impacts including noise and light pollution.

In addition to the abiotic impacts discussed, there are also potential ecological impacts from the development of shale resources. Improved science-based assessments of these environmental risks are under way, and early results suggest that the risks may be relatively low and manageable. With adequate safeguards in place, shale gas and oil can be exploited effectively and responsibly in ways that protect both the environment and human health.

Acknowledgments

Argonne National Laboratory's work was supported by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Clean Cities Program, under contract DE-AC02-06CH11357.

References

Alvarez, R. 2012. Air Pollution Issues Associated with Unconventional Natural Gas and Oil. EM, Magazine of the Air and Waste Management Association, June, pp. 22–25.

Behrens and Associates. 2006, April. *Gas Well Drilling Noise Impact and Mitigation Study*. Gas Drilling Task Force, Fort Worth, TX, 30 pp. Available at http://www.pstrust.org/docs/GasWellDrillingNoiseImpactandMitigationStudy.pdf (accessed April 27, 2012).

BENTEK Energy and Turner, Mason & Co. 2011, November. *The Great NGL Surge!* BENTEK Energy and Turner, Mason & Co., Evergreen, CO, 6 pp. Available at http://www.turnermason.com/assets/The-Great-NGL-Surge.pdf (accessed November 2, 2012).

Burnham, A., C.E. Clark, J. Han, M. Wang, J.B. Dunn, and I. Palou-Rivera. 2012. Life-Cycle Greenhouse Gas Emissions of Shale Gas, Natural Gas, Coal, and Petroleum. Environmental Science & Technology 46(2):619–627.

Burns, P., and L. Marsters. 2012, April 13. *Vermont Senate Committee Passes Ban on Fracking*. Press release. Vermont Senate Natural Resources and Energy Committee, Montpelier, VT. Available at http://vtdigger.org/2012/04/13/vermont-senate-committee-passes-ban-on-fracking/ (accessed April 23, 2012).

Clark, C.E., J. Han, A. Burnham, J.B. Dunn, and M. Wang. 2011. *Life-Cycle Analysis of Shale Gas and Natural Gas*. ANL/ESD/11-11. Argonne National Laboratory, Argonne, IL, 38 pp. Available at http://www.transportation.anl.gov/pdfs/EE/813.PDF (accessed November 2, 2012).

Colorado Department of Public Health and Environment (CDPHE). 2012. *Colorado 2008 Air Pollutant Emissions Inventory*. CDPHE, Denver, CO. http://www.colorado.gov/airquality/inv_maps_2008.aspx (accessed November 6, 2012).

Crompton, J. 2012. Flares from Marcellus Shale Wells Attracting Plenty of Attention. *Pittsburgh Post-Gazette*, February 2. Available at http://www.post-gazette.com/stories/local/neighborhoods-south/flares-from-marcellus-shale-wells-attracting-plenty-of-attention-214020/ (accessed April 27, 2012).

Ecology and Environment, Inc. 2011, August. *Economic Assessment Report for the Supplemental Generic Environmental Impact Statement on New York State's Oil, Gas, and Solution Mining Regulatory Program*. EG04 0B3371. New York Department of Environmental Conservation, Albany, NY, 251 pp. Available at http://www.dec.ny.gov/docs/materials_minerals_pdf/rdsgeisecon0811.pdf (accessed September 10, 2012).

Efstathiou, J., Jr., and C. Dolmetsch. 2012. Natural Gas 'Fracking' Ban Upheld in Second New York Town. *Bloomberg*, February 25. Available at http://www.bloomberg.com/news/2012-02-25/natural-gas-fracking-ban-upheld-in-second-new-york-town.html (accessed April 23, 2012).

Entrekin, S., M. Evans-White, B. Johnson, and E. Hagenbuch. 2011. Rapid Expansion of Natural Gas Development Poses a Threat to Surface Waters. Frontiers in Ecology and the Environment 9(9):503–511.

Goodman, M. 2012. Waterless Fracking Method Targets Natural Gas Industry's Gaze. *CBS DFW*, January 12. http://dfw.cbslocal.com/2012/01/12/waterless-fracking-method-target-for-natural-gas-industrys-gaze/ (accessed May 2, 2012).

Ground Water Protection Council and ALL Consulting. 2009, April. *Modern Shale Gas Development in the United States: A Primer*. US Department of Energy, National Energy Technology Laboratory, Washington, DC, 116 pp. Available at http://www.netl.doe.gov/technologies/oil-gas/publications/epreports/shale_gas_primer_2009.pdf (accessed November 2, 2012).

Harvey, S., V. Gowrishankar, and T. Singer. 2012 March. *Leaking Profits: The U.S. Oil and Gas Industry Can Reduce Pollution, Conserve Resources, and Make Money by Preventing Methane Waste*. Natural Resources Defense Council, New York, 68 pp. Available at http://www.nrdc.org/energy/leaking-profits.asp (accessed April 27, 2012).

Horton, S. 2012. Disposal of Hydrofracking Waste Fluid by Injection into Subsurface Aquifers Triggers Earthquake Swarm in Central Arkansas with Potential for Damaging Earthquake. Seismological Research Letters 83(2):250–260.

Interstate Oil and Gas Compact Commission (IOGCC). 2012. *Texas State Progress: Shale Gas*. IOGCC, Oklahoma City, OK. Available at http://groundwork.iogcc.org/content/texas-state-progress-shale-gas (accessed April 23, 2012).

Jaffe, M. 2011. Hickenlooper: Colorado's Frack Fluid Disclosure Rule Will Be a Model for the Nation. *Denver Post*, December 13. Available at http://www.denverpost.com/breakingnews/ci_19537142?IADID=Search-www.denverpost.com-www.denverpost.com (accessed April 27, 2012).

King, C.W., and M.E. Webber. 2008. Water Intensity of Transportation. *Environmental Science & Technology* 42(21):7866–7872.

Kirchgessner, D.A., R.A. Lott, R.M. Cowgill, M.R. Harrison, and T.M. Shires. 1997. Estimate of Methane Emissions from the U.S. Natural Gas Industry. *Chemosphere* 35(6):1365–1390.

Mantell, M.E. 2010, December 20. Personal communication between M.E. Mantell, Chesapeake Energy, and C.B. Harto, Argonne National Laboratory, Washington, DC.

Mason, J. 2011. Well Production Profiles for the Fayetteville Shale Gas Play. Oil & Gas Journal, April 4.

Maykuth, A. 2012. More States Ordering Disclosure of Fracking Chemicals. *Philadelphia Inquirer*, January 22. Available at http://articles.philly.com/2012-01-22/business/30652980_1_fracking-marcellus-shale-coalition-chemical-disclosure (accessed April 23, 2012).

Mintz, M., J. Han, M. Wang, and C. Saricks. 2010. Well-to-Wheels Analysis of Landfill Gas-Based Pathways and Their Addition to the GREET Model. ANL/ESD/10-3. Argonne National Laboratory, Argonne, IL, 65 pp. Available at http://www.transportation.anl.gov/pdfs/TA/632.PDF (accessed November 2, 2012).

Office of Energy Efficiency and Renewable Energy (EERE). 2012. US Department of Energy, Alternative Fuels and Advanced Vehicle Data Center, Washington, DC. http://www.afdc.energy.gov/afdc/data/cleancities.html (accessed April 27, 2012).

Ohio Department of Natural Resources (ODNR). 2012, March. Preliminary Report on the Northstar 1 Class II Injection Well and the Seismic Events in the Youngstown, Ohio, Area. ODNR, Columbus, OH, 24 pp. http://ohiodnr.com/downloads/northstar/UICreport.pdf (accessed April 18, 2012).

Osborn, S.G., A. Vengosh, N.R. Warner, and R.B. Jackson. 2011. Methane Contamination of Drinking Water Accompanying Gas-Well Drilling and Hydraulic Fracturing. *Proceedings of the National Academy of Sciences, USA* 108(20):8172–8176.

Pennsylvania Department of Environmental Protection (PA DEP). 2010. *Executive Summary: Oil and Gas Well Casing and Cementing (Amendments to Chapter 78)*. PA DEP, Harrisburg, PA, 2 pp. Available at http://files.dep.state.pa.us/PublicParticipation/Public%20Participation%20Center/PubPartCenterPortalFiles/Environmental%20Quality%20Board/2010/May_17_2010_Meeting/Oil_and_Gas/OG_Executive_Summary_Proposed_Casing_Regs_4_11_2010.pdf (accessed April 23, 2012).

Pennsylvania Department of Environmental Protection (PA DEP). 2011. *DEP Fines Chesapeake Energy More Than $1 Million: Penalties Address Violations in Bradford, Washington Counties*. PA DEP, Harrisburg, PA. Available at http://www.portal.state.pa.us/portal/server.pt/community/newsroom/14287?id=17405&typeid=1 (accessed April 23, 2012).

Pennsylvania Environmental Quality Board. 2011. Rules and Regulations: Title 25—Environmental Protection. 25 Pa. Code Ch. 78, Oil and Gas Wells, 41 Pa.B. 805. *Pennsylvania Bulletin*, February 5. Available at http://www.pabulletin.com/secure/data/vol41/41-6/239.html (accessed September 14, 2012).

Reed, B. 2012. Controversy Abounds over New Pennsylvania Drilling Law. *Philadelphia Inquirer*, April 17. Available at http://articles.philly.com/2012-04-17/news/31355843_1_drilling-law-unconventional-drilling-natural-gas-drilling (accessed April 23, 2012).

Rood Werpy, M., A. Burnham, and K. Bertram. 2010. Propane Vehicles: Status, Challenges, and Oopportunities. ANL/ESD/10-2. Argonne National Laboratory, Argonne, IL, 48 pp. Available at http://www.transportation.anl.gov/pdfs/AF/633.PDF (accessed November 2, 2012).

Rotman, D. 2009. Natural Gas Changes the Energy Map. *Technology Review*, October 15. Available at http://www.technologyreview.com/energy/23694/ (accessed May 4, 2012).

Secretary of Energy Advisory Board (SEAB). 2011, November 18. Shale Gas Production Subcommittee Second Ninety Day Report. SEAB, Washington, DC, 23 pp. Available at http://www.shalegas.energy.gov/resources/111811_final_report.pdf (accessed April 20, 2012).

Soraghan, M. 2012. BLM Proposes More Disclosure Than Most States. *Greenwire*, February 6. Available at http://www.eenews.net/Greenwire/2012/02/06/archive/1?terms=BLM+proposes+more+disclosure+than+most+states (accessed April 23, 2012).

State of Texas. 2011. *Hydraulic Fracturing Chemical Disclosure Requirements*. Texas Administrative Code Title 16, Part 1, Chapter 3, Rule §3.29. Secretary of State, Austin, TX. Available at http://info.sos.state.tx.us/pls/pub/readtac$ext.TacPage?sl=R&app=9&p_dir=&p_rloc=&p_tloc=&p_ploc=&pg=1&p_tac=&ti=16&pt=1&ch=3&rl=29 (accessed November 8, 2012).

Sullivan, C. 2012. Vt. House OKs 3-Year Fracking Ban. *Greenwire*, February 3. Available at http://www.eenews.net/Greenwire/2012/02/03/archive/15?terms=Vt.+House+OKs+3-year+fracking+ban (accessed April 23, 2012).

Tiemann, M., and A. Vann. 2012, July 12. Hydraulic Fracturing and Safe Drinking Water Act Issues. R41760. Congressional Research Service, Washington, DC, 42 pp. Available at http://www.fas.org/sgp/crs/misc/R41760.pdf (accessed November 2, 2012).

US Department of the Interior Bureau of Land Management (US BLM). 2012, May 11. *Proposed Rule: Oil and Gas; Well Stimulation, Including Hydraulic Fracturing, on Federal and Indian Land*. 43 CFR 3160, RIN 1004-AE26. *Federal Register* 99(92):27691–27711. Available at http://www.gpo.gov/fdsys/pkg/FR-2012-05-11/html/2012-11304.htm (accessed November 2, 2012).

US Energy Information Administration (US EIA). 2012. *Annual Energy Outlook 2012 Early Release Overview*. DOE/EIA-0383ER(2012). US EIA, Washington, DC, 13 pp. Available at http://www.eia.gov/forecasts/aeo/er/pdf/0383er(2012).pdf (accessed May 3, 2012).

US Environmental Protection Agency (US EPA). 2010. *Greenhouse Gas Emissions Reporting from the Petroleum and Natural Gas Industry*. Background Technical Support Document. US EPA, Washington, DC, 144 pp. Available at http://www.epa.gov/ghgreporting/documents/pdf/2010/Subpart-W_TSD.pdf (accessed November 2, 2012).

US Environmental Protection Agency (US EPA). 2011a, April 15. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2009*. EPA 430-R-11-005. US EPA, Washington, DC, 459 pp. Available at http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2011-Complete_Report.pdf (accessed November 2, 2012).

US Environmental Protection Agency (US EPA). 2011b, December. *Investigation of Ground Contamination near Pavillion, Wyoming* (Draft). EPA 600/R-00/000. US EPA, Washington, DC, 60 pp. Available at http://www.fossil.energy.gov/programs/gasregulation/authorizations/2011_applications/exhibits_11-162-LNG/54.1_EPA_ReportOnPavillion_Dec-8-2011_-_.pdf (accessed November 2, 2012).

US Environmental Protection Agency (US EPA). 2011c. *Reduced Emissions Completions for Hydraulically Fractured Natural Gas Wells*. US EPA, Washington, DC, 12 pp. Available at http://www.epa.gov/gasstar/documents/reduced_emissions_completions.pdf (accessed May 4, 2012).

US Environmental Protection Agency (US EPA). 2012a. *EPA's Study of Hydraulic Fracturing and Its Potential Impact on Drinking Water Resources.* US EPA, Washington, DC, 5 pp. Available at http://www.epa.gov/hfstudy/index.html (accessed April 27, 2012).

US Environmental Protection Agency (US EPA). 2012b. *Overview of Final Amendments to Air Regulations for the Oil and Natural Gas Industry* (Fact sheet). US EPA, Washington, DC, 5 pp. Available at http://www.epa.gov/airquality/oilandgas/pdfs/20120417fs.pdf (accessed April 27, 2012).

US Environmental Protection Agency (US EPA). 2012c, April 13. Proposed Rule: Standards of Performance for Greenhouse Gas Emissions for New Stationary Sources: Electric Utility Generating Units. 40 CFR 60. *Federal Register* 77(72):22391–11441. Available at https://www.federalregister.gov/articles/2012/04/13/2012-7820/standards-of-performance-for-greenhouse-gas-emissions-for-new-stationary-sources-electric-utility (accessed April 27, 2012).

US Environmental Protection Agency (US EPA). 2012d, February 14. Proposed Rules: Implementation of the 2008 National Ambient Air Quality Standards for Ozone: Nonattainment Area Classifications Approach, Attainment Deadlines and Revocation of the 1997 Ozone Standards for Transportation Conformity Purposes. 40 CFR 50 and 51. *Federal Register* 77(30):8197–8209. Available at http://www.gpo.gov/fdsys/pkg/FR-2012-02-14/pdf/2012-3284.pdf (accessed April 23, 2012).

US Environmental Protection Agency (US EPA). 2012e, April 3. Rules and Regulations: Secondary National Ambient Air Quality Standards for Oxides of Nitrogen and Sulfur. 40 CFR 50. *Federal Register* 77(64):20218–20272. Available at http://www.gpo.gov/fdsys/pkg/FR-2012-04-03/pdf/2012-7679.pdf (accessed April 23, 2012).

Veil, J.A. 2010, July. Water Management Technologies Used by Marcellus Shale Gas Producers. ANL/EVS/R-10/3. US Department of Energy, National Energy Technology Laboratory, Washington, DC, 59 pp. Available at http://www.ead.anl.gov/pub/dsp_detail.cfm?PubID=2537 (accessed April 20, 2012).

Veil, J.A., and C.E. Clark. 2011. Produced Water Volume Estimates and Management Practices. *SPE Production & Operations* 26(3):234–239.

Warren, K.J. 2010. Pennsylvania's Regulation of Total Dissolved Solids. Legal Intelligencer, September 16. Available at http://www.hangley.com/ufiles/warren-pa-total-dissolved-solids.pdf (accessed July 11, 2012).

Wu, M., M. Mintz, M. Wang, S. Arora, and Y. Chiu. 2011. Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline—2011 Update. ANL/ESD/09-1. Argonne National Laboratory, Argonne, IL, 100 pp. Available at http://greet.es.anl.gov/publication-consumptive_water (accessed November 2, 2012).

Zuckerman, L. 2012. Groups Seek Fuller Disclosure of Fracking in Wyoming. *Reuters*, March 26. Available at http://www.reuters.com/article/2012/03/27/us-usa-fracking-wyoming-idUSBRE82Q02F20120327 (accessed May 4, 2012).

Submitted May 15, 2012; revised August 31, 2012; accepted September 20, 2012.