Hydraulic Fracturing and Shale Gas Production: Technology, Impacts, and Policy

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Glossary[1]

Annulus: The space between the casing and the wellbore or surrounding rock.

Biocide: An additive used in hydraulic fracturing fluids (and often drilling muds) to kill bacteria that could otherwise reduce permeability and fluid flow.

Casing: Steel pipe inserted into a wellbore and cemented into place. It is used to protect freshwater aquifers or otherwise isolate a zone.

Class II injection well: A well that injects fluids into a formation rather than produces fluids. A Class II injection well is a well associated with oil or natural gas production. Such wells include enhanced recovery wells, disposal wells, and hydrocarbon storage wells.

Completion: Includes the steps required to drill and assemble casing, tubes, and equipment to efficiently produce oil or gas from a well. For shale gas wells, this includes hydraulic fracturing activities.

Flowback water: The water that returns to the surface from the wellbore within the first few weeks after hydraulic fracturing. It is composed of fracturing fluids, sand, and water from the formation, which may contain hydrocarbons, salts, minerals, naturally occurring radioactive materials.

Hydraulic fracturing (fracking or fracing): A stimulation technique performed on low-permeability reservoirs such as shale to increase oil and/or gas flow from the formation and improve productivity. Fluids and proppant are injected at high pressure and flow rate into a reservoir to create fractures perpendicular to the wellbore according to the natural stresses of the formation and maintain those openings during production.

Liquefied petroleum gas (LPG): Hydrocarbons, primarily composed of propane and butane, obtained during processing of crude oil, which are liquefied at low temperatures and moderate pressure. It is similar to NGL but originates from crude oil sources.

Natural gas liquids (NGL): Hydrocarbons, typically composed of propane, butane, pentane, hexane, and heptane, obtained from natural gas production or processing which are liquefied at low temperatures and moderate pressure. They are similar to LPG but originate from natural gas sources.

Perforation: A hole in the casing, often generated by means of explosive charges, which enables fluid and gas flow between the wellbore and the reservoir.

Play: A geologic area where hydrocarbon accumulations occur. For shale gas, examples include the Barnett and Marcellus plays.

Produced water: The water that is brought to the surface during the production of oil and gas. It typically consists of water already existing in the formation, but may be mixed with fracturing fluid if hydraulic fracturing was used to stimulate the well.

Proppant: Particles mixed with fracturing fluid to maintain fracture openings after hydraulic fracturing. These typically include sand grains, but they may also include engineered proppants.

Reduced emission completion (REC or green completion): An alternative practice that captures and separates natural gas during well completion and workovers activities instead of allowing it to vent into the atmosphere.

Seismic event: An earthquake. Induced seismicity is an earthquake caused by human activities.

Wellbore: Also referred to as borehole. This includes the inside diameter of the drilled hole bounded by the rock face.

Wellhead: The structure on the well at ground level that provides a means for installing and hanging casing, production tubing, flow control equipment, and other equipment for production.

Workover: The repair or refracturing of an existing oil or gas well to enhance or prolong production.

[1] This glossary provides definitions of technical terms used throughout this paper. The first time each term is used it is *italicized*.

1 Introduction to Hydraulic Fracturing and Shale Gas Production

Hydraulic fracturing is a key technique that has enabled the economic production of natural gas from shale deposits, or *plays*. The development of large-scale shale gas production is changing the U.S. energy market, generating expanded interest in the usage of natural gas in sectors such as electricity generation and transportation. At the same time, there is much uncertainty of the environmental implications of hydraulic fracturing and the rapid expansion of natural gas production from shale plays. The goal of this white paper is to explain 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.

Unlike conventional mineral formations containing natural gas deposits, shale has low permeability, which naturally limits the flow of gas or water. In shale plays, natural gas is held in largely unconnected pores and natural fractures. Hydraulic fracturing is the method commonly used to connect these pores and allow the gas to flow. 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 the well, *casing*, perforating, hydraulic fracturing, *completion*, production, abandonment, and reclamation.

1.1 Road and Well Pad Construction

A well requires a prepared area on the surface, called a 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 equipment. Preparing a pad involves clearing and leveling several acres of land. Its size depends on the depth of the well and the number of wells to be drilled on the site. In addition to land disturbed for building the well pad, three to four acres are disturbed per pad for roads and utilities to service the pad.

1.2 Drilling

Most shale gas resources are located at depths of 6,000 feet or more below ground level, and can be relatively thin (for example, the Marcellus shale formation is between 50–200 feet thick depending on location). The efficient extraction of gas from such a thin layer of rock requires drilling horizontally through the shale as shown in Figure 1. This is accomplished by drilling vertically downward until the drill bit reaches a distance of around 900 feet from the shale formation. At this point, a directional drill is used to create a gradual 90-degree curve, so that the *wellbore* becomes horizontal as it reaches optimal depth within the shale. The wellbore then follows the shale formation horizontally for 5,000 feet or more (Rotman 2009). Multiple horizontal wells accessing different parts of the shale formation can be drilled from a single pad. Thus, horizontal drilling reduces the footprint of these operations by enabling a large area of shale to be accessed from a single pad.

1.3 Casing and Perforating

At various stages in the drilling process, drilling is stopped and steel casing pipe is installed in the wellbore. Cement is pumped into the *annulus*, or void space between the casing and the surrounding mineral formation. After the wellbore reaches a depth below the deepest freshwater aquifer, casing and cement are installed to protect the water from contamination due to the drilling process. Additional casing and cementing along the entire wellbore occurs after the well has reached its full horizontal length. This process is intended to prevent leakage of natural gas from the well to the rock layers between the shale formation and the surface, as well as to prevent the escape of natural gas to the surface through the annulus. The casing surrounding the horizontal section of the well through the shale formation is then perforated using small explosives to enable the flow of hydraulic fracturing fluids out of the well into the shale and the eventual flow of natural gas out of the shale into the well.

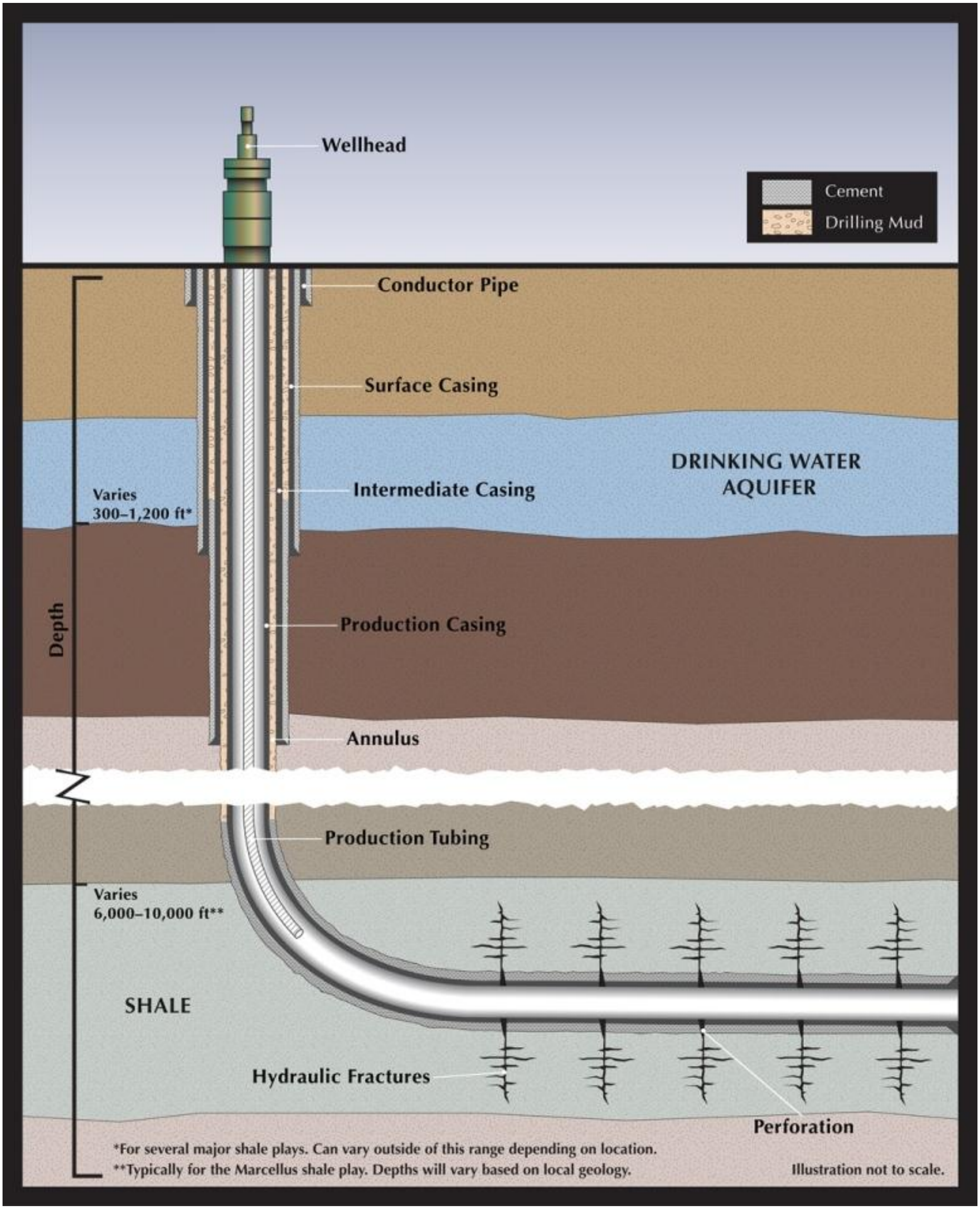

Figure 1 Typical Configuration for a Horizontally Drilled, Hydraulically Fractured Shale Gas Well

1.4 Hydraulic Fracturing and Completion

Even though the well casing is perforated, little natural gas will flow freely into the well from the shale. Fracture networks must be created in the shale to allow gas to escape from the pores and natural fractures where it is trapped in the rock. This is accomplished through the process of hydraulic fracturing. In this process, typically several million gallons of a fluid composed of 98–99.5% water and *proppant* (usually sand) is pumped at high pressure into the well (GWPC and ALL 2009). The rest of the fracking fluid (0.5–2% by volume) is composed of a blend of chemicals, often proprietary, that enhance the fluid's properties. These chemicals typically include acids to "clean" the shale 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 flow and improve the ability of the fluid to infiltrate and carry the proppant into small fractures in the shale (GWPC and ALL 2009).

This fluid pushes through the *perforations* in the well casing and forces fractures open in the shale—connecting pores and existing fractures and creating a pathway for natural gas to flow back to the well. The proppant lodges in the fractures and keeps them open once the pressure is reduced and the fluid flows back out of the well. Approximately 1,000 feet 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. Cement plugs isolate each hydraulic fracture stage and must be drilled out to enable the flow of natural gas up the well after all hydraulic fracturing is complete.

Once the pressure is released, fluid (commonly referred to as *flowback water*) flows back out the top of the well. The fluid that is recovered not only contains the proprietary blend of chemicals present in the hydraulic fracturing fluid, but may also contain chemicals naturally present in the reservoir, including hydrocarbons, salts, minerals, and naturally occurring radioactive materials (NORM) that leach into the fluid from the shale or result from mixing of the hydraulic fracturing fluid with brine (e.g. salty water) already present in the formation. The chemical composition of the water produced from the well varies significantly according to the formation and the time after well completion, with early flowback water resembling the hydraulic fracturing fluid but later converging on properties more closely resembling the brine naturally present in the formation.

In many cases, flowback water can be reused in subsequent hydraulic fracturing operations; this depends 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 direct dumping into surface waters or deposit at ill-equipped wastewater treatment plants, most disposal now occurs at *Class II injection wells* as regulated by the U.S. Environmental Protection Agency's (EPA's) Underground Injection Control Program. These injection wells place the flowback water in underground formations isolated from drinking water sources.

1.5 Production, Abandonment, and Reclamation

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. Because large-scale shale gas production has only been occurring very recently, the production lifetime of shale gas wells is not fully established. Although there is substantial debate on the issue, it is generally observed that shale gas wells experience quicker production declines than conventional natural gas production. In the Fayetteville play in north-central Arkansas, it has been estimated that half of a well's lifetime production, or estimated ultimate recovery, occurs within its first five years (Mason 2011). Once a well no longer produces at an economic rate, the wellhead is removed, the wellbore is filled with cement to prevent leakage of gas into the air, the surface is reclaimed (either to its pre-well state or to another condition agreed upon with the landowner), and the site is abandoned to the holder of the land's surface rights.

2 Shale Gas Resource and Opportunities

The Energy Information Administration (EIA) 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 and more than offsetting declining production from other sources (EIA 2012). While the U.S. has significant shale resources, forecasts have a high degree of uncertainty. In 2011, the EIA estimated 827 trillion cubic feet of unproved technically recoverable resource, but it reduced the estimate in 2012 by approximately 40%, to 482 trillion cubic feet (EIA 2012). Shale plays that are considered important include the Marcellus, Haynesville, Fayetteville, Barnett, Eagle Ford, and Bakken. Other major plays include the Antrim, Utica, Niobrara, New Albany, and Woodford (Figure 2).

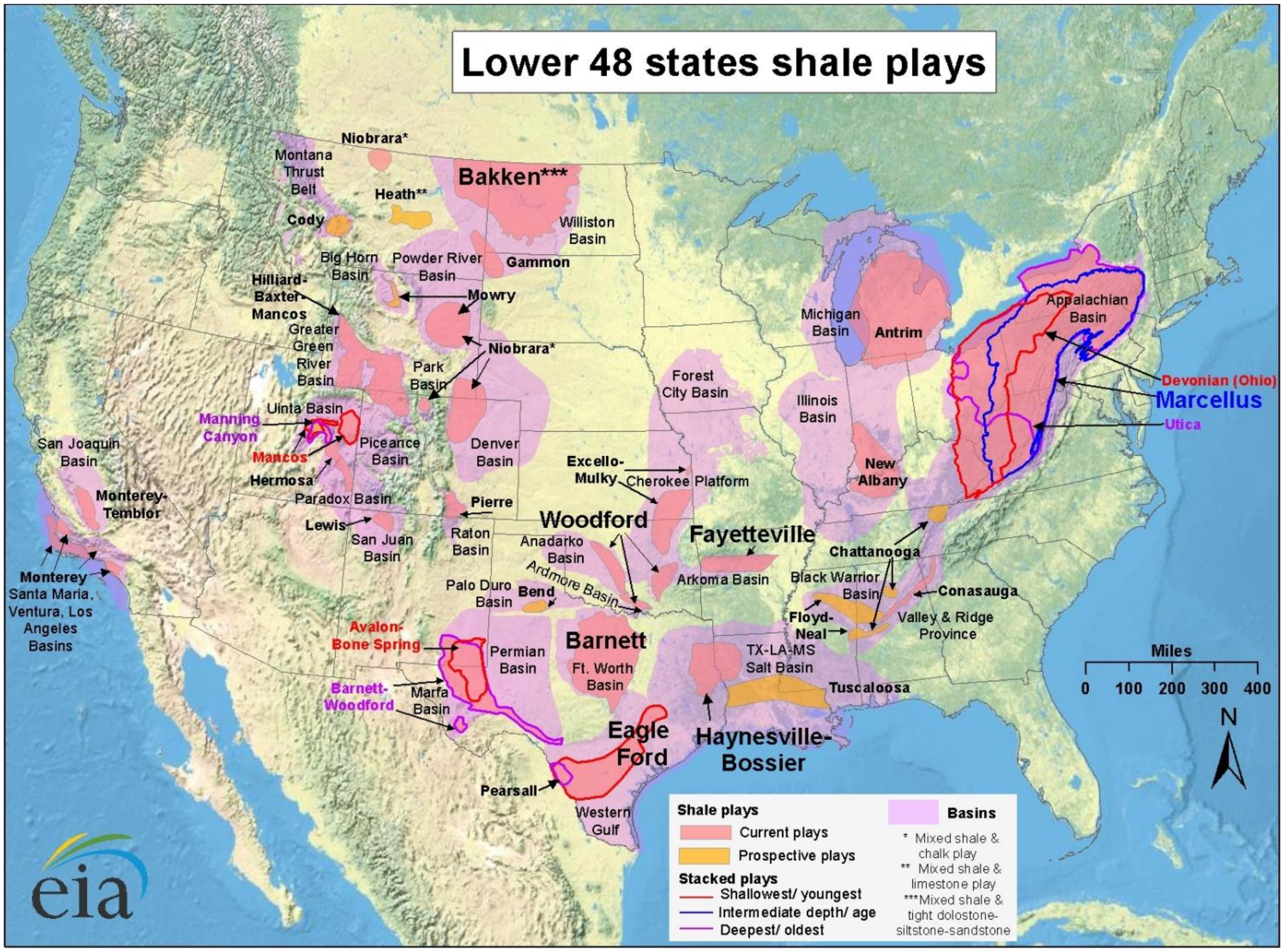

Figure 2 U.S. Shale Gas Plays (EIA, 2011)

Growth in the production of shale gas over the past few years has led to rapid growth in domestic natural gas supplies and significant decreases in prices. The combination of greater supply and lower prices has created interest in expanding the use of natural gas for both electricity production and as a transportation fuel. As natural gas power plants burn more cleanly than coal plants, the increase in supply may assist utilities in meeting Clean Air Act National Ambient Air Quality Standards for ozone (proposed) (Federal Register 2012a) and for nitrogen and sulfur oxides (final) (Federal Register 2012b), as well as the EPA's Carbon Pollution Standard for New Power Plants (proposed) (Federal Register 2012c).

Natural gas vehicles have been a key technology in the U.S. Department of Energy (DOE) Clean Cities program's portfolio to reduce petroleum consumption in transportation. Between 2004 and 2010, natural gas vehicles accounted for nearly 50% of the petroleum savings from alternative fuel vehicles deployed by Clean Cities, approximately 740 million gasoline gallon equivalents (EERE 2012). A particular success has been the deployment of high-fuel-use fleet vehicles capable of central refueling, such as buses and refuse haulers; 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, or specialty task truck (e.g. cement mixer, dump truck), markets.

Shale gas development has also expanded the supply of propane and other *natural gas liquids (NGLs)*, as the low prices created by the surplus in natural gas supply has pushed producers to develop plays rich in NGLs. Over the next five years, U.S. NGL production is expected to increase by more than 40%, while the heating market's demand for propane will likely continue to drop because of improvements in energy efficiency and conversion to natural gas, geothermal, and electricity (BENTEK 2012, Rood Werpy 2010). This change could lead fuel distributors to more aggressively promote propane as a vehicle fuel and allow fleets to negotiate favorable long-term fuel prices.

3 Potential Environmental Impacts Associated with Shale Gas Development

Environmental impacts associated with shale gas development occur at the global and local levels. These include impacts to climate change, local air quality, water availability, water quality, seismicity, and local communities.

3.1 Life-Cycle GHG Emissions

Natural gas has been referred to as a low-carbon fuel, as its combustion produces significantly less carbon dioxide emissions than coal and petroleum-based fuels. However, to understand the implications for climate change, one must look at not only the greenhouse gas (GHG) emissions from combustion in a vehicle or power plant but also those from production activities. For natural gas, the primary concern is leakage and venting throughout the supply chain, as methane (CH_4), a potent greenhouse gas, is its primary constituent.

In 2011, the EPA doubled its estimates of CH_4 leakage for the U.S. natural gas industry, in part because of the inclusion of emissions from shale gas production for the first time (EPA 2011a). One key activity that can produce significant CH_4 emissions is shale gas well completions. When flowback water is removed from the well prior to the beginning of gas production, natural gas can be vented to the atmosphere over the course of several days. Periodically, a shale gas well may need a *workover* to improve gas flow, which can involve hydraulically fracturing the well again, and thus further CH_4 emissions can occur if these operations are not controlled.

In reality, natural gas operators often take steps to limit these emissions. The EPA's Natural Gas STAR program, an industry and government partnership to reduce CH_4 emissions, has been reporting significant (approximately 50%) emission reductions through the use of flaring and *reduced emissions completions (RECs)*, which allow them to capture gas that otherwise would have been vented to the atmosphere (Burnham et al. 2012). However, the estimates of savings lack transparency, as they are highly aggregated to protect confidential business information. Another area of uncertainty when estimating the impacts of these emissions is projecting future well productivity, which is an important factor in life-cycle calculations. Because shale gas production is so new, these projections range widely, and if wells are less productive than the industry projects, then the emissions impacts of well completions will be of greater importance.

Several studies have been released that have estimated the life-cycle GHG emissions of shale gas; however, results have varied due to differences in methodology and data assumptions (Howarth et al. 2011, Skone et al. 2011, Jiang et al. 2011, Burnham et al. 2012). Argonne researchers estimated a base case leakage rate for large-scale shale gas of 2.0% over the entire life cycle and 1.2% for production activities (Burnham et al. 2012). The EPA does not explicitly examine shale gas leakage, rather examines the entire natural gas industry; however, previous EPA estimates for natural gas leakage prior to large-scale shale gas production were 1.4% for the life cycle and 0.4% for the production phase (EPA 2011a, 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 pipelines, thereby reducing the overall impact. On the other hand, Cornell researchers estimated a base case leakage rate for shale gas of 5.8% for the life cycle; however, they do not account for technologies that capture vented CH_4 and include several data points that likely overestimate emissions, such as using Russian pipeline information in place of U.S. data (Howarth et al. 2011).

Using current leakage estimates for large-scale production, natural gas CH_4 emissions account for approximately 15% of the total life-cycle GHG emissions on a 100-year time scale and the relative benefits of natural gas depend on how it is ultimately used. For example, most studies show that 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 (Skone et al. 2011, Jiang et al. 2011, Burnham et al. 2012). For light-duty vehicles, use of compressed natural gas may provide nearly a 10% reduction in GHG emissions as compared to gasoline (Burnham et al. 2012). 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.

3.2 Local Air Pollution

Shale gas 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 these emissions.

Several state emission inventories have shown that oil and natural gas operations are significant sources of local air pollution (e.g., the 2008 Colorado emission inventory showed that they accounted for 48% of VOCs, 18% of NOx, and 15% of benzene) and that shale gas operations may lead to increased levels of ozone and HAPs near these areas (Wells 2012). However, uncertainty about the impacts of these emissions exists, as air quality is highly dependent on local conditions. For example, in some areas VOC emissions will not be the primary driver of ozone formation; therefore, detailed modeling is required to understand the impact of emissions on local air quality. In addition, while elevated levels of benzene emissions have been found near production sites, concentrations have been below health-based screening levels, and with little data on how these HAP emissions impact human health, further examination is needed (Alvarez 2012).

Another local air pollutant of growing concern is crystalline silica dust, which can be generated from the sand proppant. Silica dust can be generated in the mining and transporting of sand to the well site and in the process of moving and mixing sand into the hydraulic fracturing fluid on the well pad. Crystalline silica dust within the respirable size range (<4 microns) is considered a HAP and a carcinogen. In addition to an increased risk of lung cancer, exposure to crystalline silica can lead to a chronic, inflammatory lung disease called silicosis (Wisconsin Department of Natural Resources 2011). A recent field study of 11 different hydraulic fracturing sites in five different states by researchers at the National Institute for Occupational Safety and Health (NIOSH) found levels of crystalline silica that exceeded NIOSH recommended exposure limits (REL) in 79% of the samples and far exceeded the REL by a factor of 10 or more in 31% of the samples. The researchers concluded that existing safeguards may not be sufficiently protective of worker health and that additional safeguards should be put in place (Esswein et al. 2012).

3.3 Water Consumption

Although water is used in several stages of the shale gas life cycle, the majority of water is typically consumed during the production stage. This is primarily due to the large volumes of water (2.3–5.5 million gallons) required to hydraulically fracture a well (Clark et al. 2011). Water in amounts of 190,000–310,000 gallons is 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). It should be noted that there is no clear distinction between so-called flowback water and produced water, with the terms typically being defined by operators based upon the timing, flow rate, or sometimes composition of the water produced. The rate at which water returns to the surface is highly dependent upon the geology of the formation. In the Marcellus play, operators recycle 95% of the flowback, whereas in the Barnett and Fayetteville plays, operators typically recycle 20% of the flowback. Water management and reuse are local issues and often depend upon the quality and quantity of water and the availability and affordability of management options. Over a 30-year life cycle, assuming a typical well is hydraulically fractured three times during that time period (EPA 2010), construction and production of shale gas typically consumes between 7,090,000 and 16,810,000 gallons of water per well.

Once the gas is produced, it is processed, transported and distributed, and ultimately used. Water consumption occurs in each of these stages as well, with the most significant non-production 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 gallon per gasoline gallon equivalent (GGE), according to King and Webber (2011), making the total consumption for the vehicle life cycle 1.0–2.5 gal/GGE depending upon location and the extent that flowback water is recycled. For comparison, vehicle life cycle water consumption associated with the use of conventional natural gas is between 0.9 and 1.1 gal/GGE, gasoline is between 2.6 and 6.6 gal/GGE, and corn ethanol is between 26 and 359 gal/GGE (Wu et al. 2011).

3.4 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 EPA’s ongoing groundwater investigation in Pavillion, Wyoming, where as little as 400 feet separated gas deposits from drinking water resources.

For deep formations, contamination may occur due to defects in the wellbore. When the annulus between the well casing and surrounding geology is not adequately sealed 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 took place (PADEP 2011). In addition to faulty well construction, Osborn et al. (2011) suggest that uncased, abandoned wells may also provide pathways for methane migration to occur. The most obvious, and perhaps 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 from the mineral formation, such as NORM, or from additives to the hydraulic fracturing fluid can be a health concern when present in significant concentrations. 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.

3.5 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 injection. 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 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. In order 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 a long enough time to cause failure along the fault or system of faults. A recent National Research Council study concludes that the majority of disposal wells for hydraulic fracturing wastewater do not pose a hazard for induced seismicity. This report also concludes that the process of hydraulic fracturing itself does not pose a high risk for inducing felt seismic events (NRC 2012).

3.6 Community Impacts

Oil and gas 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 the hydraulic fracturing process, and many more to remove the flowback water generated by the process. This intense traffic places enormous stress on local roads, which may not have been built to handle heavy truck traffic, 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, especially when in close proximity to occupied residences. Furthermore, this activity can have a negative impact upon local property values, especially in residential areas, owing to a combination of real and perceived risks and impacts. However, some aspects of shale gas 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 of time, these roads are subject to heavy traffic for only a brief period, making road upgrades a difficult decision for local or state governments.

4 Mitigating Impacts: Strategies and Practices

Some of the largest shale gas deposits are located in states that do not have a recent history of oil and gas production. This leads to two potential challenges: regulatory sufficiency and public acceptance. The first challenge is that state agencies may not be well positioned to deal with rapid growth in oil and gas development. The experience of Pennsylvania from 2008 to 2012 can be a lesson to other states. State officials were caught somewhat off-guard by the boom in development in the Marcellus shale. In the process, they identified outdated laws regulating the disposal of produced water and well construction standards. Upon identification of deficiencies, 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.

Another challenge is that in areas without a recent history of oil and gas development, the public tends to be more skeptical of new development and the risks involved. This skepticism can manifest itself in public opposition to development that can be costly for operators to overcome. Additional, credible scientific research is needed to improve quantification of the actual versus perceived risks and to improve public trust. Adequate communication, coordination, and planning involving operators, regulators, and stakeholders prior to development can also be important to help address public concerns and ensure that best practices are being used to mitigate impacts and risks.

Some of the following best practices include using technologies to reduce air emissions and recycling flowback water to reduce freshwater demand and minimize wastewater disposal.

4.1 Greenhouse Gas Emissions and Local Air Pollution

Historically, the method for reducing methane emissions (typically for safety reasons) has been flaring, which involves sending the flowback water to an open pit or tank where the gas is combusted. The benefits of this practice are about a 90% reduction in GHG emissions as compared to venting, as CO_2 is produced from the flare (Mintz 2010). With regard to air quality, VOCs and hazardous air pollutants are significantly reduced through flaring; however, nitrous oxides, 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, reduced emissions completions (RECs), or "green completions," which capture and separate natural gas during well completion and workover activities, have become a key technology to limit the amounts of methane, VOCs, and HAPs that can be vented during the flowback period without the disadvantages of flaring. RECs use portable equipment that allows operators to capture natural gas from the flowback water. After the mixture passes through a sand trap, a three-phase separator removes natural gas liquids and water from the gas, which is then sent to sales pipelines for distribution. Fortunately, REC operations have been found to be very cost-effective even with low natural gas prices (EPA 2011b).

Numerous 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 et al. 2012). In addition, to further reduce the emission impacts at well sites in densely populated areas, electric motors could be used instead of internal combustion engines.

A number of strategies exist to reduce emission and exposure to crystalline silica including product substitutions, engineering controls and improved personal protective equipment. Some examples include the use of less hazardous, non-silica proppants (i.e. ceramic), modifications to sand handling equipment to reduce or capture dust emissions, dust suppression and control practices, limits to the number of workers and the time that they are exposed to high concentrations of silica dust, improved worker training, and the use of appropriate respiratory protection equipment (Esswein et al. 2012). The Occupational Safety and Health Administration and NIOSH recently issued a hazard alert that discusses these mitigation strategies and others to minimize worker exposure (OSHA and NIOSH 2012).

4.2 Water Quantity and Quality

Increasing volumes of flowback water are 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 fresh water, 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 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.

4.3 Community Impacts

Public engagement will be essential for managing the short-term and cumulative impacts of shale gas operations. While each community is unique and a simple prescription will not necessarily apply to every case, several practices can be used to mitigate local issues. A growing trend is the drilling of multiple wells from a single well pad to reduce the footprint of shale gas 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 et al. 2006). EPA considers 70 decibels as the level of environmental noise that will prevent any measurable hearing loss over a lifetime (EPA 1974). In addition to the GHG and air pollution benefits, RECs eliminate light pollution from flare stacks, which can produce flames approximately 20 feet high (Crompton 2012). 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 natural gas industry to continue to follow and improve best practices to manage local community impacts from shale gas production activities.

5 Policy Issues, Studies, and Implications

The Energy Policy Act of 2005, section 322, limits EPA's authority on hydraulic fracturing issues by excluding from its regulatory authority under the Safe Drinking Water Act the underground injection of any fluid, other than diesel fuels, pursuant to hydraulic fracturing operations. Several Congressional efforts have been made to end this exemption, including H.R. 1084, Fracturing Responsibility and Awareness of Chemicals Act of 2011, and S. 587, which is similarly titled, (Tiemann and Vann 2012). Meanwhile, other regulatory efforts have been underway on the Federal, state, and local levels.

5.1 Federal Requirements

The Bureau of Land Management's (BLM) of the Department of the Interior proposed draft rules for oil and gas production on public lands require disclosure of the chemical components used in hydraulic fracturing fluids, among other groundwater protections (Soraghan 2012, BLM 2012). The proposed rule requires the operator to submit an operation plan prior to hydraulic fracturing that would allow BLM 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 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.

In addition to EPA's regulatory authority under the Safe Drinking Water Act, EPA is exploring the possibility of developing rules under the Toxic Substances Control Act (TSCA) to regulate the reporting of hydraulic fracturing fluid information (EPA 2011c, 2011d). The EPA also has authority under the Clean Air Act to regulate hazardous air emissions from hydraulic fracturing operations. On April 17, 2012, 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% (EPA 2012a), while reducing the natural gas industry's total VOC, HAP, and CH_4 emissions by approximately 10%.

5.2 State Requirements

As previously mentioned, EPA lacks the authority to require shale gas 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 they used in hydraulic fracturing fluids, but this requirement contained an exemption for confidential commercial information, or trade secrets. 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 web site FracFocus.org and requires the disclosure of fluid and water volumes used in addition to chemical additives (Gronewold 2012). 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 has 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 (IOGCC 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 (PADEP 2010).

Faced with uncertainty over, or public opposition to, the potential environmental and human health effects of hydraulic fracturing, several states have resorted to establishing moratoria or outright bans on the procedure. 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 (Sullivan 2012, Burns and Marsters 2012).

5.3 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 shale gas development, but require it to have less impact on human health and the environment. For example, Fort Worth and Southlake, Texas, require green completions on all natural gas wells (EPA 2012a).

5.4 EPA Study

EPA is undertaking a study of hydraulic fracturing to improve understanding of its potential impacts on drinking water and groundwater (EPA 2012b). The purpose of the study 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 management of flowback water. 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.

5.5 Secretary of Energy Advisory Board Recommendations

In addition to efforts by BLM and EPA to understand potential impacts associated with shale gas production, the Shale Gas Production Subcommittee of DOE'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). SEAB Subcommittee 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 using proven technologies and practices. The subcommittee also recommended the improvement of public information about shale gas operations.

6 Summary and Implications

Shale gas production represents a large, new potential source of natural gas for the nation. Development of this resource is, however, not without risks to natural resources. Potential impacts include the following:

- Greenhouse gas 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 of flowback water,
- Water quality impacts to surface water or aquifer from faulty well design and construction or improper flowback water management, and
- Additional community impacts including noise and light pollution.

Improved science-based assessments of these risks are underway, but early results indicate that the risks can be managed and lowered through existing practices including the following:

- RECs that limit VOC, HAP, and CH_4 emissions and reduce flaring,
- Engineering controls and appropriate personal protective equipment to reduce worker exposure to crystalline silica,
- Reusing flowback water to limit fresh water withdrawal requirements and reduce water management burdens,
- Drilling of multiple wells from a single well pad to reduce the footprint of operations,
- Proper siting, design, and construction of gas production and fluid disposal wells, and
- Groundwater quality monitoring coupled with fracturing fluid chemical disclosures.

With adequate safeguards in place, shale gas can be exploited responsibly in ways that protect both the environment and human health.

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