RFF REPORT

The Natural Gas Revolution

Resource Library

Kristin Hayes and Skyler Roeshot

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RESOURCES FOR THE FUTURE

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THE NATURAL GAS REVOLUTION: RESOURCE LIBRARY

Kristin Hayes and Skyler Roeshot[1]

Introduction

In April 2014, researchers at Resources for the Future (RFF) released *The Natural Gas Revolution: Critical Questions for a Sustainable Energy Future*.[2] The report reviews the literature in a number of different areas related to the enormous growth in natural gas production and use in the United States, as well as the international consequences of this natural gas revolution. It draws on this vast literature to help elucidate remaining critical research questions—those issues that, if resolved, would fundamentally advance the debate about how to best ensure long-term, sustainable natural gas development.

This companion piece, the Resource Library, characterizes and categorizes (with brief added detail) the literature reviewed in researching and writing the report. The library includes many of the original report references and also adds a number of additional resources, organized within the same seven categories as outlined in the report: natural gas supply, demand, economic impacts, environmental impacts, climate implications, regulatory structures and best practices, and international issues. A set of broad, general resources is also noted at the beginning.

A few important notes about the Resource Library:

- Links are provided to all available references. For most journal articles, the link points to the primary journal page, but it is possible that these references are also available online in other locations.
- Readily available reference abstracts are included with many entries. In most cases, these abstracts have been lightly edited for clarity, but the content is, for all intents and purposes, unchanged. Our minor changes include, for example, edits to avoid the original authors' first-person voices, as well as judicious cuts that helped achieve consistency in length but did not change conclusions or tone.
- Finally, references preceded with a ($) symbol are behind a paywall, and require payment (or a journal subscription) for full access.

Information on natural gas development continue to come out daily, and the authors acknowledge that this Resource Library is by no means complete. Nonetheless, we hope that this extensive list will provide valuable information and support to other scholars undertaking research in this area.

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[2] Krupnick, Alan J., Raymond J. Kopp, Kristin Hayes, and Skyler Roeshot. 2014. *The Natural Gas Revolution: Critical Questions for a Sustainable Energy Future*. Washington, DC: Resources for the Future.

General

BP (British Petroleum). 2013. BP Statistical Review of World Energy June 2013. London: BP.

BPC (Bipartisan Policy Center). 2012. Shale Gas: New Opportunities, New Challenges. Washington, DC: BPC.

Deloitte Center for Energy Solutions and Deloitte MarketPoint. 2011. Navigating a Fractured Future: Insights into the Future of the North American Natural Gas Market. Washington, DC: Deloitte.

EIA (US Energy Information Administration). 2012. Annual Energy Outlook 2012 with Projections to 2035. Washington, DC: EIA.

EIA (US Energy Information Administration). 2012. Assumptions to the Annual Energy Outlook 2012, Oil and Gas Supply Module. Washington, DC: EIA.

EIA (US Energy Information Administration). 2013. Annual Energy Outlook 2013 with Projections to 2040. Washington, DC: EIA.

EIA (US Energy Information Administration). 2013. Glossary: Natural Gas. Washington, DC: EIA.

EIA (US Energy Information Administration). 2014. Henry Hub Natural Gas Spot Price. Washington, DC: EIA.

EIA (US Energy Information Administration). 2014. Short-Term Energy Outlook. Washington, DC: EIA.

EMF (Energy Modeling Forum). 2013. Changing the Game? Emissions Markets and Implications of New Natural Gas Supplies. Stanford, CA: Stanford University.

GAO (US Government Accountability Office). 2012. Information on Shale Resources, Development, and Environmental and Public Health Risks. Washington, DC: GAO.

Gowrishankar, Vignesh. 2012. EPA's Regulations Would Not Be a Burden on the Natural Gas Industry, Says Bloomberg Government. Natural Resources Defense Council *Switchboard*, August 1.

Groundwater Protection Council and ALL Consulting. 2009. Modern Shale Gas Development in the United States: A Primer. Washington, DC: US Department of Energy Office of Fossil Energy and National Energy Technology Laboratory.

Hughes, J. David. 2011. Will Natural Gas Fuel America in the 21st Century? Santa Rosa, CA: Post Carbon Institute.

Hughes, J. David. 2013. Drill, Baby, Drill: Can Unconventional Fuels Usher in a New Era of Energy Abundance? Santa Rosa, CA: Post Carbon Institute.

This report provides an in-depth evaluation of the various unconventional energy resources behind the recent "energy independence" rhetoric, particularly shale gas, tight oil (shale oil), and tar sands. In particular, the shale portions of this report are based on the analysis of production data for 65,000 wells from 31 shale plays using the DI Desktop/HPDI database, which is widely used in industry and government.

IEA (International Energy Agency). 2012. Golden Rules for a Golden Age of Gas. Paris: IEA.

($) IEA (International Energy Agency). 2013. World Energy Outlook 2013. Paris: IEA.

IHS. 2012. America's New Energy Future: The Unconventional Oil and Gas Revolution and the US Economy. Washington, DC: IHS. (*Requires registration.*)

King, George E. 2012. Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know about Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil

Wells. Paper presented at the Society of Petroleum Engineers Hydraulic Fracturing Technology Conference, The Woodlands, TX, February.

Krupnick, Alan J., Raymond J. Kopp, Kristin Hayes, and Skyler Roeshot. 2014. The Natural Gas Revolution: Critical Questions for a Sustainable Energy Future. Washington, DC: Resources for the Future.

MIT (Massachusetts Institute of Technology) Energy Initiative. 2011. The Future of Natural Gas. Cambridge: Massachusetts Institute of Technology.

NETL (National Energy Technology Laboratory). 2013. Modern Shale Gas Development in the United States: An Update. Washington, DC: US Department of Energy.

Shale Gas Production Subcommittee of the Secretary of Energy Advisory Board. 2011. Shale Gas Production Subcommittee Second Ninety Day Report. Washington, DC: US Department of Energy.

Whitney, Gene, Carl E. Behrens, and Carol Glover. 2010. U.S. Fossil Fuel Resources: Terminology, Reporting, and Summary. Washington, DC: Congressional Research Service.

Supply

($) Browning, John, Svetlana Ikonnikova, Gurcan Gulen, and Scott W. Tinker. 2013. Barnett Shale Production Outlook. *SPE Economics & Management* 5 (3): 89–104. doi:10.2118/165585-PA.

The authors developed a production-outlook model on the basis of an interdisciplinary analysis of production data from more than 15,000 wells and geologic data on the Barnett play. The model is the most granular to date because it incorporates 10 tiers of varying productivity and well economics of average wells by tier; it covers close to 8,000 square-mile blocks across partly drained and undrilled acreage, divided between low-Btu and high-Btu segments, and uses drillwell potential by tier for the total area; and it is unique in its use of production profiles on the basis of transient linear drainage. Drilling pace is adjusted to changes in natural gas price relative to well economics, historical attrition rates, and logistical constraints. The authors analyze scenarios and conduct a simulation analysis on the basis of reasonable ranges for natural gas price, remaining acreage developable in partly drained and undrilled blocks, improvement in technology and well cost performance, and economic limit for shutting in a well. The Barnett is the most exploited shale play in the world; cumulative production to 2012 is 13 trillion cubic feet. The analysis indicates remaining recovery of approximately 2.5 times of cumulative production in the base case, but this is subject to many uncertainties. Base case results are consistent with actual production in 2011 and 2012.

Browning, John, Scott W. Tinker, Svetlana Ikonnikova, Gurcan Gulen, Eric Potter, Qilong Fu, Susan Horvath, Tad Patzek, Frank Male, William Fisher, Forrest Roberts, and Ken Medlock III. 2013. Study Develops Decline Analysis, Geologic Parameters for Reserves, Production Forecast. *Oil & Gas Journal* 111 (8): 62–73.

($) Davies, Richard J., Simon Mathias, Jennifer Moss, Steinar Hustoft, and Leo Newport. 2012. Hydraulic Fractures: How Far Can They Go? *Marine and Petroleum Geology* 37 (1): 1–6.

The maximum reported height of an upward propagating hydraulic fracture from several thousand fracturing operations in the Marcellus, Barnett, Woodford, Eagle Ford, and Niobrara Shales in the United States is ~588 meters (m). Of the 1,170 natural hydraulic fracture pipes imaged with three-dimensional seismic data offshore of West Africa and mid-Norway, the maximum height is ~1106 m. Based on these empirical data, the probability of a stimulated and natural hydraulic fracture extending vertically >350 m is ~1 percent and ~33 percent,

respectively. Constraining the probability of stimulating unusually tall hydraulic fractures in sedimentary rocks is extremely important as an evidence base for decisions on the safe vertical separation between the depth of stimulation and rock strata not intended for penetration.

EIA (US Energy Information Administration). 2011. Natural Gas Processing Plants in the United States: 2010 Update. Washington, DC: EIA.

EIA (US Energy Information Administration). 2013. About U.S. Natural Gas Pipelines: Transporting Natural Gas. Washington, DC: EIA.

EIA (US Energy Information Administration). 2013. Natural Gas Reserves Summary as of Dec. 31. Washington, DC: EIA.

EIA (US Energy Information Administration). 2013. Natural Gas Storage Working Capacity Grows 2% in 2012. Today in Energy. Washington, DC: EIA.

EIA (US Energy Information Administration). 2013. Shale Gas (Billion Cubic Feet): Proved Reserves as of Dec. 31. Washington, DC: EIA.

EIA (US Energy Information Administration). 2013. Shale Oil and Shale Gas Resources Are Globally Abundant. Washington, DC: EIA.

EIA (US Energy Information Administration). 2013. Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries outside the United States. Washington, DC: EIA.

Geman, Hélyette, and Steve Ohana. 2009. Forward Curves, Scarcity and Price Volatility in Oil and Natural Gas Markets. *Energy Economics* 31 (4): 576–85. doi:10.1016/j.eneco.2009.01.014.

The role of inventory in explaining the shape of the forward curve and spot price volatility in commodity markets is central in the theory of storage developed by Kaldor and has since been documented in a vast body of financial literature, including the reference paper by Fama and French on metals. In this paper, the authors seek to validate in the case of oil and natural gas the use of the slope of the forward curve as a proxy for inventory (the slope being defined in a way that filters out seasonality) and analyze directly for these two major commodities the relationship between inventory and price volatility. In agreement with the theory of storage, they find that the negative correlation between price volatility and inventory is globally significant for crude oil, and that this negative correlation prevails only during those periods of scarcity when the inventory is below the historical average and increases importantly during the winter periods for natural gas. Their results are illustrated by analysis of a 15-year database of US oil and natural gas prices and inventory.

($) Gülen, Gürcan, John Browning, Svetlana Ikonnikova, and Scott W. Tinker. 2013. Well Economics across Ten Tiers in Low and High Btu (British Thermal Unit) Areas, Barnett Shale, Texas. *Energy* 60:302–15. doi:10.1016/j.energy.2013.07.041.

This article evaluates the economics of drilling new wells in the Barnett Shale, Fort Worth Basin, Texas. The analysis was the most granular public study to date, based on 10 productivity tiers and treating low and high British thermal unit (Btu) segments of the play differently. It uses transient linear drainage production profiles that match the physics of the system and fit the production history in the Barnett very well. Average low Btu wells in the top two tiers are viable at $4/MMBtu, whereas average high Btu wells in the same tiers are economic at $2/MMBtu. Dry gas wells are the most sensitive to fluctuations in the price of natural gas, whereas high Btu wells are also sensitive to the prices of oil and natural gas liquids. There is a distribution of productivity within each tier, with better wells requiring a much lower price to be viable than the average well. The granular subdivision of productivity, low versus high Btu,

and intratier quality variation help explain historical drilling patterns and also allow the authors to predict future development patterns in the field accurately.

IER (Institute for Energy Research). 2011. North American Energy Inventory. Washington, DC: Institute for Energy Research.

INGAA (Interstate Natural Gas Association of America) Foundation. 2011. North American Natural Gas Midstream Infrastructure through 2035: A Secure Energy Future. Washington, DC: INGAA Foundation.

This study assesses midstream natural gas infrastructure needs through 2035 and includes an extensive update of natural gas, natural gas liquids (NGL), and oil production trends based on projections of drilling activity, the recoverable resource base, and prevailing market conditions. A new methodology has been employed to better estimate the new well connection, gathering system, and gas processing plant capacity that will be needed over time. With extensive upstream development occurring outside traditional, conventional gas supply regions that generally are well served by existing pipelines, new midstream natural gas infrastructure represents a critical link that will benefit both natural gas producers and consumers.

IPAA (Independent Petroleum Association of America). 2013. Oil and Natural Gas "Reserves"—Definitions Matter. Washington, DC: IPAA.

($) Kirkland, Joel. 2013. Marcellus Production Gets Big Boost from New Pipes and Processors—Bentek. *EnergyWire*, August 16.

($) Lin, Boqiang, and Presley K. Wesseh Jr. 2013. What Causes Price Volatility and Regime Shifts in the Natural Gas Market. *Energy* 55 (15): 553–63.

Gas sector volatility is of interest because it affects decisions made by producers and consumers and also influences investors' decisions in gas-related investments, portfolio allocation, and risk management. This paper therefore attempts to explain the behavior of natural gas index returns and in so doing proposes application of a pure Markov-switching volatility model whose variance is subject to shift in regime. The authors show that regime switching is clearly present in the natural gas market and should not be ignored. All autoregressive conditional heteroskedasticity (ARCH) effects that show up in weekly natural gas index returns data die out almost completely after allowing for Markov-switching variance. Volatility regimes identified by the model correlate well with major events affecting supply and demand for natural gas. Out-of-sample tests indicate that the regime-switching model performs noticeably better than a wide range of volatility models considered regardless of evaluation criteria, thus providing a better framework for the policymaker or financial historian interested in studying factors behind the evolution of volatility and for natural gas futures traders interested in short-term volatility forecasts. As risk-hedging decisions rely critically on assumptions about volatility, policies based on the transition probabilities are likely to be more conservative.

ND (North Dakota) Pipeline Authority. 2013. Facts on Natural Gas and Flaring in North Dakota. Bismarck: ND Pipeline Authority.

PGC (Potential Gas Committee). 2013. Potential Gas Committee Reports Significant Increase in Magnitude of U.S. Natural Gas Resource Base. Golden, CO: PGC.

Demand

BNSF (Burlington Northern Santa Fe) Railway. 2013. BNSF to Test Liquefied Natural Gas in Road Locomotives. Fort Worth, TX: BNSF.

Bromberg, L., and W. K. Cheng. 2010. Methanol as an Alternative Transportation Fuel in the United States: Options for Sustainable and/or Energy-Secure Transportation. Cambridge, MA: Sloan Automotive Laboratory.

Methanol has been promoted as an alternative transportation fuel from time to time over the past 40 years. In spite of significant efforts to realize the vision of methanol as a practical transportation fuel in the United States, such as the California methanol fueling corridor of the 1990s, it did not succeed on a large scale. This white paper covers all important aspects of methanol as a transportation fuel.

Burtraw, Dallas, Karen Palmer, Anthony Paul, and Matthew Woerman. 2012. Secular Trends, Environmental Regulations and Electricity Markets. *Electricity Journal* 25 (6): 35–47.

The confluence of several pending environmental rulemakings will require billions of dollars of investment across the industry and changes in the operation of facilities. These changes may lead to retirement of some facilities, and there has been much debate about their potential effects on electricity reliability. Only very exceptional circumstances would trigger supply disruptions; however, the changes may affect electricity prices, the generation mix, and industry revenues. Coincident with these new rules, expectations about natural gas prices and future electricity demand growth are changing in ways that also will have substantial effects on the industry. This paper addresses these two sets of issues using a detailed simulation model of the US electricity market. The findings suggest that recent downward adjustments in natural gas prices and electricity demand projections have a substantially larger impact on electricity prices and generation mix than do the new environmental rules.

Center for Climate and Energy Solutions (C2ES). 2012. Natural Gas in the Industrial Sector. Arlington, VA: C2ES.

Center for Climate and Energy Solutions (C2ES). 2012. Natural Gas Use in the Transportation Sector. Arlington, VA: C2ES.

Clean Energy. 2013. Clean Energy, Ferus Natural Gas Fuels, GE Join Forces to Jointly Deliver Liquefied Natural Gas. Newport Beach, CA: Clean Energy Fuels Corp.

Coskata. 2014. Feedstock Potential. Warrenville, IL: Coskata.

Deloitte Center for Energy Solutions. 2013. The Rise of the Midstream: Shale Reinvigorates Midstream Growth. Washington, DC: Deloitte Center for Energy Solutions.

Deloitte Center for Energy Solutions and Deloitte MarketPoint. 2011. Made in America: The Economic Impact of LNG Exports from the United States. Washington, DC: Deloitte.

EIA (US Energy Information Administration). 2012. Effect of Increased Natural Gas Exports on Domestic Energy Markets. Washington, DC: EIA.

EIA (US Energy Information Administration). 2013. Natural Gas Consumption by End Use. Washington, DC: EIA.

EIA (US Energy Information Administration). 2013. U.S. Natural Gas Exports and Re-exports by Country. Washington, DC: EIA.

EIA (US Energy Information Administration). 2014. US Natural Gas Exports and Re-exports by Point of Exit. Washington, DC: EIA.

EY (Ernst & Young). 2013. Global LNG: Will New Demand and New Supply Mean New Pricing? London, UK: EY.

Fraas, Arthur G., Winston Harrington, and Richard D. Morgenstern. 2013. Cheaper Fuels for the Light-Duty Fleet: Opportunities and Barriers. Discussion paper 13-28. Washington, DC: Resources for the Future.

The shale gas revolution in the United States has dropped the price of natural gas (NG) significantly. Combined with new fuel and vehicle technologies, an opportunity exists to expand the use of NG throughout the economy, including in the light-duty fleet of cars and trucks. This expansion could involve the direct combustion of the gas in the form of compressed natural gas or liquid petroleum gas or, alternatively, the use of NG-based liquid fuels such as ethanol or methanol. This paper examines the potential economic, environmental, and national security gains from replacing a portion of the domestic gasoline use in the light-duty fleet with these various NG-based fuels. Also examined are the regulatory barriers to the expanded use of the fuels. The authors find that these NG-based fuels could yield significant fuel cost savings relative to conventional gasoline in the light-duty fleet, along with gains to national security and possibly some environmental benefits.

Hughes, J. David. 2011. Will Natural Gas Fuel America in the 21st Century? Santa Rosa, CA: Post Carbon Institute.

Krupnick, Alan J. 2011. Will Natural Gas Vehicles Be in Our Future? Issue brief 11-06. Washington, DC: Resources for the Future.

Recently, interest in natural gas as a transportation fuel has grown as the availability of shale gas resources has dramatically expanded and gasoline prices have spiked. This issue brief investigates the evidence for and against natural gas vehicles (NGVs) as a reasonable option to their closest alternatives, focusing on both light-duty vehicles (LDVs) running on compressed natural gas (CNG), compared with conventional gasoline vehicles and electric hybrids, and heavy-duty trucks running on liquefied natural gas (LNG), compared with diesel trucks. Comparisons are based on several original analyses, using data from the National Energy Modeling System (as modified by RFF), automobile manufacturers, and other key sources. The results suggest that LNG trucks can, under certain conditions, be a good deal for society in reducing oil and CO_2 emissions with reasonably competitive cost-effectiveness, even without government subsidies or mandates. Indeed, under certain more restrictive conditions, they can have attractive payback periods. Infrastructure issues may be less challenging than commonly thought, because the interstate trucking industry is moving increasingly from a long-haul route structure to a "hub and spoke" structure—a development that could facilitate more judicious placement of LNG refueling stations and therefore make use of LNG trucks more prevalent. For LDVs, however, natural gas as a fuel remains a tough sell without policies that price carbon or otherwise favor gas over oil.

Krupnick, Alan, Zhongmin Wang, and Yushuang Wang. 2013. Sector Effects of the Shale Gas Revolution in the United States. Washington, DC: Resources for the Future.

This paper reviews the impact of the shale gas revolution on the sectors of electricity generation, transportation, and manufacturing in the United States. Natural gas is being substituted for other fuels, particularly coal, in electricity generation, resulting in lower greenhouse gas emissions from this sector. The use of natural gas in the transportation sector is currently negligible but is projected to increase with investments in refueling infrastructure and natural gas vehicle technologies. Petrochemical and other manufacturing industries have responded to lower natural gas prices by investing in domestically located manufacturing projects. The authors also speculate on the impact of a possible shale gas boom in China.

Lee, April, Owen Zinaman, and Jeffrey Logan. 2012. Opportunities for Synergy between Natural Gas and Renewable Energy in the Electric Power and Transportation Sectors. Washington, DC: NREL (National Renewable Energy Laboratory) and JISEA (Joint Institute for Strategic Energy Analysis).

Lee, April, Owen Zinaman, Jeffrey Logan, Morgan Bazilian, Douglas Arent, and Robin L. Newmark. 2012. Interactions, Complementarities and Tensions of the Nexus of Natural Gas and Renewable Energy. *Electricity Journal* 25 (10): 38–48. doi:10.1016/j.tej.2012.10.021.

Natural gas and renewable energy technologies enjoy many complementarities spanning economic, technical, environmental, and political considerations. The authors discuss how these complementarities arise from their similarities, which include improved environmental performance compared with coal and oil and their ability to contribute to a robust US economy, but note that it is from their dissimilarities that the biggest opportunities for mutually beneficial collaboration can be found.

Logan, Jeffrey, Garvin Heath, Jordan Macknick, Elizabeth Paranhos, William Boyd, and Ken Carlson. 2012. Natural Gas and the Transformation of the U.S. Energy Sector: Electricity. Denver: Joint Institute for Strategic Energy Analysis.

Logan, Jeffrey, Anthony Lopez, Trieu Mai, Carolyn Davidson, Morgan Bazilian, and Douglas Arent. 2013. Natural Gas Scenarios in the US Power Sector. *Energy Economics* 40:183–195.

The US power sector is being transformed by the recent rise in the availability and use of unconventional natural gas, specifically shale gas. That transformation has already produced some of the most significant changes in the operation of the portfolio of electricity generation since World War II. Further implications are likely. To that end, this article presents results from numerical modeling of different US power sector futures. These futures assess questions affecting today's natural gas and electric power markets, including the impacts of forthcoming EPA rules on power plants, decarbonization options such as a clean energy standard (CES), potential improvements in key generation technologies, expanded use of natural gas outside the power generation sector, and higher costs for natural gas production, assumed to arise from more robust environmental and safety practices in the field. The simulations were done using the Regional Energy Deployment System (ReEDS) model looking out to the year 2050. This capacity expansion model determines the least-cost combination of generation options that fulfill a variety of user-defined constraints such as projected load, capacity reserve margins, emissions limitations, and operating lifetimes. The baseline scenario shows strong growth in natural gas generation, leading to a roughly 2.5-fold increase in gas demand by 2050. Many other scenarios also see strong growth in gas-fired generation, highlighting questions about portfolio diversity, climate change, and research and development prioritization.

Montgomery, W. David, and Sugandha D. Tuladhar. 2013. Macroeconomic Impacts of LNG Exports from the United States. Washington, DC: NERA Economic Consulting.

Murkowski, Lisa. 2013. The Narrowing Window: America's Opportunity to Join the Global Gas Trade. Washington, DC: Office of Senator Lisa Murkowski.

Paul, Anthony, Blair Beasley, and Karen L. Palmer. 2013. Taxing Electricity Sector Carbon Emissions at Social Cost. Discussion paper 13-23-REV. Washington, DC: Resources for the Future.

Concerns about budget deficits, tax reform, and climate change are fueling discussions about taxing carbon emissions to generate revenue and reduce greenhouse gas emissions, which this paper considers. Imposing a carbon tax on electricity production based on the social cost of carbon (SCC) could generate between $21 and $82 billion in revenues in 2020 and would have important effects on electricity markets. The sources of emissions reductions in the sector

depend on the level of the tax. A carbon tax based on lower SCC estimates reduces emissions by reducing demand and through the substitution of gas for coal, whereas taxes based on higher SCC estimates induce switching to wind and nuclear generation. The slow rate of growth of the SCC estimates means that any SCC-based carbon tax trajectory provides weaker long-run incentives for expanded renewable and nuclear generation than a cap-and-trade program that achieves an equivalent level of cumulative carbon dioxide emissions reductions. Taxing carbon at the SCC is welfare enhancing, but the SCC may not be the optimal tax rate.

PWC (PricewaterhouseCoopers). 2012. Shale Gas: Reshaping the Chemicals Industry. New York, NY: PWC.

This paper examines the impact of shale gas on domestic chemical companies, which has been to decrease the costs of both raw materials and energy. It is estimated that the US chemicals industry investment in ethylene production has increased capacity by 33 percent. As these investments take hold, yielding more supply, the United States could become a major global low-cost provider of energy. Volumes from natural gas separation plants are expected to increase more than 40 percent over the next five years.

Ratner, Michael, Paul W. Parfomak, Ian F. Fergusson, and Linda Luther. 2013. U.S. Natural Gas Exports: New Opportunities, Uncertain Outcomes. Washington, DC: Congressional Research Service.

Economic

ACC (American Chemistry Council). 2011. Shale Gas and New Petrochemicals Investment: Benefits for the Economy, Jobs, and US Manufacturing. Washington, DC: ACC.

ACC (American Chemistry Council). 2012. Shale Gas, Competitiveness and New US Investment: A Case Study of Eight Manufacturing Industries. Washington, DC: ACC.

This case study analyzes the effects of renewed competitiveness and the supply response among eight key manufacturing industries: paper, chemicals, plastic and rubber products, glass, iron and steel, aluminum, foundries, and fabricated metal products industries. ACC finds a tremendous opportunity for shale gas to strengthen US manufacturing, boost economic output, and create jobs.

Allcott, Hunt, and Daniel Keniston. 2014. Dutch Disease or Agglomeration? The Local Economic Effects of Natural Resource Booms in Modern America. Working paper. New York: New York University Department of Economics.

Does natural resource production benefit producer economies, or does it instead create a "Natural Resource Curse," perhaps as Dutch Disease crowds out the manufacturing sector? The authors combine a new panel dataset of oil and gas production and reserves with public data and restricted-access microdata from the Census of Manufactures and Longitudinal Business Database to estimate how oil and gas booms have affected growth in US counties since the 1960s. They find that a boom that doubles national oil and gas employment increases total employment by 3.5 percent in a county with one standard deviation larger oil and gas endowment. Despite substantial migration, wages also rise. Notwithstanding, manufacturing employment and output are actually procyclical with resource booms, because many manufacturers in resource-abundant counties supply inputs to the oil and gas sector, while many others sell locally traded goods and benefit from increases in local demand. Manufacturers' revenue productivity and value added per worker are also procyclical with oil and gas, especially in linked and local industries, but there is no evidence that output prices rise. The results demonstrate how a meaningful share of manufacturers produce locally traded

goods and highlight how linkages to natural resources can be a driver of manufacturing growth.

Barth, Jannette M. 2010. Unanswered Questions about the Economic Impact of Gas Drilling in the Marcellus Shale: Don't Jump to Conclusions. Croton on Hudson, NY: JM Barth & Associates.

Barth, Jannette M.2013. The Economic Impact of Shale Gas Development on State and Local Economies: Benefits, Costs, and Uncertainties. *New Solutions* 23 (1): 85–101.

It is often assumed that natural gas exploration and development in the Marcellus Shale will bring great economic prosperity to state and local economies. Policymakers need accurate economic information on which to base decisions regarding permitting and regulation of shale gas extraction. This paper provides a summary review of research findings on the economic impacts of extractive industries, with an emphasis on peer-reviewed studies. The conclusions from the studies are varied and imply that further research, on a case-by-case basis, is necessary before definitive conclusions can be made regarding both short- and long-term implications for state and local economies.

Batheja, Aman. 2013. Cash for Road Repair in Shale Areas Proves Elusive. *Texas Tribune*, April 26.

Brown, Cassarah. 2013. State Revenues and the Natural Gas Boom: An Assessment of State Oil and Gas Production Taxes. Washington, DC: National Conference of State Legislatures.

Brown, Stephen P. A., and Alan J. Krupnick. 2010. Abundant Shale Gas Resources: Long-Term Implications for US Natural Gas Markets. Discussion paper 10-41. Washington, DC: Resources for the Future.

According to recent assessments, the United States has considerably more recoverable natural gas in shale formations than was previously thought. Such a development raises expectations that US energy consumption will shift toward natural gas. To examine how the apparent abundance of natural gas and projected growth of its use might affect natural gas prices, production, and consumption, the authors use the NEMS-RFF model for a number of scenarios—reflecting different perspectives on natural gas availability, the availability of competing resources, demand for natural gas, and climate policy—through 2030. They find that more abundant shale gas resources create an environment in which natural gas prices are likely to remain attractive to consumers—even as policy advances additional uses of natural gas to reduce carbon dioxide emissions and bolster energy security.

Brown, Stephen P. A., and Mine K. Yücel. 2013. The Shale Gas and Tight Oil Boom: US States' Economic Gains and Vulnerabilities. New York: Council on Foreign Relations.

Brundage, Tracy L., Timothy W. Kelsey, Janice Lobdell, Larry L. Michael, Jeffrey Jacquet, James R. Ladlee, Jeffrey F. Lorson, and Thomas B. Murphey. 2011. Pennsylvania Statewide Marcellus Shale Workforce Needs Assessment. Williamsport, PA: Marcellus Shale Education and Training Center.

Burtraw, Dallas, Karen Palmer, Anthony Paul, and Matthew Woerman. 2012. Secular Trends, Environmental Regulations and Electricity Markets. *Electricity Journal* 25 (6): 35–47.

The confluence of several pending environmental rulemakings will require billions of dollars of investment across the industry and changes in the operation of facilities. These changes may lead to retirement of some facilities, and there has been much debate about their potential effects on electricity reliability. Only very exceptional circumstances would trigger supply disruptions; however, the changes may affect electricity prices, the generation mix, and industry revenues. Coincident with these new rules, expectations about natural gas prices and future electricity demand growth are changing in ways that also will have substantial effects

on the industry. This paper addresses these two sets of issues using a detailed simulation model of the US electricity market. The findings suggest that recent downward adjustments in natural gas prices and electricity demand projections have a substantially larger impact on electricity prices and generation mix than do the new environmental rules.

Christopherson, Susan, and Ned Rightor. 2011. How Should We Think about the Economic Consequences of Shale Gas Drilling? Working Paper Series. Ithaca, NY: Cornell University.

In New York and Pennsylvania, the public debate about the prospect or continuation of high volume hydraulic fracturing (HVHF) for shale gas has revolved around its environmental impacts, particularly its effects on water quality, while taking as a given that exploitation of this new natural gas asset will produce significant economic benefits for the states' economies. This paper argues that the economic impact models that have been used to project potential benefits and job creation provide only a fraction of the information needed to understand how this new kind of natural gas drilling will affect communities in Pennsylvania and New York. The authors point out that to fully assess the economic effects, policymakers and citizens need to understand what will drive the pace and scale of drilling and the associated boom-bust cycle. This cycle will have implications for jobs, revenues, the cumulative impact of shale gas development, and the longer-term economic development prospects for drilling regions within the Marcellus Shale area.

Considine, Timothy J. 2010. The Economic Impacts of the Marcellus Shale: Implications for New York, Pennsylvania, and West Virginia. Laramie, WY: American Petroleum Institute.

Considine, Timothy J., Robert Watson, and Seth Blumsack. 2010. The Economic Impact of the Pennsylvania Marcellus Shale Natural Gas Play: An Update. University Park: Pennsylvania State University.

Considine, Timothy J., Robert Watson, and Seth Blumsack. 2011. The Pennsylvania Marcellus Natural Gas Industry: Status, Economic Impacts and Future Potential. University Park: Pennsylvania State University.

Considine, Timothy J., Robert W. Watson, and Nicholas B. Considine. 2011. The Economic Opportunities of Shale Energy Development. New York: Manhattan Institute.

Continental Economics. 2012. The Economic Impacts of U.S. Shale Gas Production on Ohio Consumers. Sandia Park, NM: Continental Economics.

Costanza, Charles, and Timothy W. Kelsey. 2012. Marcellus Shale and Local Collection of State Taxes: What the 2011 Pennsylvania Tax Data Say. CECD Research Paper Series: Strengthening Pennsylvania's Communities. University Park: Pennsylvania State University, Center for Economic and Community Development (CECD).

Deloitte Center for Energy Solutions. 2013. The Rise of the Midstream: Shale Reinvigorates Midstream Growth. Washington, DC: Deloitte Center for Energy Solutions.

Deloitte Center for Energy Solutions and Deloitte MarketPoint. 2011. Made in America: The Economic Impact of LNG Exports from the United States. Washington, DC: Deloitte.

Ecology and Environment. 2011. Economic Assessment Report for the Supplemental Generic Environmental Impact Statement on New York State's Oil, Gas, and Solution Mining Regulatory Program. Prepared for New York State Department of Environmental Conservation. Lancaster, NY: Ecology and Environment.

Food & Water Watch. 2013. The Social Cost of Fracking: A Pennsylvania Case Study. Washington, DC: Food & Water Watch.

($) Gopalakrishnan, Sathya, and H. Allen Klaiber. 2014. Is the Shale Energy Boom a Bust for Nearby Residents? Evidence from Housing Values in Pennsylvania. *American Journal of Agricultural Economics* 96 (1): 43–66. doi:10.1093/ajae/aat065.

Profitable extraction of previously inaccessible shale energy reserves has led to the rapid expansion of shale exploration across the United States. This article presents one of the first empirical studies to measure the impact of early shale exploration on surrounding homeowners using data from Washington County, Pennsylvania, from 2008 to mid-2010. The authors find that property values are negatively impacted by shale gas exploration activity, but this impact depends on the proximity and intensity of shale activity and is largely transitory. The negative effects are larger for households located close to major highways and sourced with private well water.

Green, Mark. 2013. Our Promising Energy Present and Future. *Energy Tomorrow Blog*, September 4.

Haggerty, Julia, Patricia H. Gude, Mark Delorey, and Ray Rasker. 2013. Oil and Gas Extraction as an Economic Development Strategy in the American West: A Longitudinal Performance Analysis, 1980–2011. Bozeman, MT: Headwaters Economics.

This study evaluates the relationships between oil and natural gas specialization and socioeconomic well-being during 1980–2011 in a large sample of counties within the six major oil- and gas-producing states in the interior US West: Colorado, Montana, New Mexico, North Dakota, Utah, and Wyoming. The authors consider the effects of participation in the early 1980s oil and gas boom and long-term specialization as possible drivers of socioeconomic outcomes. They use generalized estimating equations to regress 11 measures of economic growth and quality of life on oil and gas specialization while accounting for various confounding factors, including degree of access to markets, initial socioeconomic conditions in 1980, and dependence on other economic sectors. They observe long-term oil and gas specialization to have negative effects on change in per capita income, crime rate, and education rate. Participation in the early 1980s boom is positively associated with change in per capita income; however, the positive effect decreases the longer counties remain specialized in oil and gas. The authors' findings contribute to a broader public dialogue about the consequences of resource specialization involving oil and natural gas and call into question the assumption that long-term oil and gas development confers economic advantages on host communities.

Hefley, William E., Shaun M. Seydor, Michelle K. Bencho, Ian Chappel, Max Dizard, John Hallman, Julia Herkt, Pei Jiuan Jiang, Matt Kerec, Fabian Lampe, Christopher L. Lehner, Tingyu (Grace) Wei, Bill Birsic, Emily Coulter, Erik M. Hatter, Donna Jacko, Samuel Mignogna, Nicholas Park, Kaitlin Riley, Tom Tawoda, Eric Clements, and Roman Harlovic. 2011. The Economic Impact of the Value Chain of a Marcellus Shale Well. Pittsburgh, PA: University of Pittsburgh.

This study seeks to fill a critical information gap on the impact of gas drilling and extraction from Marcellus Shale deposits deep underground. It is an assessment of the economic impacts emphasizing the direct economic impact of a Marcellus Shale well in southwestern Pennsylvania, rather than just focusing on the perceived benefits and impacts affecting the region. The analysis is based on extensive field research, including a site visit and interviews with industry participants. It is further cross-validated by examining similar costs for development of Marcellus wells by a vertically integrated exploration and production firm.

($) Houser, Trevor, and Shashank Mohan. 2014. Fueling Up: The Economic Implications of America's Oil and Gas Boom. Washington, DC: Peterson Institute for International Economics.

IHS. 2012. The Economic and Employment Contributions of Unconventional Gas Development in State Economies. Washington, DC: IHS.

IHS Global Insight. 2011. The Economic and Employment Contributions of Shale Gas in the United States. Washington, DC: IHS Global Insight (USA).

INGAA (Interstate Natural Gas Association of America) Foundation. 2012. Jobs & Economic Benefits of Midstream Infrastructure Development: US Economic Impacts through 2035. Washington, DC: INGAA Foundation.

This study estimates the economic impact of the $200 billion (in 2011$) in midstream investments that will be required to accommodate the development of natural gas, oil, and natural gas liquid (NGL) resources from 2012 through 2035. Near-term estimates through 2013 and through 2016 also are developed. The estimated economic impact of these investments is measured in terms of employment creation, income generation, output, taxes generated, and value added to the US economy and study regions.

Kelsey, Timothy W. n.d.2010. Regional and Local Community Economic Impacts of Natural Gas Development. Presented at the Pennsylvania State University Legislative Information Session, University Park, PA, August.

Kelsey, Timothy W., Riley Adams, and Scott Milchak. 2012. Real Property Tax Base, Market Values, and Marcellus Shale: 2007 to 2009. University Park, PA: Pennsylvania State University.

Kelsey, Timothy W., Martin Shields, James R. Ladlee, and Melissa Ward. 2011. Economic Impacts of Marcellus Shale in Susquehanna County: Employment and Income in 2009. University Park, PA: Marcellus Shale Education and Teaching Center.

This study examines the economic impact of several key unexplored aspects of Marcellus Shale natural gas development in Pennsylvania. Previous economic studies did not examine where leasing and royalty dollars are actually going and how they are being spent. The economic impact will differ depending on how many dollars go to Pennsylvania households, to the state government, and to nonresidents. How much of that money is immediately spent by recipients and how much is saved will also make a difference, as will the proportion of wages being paid to non-Pennsylvania workers. The findings of this study suggest that the economic impact of Marcellus Shale activity in Pennsylvania ranged between 23,385 and 23,884 jobs and $3.1 and $3.2 billion in 2009. This included about $1.2 billion in labor income and almost $1.9 billion in value added to the state's economy. In addition, the 2009 activity will have additional economic impacts in future years as mineral rights owners spend the leasing and royalty income they received that year but saved for later use. These are large economic impacts, especially as much of this impact is occurring in relatively small counties. This study did not estimate the tax impacts.

Kelsey, Timothy W., Martin Shields, James R. Ladlee, and Melissa Ward. 2012. Economic Impacts of Marcellus Shale in Susquehanna County: Employment and Income in 2010. University Park, PA: Marcellus Shale Education and Teaching Center.

Kowalski, Lindsay, and Gary Zajac. 2012. A Preliminary Examination of Marcellus Shale Drilling Activity and Crime Trends in Pennsylvania. University Park: Pennsylvania State University.

Comparing the pre-Marcellus (2006–2007) and post-Marcellus (2008–2010) breakout periods, this study finds no consistent increases in Pennsylvania State Police (PSP) incidents/calls for service or uniform crime report (UCR) arrest statistics in the counties with top Marcellus Shale activity. However, the trend in PSP incidents/calls for service in the rural counties that have had no Marcellus activity is dissimilar to that of the Marcellus-active counties; specifically, PSP calls for service have been steadily declining in non-Marcellus areas during the post-Marcellus breakout period, but the Marcellus areas have experienced a more variable pattern of both PSP calls and UCR arrests. It is difficult to detect strong trends within such a short time period, and

any observed changes may be due to natural variation. More time needs to elapse in the post-Marcellus era in order to measure the impact on PSP activity or UCR arrest data. Moreover, this study would be enhanced by exploring additional measures of crime and by more specific comparisons to non-Marcellus regions.

Levy, Marc. 2011. Rowdiness Follows Employment Boom in Pennsylvania's Fracking Frontier. *Fort Wayne News-Sentinel*, October 31.

McElfish, James M., Jr. 2014. Shale Gas Impact Fees in Pennsylvania Communities. Presented at Resources for the Future's Exploring the Local Impacts of Shale Gas Development seminar, Washington, DC, April.

($) Michaels, Guy. 2011. The Long Term Consequences of Resource-Based Specialisation. *Economic Journal* 121 (551): 31–57.

Using geological variation in oil abundance in the southern United States, the author examines the long-term effects of resource-based specialization through economic channels. In 1890, oil-abundant counties were similar to other nearby counties, but after oil was discovered, they began to specialize in its production. From 1940 to 1990, oil abundance increased local employment per square kilometer, especially in mining but also in manufacturing. Oil-abundant counties had higher population growth, higher per capita income, and better infrastructure.

Montgomery, W. David, and Sugandha D. Tuladhar. 2013. Macroeconomic Impacts of LNG Exports from the United States. Washington, DC: NERA Economic Consulting.

Muehlenbachs, Lucija, Elisheba Spiller, and Christopher Timmins. 2013. The Housing Market Impacts of Shale Gas Development. Discussion paper 13-39. Washington, DC: Resources for the Future.

Using data from Pennsylvania and New York and an array of empirical techniques to control for confounding factors, the authors recover hedonic estimates of property value impacts from shale gas development that vary with geographic scale, water source, well productivity, and visibility. Results indicate large negative impacts on nearby groundwater-dependent homes, while piped-water-dependent homes exhibit smaller positive impacts, suggesting benefits from lease payments. On a broader geographic scale, the authors find that new wellbores increase property values, but that these effects diminish over time. Undrilled permits cause property values to decrease. The results have implications for the debate over regulation of shale gas development.

Muehlenbachs, Lucija, Elisheba Spiller, and Christopher Timmins. 2013. Shale Gas Development and the Costs of Groundwater Contamination. Discussion paper 12-40-REV. Washington, DC: Resources for the Future.

While shale gas development can result in rapid local economic development, negative externalities associated with the process may adversely affect the prices of nearby homes. This study uses a difference-in-differences estimator with additional controls for house fixed effects and the boundary of the public water service area in Washington County, Pennsylvania, to identify the capitalization of groundwater contamination risk in property values, differentiating it from other externalities, lease payments to homeowners, and local economic development. The authors find that proximity to wells increases property values. However, groundwater contamination concerns fully offset those gains by reducing property values up to 26 percent.

Orr, Steve. 2011. Fracking: Bane or Boon? A Look into Industry's Presence in PA. *Rochester (NY) Democrat & Chronicle*, December 18.

Ozpehriz, Niyazi. 2010. The State Taxation of Natural Gas Severance in the United States: A Comparative Analysis of Tax Base, Rate, and Fiscal Importance. Pittsburgh: Heinz School of Public Policy, Carnegie Mellon University.

PBPC (Pennsylvania Budget and Policy Center). 2012. All Counties with Producing Marcellus Shale Wells Adopt Impact Fee. Harrisburg: PBPC.

PBPC (Pennsylvania Budget and Policy Center). 2013. Pa.'s Marcellus Impact Fee Comes Up Short: Fee Revenue Fails to Keep Up with Rising Value of Gas Production. Harrisburg: PBPC.

Plumer, Brad. 2013. Here's How the Shale Gas Boom Is Saving Americans Money. *Wonkblog*, *Washington Post*, December 18.

($) Scafft, Kai A., Yetkin Borlu, and Leland Glenna. 2013. The Relationship between Marcellus Shale Gas Development in Pennsylvania and Local Perceptions of Risk and Opportunity. *Rural Sociology* 78 (2): 143–66. doi:10.1111/ruso.12004.

Recent advances in gas and oil drilling technology have led to dramatic boomtown development in many rural areas that have endured extended periods of economic decline. In Pennsylvania's Marcellus gas fields, the recent development of unconventional shale gas resources has not been without controversy. It has been variously framed as a major opportunity for economic revitalization at the local and regional levels and energy independence at the national level, but also as a significant environmental risk, with uncertain and uneven economic benefits. The authors use data from a survey conducted in 309 school districts located within Pennsylvania's Marcellus Shale region to study the ways local stakeholders perceive both risk and opportunity associated with gas extraction from Marcellus Shale. Their analyses indicate a strong positive association between perceptions of risk and opportunity associated with gas extraction. Further, the intensity of perception of both risk and opportunity is directly associated with the amount of local drilling, suggesting the complexity of local contexts within which local stakeholders evaluate rapid boomtown-associated community change. In total, these findings complicate the framing of unconventional gas extraction in the Marcellus Shale region, and indeed boomtown growth overall, as fundamentally polarizing issues.

Weber, Jeremy G. 2012. The Effects of a Natural Gas Boom on Employment and Income in Colorado, Texas, and Wyoming. *Energy Economics* 34 (5): 1580–88. doi:10.1016/j.eneco.2011.11.013.

Improvements in technology have made it profitable to tap unconventional gas reservoirs in relatively impermeable shale and sandstone deposits, which are spread throughout the United States, mostly in rural areas. Proponents of gas drilling point to the activity's local economic benefits, yet no empirical studies have systematically documented the magnitude or distribution of economic gains. The author estimates these gains for counties in Colorado, Texas, and Wyoming, three states where natural gas production expanded substantially since the late 1990s. He finds that a large increase in the value of gas production caused modest increases in employment, wage and salary income, and median household income. The results suggest that each million dollars in gas production created 2.35 jobs in the county of production, which led to an annualized increase in employment that was 1.5 percent of the preboom level for the average gas boom county. Comparisons show that ex-ante estimates of the number of jobs created by developing the Fayetteville and Marcellus Shale gas formations may have been too large.

Williamson, Jonathan, and Bonita Kolb. 2011. Marcellus Natural Gas Development's Effect on Housing in Pennsylvania. Williamsport: Center for the Study of Community and the Economy.

Environmental

Abdalla, Charles W. 2010. Water Withdrawals for Development of Marcellus Shale Gas in Pennsylvania. University Park: Pennsylvania State University.

Adams, Mary Beth, Pamela J. Edwards, W. Mark Ford, Joshua B. Johnson, Thomas M. Schuler, Melissa Thomas-Van Gundy, and Frederica Wood. 2011. Effects of Development of a Natural Gas Well and Associated Pipeline on the Natural and Scientific Resources of the Fernow Experimental Forest. Newtown Square, PA: US Department of Agriculture.

Development of a natural gas well and pipeline on the Fernow Experimental Forest, West Virginia, was begun in 2007. Concerns were raised about the effects on the natural and scientific resources of the Fernow, set aside in 1934 for long-term research. A case study approach was used to evaluate effects of the development. This report includes results of monitoring projects as well as observations related to unexpected impacts on the resources of the Fernow. Two points are obvious: that some effects can be predicted and mitigated through cooperation between landowner and energy developer, and that unexpected impacts will occur. These unexpected impacts may be most problematic.

Adams, Mary Beth, W. Mark Ford, Thomas M. Schuler, and Melissa Thomas-VanGundy. 2011. Effects of Natural Gas Development on Forest Ecosystems. Paper presented at the 17th Central Hardwood Forest Conference, Lexington, KY, April 2010.

In 2004, an energy company leased the privately owned minerals that underlie the Fernow Experimental Forest in West Virginia. The Fernow, established in 1934, is dedicated to long-term research. In 2008, a natural gas well was drilled on the Fernow and a pipeline and supporting infrastructure were constructed. The authors describe the impacts of natural gas development on the Fernow's natural resources and develop recommendations for landowners and land managers based on their experiences. Some of the effects (forest clearing, erosion, road damage) were expected and predictable, and others (vegetation death from land application of fluids, an apparent increase in white-tailed deer presence) were unexpected. Although this is a case study, and thus the results and conclusions are not applicable to all hardwood forests, information about gas development impacts is sufficiently rare that forest managers, research scientists, and the concerned public can learn from the authors' experience.

ADEQ (Arkansas Department of Environmental Quality). 2011. Emissions Inventory & Ambient Air Monitoring of Natural Gas Production in the Fayetteville Shale Region. North Little Rock: ADEQ.

Adgate, John L., Bernard D. Goldstein, and Lisa M. McKenzie. 2013. Public Health Risks of Shale Gas Development. Paper presented at the NRC Shale Gas Committee Workshop, Washington, DC, May.

This review summarizes the existing literature on the human health risks associated with shale gas development in the United States. Using a public health approach, the authors examine the chemical and nonchemical stressors associated with high-volume hydraulic fracturing, a technological advance that has led to a rapid increase in the development and recovery of shale gas resources. They explore potential health effects in workers and communities, existing quantitative health risk estimates, and the perceived risks from development. They also identify major uncertainties to address when prioritizing research needed to inform the cumulative risk estimation process.

($) Adgate, John L., Bernard D. Goldstein, and Lisa M. McKenzie. 2014. Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development. *Environmental Science & Technology* Article ASAP (February):14. doi:10.1021/es404621d.

The rapid increase in unconventional natural gas (UNG) development in the United States during the past decade has brought wells and related infrastructure closer to population centers. This review evaluates risks to public health from chemical and nonchemical stressors associated with UNG, describes likely exposure pathways and potential health effects, and identifies major uncertainties to address with future research. The most important occupational stressors include mortality, exposure to hazardous materials, and increased risk of industrial accidents. For communities near development and production sites, the major stressors are air pollutants, ground and surface water contamination, truck traffic and noise pollution, accidents and malfunctions, and psychosocial stress associated with community change.

ALA (American Lung Association), APHA (American Public Health Association), ATS (American Thoracic Society), AAFA (Asthma and Allergy Foundation of America), and TAH (Trust for America's Health). 2011. Comments on Oil and Natural Gas Sector: Reviews of New Source Performance Standards and National Emissions Standards for Hazardous Air Pollutants, Docket ID No. EPA-HQ-OAR-2010-0505.

Alder, R., H. J. Boermans, J. E. Moulton, and D. A. Moore. 1992. Toxicosis in Sheep Following Ingestion of Natural Gas Condensate. *Veterinary Pathology Online* 29 (11): 11–20. doi:10.1177/030098589202900102.

Thirty of 200 ewes died or were euthanized during a 21-day period following a l-day accidental exposure to natural gas condensate, a complex mixture of hydrocarbons obtained during collection of natural gas from wells. Despite access to potable well water, the poisoned ewes willingly consumed toxic doses of condensate that contaminated surface water. Eight animals died without premonitory signs; the remainder became ill over the course of a few days to 3 weeks. The principal cause of mortality was aspiration pneumonia, but myocardial degeneration and necrosis, renal tubular damage, gastritis, enteritis, and meningeal edema and hyperemia were also observed. Gas chromatographic analysis identified chemical traces of the hydrocarbons in the tissues, and "fingerprinting," the process of matching chromatographic tracings, provided forensic proof of the contamination source. Atomic absorption spectroscopy and cholinesterase analyses were performed to eliminate the possibility of toxicosis by heavy metal contaminants or other constituents. This appears to be the first reported incidence of natural gas condensate toxicity involving sheep or other ruminants.

Bamberger, Michelle, and Robert E. Oswald. 2012. Impacts of Gas Drilling on Human and Animal Health. *New Solutions* 22 (1): 51–77. doi:10.2190/NS.22.1.e.

With the expansion of shale gas drilling operations, environmental concerns surrounding drilling for gas are intense. Controversy surrounding the impact of drilling on air and water quality has pitted industry and leaseholders against individuals and groups concerned with environmental protection and public health. Because animals often are exposed continually to air, soil, and groundwater and have more frequent reproductive cycles, they can be used as sentinels to monitor impacts to human health. This study involved interviews with animal owners who live near gas drilling operations. The findings illustrate which aspects of the drilling process may lead to health problems and suggest modifications that would lessen but not eliminate impacts. Complete evidence regarding health impacts of gas drilling cannot be obtained because of incomplete testing and disclosure of chemicals, and nondisclosure

agreements. Without rigorous scientific studies, the gas drilling boom sweeping the world will remain an uncontrolled health experiment on an enormous scale.

($) Bernstein, Paula, Thomas C. Kinnaman, and Mengqi Wu. 2013. Estimating Willingness to Pay for River Amenities and Safety Measures Associated with Shale Gas Extraction. *Eastern Economic Journal* 39 (1): 28–44.

This paper uses a contingent valuation method survey of a random sample of residents to estimate that households are willing to pay an average of US$12 per month for public projects designed to improve river access and US$10.46 per month for additional safety measures that would eliminate risks to local watersheds from drilling for natural gas from underground shale formations. These estimates can be compared with the costs of providing each of these two amenities to help foster the formation of efficient policy decisions.

Bowen, Zachary H., and Aida Farag. 2013. Ecological Considerations in Shale Gas Development. Presented at the Workshop on Risks of Unconventional Shale Gas Development, Washington, DC, May.

($) Braiser, Kathryn J., Diane K. McLaughlin, Danielle Rhubart, Richard C. Stedman, Matthew R. Filteau, and Jeffrey Jacqet. 2013. Risk Perceptions of Natural Gas Development in the Marcellus Shale. *Environmental Practice* 15 (2): 108–22. doi:10.10170S1466046613000021.

Exploration and extraction of natural gas from the Marcellus Shale have created considerable controversy. At the core of these debates are differing perceptions of the level and types of risks involved with the extraction activities, such as hydraulic fracturing, truck traffic, air emissions, and population growth. Risks described include the potential for human and environmental health implications, as well as community change and economic gain. This article explores the nature of perceived risks associated with Marcellus Shale development by using data from a household survey (*N* = 1,917) conducted in 2009–2010 in Pennsylvania and New York counties located in the core areas of the Marcellus Shale region. The article describes a quantitative measure of risk perceptions. Statistical analyses of the data indicate that trust in institutions responsible for managing the risks associated with development and attitudes related to relationships between people and nature are associated strongly with perceptions of risk. Other associated variables include reported knowledge of environmental, social, and economic impacts; mineral rights ownership; demographic characteristics (gender, income); and state of residence. Implications of these findings are discussed, particularly as related to improving local discourse surrounding Marcellus Shale development.

Brown, David R. 2013. Southwest Pennsylvania Environmental Health Project. Presented at the Workshop on Risks of Unconventional Shale Gas Development, Washington, DC, May 30–31.

Brufatto, Cladio, Jamie Cochran, Lee Conn, David Power, Said Zaki Abd Alla El-Zeghaty, Berard Fraboulet, Tom Griffin, Simon James, Trevor Munk, Frederico Justus, Joseph R. Levine, Carl Mongomery, Dominic Murphy, Jochen Pfeiffer, Tiraputra Pompoch, and Lara Richmani. 2003. From Mud to Cement—Building Gas Wells. *Oilfield Review* 15 (3): 62–76.

CBD (Center for Biological Diversity), LPFW (Los Padres Forest Watch), and Sierra Club. 2011. Protest of BLM's September 14, 2011, Competitive Oil and Gas Sale. Tucson, AZ, Santa Barbara, CA, San Francisco, CA: CBD, LPFW, and Sierra Club.

($) Colborn, Theo, Carol Kwiatkowski, Kim Schultz, and Mary Bachran. 2011. Natural Gas Operations from a Public Health Perspective. *Human and Ecological Risk Assessment: An International Journal* 17 (5): 1039–56. doi:10.1080/10807039.2011.605662.

The technology to recover natural gas depends on undisclosed types and amounts of toxic chemicals. The authors compiled a list of 944 products containing 632 chemicals used during natural gas operations, then conducted literature searches to determine potential health effects of the 353 chemicals identified by Chemical Abstract Service (CAS) numbers. They find that more than 75 percent of the chemicals could affect the skin, eyes, and other sensory organs and the respiratory and gastrointestinal systems. Approximately 40–50 percent could affect the brain/nervous system, immune and cardiovascular systems, and kidneys; 37 percent could affect the endocrine system; and 25 percent could cause cancer and mutations. These results indicate that many chemicals used during the fracturing and drilling stages of gas operations may have long-term health effects that are not immediately expressed. In addition, the authors provide an example of waste evaporation pit residuals that contained numerous chemicals on the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Emergency Planning and Community Right-to-Know Act (EPCRA) lists of hazardous substances. The discussion highlights the difficulty of developing effective water quality monitoring programs. To protect public health, the authors recommend full disclosure of the contents of all products, extensive air and water monitoring, coordinated environmental/human health studies, and regulation of fracturing under the US Safe Drinking Water Act.

($) Colborn, Theo, Kim Schultz, Lucille Herrick, and Carol Kwiatkowski. 2012. An Exploratory Study of Air Quality near Natural Gas Operations. *Human and Ecological Risk Assessment: An International Journal* 20 (1): 86–105.

This exploratory study was designed to assess air quality in a rural western Colorado area where residences and gas wells coexist. Sampling was conducted before, during, and after drilling and hydraulic fracturing of a new natural gas well pad. Weekly air sampling for one year revealed that the number of nonmethane hydrocarbons (NMHCs) and their concentrations were highest during the initial drilling phase and did not increase during hydraulic fracturing in this closed-loop system. Methylene chloride, a toxic solvent not reported in products used in drilling or hydraulic fracturing, was detected 73 percent of the time, several times in high concentrations. A literature search of the health effects of the NMHCs revealed that many had multiple health effects, including 30 that affect the endocrine system, which is susceptible to chemical impacts at very low concentrations, far less than government safety standards. Selected polycyclic aromatic hydrocarbons (PAHs) were at concentrations greater than those at which prenatally exposed children in urban studies had lower developmental and IQ scores. The human and environmental health impacts of the NMHCs, which are ozone precursors, should be examined further given that the natural gas industry is now operating in close proximity to human residences and public lands.

($) Cotton, Matthew. 2013. NIMBY or Not? Integrating Social Factors into Shale Gas Community Engagements. *Natural Gas & Electricity Journal* 29 (9): 8–12. doi:10.1002/gas.21678.

Currie, Janet, Joshua S. Graff Zivin, Katherin Meckel, Matthew J. Neidell, and Wolfram Schlenker. 2013. Something in the Water: Contaminated Drinking Water and Infant Health. Cambridge, MA: National Bureau of Economic Research.

This paper provides estimates of the effects of in utero exposure to contaminated drinking water on fetal health. The authors examined birth records and drinking water testing results for the state of New Jersey from 1997 to 2007. Their data enabled them to compare outcomes across siblings who were potentially exposed to differing levels of harmful contaminants from drinking water while in utero. They find small effects of drinking water contamination on all children, but large and statistically significant effects on birth weight and gestation of infants born to less educated mothers. The study also shows that those mothers who were most

affected by contaminants were the least likely to move between births in response to contamination.

Davies, Richard J., Sam Almond, Robert S. Ward, Robert B. Jackson, Charlotte Adams, Fred Worrall, Liam G. Herringshaw, Jon G. Gluyas, and Mark A. Whitehead. 2014. Oil and Gas Wells and Their Integrity: Implications for Shale and Unconventional Resource Exploitation. *Marine and Petroleum Geology*. doi:10.1016/j.marpetgeo.2014.03.001.

DiGiulio, Dominic C., Richard T. Wilkin, Carlyle Miller, and Gregory Oberley. 2011. Investigation of Ground Water Contamination near Pavillion, Wyoming. Ada, OK: US Environmental Protection Agency.

DOI (US Department of the Interior). 2010. 12-Month Findings for Petitions to List the Greater Sage-Grouse (*Centrocercus urophasianus*) as Threatened or Endangered. 75 Fed. Reg. 13910–14014 (March 23).

DRBC (Delaware River Basin Commission). 2009. Determination of the Executive Director Concerning Natural Gas Extraction Activities in Shale Formations within the Drainage Area of Special Protected Waters. West Trenton, NJ: DRBC.

($) Drohan, P. J., M. Brittingham, J. Bishop, and K. Yoder. 2012. Early Trends in Landcover Change and Forest Fragmentation Due to Shale-Gas Development in Pennsylvania: A Potential Outcome for the Northcentral Appalachians. *Environmental Management* 49 (5): 1061–75. doi:10.1007/s00267-012-9841-6.

Worldwide shale gas development has the potential to cause substantial landscape disturbance. The northeastern United States, specifically the Allegheny Plateau in Pennsylvania, West Virginia, Ohio, and Kentucky, is experiencing rapid exploration. Using Pennsylvania as a proxy for regional development across the plateau, the authors examine land cover change due to shale gas exploration, with emphasis on forest fragmentation. Pennsylvania's shale gas development is greatest on private land and is dominated by pads with one to two wells; less than 10 percent of pads have five wells or more. Approximately 45–62 percent of pads occur on agricultural land and 38–54 percent in forestland (many in core forest on private land). Development of permits granted as of June 3, 2011, would convert at least 644–1,072 hectares (ha) of agricultural land and 536–894 ha of forestland. Agricultural land conversion suggests that drilling is somewhat competing with food production. Accounting for existing pads and development of all permits would result in at least 649 kilometers of new road, which, along with pipelines, would fragment forest cover. The Susquehanna River basin (feeding the Chesapeake Bay) is most developed, with 885 pads (26 percent in core forest); permit data suggests the basin will experience continued heavy development. The intensity of core forest disturbance, where many headwater streams occur, suggests that such streams should become a focus of aquatic monitoring. Given the intense development on private lands, the authors believe a regional strategy is needed to help guide infrastructure development so that habitat loss, farmland conversion, and the risk to waterways are better managed.

($) Drohan, Patrick J., James C. Finley, Paul Roth, Thomas M. Schuler, Susan L. Stout, Margaret C. Brittingham, and Nels C. Johnson. 2012. Oil and Gas Impacts on Forest Ecosystems: Findings Gleaned from the 2012 Goddard Forum at Penn State University. *Environmental Practice* 14 (4): 394–99. doi:10.10170S1466046612000300.

This article looks at findings from the 2012 Goddard Forum, "Oil and Gas Development Impacts on Forested Ecosystems: Research and Management Challenges," hosted by the Pennsylvania State University. Energy production presents numerous challenges to both

industry and land managers across the globe. The recent development of unconventional (shale gas) plays around the world has brought attention to the potential for rapid change in affected landscapes and associated ecosystem services. While shale gas development specifically has been the focus of recent research on how landscapes are changing, continued scientific investigation can lessen the resulting ecosystem disturbance across all energy infrastructure.

($) Entrekin, Sally, Michelle Evans-White, Brent Johnson, and Elisabeth Hagenbuch. 2011. Rapid Expansion of Natural Gas Development Poses a Threat to Surface Waters. *Frontiers in Ecology and the Environment* 9 (9): 503–11. doi:10.1890/110053.

This article examines the multiple environmental threats to surface waters posed by the extraction of natural gas from hard-to-reach reservoirs, which has rapidly expanded around the world. Improved drilling and extraction technology used to access low permeability natural gas requires millions of liters of water and a suite of chemicals that may be toxic to aquatic biota. There is growing concern among the scientific community and the general public that rapid and extensive natural gas development in the United States could lead to degradation of natural resources. Gas wells are often close to surface waters that could be impacted by elevated sediment runoff from pipelines and roads, alteration of streamflow as a result of water extraction, and contamination from introduced chemicals or the resulting wastewater. However, the data required to fully understand these potential threats are currently lacking. The authors conclude that scientists therefore need to study the changes in ecosystem structure and function caused by natural gas extraction and use such data to inform sound environmental policy.

EPA (US Environmental Protection Agency). 2011. Addressing Air Emissions from the Oil and Natural Gas Industry. Washington, DC: EPA.

EPA (US Environmental Protection Agency). 2012. Overview of Final Amendments to Air Regulations for the Oil and Natural Gas Industry. Washington, DC: EPA.

EPA (US Environmental Protection Agency). 2012. Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources: Progress Report. Office of Research and Development. Washington, DC: EPA.

ERG (Eastern Research Group) and Sage Environmental Consulting Group. 2011. City of Fort Worth Natural Gas Air Quality Study. Fort Worth: City of Fort Worth.

Everly, Steve. 2012. *UPDATE IV* Eight Worst Inputs Used in Colorado Health Study. Washington, DC: Energy in Depth.

($) Ferrar, Kyle J., Jill Kriesky, Charles L. Christen, Lynne P. Marshall, Samantha L. Malone, Ravi K. Sharma, Drew R. Michanowicz, and Bernard D. Goldstein. 2013. Assessment and Longitudinal Analysis of Health Impacts and Stressors Perceived to Result from Unconventional Shale Gas Development in the Marcellus Shale Region. *International Journal of Occupational and Environmental Health* 19 (2): 104–12.

Concerns for health and social impacts have arisen as a result of Marcellus Shale unconventional natural gas development. This paper documents the self-reported health impacts and mental and physical health stressors perceived to result from Marcellus Shale development. The authors conducted two sets of interviews with a convenience sample of community members living proximal to Marcellus Shale development. They coded the symptoms of health impacts and sources of psychological stress, and quantified symptom and stressor counts for each interview. The counts for each participant were compared longitudinally. The results show that participants attributed 59 unique health impacts and 13

stressors to Marcellus Shale development. Stress was the most frequently reported symptom. Over time, perceived health impacts increased while stressors remained constant. The authors conclude that exposure-based epidemiological studies are needed to address identified health impacts and those that may develop as unconventional natural gas extraction continues. They further note that many of the stressors can be addressed immediately.

($) Ferrar, Kyle J., Drew R. Michanowicz, Charles L. Christen, Ned Mulcahy, Samantha L. Malone, and Ravi K. Sharma. 2013. Assessment of Effluent Contaminants from Three Facilities Discharging Marcellus Shale Wastewater to Surface Waters in Pennsylvania. *Environmental Science & Technology* 47 (7): 3472–81.

Unconventional natural gas development in Pennsylvania has created a new wastewater stream. In an effort to stop the discharge of Marcellus Shale unconventional natural gas development wastewaters into surface waters, on May 19, 2011, the Pennsylvania Department of Environmental Protection (PADEP) requested that drilling companies stop disposing their wastewater through wastewater treatment plants (WWTPs). This assessment includes a chemical analysis of effluents discharged from three WWTPs before and after the aforementioned request. The WWTPs sampled include two municipal, publicly owned treatment works and a commercially operated industrial wastewater treatment plant. The authors quantified analyte concentrations and then compared them to water quality criteria, including US Environmental Protection Agency (EPA) maximum contaminant levels (MCLs) and "human health criteria." They measured certain analytes, including barium, strontium, bromides, chlorides, total dissolved solids, and benzene, in the effluent at concentrations above criteria. They then compared analyte concentrations measured in effluent samples before and after the PADEP's request for each facility. Analyte concentrations in the effluents decreased in the majority of samples after the PADEP's request ($p < .05$). The authors conclude that this research provides preliminary evidence that these and similar WWTPs may not be able to provide sufficient treatment for this wastewater stream, and they recommend more thorough monitoring.

($) Flewelling, Samuel A., and Manu Sharma. 2013. Constraints on Upward Migration of Hydraulic Fracturing Fluid and Brine. *Groundwater* 52 (1): 9–19. doi:10.1111/gwat.12095.

Recent increases in the use of hydraulic fracturing (HF) to aid extraction of oil and gas from black shales have raised concerns regarding potential environmental effects associated with predictions of upward migration of HF fluid and brine. Some recent studies have suggested that such upward migration can be large and that timescales for migration can be as short as a few years. This article discusses the physical constraints on upward fluid migration from black shales (e.g., the Marcellus, Bakken, and Eagle Ford) to shallow aquifers, taking into account the potential changes to the subsurface brought about by HF. A review of the literature indicates that HF affects a limited portion of the entire thickness of the overlying bedrock and therefore is unable to create direct hydraulic communication between black shales and shallow aquifers via induced fractures. As a result, upward migration of HF fluid and brine is controlled by preexisting hydraulic gradients and bedrock permeability. The authors show that in cases where there is an upward gradient, permeability is low, upward flow rates are low, and mean travel times are long (often >106 years). Consequently, the authors conclude that the recently proposed rapid upward migration of brine and HF fluid, predicted to occur as a result of increased HF activity, does not appear to be physically plausible. They argue that unrealistically high estimates of upward flow are the result of invalid assumptions about HF and the hydrogeology of sedimentary basins.

($) Fontenot, Brian E., Laura R. Hunt, Zacariah L. Hildenbrand, Doug D. Carlton Jr., Hyppolite Oka, Jayme L. Walton, Dan Hopkins, Alexandra Osorio, Bryan Bjorndal, Qinhong H. Hu, and Kevin A.

Schug. 2013. An Evaluation of Water Quality in Private Drinking Water Wells near Natural Gas Extraction Sites in the Barnett Shale Formation. *Environmental Science & Technology* 47 (17): 10032–40. doi:10.1021/es4011724.

Natural gas has become a leading source of alternative energy with the advent of techniques to economically extract gas reserves from deep shale formations. This article presents an assessment of private well water quality in aquifers overlying the Barnett Shale formation of North Texas. We evaluated samples from 100 private drinking water wells using analytical chemistry techniques. Analyses revealed that arsenic, selenium, strontium and total dissolved solids (TDS) exceeded the Environmental Protection Agency's Drinking Water Maximum Contaminant Limit (MCL) in some samples from private water wells located within 3 km of active natural gas wells. Lower levels of arsenic, selenium, strontium, and barium were detected at reference sites outside the Barnett Shale region as well as sites within the Barnett Shale region located more than 3 km from active natural gas wells. Methanol and ethanol were also detected in 29% of samples. Samples exceeding MCL levels were randomly distributed within areas of active natural gas extraction, and the spatial patterns in our data suggest that elevated constituent levels could be due to a variety of factors including mobilization of natural constituents, hydrogeochemical changes from lowering of the water table, or industrial accidents such as faulty gas well casings.

Food & Water Watch. 2013. The Social Cost of Fracking: A Pennsylvania Case Study. Washington, DC: Food & Water Watch.

Forrest, Richard. 2011. No More Drilling in the Dark: Exposing the Hazards of Natural Gas Production and Protecting America's Drinking Water and Wildlife Habitats. Reston, VA: National Wildlife Federation.

Freyman, Monika. 2014. Hydraulic Fracturing & Water Stress: Water Demand by the Numbers. Boston: Ceres.

Freyman, Monika, and Ryan Salmon. 2013. Hydraulic Fracturing and Water Stress: Growing Competitive Pressures for Water. Boston: Ceres.

Frohlich, Cliff, and Michael Brunt. 2013. Two-Year Survey of Earthquakes and Injection/Production Wells in the Eagle Ford Shale, Texas, Prior to the Mw4.8 20 October 2011 Earthquake. *Earth and Planetary Science Letters* 379:56–63.

Between November 2009 and September 2011, temporary seismographs deployed under the EarthScope USArray program were situated on a 70 kilometer (km) grid covering the Barnett Shale in Texas, recording data that allowed sensing and locating regional earthquakes with magnitudes 1.5 and larger. The authors analyzed these data and located 67 earthquakes, more than eight times as many as reported by the National Earthquake Information Center. All 24 of the most reliably located epicenters occurred in eight groups within 3.2 km of one or more injection wells. These included wells near Dallas–Fort Worth and Cleburne, where earthquakes near injection wells were reported by the media in 2008 and 2009, plus wells in six other locations, including several where no earthquakes had been reported previously. This suggests that injection-triggered earthquakes are more common than is generally recognized. All the wells nearest to the earthquake groups reported maximum monthly injection rates exceeding 150,000 barrels (24,000 cubic meters) of water per month since October 2006. However, while 9 of 27 such wells in Johnson County were near earthquakes, elsewhere no earthquakes occurred near wells with similar injection rates. The authors conclude that a plausible hypothesis to explain these observations is that injection triggers earthquakes only if injected fluids reach and relieve friction on a suitably oriented nearby fault that is experiencing regional tectonic stress. Testing this hypothesis would require identifying geographic regions

where interpreted subsurface structure information is available to determine whether there are faults near seismically active and seismically quiescent injection wells.

($) Fryzek, Jon, Susan Pastula, Xiaohui Jiang, and David H. Garabrant. 2013. Childhood Cancer Incidence in Pennsylvania Counties in Relation to Living in Counties with Hydraulic Fracturing Sites. *Journal of Occupational and Environmental Medicine* 55 (7): 796–801. doi:10.1097/JOM.0b013e318289ee02.

Galbraith, Kate. 2012. Texas Fracking Disclosures to Include Water Totals. *Texas Tribune*, January 16.

Gaudlip, A. W., and L. O. Paugh. 2008. Marcellus Shale Water Management Challenges in Pennsylvania. Richardson, TX: Society of Petroleum Engineers.

Gilmer, Ellen M. 2013. Geologists Link Oklahoma's Largest Quake to Injection Wells. *EnergyWire*, March.

Gleason, Robert, Tara Chesley-Preston, Todd Preston, Bruce Smith, Brian Tangen, and Joanna Thamke. 2011. Examination of Brine Contamination Risk to Aquatic Resources from Petroleum Development in the Williston Basin. Jamestown, ND: US Geological Survey.

Goodwin, Stephen, Ken Carlson, Caleb Douglas, and Ken Knox. 2012. Life Cycle Analysis of Water Use and Intensity of Oil and Gas Recovery in Wattenberg Field, Colo. *Oil & Gas Journal* 110 (5): 48–59.

Recent technological advances have stimulated growth in oil and gas development and operations, increasing the industry's need for water resources. Efficiency is an ever more important priority to meet this greater water resource demand, particularly in the US West. This study provides an analysis of the volume of water required for unconventional shale gas and oil development and how efficiently the water is used. It uses a general material balance to assess the life cycle of water and energy resources of 445 Noble Energy wells in Wattenberg Field in Colorado. The authors collected water use and oil and gas production data from these wells and separated them by well type (horizontal or vertical) and water use (drilling or hydraulic fracturing). They used a decline curve analysis to calculate the estimated ultimate recovery (EUR) from each individual well. Exponential and harmonic decline curves were fit to the production data to project low- and high-production scenarios. The authors then used a ratio of the water consumed and the EUR for each well to estimate the water intensity. They find the water intensity of shale gas extraction to be one of the lowest compared with other energy sources.

($) Gregory, Kelvin B., Radisav D. Vidic, and David A. Dzombak. 2011. Water Management Challenges Associated with the Production of Shale Gas by Hydraulic Fracturing. *Elements* 7 (3): 181–86. doi:10.2113/gselements.7.3.181.

Development of unconventional, onshore natural gas resources in deep shales is rapidly expanding to meet global energy needs. This article looks at the challenges of water management, which has emerged as a critical issue in the development of these inland gas reservoirs. After hydraulic fracturing is used to liberate the gas, large volumes of water containing very high concentrations of total dissolved solids (TDS) return to the surface. The TDS concentration in this wastewater, or "flowback," can reach five times that of seawater. Wastewaters that contain high TDS levels are challenging and costly to treat. Economical production of shale gas resources will require creative management of flowback to ensure protection of groundwater and surface water resources. Currently, deep-well injection is the primary means of management. However, in many areas where shale gas production will be abundant, deep-well injection sites are not available. The authors conclude that with global concerns over the quality and quantity of freshwater, novel water management strategies and

treatment technologies that enable environmentally sustainable and economically feasible natural gas extraction are critical for the development of this vast energy source.

Hansen, Evan, Dustin Mulvaney, and Meghan Betcher. 2013. Water Resource Reporting and Water Footprint from Marcellus Shale Development in West Virginia and Pennsylvania. Durango, CO: Earthworks Oil & Gas Accountability Project.

Harris, Colin G., and Ivan L. London. 2012. There's Something in the Air: New and Evolving Air Quality Regulations Impacting Oil and Gas Development. Paper presented at the 58th Annual Rocky Mountain Mineral Law Institute, Newport Beach, CA, July 19–21.

Heisig, Paul M., and Tia-Marie Scott. 2013. Occurrence of Methane in Groundwater of South-Central New York State, 2012—Systematic Evaluation of a Glaciated Region by Hydrogeologic Setting. Reston, VA: US Geological Survey.

This survey documents methane occurrence in groundwater on the basis of hydrogeologic setting within a glaciated area of south-central New York. Classes are based on topographic position (valley and upland), confinement or nonconfinement of groundwater by glacial deposits, well completion in fractured bedrock or sand and gravel, and hydrogeologic subcategories. Only domestic wells and similar purposed supply wells with well construction and log information were selected for classification. Field water quality characteristics (pH, specific conductance, dissolved oxygen, and temperature) were measured at each of 66 wells, and samples were collected and analyzed for dissolved gases, including methane and short-chain hydrocarbons. Results of sampling indicate strong positive and negative associations between hydrogeologic settings and methane occurrence, and that occurrence of methane in groundwater of the region is common. Wells completed in bedrock within valleys and under confined groundwater conditions were most closely associated with the highest methane concentrations. Methane in valley wells was predominantly thermogenic in origin, likely as a result of close vertical proximity to underlying methane-bearing saline groundwater and brine and possibly as a result of enhanced bedrock fracture permeability beneath valleys that provides an avenue for upward gas migration. This paper shows the importance of subsurface information (hydrogeology, well construction) in understanding methane occurrence and provides an initial conceptual framework that can be used in investigation of stray gas in the region.

Hill, Elaine. 2013. Shale Gas Development and Infant Health: Evidence from Colorado. Presented at the Population Association of American 2013 Annual Meeting, New Orleans, LA, April.

Building on the first study to find a causal relationship between shale gas development and infant health at birth, one conducted in Pennsylvania, this presentation uses Colorado to provide external validity by exploring health-at-birth implications of other shale plays and explores the risks associated with shale development compared with other forms of drilling. Detailed vital statistics and mothers' residential addresses are used to define close proximity to drilling activity and thereby exposure. It employs a triple difference estimator, controls for historical drilling, and uses the public water district boundaries to identify the impacts of groundwater contamination on infant health, which were not previously identified.

Hill, Elaine. 2013. Shale Gas Development and Infant Health: Evidence from Pennsylvania. Ithaca, NY: Cornell University.

This research on the impacts of shale gas development on infant health was in response to growing controversy around the drilling method of hydraulic fracturing increasingly employed on shale gas wells. Using detailed location data consisting of maternal addresses and geographic information system (GIS) coordinates of gas wells, this study examines singleton

births to mothers residing close to a shale gas well from 2003 to 2010 in Pennsylvania. The study finds that the introduction of drilling increased low birth weight and decreased term birth weight on average among mothers within close proximity to a well. Adverse effects were also detected using measures such as small for gestational age and Apgar scores, but no effects on gestation periods were found. These results are robust to other measures of infant health, many changes in specification, and falsification tests. The results do not differ across water source (public piped water or ground well water) and suggest that the mechanism is air pollution or stress from localized economic activity. These findings suggest that shale gas development poses significant risks to human health and have policy implications for regulation.

Hopey, Don. 2013. Marcellus Shale Drillers Face New Rules on Pollution. *Pittsburgh Post-Gazette*, August 9.

Iglar, Andrea. 2014. Findlay Residents near Airport Raise Concerns about Proximity of Gas Well Drilling to their Homes. *Pittsburgh Post-Gazette*, February 27.

Jackson, Robert B., Avner Vengosh, Thomas H. Darrah, Nathaniel R. Warner, Adrian Down, Robert J. Poreda, Stephen G. Osborn, Kaiguang Zhao, and Jonathan D. Karr. 2013. Increased Stray Gas Abundance in a Subset of Drinking Water Wells Near Marcellus Shale Gas Extraction. *Proceedings of the National Academy of Sciences* 110 (28): 11250–55.

Horizontal drilling and hydraulic fracturing are transforming energy production, but their potential environmental effects remain controversial. The authors analyzed 141 drinking water wells across the Appalachian Plateaus physiographic province of northeastern Pennsylvania, examining natural gas concentrations and isotopic signatures with proximity to shale gas wells. Methane was detected in 82 percent of drinking water samples. For homes less than 1 kilometer (km) from natural gas wells, average concentrations of methane were 6 times higher, ethane was 23 times higher, and propane was detected in 10 water wells. Of three factors previously proposed to influence gas concentrations in shallow groundwater, distance to gas wells was highly significant for methane concentrations, whereas distances to valley bottoms and the Appalachian Structural Front (a proxy for tectonic deformation) were not significant. Distance to gas wells also was the most significant factor for Pearson and Spearman correlation analyses. For ethane concentrations, distance to gas wells was the only statistically significant factor. Isotopic signatures, hydrocarbon ratios (methane to ethane and propane), and the ratio of the noble gas ^{4}He to methane in groundwater were characteristic of a thermally postmature Marcellus-like source in some cases. The authors conclude that overall, the data suggest that some homeowners living less than 1 km from gas wells have drinking water contaminated with stray gases.

Johnson, Nels, Tamara Gagnolet, Rachel Ralls, and Jessica Stevens. 2011. Natural Gas Pipelines: Excerpt from Report 2 of the Pennsylvania Energy Impacts Assessment. Arlington, VA: The Nature Conservancy.

Kasperson, Roger E., and Bonnie J. Ram. 2013. The Public Acceptance of New Energy Technologies. *Daedalus: The Journal of the American Academy of Arts & Sciences* 142 (1): 90–96.

($) Kassotis, Christopher D., Donald E. Tillitt, J. Wade Davis, Annette M. Hormann, and Susan C. Nagel. 2014. Estrogen and Androgen Receptor Activities of Hydraulic Fracturing Chemicals and Surface and Ground Water in a Drilling-Dense Region. *Endocrinology* 155 (3): 897–907. doi:10.1210/en.2013-1697.

The rapid rise in natural gas extraction using hydraulic fracturing increases the potential for contamination of surface water and groundwater from chemicals used throughout the process.

Hundreds of products containing more than 750 chemicals and components are potentially used throughout the extraction process, including more than 100 known or suspected endocrine-disrupting chemicals. The authors hypothesized that a selected subset of chemicals used in natural gas drilling operations and found in surface water and groundwater samples collected in a drilling-dense region of Garfield County, Colorado, would exhibit estrogen and androgen receptor activities. Water samples were collected, solid-phase extracted, and measured for estrogen and androgen receptor activities using reporter gene assays in human cell lines. Of the 39 unique water samples, 89 percent, 41 percent, 12 percent, and 46 percent exhibited estrogenic, antiestrogenic, androgenic, and antiandrogenic activities, respectively. Testing of a subset of natural gas drilling chemicals revealed novel antiestrogenic, novel antiandrogenic, and limited estrogenic activities. The Colorado River, the drainage basin for this region, exhibited moderate levels of estrogenic, antiestrogenic, and antiandrogenic activities, suggesting that higher localized activity at sites with known natural gas–related spills surrounding the river might be contributing to the multiple receptor activities observed in this water source. The majority of water samples collected from sites in a drilling-dense region of Colorado exhibited more estrogenic, antiestrogenic, or antiandrogenic activities than reference sites with limited nearby drilling operations. These data suggest that natural gas drilling operations may result in elevated endocrine-disrupting chemical activity in surface water and groundwater.

Keranen, Katie M., Heather M. Savage, Geoffrey A. Abers, and Elizabeth S. Cochran. 2013. Potentially Induced Earthquakes in Oklahoma, USA: Links between Wastewater Injection and the 2011 Mw 5.7 Earthquake Sequence. *Geology* 41:699–702. doi:10.1130/G34045.1.

Significant earthquakes are increasingly occurring within the continental interior of the United States, including five of moment magnitude (Mw) ≥ 5.0 in 2011 alone. Concurrently, the volume of fluid injected into the subsurface related to the production of unconventional resources continues to rise. This study identifies the largest earthquake potentially related to injection, an Mw 5.7 earthquake in November 2011 in Oklahoma. The earthquake was felt in at least 17 states and caused damage in the epicentral region. It occurred in a sequence, with two earthquakes of Mw 5.0 and a prolific sequence of aftershocks. The study uses the aftershocks to illuminate the faults that ruptured in the sequence and show that the tip of the initial rupture plane is within ~200 meters of active injection wells and within ~1 kilometers of the surface; 30 percent of early aftershocks occur within the sedimentary section. Subsurface data indicate that fluid was injected into effectively sealed compartments, and the authors interpret that a net fluid volume increase after 18 years of injection lowered effective stress on reservoir-bounding faults. Significantly, this case indicates that decades-long lags between the commencement of fluid injection and the onset of induced earthquakes are possible and modifies the authors' common criteria for fluid-induced events. The progressive rupture of three fault planes in this sequence suggests that stress changes from the initial rupture triggered the successive earthquakes, including one larger than the first.

Kibble, A., T. Cabianca, Z. Daraktchieva, T. Gooding, J. Smithard, G. Kowalczyk, N. P. McColl, M. Singh, S. Vardoulakis, and R. Kamanyire. 2013. Review of the Potential Public Health Impacts of Exposures to Chemical and Radioactive Pollutants as a Result of Shale Gas Extraction. London: Public Health England.

($) Kim, Won-Young. 2013. Induced Seismicity Associated with Fluid Injection into a Deep Well in Youngstown, Ohio. *Journal of Geophysical Research: Solid Earth* 118:3506–18. doi:10.1002/jgrb.50247.

More than 109 small earthquakes (Mw 0.4–3.9) were detected between January 2011 and February 2012 in the Youngstown, Ohio, area, where there had been no known earthquakes in

the past. These shocks were close to a deep fluid injection well. Among these shocks, 12 events greater than Mw 1.8 were detected by regional network and accurately relocated, whereas 97 smaller earthquakes were detected by the waveform correlation detector. Accurately located earthquakes were along a subsurface fault trending ENE-WSW—consistent with the focal mechanism of the main shock and occurring at depths of 3.5–4.0 kilometers in the Precambrian basement. The authors conclude that these earthquakes had been induced by the fluid injection at a deep injection well due to increased pore pressure along the preexisting subsurface faults located close to the wellbore. They find that the seismicity initiated at the eastern end of the subsurface fault, close to the injection point, and migrated toward the west, away from the wellbore, indicating that the expanding high fluid pressure front increased the pore pressure along its path and progressively triggered the earthquakes. They observe that several periods of quiescence of seismicity follow the minima in injection volumes and pressure, which may indicate that the earthquakes were directly caused by the pressure buildup and stopped when pressure dropped.

($) King, George E., and Daniel E. King. 2013. Environmental Risk Arising from Well-Construction Failure: Differences between Barrier and Well Failure, and Estimates of Failure Frequency across Common Well Types, Locations, and Well Age. *SPE Production & Operations* 28 (4): 22. doi:10.2118/166142-PA.

Kinik, Koray. 2012. Risk of Well Integrity Failure due Sustained Casing Pressure. Baton Rouge: Department of Petroleum Engineering, Louisiana State University.

Sustained casing pressure (SCP) is considered a well integrity problem. This study looks at SCP as environmental risk due to hydrocarbon release. Currently, the risk is qualified by the value of surface pressure (Pcsg) that may cause failure of the casing head. However, the resulting rate of gas emission to the atmosphere is not considered, nor is the possibility of breaching the casing shoe due to transmission of Pcsg downhole. This study develops methods for measuring maximum possible air emission rates (MER) and risk of subsurface well integrity failure due to SCP. Mathematical models and software are developed for computing MER, casing shoe strength (CSS) determined by leak-off test (LOT), and casing shoe pressure load resulting from SCP (SCPd). The models are used to find controlling parameters, identify the best and least-desirable scenarios, and assess environmental risk. The study concludes that emission potential of SCP wells with high wellhead pressure can be quite small.

Kinslow, Carla. 2011. Health Effects Review of Ambient Air Monitoring Data Collected by Titan Engineering, Inc. for Barnett Shale Energy Education Council. Austin, TX: Texas Commission on Environmental Quality.

($) Kiviat, Erik. 2013. Risks to Biodiversity from Hydraulic Fracturing for Natural Gas in the Marcellus and Utica Shales. *Annals of the New York Academy of Sciences* 1286 (1): 1–14. doi:10.1111/nyas.12146.

High-volume horizontal hydraulic fracturing (HVHHF) for mining natural gas from the Marcellus and Utica Shales is widespread in Pennsylvania and potentially throughout approximately 280,000 square kilometers of the Appalachian Basin. This study examines the risks to biodiversity from this activity. Physical and chemical impacts of HVHHF include pollution by toxic synthetic chemicals, salt, and radionuclides; landscape fragmentation by wellpads, pipelines, and roads; alteration of stream and wetland hydrology; and increased truck traffic. Despite concerns about human health, there has been little study of the impacts on habitats and biota. Taxa and guilds potentially sensitive to HVHHF impacts include freshwater organisms (e.g., brook trout, freshwater mussels), fragmentation-sensitive biota (e.g., forest-interior breeding birds, forest orchids), and species with restricted geographic

ranges (e.g., Wehrle's salamander, tongue-tied minnow). Impacts are potentially serious because of the rapid development of HVHHF over a large region.

($) Krauss, R. F. 2013. Addressing Well and Field Infrastructure Siting Challenges in the Wetlands and Streams of the Haynesville, Marcellus, Utica and Eagle Ford Shale Plays. Paper presented at the Society of Petroleum Engineers Americas E&P Health, Safety, Security and Environmental Conference, Galveston, TX, March.

As US shale play development for oil, natural gas, and natural gas liquids moves from appraisal to production phase, it is increasingly difficult for surface operations to avoid impacts to environmentally sensitive wetlands and streams. Many shale plays are in areas more visible to the general public than ever before, resulting in increased scrutiny by agencies. This paper examines the challenges faced by producers and operators, who must be more proactive in the siting of wells and associated field infrastructure and navigate complex regulatory regimes. Working under new rules since 2008, regulatory agencies require offsets for unavoidable impacts to wetlands and streams in the watershed where the impacts will occur. With limited mitigation acreage available in areas where surface rights are locked up by landowners and operators, and the increased visibility of environmental risk and liability from field operations, the need for proactive, creative wetland and stream mitigation solutions is evident. Only through proactive understanding of complex regulatory regimes in each shale play can operators, producers, and infrastructure providers plan for solutions early in their project life cycle to eliminate operational risk and control their own destiny with regard to managing risk and operational liability in environmentally sensitive areas.

Krupnick, Alan J., Hal Gordon, and Sheila Olmstead. 2012. Risk Matrix for Shale Gas Development. Washington, DC: Resources for the Future.

Krupnick, Alan, Hal Gordon, and Sheila Olmstead. 2013. Pathways to Dialogue: What the Experts Say about the Environmental Risks of Shale Gas Development. Washington, DC: Resources for the Future.

Krupnick, Alan, and Sheila Olmstead. Forthcoming. Cumulative Risks Associated with Shale Gas Development. Washington, DC: Resources for the Future.

The large-scale development of natural gas resources from deep shale formations has raised a host of concerns about risks to the environment and human health. The concerns of the general public, reflected in media coverage of this issue, may be due in part to the dearth of empirical evidence quantifying the scope, nature, and magnitude of environmental risks, as the physical and social science literatures regarding these risks are still very thin. This paper describes a risk matrix that identifies 264 risk pathways linking shale gas development activities to environmental burdens and the media in which they appear (e.g., air quality, surface water quality, groundwater, species habitat, and other environmental endpoints). This risk matrix provided the underlying structure for an expert survey, which highlights risks identified by all four respondent groups as deserving of high priority for management activity, either on a voluntary basis by industry or through regulatory mechanisms. The authors briefly review the literature on each of these high-priority risks and then speculate on how risks from any pathway or combination of pathways relate to the scale of drilling activities in a given geographic region. They identify potential interactions in which multiple risk pathways may act synergistically to increase risks and consider how risk mitigation strategies may simultaneously affect multiple risk pathways.

Kuwayama, Yusuke, Sheila Olmstead, and Alan Krupnick. 2013. Water Resources and Unconventional Fossil Fuel Development. Washington, DC: Resources for the Future.

The production of crude oil and natural gas from unconventional reservoirs has become a growth sector within the North American energy industry, and current projections indicate that the production of some of these unconventional fossil fuels will continue accelerating in the foreseeable future. This shift in the energy industry has been accompanied by rising concerns over potential impacts on water resources, because producing these fuels is thought to require more water per unit of energy produced than conventional sources and may lead to greater degradation of water quality. This paper provides a comprehensive overview of the existing literature on the water quantity and quality implications of producing the main unconventional fossil fuels in North America and characterizes the differences in social costs that arise from the extraction and production of these fuels versus those from conventional fossil fuel production.

Larson, Danny, Ruth Breech, Jessica Hendricks, Mark Chernaik, Amy Mall, Frank Smith, Josh Joswick, and Mike Eisenfeld. 2011. Gassed! Citizen Investigation of Toxic Air Pollution from Natural Gas Development. El Cerrito, CA: Global Community Monitor.

($) Laurenzi, Ian J., and Gilbert R. Jersey. 2013. Life Cycle Greenhouse Gas Emissions and Freshwater Consumption of Marcellus Shale Gas. *Environmental Science & Technology* 47 (9): 4896–4903. doi:10.1021/es305162w.

This article presents the results of a life cycle assessment (LCA) of Marcellus Shale gas used for power generation. The analysis employs the most extensive dataset of any LCA of shale gas to date, encompassing data from actual gas production and power generation operations. Operations associated with hydraulic fracturing constitute only 1.2 percent of the life cycle GHG emissions and 6.2 percent of the life cycle freshwater consumption. These results are influenced most strongly by the estimated ultimate recovery of the well and the power plant efficiency: increase in either quantity will reduce both life cycle freshwater consumption and GHG emissions relative to power generated at the plant. The authors compare the life cycle impacts of Marcellus gas and US coal, finding that the carbon footprint of Marcellus gas is 53 percent lower than coal, and its freshwater consumption is about 50 percent of that of coal. They conclude that substantial GHG reductions and freshwater savings may result from the replacement of coal-fired with gas-fired power generation.

($) Li, Huishu, and Kenneth H. Carlson. 2014. Distribution and Origin of Groundwater Methane in the Wattenberg Oil and Gas Field of Northern Colorado. *Environmental Science & Technology* 48:1484–91. doi:10.1021/es404668b.

Litovitz, Aviva, Aimee Curtright, Shmuel Abramzon, Nicholas Burger, and Constantine Samaras. 2013. Estimation of Regional Air-Quality Damages from Marcellus Shale Natural Gas Extraction in Pennsylvania. *Environmental Research Letters* 8 (1): 1–8.

This letter provides a first-order estimate of conventional air pollutant emissions, and the monetary value of associated environmental and health damages, from the extraction of unconventional shale gas in Pennsylvania. Region-wide estimated damages ranged from $7.2 to $32 million for 2011. The emissions from Pennsylvania shale gas extraction represented only a few percent of total statewide emissions, and the resulting statewide damages were less than those estimated for each of the state's largest coal-based power plants. On the other hand, in counties where activities are concentrated, NO_x emissions from all shale gas activities were 20 to 40 times higher than allowable for a single minor source, although individual new gas industry facilities generally fall below the major source threshold for NO_x. Most emissions are related to the ongoing activities of gas production and compression, which can be expected to persist beyond initial development and are largely unrelated to the unconventional nature of the resource. The authors conclude that regulatory agencies and the shale gas industry, in

developing regulations and best practices, should consider air emissions from these long-term activities, especially if development occurs in more populated areas where per-ton emissions damages are significantly higher.

($) Lutz, Brian D., Aurana N. Lewis, and Martin W. Doyle. 2013. Generation, Transport, and Disposal of Wastewater Associated with Marcellus Shale Gas Development. *Water Resources Research* 49 (2): 647–656. doi:10.1002/wrcr.20096.

Hydraulic fracturing has made vast quantities of natural gas from shale available, reshaping the energy landscape of the United States. Extracting shale gas, however, generates large, unavoidable volumes of wastewater, which to date lacks accurate quantification. For the Marcellus Shale, by far the largest shale gas resource in the United States, the authors quantify gas and wastewater production using data from 2,189 wells throughout Pennsylvania. Contrary to current perceptions, Marcellus wells produce significantly less wastewater per unit of gas recovered (approximately 35 percent) than conventional natural gas wells. Further, well operators classified only 32.3 percent of wastewater from Marcellus wells as flowback from hydraulic fracturing; most wastewater was classified as brine, generated over multiple years. Despite producing less wastewater per unit of gas, developing the Marcellus Shale has increased the total wastewater generated in the region by approximately 570 percent since 2004, overwhelming current wastewater disposal infrastructure capacity.

Lyman, Seth, and Howard Shorthill. 2013. 2012 Uintah Basin Winter Ozone & Air Quality Study. Logan: Utah State University.

Madsen, Travis, Jordan Schneider, and Erika Staaf. 2011. In the Shadow of the Marcellus Boom: How Shale Gas Extraction Puts Vulnerable Pennsylvanians at Risk. Philadelphia: PennEnvironment Research and Policy Center.

Martin, Randal, Kori Moore, Marc Mansfield, Scott Hill, Kiera Harper, and Howard Shorthill. 2011. Uinta Basin Winter Ozone and Air Quality Study. Vernal: Utah State University.

McDaniels, Jessica, and Arash Shadravan. 2013. Zonal Isolation Critical in Developing Unconventional Resources. *American Oil & Gas Reporter* (August).

($) McKenzie, Lisa M., Roxana Z. Witter, Lee S. Newman, and John L. Adgate. 2012. Human Health Risk Assessment of Air Emissions from Development of Unconventional Natural Gas Resources. *Science of the Total Environment* 424:79–87. doi:10.1016/j.scitotenv.2012.02.018.

Technological advances such as directional drilling and hydraulic fracturing have led to increases in unconventional natural gas development (NGD), raising questions about health impacts. The authors estimate health risks for exposures to air emissions from an NGD project in Garfield County, Colorado, with the objective of supporting risk prevention recommendations in a health impact assessment (HIA). They use EPA guidance to estimate chronic and subchronic noncancer hazard indices and cancer risks from exposure to hydrocarbons for two populations: residents living > ½ mile from wells and those living ≤ ½ mile from wells. The results show that residents living ≤ ½ mile from wells are at greater risk for health effects from NGD than are residents living > ½ mile from wells. Subchronic exposures to air pollutants during well completion activities present the greatest potential for health effects. The authors conclude that risk assessment can be used in HIAs to direct health risk prevention strategies. Risk management approaches should focus on reducing exposures to emissions during well completions. Health effects resulting from air emissions during unconventional NGD warrant further study.

Michaels, Craig, James L. Simpson, and William Wegner. 2010. Fractured Communities: Case Studies of the Environmental Impacts of Industrial Gas Drilling. Ossining, NY: Riverkeeper.

Molofsky, Lisa J., John A. Connor, Albert S. Wylie, Tom Wagner, and Shahla K. Farhat. 2013. Evaluation of Methane Sources in Groundwater in Northeastern Pennsylvania. *Groundwater* 51 (3): 333–49. doi:10.1111/gwat.12056.

Testing of 1,701 water wells in northeastern Pennsylvania shows that methane is ubiquitous in groundwater, with higher concentrations observed in valleys than in upland areas and in association with waters rich in calcium-sodium-bicarbonate, sodium-bicarbonate, and sodium-chloride, indicating that on a regional scale, methane concentrations are best correlated with topographic and hydrogeologic features, rather than shale gas extraction. In addition, the authors' assessment of isotopic and molecular analyses of hydrocarbon gases in Dimock Township suggests that gases present in local water wells are more consistent with Middle and Upper Devonian gases sampled in the annular spaces of local gas wells than with Marcellus production gas. Combined, these findings suggest that the methane concentrations in Susquehanna County water wells can be explained without the migration of Marcellus Shale gas through fractures, an observation that has important implications for understanding the nature of risks associated with shale gas extraction.

Moore, Christopher W., Barbara Zielinska, and Robert B. Jackson. 2013. Air Impacts of Shale Gas Extraction and Distribution. Presented at the Workshop on Risks of Unconventional Shale Gas Development, Washington, DC, May.

Muehlenbachs, Lucija, and Alan J. Krupnick. 2013. Shale Gas Development Linked to Traffic Accidents in Pennsylvania. *Common Resources*, September 27.

($) Murali Mohan, Arvind, Angela Hartsock, Richard W. Hammack, Radisav D. Vidic, and Kelvin B. Gregory. 2013. Microbial Communities in Flowback Water Impoundments from Hydraulic Fracturing for Recovery of Shale Gas. *FEMS Microbial Ecology* 86 (3): 567–80. doi:10.1111/1574-6941.12183.

Hydraulic fracturing for natural gas extraction from shale produces waste brine known as flowback, which is impounded at the surface prior to reuse and/or disposal. During impoundment, microbial activity can alter the fate of metals including radionuclides, give rise to odorous compounds, and result in biocorrosion that complicates water and waste management and increases production costs. This article describes the microbial ecology at multiple depths of three flowback impoundments from the Marcellus Shale that were managed differently. Use of 16S rRNA gene clone libraries revealed that bacterial communities in the untreated and biocide-amended impoundments were depth dependent, diverse, and most similar to species within the taxa γ-proteobacteria, α-proteobacteria, δ-proteobacteria, Clostridia, Synergistetes, Thermotogae, Spirochetes, and Bacteroidetes. The bacterial community in the pretreated and aerated impoundment was uniform with depth, less diverse, and most similar to known iodide-oxidizing bacteria in the α-proteobacteria. Archaea were identified only in the untreated and biocide-amended impoundments and were affiliated to the Methanomicrobia class. This is the first study of microbial communities in flowback water impoundments from hydraulic fracturing. The findings expand the knowledge of microbial diversity of an emergent and unexplored environment and may guide the management of flowback impoundments.

($) Myers, Tom. 2012. Potential Contaminant Pathways from Hydraulically Fractured Shale to Aquifers. *Groundwater* 50 (6): 872–82. doi:10.1111/j.1745-6584.2012.00933.x.

Hydraulic fracturing of deep shale beds to develop natural gas has caused concern regarding the potential for various forms of water pollution. Two potential pathways—advective transport through bulk media and preferential flow through fractures—could allow the transport of contaminants from the fractured shale to aquifers. There is substantial geologic

evidence that natural vertical flow drives contaminants, mostly brine, to near the surface from deep evaporite sources. This study uses interpretive modeling to show that advective transport could require up to tens of thousands of years to move contaminants to the surface, but also that fracking the shale could reduce that transport time to tens or hundreds of years. Conductive faults or fracture zones, as found throughout the Marcellus Shale region, could reduce the travel time further. Injection of up to 15 million liters of fluid into the shale generates high pressure at the well, which decreases with distance from the well and with time after injection as the fluid advects through the shale. The advection displaces native fluids, mostly brine, and fractures the bulk media, widening existing fractures. Simulated pressure returns to preinjection levels in about 300 days. The overall system requires from 3 to 6 years to reach a new equilibrium, reflecting the significant changes caused by fracking the shale, which could allow advective transport to aquifers in less than 10 years. The rapid expansion of hydraulic fracturing requires that monitoring systems be employed to track the movement of contaminants and that gas wells have a reasonable offset from faults.

Nakagawa, Tatsuya. 2013. 4 Ways the Oil Industry Can Create Raving Fans & Brand Advocates. *Drilling Info*, November 14.

Nance, H. S. 2006. Tracking Salinity Sources to Texas Streams: Examples from West Texas and the Texas Gulf Coastal Plain. *Gulf Coast Association of Geological Societies Transactions* 56: 675–93.

Upper Colorado River (West Texas) and Petronila Creek (Texas Coastal Plain) salinities exceed state regulatory standards. This article looks at a recent study in which airborne conductivity surveys located points of saline influx. Hydrochemical analyses defined salinity trends and potential sources. Both streams comprise Na-Cl hydrochemical facies and are near hydrocarbon production operations. Upper Colorado River salinity decreases downstream overall, with local trend reversals. Stream-proximal shallow Permian groundwaters are sulfate enriched from evaporite dissolution. Stream-water chloride predominance is mitigated downstream by sulfate-enriched base flow. Anomalous chloride increases along the stream path correlate with proximity to anomalously saline water wells and oil fields. Conservative (Br/Cl) mixing models suggest hydraulic connection among saline wells, deep-basin brines, and saline streams. Petronila Creek salinity increases downstream. The highest salinity in the study area is observed in a tributary ditch that previously was used for oilfield brine discharge. Conservative mixing models suggest that either Tertiary-age oilfield brine or seawater might constitute the source of salinity. However, boron and chloride data suggest that oilfield brine is probably the source. Sulfate (relative to chloride) is more concentrated in surface water than is expected from evaporation of oilfield brine or seawater and probably reflects soil-gypsum dissolution.

Nelson, Drew. 2012. Minimizing Environmental Impacts across the Natural Gas Value Chain. Presented at the Base-load Electricity from Natural Gas and Nuclear Power: The Role of Federal and State Policy Symposium, Knoxville, TN, September 20-21.

($) Nicot, Jean-Philippe, and Bridget R. Scanlon. 2012. Water Use for Shale-Gas Production in Texas, US. *Environmental Science & Technology* 46 (6): 3580–86. doi:dx.doi.org/10.1021/es204602t.

Shale gas production using hydraulic fracturing of mostly horizontal wells has led to considerable controversy over water resource and environmental impacts. This study quantifies net water use for shale gas production using data from Texas, the dominant producer of shale gas in the United States, with a focus on three major plays: the Barnett Shale (15,000 wells, mid-2011), Texas-Haynesville Shale (390 wells), and Eagle Ford Shale (1,040 wells). It estimates past water use from well completion data and future water use from past water use constrained by shale gas resources. Water use for shale gas is less than 1 percent of

statewide water withdrawals; however, local impacts vary with water availability and competing demands. The authors note that current freshwater use may shift to brackish water to reduce competition with other users.

Olmstead, Sheila M., Lucija A. Muehlenbachs, Jhih-Shyang Shih, Ziyan Chu, and Alan J. Krupnick. 2012. Shale Gas Development Impacts on Surface Water Quality in Pennsylvania. *Proceedings of the National Academy of Science* 110 (13): 4962–67.

Concern has been raised in the scientific literature about the environmental implications of extracting natural gas from deep shale formations, and published studies suggest that shale gas development may affect local groundwater quality. The potential for surface water quality degradation has been discussed in prior work, although no empirical analysis of this issue has yet been published. The potential for large-scale surface water quality degradation has affected regulatory approaches to shale gas development in some states, despite the dearth of evidence. This paper conducts a large-scale examination of the extent to which shale gas development activities affect surface water quality. Focusing on the Marcellus Shale in Pennsylvania, the authors estimate the effect of shale gas wells and the release of treated shale gas waste by permitted treatment facilities on observed downstream concentrations of chloride (Cl−) and total suspended solids (TSS), controlling for other factors. Results suggest that the treatment of shale gas waste by treatment plants in a watershed raises downstream Cl− concentrations but not TSS concentrations, and that the presence of shale gas wells in a watershed raises downstream TSS concentrations but not Cl− concentrations. These results can inform future voluntary measures by shale gas operators and policy approaches by regulators to protect surface water quality as the scale of this economically important activity increases.

Osborn, Stephen, Avner Vengosh, Nathaniel R. Warner, and Robert B. Jackson. 2011. Methane Contamination of Drinking Water Accompanying Gas-Well Drilling and Hydraulic Fracturing. *Proceedings of the National Academy of Science* 108 (20): 8172–76.

Directional drilling and hydraulic-fracturing technologies are dramatically increasing natural gas extraction. In aquifers overlying the Marcellus and Utica Shale formations of northeastern Pennsylvania and upstate New York, the authors document systematic evidence for methane contamination of drinking water associated with shale gas extraction. In active gas extraction areas (one or more gas wells within 1 kilometer), average and maximum methane concentrations in drinking water wells increased with proximity to the nearest gas well and were a potential explosion hazard; in contrast, dissolved methane samples in neighboring nonextraction sites (no gas wells within 1 kilometer) within similar geologic formations and hydrogeologic regimes had lower concentrations. These data are consistent with deeper thermogenic methane sources such as the Marcellus and Utica Shales at the active sites and match gas geochemistry from gas wells nearby. In contrast, lower-concentration samples from shallow groundwater at nonactive sites had isotopic signatures reflecting a more biogenic or mixed biogenic/thermogenic methane source. The authors found no evidence for contamination of drinking water samples with deep saline brines or fracturing fluids. They conclude that greater stewardship, data, and possibly regulation are needed to ensure the sustainable future of shale gas extraction and improve public confidence in its use.

PA DCNR (Pennsylvania Department of Conservation and Natural Resources). 2014. Shale-Gas Monitoring Report. Harrisburg, PA: DCNR.

Pennsylvania Land Trust Association. 2010. Marcellus Shale Drillers in Pennsylvania Amass 1614 Violations since 2008. Harrisburg: Pennsylvania Land Trust Association.

Pétron, Gabrielle, Gregory J. Frost, Benjamin R. Miller, Jonathan Kolfer, Stephen A. Montzka, Anna Karion, Colm Sweeney, Arlyn E. Andrews, Ed Dlugokencky, Michael Trainer, and Pieter Tans.

2013. Estimation of Emissions from Oil and Natural Gas Operations in Northeastern Colorado. Boulder, CO: Earth System Research Laboratory, National Oceanic and Atmospheric Administration.

This article presents top-down VOC and CH_4 emissions evaluation results from a pilot study conducted in the Denver-Julesburg fossil fuel basin (DJB) in northeastern Colorado. The authors use in-situ and canister data collected from a 300-meter-tall tower located in the DJB and an instrumented vehicle. Their analysis suggests that the emissions of the measured species are most likely underestimated in current inventories.

($) Preston, Todd M., Tara L. Chesley-Preston, and Joanna N. Thamkec. 2014. A GIS-Based Vulnerability Assessment of Brine Contamination to Aquatic Resources from Oil and Gas Development in Eastern Sheridan County, Montana. *Science of the Total Environment* 472:1152–62.

Prezioso, Jeanine. 2012. Natgas Drillers' Water Use Cut due to Pennsylvania Drought. *Chicago Tribune*, July 16.

Rieman, Jerimiah L. 2013. Air Pollution Impacts and Implications. Presented at the Governor's Policy Forum on Shale Energy Development, Broomfield, CO, September.

Roberson, Terry W. 2012. Environmental Concerns of Hydraulically Fracturing a Natural Gas Well. *Utah Environmental Law Review* 32 (1): 67–136.

This article explores whether the natural gas drilling process of hydraulic fracturing in shale gas formations causes drinking water contamination or creates additional environmental concerns. It provides some background on the geology and history of shale gas and hydraulic fracturing, then describes the drilling and hydraulic fracturing stimulation process of a natural gas well. It goes on to address federal regulation of natural gas exploration and production; survey state regulations in Texas, New York, and Pennsylvania; examine the case of Range Resources and the Railroad Commission of Texas versus the Environmental Protection Agency regarding the alleged contamination of a drinking water well in the Barnett Shale; and delineate congressional legislation facing hydraulic fracturing. It then looks at six key studies on hydraulic fracturing and concludes with a discussion of the environmental concerns related to hydraulic fracturing and the industry's response.

Rowan, E. L., M. A. Engle, C. S. Kirby, and T. F. Kraemer. 2011. Radium Content of Oil- and Gas-Field Produced Waters in the Northern Appalachian Basin (USA): Summary and Discussion of Data. Reston, VA: US Geological Survey.

Radium activity data for waters coproduced with oil and gas in New York and Pennsylvania have been compiled from publicly available sources and are here presented together with new data for six wells, including one time series. When available, total dissolved solids (TDS) and gross alpha and gross beta particle activities also were compiled. Data from the 1990s and earlier are from sandstone and limestone oil/gas reservoirs of Cambrian-Mississippian age; however, the recent data are almost exclusively from the Middle Devonian Marcellus Shale, which represents a vast resource of natural gas the size and significance of which have only recently been recognized. Exploitation of the Marcellus involves hydraulic fracturing of the shale to release tightly held gas. Analyses of the water produced with the gas commonly show elevated levels of salinity and radium. The authors discuss similarities and differences in radium data from reservoirs of different ages and lithologies. A positive correlation between the logs of TDS and radium activity can be demonstrated for the entire dataset, and controlling for this TDS dependence, Marcellus-produced water samples contain statistically more radium than non-Marcellus samples. The radium isotopic ratio, Ra-228/Ra-226, in samples from the Marcellus Shale is generally less than 0.3, distinctly lower than the median values from other

reservoirs. This ratio may serve as an indicator of the provenance or reservoir source of radium in samples of uncertain origin.

($) Rozell, Daniel J., and Sheldon J. Reaven. 2012. Water Pollution Risk Associated with Natural Gas Extraction from the Marcellus Shale. *Risk Analysis* 32 (8): 1382–93. doi:10.1111/j.1539-6924.2011.01757.x.

In recent years, shale gas formations have become economically viable through the use of horizontal drilling and hydraulic fracturing. These techniques carry potential environmental risk because of their high water use and substantial risk for water pollution. Using probability bounds analysis, the authors assess the likelihood of water contamination from natural gas extraction in the Marcellus Shale. Probability bounds analysis is well suited when data are sparse and parameters are highly uncertain. The study model identifies five pathways of water contamination: transportation spills, well casing leaks, leaks through fractured rock, drilling site discharge, and wastewater disposal. Probability boxes are generated for each pathway. The potential contamination risk and epistemic uncertainty associated with hydraulic fracturing wastewater disposal are several orders of magnitude larger than for the other pathways. Even in a best-case scenario, it is very likely that an individual well will release at least 200 cubic meters of contaminated fluids. Because the total number of wells in the Marcellus Shale region could range into the tens of thousands, this substantial potential risk suggests that additional steps be taken to reduce the potential for contaminated fluid leaks. To reduce the considerable epistemic uncertainty, the authors recommend that more data be collected on the ability of industrial and municipal wastewater treatment facilities to remove contaminants from used hydraulic fracturing fluid.

Sadasivam, Naveena. 2013. New Pa. Gas Pipelines Endanger Some Wild Animals, Cause Others to Migrate. Philly.com, December 16.

Saiers, James E., and Erica Barth. 2012. Discussion of Paper: "Potential Contaminant Pathways from Hydraulically Fractured Shale Aquifers," by T. Myers. *Groundwater* 50 (6): 826–28. doi:10.1111/j.1745-6584.2012.00990.x.

Satija, Neena. 2013. San Antonio Considers Shale Drilling's Effect on Ozone. *Texas Tribune*, August 1.

Sawyer, Hall, and Ryan Nielson. 2010. Mule Deer Monitoring in the Pinedale Anticline Project Area: 2010 Report. Cheyenne, WY: Western Ecosystems Technology.

As part of the record of decision for gas development in the Pinedale Anticline Project Area (PAPA), the Bureau of Land Management (BLM) developed a Wildlife Monitoring and Mitigation Matrix (WMMM), which provides direction for development-phase wildlife monitoring. For mule deer, the matrix was intended to identify monitoring parameters that allow changes in mule deer abundance and avoidance of infrastructure to be quantitatively assessed. Additionally, data from GPS-collared deer can be used for estimating annual survival rates and migration routes. Monitoring was intended to be consistent with previous efforts that began in 2001 and continued through 2007, so that reasonable comparisons across years could be made. Here, the authors report monitoring results for the winters of 2007–08, 2008–09, and 2009–10. Where appropriate (e.g., for population trends), they include data from previous years of study.

Sawyer, Hall, Ryan M. Nielson, Fred Lindzey, and Lyman L. McDonald. 2006. Winter Habitat Selection of Mule Deer Before and During Development of a Natural Gas Field. *Journal of Wildlife Management* 70 (2): 396–403.

Increased levels of natural gas exploration, development, and production across the intermountain West have created a variety of concerns for mule deer populations, including

direct habitat loss to road and well-pad construction and indirect habitat losses that may occur if deer use declines near roads or well pads. The authors examine winter habitat selection patterns of adult female mule deer before and during the first three years of development in a natural gas field in western Wyoming. They use Global Positioning System (GPS) locations collected from a sample of adult female mule deer to model relative frequency or probability of use as a function of habitat variables. Model coefficients and predictive maps suggest that mule deer are less likely to occupy areas in close proximity to well pads than those farther away. Changes in habitat selection appear to have been immediate (year 1 of development), and no evidence of well-pad acclimation occurred through the course of the study; rather, mule deer selected areas farther from well pads as development progressed. Lower predicted probabilities of use within 2.7 to 3.7 kilometers of well pads suggest that indirect habitat losses may be substantially larger than direct habitat losses. Additionally, some areas classified as high probability of use by mule deer before gas field development changed to areas of low use following development, and others originally classified as low probability of use were used more frequently as the field developed. If areas with high probability of use before development were those preferred by the deer, observed shifts in their distribution as development progressed were toward less preferred and presumably less suitable habitats.

Scanlon, Bridget R., Ian Duncan, and Robert C. Reedy. 2013. Drought and the Water-Energy Nexus in Texas. *Environmental Research Letters* 8 (4): 045033. doi:10.1088/1748-9326/8/4/045033.

Texas experienced the most extreme drought on record in 2011 with up to 100 days of triple-digit temperatures resulting in record electricity demand and historically low reservoir levels. The authors quantified water and electricity demand and supply for each power plant during the drought relative to 2010 (baseline). Drought raised electricity demands/generation by 6 percent, increasing water demands/consumption for electricity by 9 percent. Reductions in monitored reservoir storage <50 percent of capacity in 2011 would suggest drought vulnerability, but data show that the power plants were flexible enough at the plant level to adapt by switching to less water-intensive technologies. Natural gas, now ~50 percent of power generation in Texas, enhances drought resilience by increasing the flexibility of power plant generators, including gas combustion turbines to complement increasing wind generation and combined cycle generators with ~30 percent of cooling water requirements of traditional steam turbine plants. These reductions in water use are projected to continue to 2030 with increased use of natural gas and renewables. Although water use for gas production is controversial, these data show that water saved by using natural gas combined cycle plants relative to coal steam turbine plants is 25 to 50 times greater than the amount of water used in hydraulic fracturing to extract the gas.

($) Schnell, Russell C., Samuel J. Oltmans, Ryan R. Neely, Maggie S. Endres, John V. Molenar, and Allen B. White. 2009. Rapid Photochemical Production of Ozone at High Concentrations in a Rural Site during Winter. *Nature Geoscience* 2:120–22. doi:10.1038/ngeo415.

Ozone is an air pollutant that can cause severe respiratory health effects. Photochemical ozone production near Earth's surface is considered a summertime urban phenomenon, where hourly average ozone concentrations can exceed 150 ppb, compared with background values of about 50 ppb, and wintertime ozone concentrations in the United States are usually in the range of 35–50 ppb. Here, the authors report rapid, diurnal photochemical production of ozone during air temperatures as low as –17°C in the rural Upper Green River Basin, Wyoming, in the vicinity of the Jonah–Pinedale Anticline natural gas field. They find that hourly average ozone concentrations rise from 10 to 30 ppb at night to more than 140 ppb shortly after solar noon, under the influence of a stagnant high-pressure system that promotes cold temperatures, low wind speeds, and limited cloudiness. Under these conditions, an intense, shallow temperature

inversion develops in the lowest 100 meters of the atmosphere, which traps high concentrations of ozone precursors at night. During daytime, photolytic ozone production then leads to the observed high concentrations. The authors suggest that similar ozone production during wintertime is probably occurring around the world under comparable industrial and meteorological conditions.

($) Schoell, Martin. 1980. The Hydrogen and Carbon Isotopic Composition of Methane from Natural Gases of Various Origins. *Geochimica et Cosmochimica* 44 (5): 649–61.

The deuterium concentrations of biogenic methanes from worldwide occurrences range from −180 to −280 percent and were found to be depleted in deuterium by approximately 160 percent compared with the deuterium concentration of their associated waters. Theoretical considerations support this relationship to be the result of bacterial transformation of CO_2 to methane and therefore indicative of the biogenic origin of methane. Thermogenic gases with high C2+ concentrations (wet gases associated with crude oil) have D/H ratios from −260 to −150 percent, with deuterium contents tending to increase with decreasing wetness. Dry gases that are not associated with petroleum are more enriched in deuterium (−180 to −130 percent) and show an increase in deuterium with increasing rank of the source beds as it is similarly known for carbon-13. Many dry gases in young sedimentary basins were found to contain significant amounts of C2+ hydrocarbons. These gases cannot be grouped with either the biogenic or thermogenic gases, and their methane is concluded to be of mixed biogenic and thermochemical origin. Using a diagrammatic display of the isotope data of methanes, the various genetic groups of natural gases can be defined more clearly.

Schon, Samuel C. 2011. Hydraulic Fracturing Not Responsible for Methane Migration. *Proceedings of the National Academy of Science* 108 (37): E664.

Shipley, Frank S. 1991. Oil Field-Produced Brines in a Coastal Stream: Water Quality and Fish Community Recovery Following Long Term Impacts. *Texas Journal of Science* 43 (1): 51–64.

Siikamäki, Juha, and Alan J. Krupnick. 2013. Attitudes and the Willingness to Pay for Reducing Shale Gas Risks. In Managing the Risks of Shale Gas: Key Findings and Further Research, edited by Alan J. Krupnick, 4–5. Washington, DC: Resources for the Future.

Slonecker, E. T., L. E. Milheim, C. M. Roig-Silva, A. R. Malizia, D. A. Marr, and G. B. Fisher. 2012. Landscape Consequences of Natural Gas Extraction in Bradford and Washington Counties, Pennsylvania, 2004–2010. Reston, VA: US Geological Survey.

Increased demands for cleaner-burning energy, coupled with the relatively recent technological advances in accessing unconventional hydrocarbon-rich geologic formations, have led to an intense effort to find and extract natural gas from various underground sources around the country. One of these sources, the Marcellus Shale, located in the Allegheny Plateau, is undergoing extensive drilling and production. The technology used to extract gas in the Marcellus Shale, known as hydraulic fracturing, has garnered much attention because of its use of large amounts of fresh water, its use of proprietary fluids, its potential to release contaminants into the environment, and its potential effect on water resources. Nonetheless, development of natural gas extraction wells in the Marcellus Shale is only part of the overall natural gas story in the area of Pennsylvania. Coalbed methane, which is sometimes extracted using the same technique, is often located in the same general area as the Marcellus Shale and is frequently developed in clusters across the landscape. The combined effects of these two natural gas extraction methods create potentially serious patterns of disturbance on the landscape. This document quantifies the landscape changes and consequences of natural gas extraction for Bradford and Washington Counties in Pennsylvania between 2004 and 2010. Patterns of landscape disturbance related to natural gas extraction activities were collected

and digitized using National Agriculture Imagery Program (NAIP) imagery for 2004, 2005–06, 2008, and 2010. The disturbance patterns were then used to measure changes in land cover and land use using the National Land Cover Database (NLCD) of 2001. A series of landscape metrics is used to quantify these changes and is included in this publication.

Song, Lisa. 2013. Is Texas's Ozone Problem Linked to Fracking? *Inside Climate News*, October 25.

($) Soraghan, Mike. 2013. Tremors Shaking OKC Could Be Linked to Oil and Gas. *EnergyWire*, November 5.

($) Soraghan, Mike. 2014. Ohio Makes Strongest Link Yet between Shaking and Fracking. *EnergyWire*, April 14.

States, Stanley, Gina Cyprych, Mark Stoner, Faith Wydra, Jay Kuchta, Leonard Casson, and Jason Monnell. 2012. Bromide, TDS, and Radionuclides in the Allegheny River: A Possible Link with Marcellus Shale Operations. Presented at the Pennsylvania Section–American Water Works Association's (PA-AWWA) 63rd Annual Conference, Hershey, PA, April 2011.

Steinzor, Nadia, Wilma Subra, and Lisa Sumi. 2013. Investigating Links between Shale Gas Development and Health Impacts Through a Community Survey Project in Pennsylvania. *New Solutions* 23 (1): 55–84.

Across the United States, the race for new energy sources is picking up speed and reaching more places, with natural gas in the lead. While the toxic and polluting qualities of substances used and produced in shale gas development and the general health effects of exposure are well established, scientific evidence of causal links has been limited, creating an urgent need to understand health impacts. This article examines the results of self-reported survey research documenting the symptoms experienced by people living in proximity to gas facilities, which, coupled with environmental testing, elucidates plausible links that warrant both response and further investigation. This method, recently applied to the gas development areas of Pennsylvania, indicates the need for a range of policy and research efforts to safeguard public health.

Stoechenius, Till, and Lan Ma. 2010. A Conceptual Model of Winter Ozone Episodes in Southwest Wyoming. Novato, CA: Environ International Corporation.

Taylor, Rebecca L., David E. Naugle, and L. Scott Mills. 2012. Viability Analyses for Conservation of Sage-Grouse Populations: Buffalo Field Office, Wyoming. Buffalo, WY: Bureau of Land Management.

($) Theodori, Gene L., Brooklynn J. Wynveen, William E. Fox, and David B. Burnett. 2009. Public Perception of Desalinated Water from Oil and Gas Field Operations: Data from Texas. *Society and Natural Resources* 22 (7): 674–85. doi:10.1080/08941920802039804.

This is a technical document detailing research on public perception of desalinated water and its safety. Data collected from two counties in central Texas were used to explore issues associated with public perception of desalinated water from oil and gas field operations. The data show that small percentages of respondents are familiar with the process of desalination and extremely confident that desalinated water could meet human drinking water quality and purity standards. Respondents are more favorably disposed toward the use of desalinated water for purposes other than ingestion by humans or animals. Respondents who are more familiar with desalination technology are more likely to believe that desalinated oil and gas field water could be safely used.

USGS (US Geological Survey). 2012. Water Quality Studied in Areas of Unconventional Oil and Gas Development, Including Areas Where Hydraulic Fracturing Techniques are Used, in the United States. Reston, VA: USGS.

USGS (US Geological Survey). 2013. Earthquake Swarm Continues in Central Oklahoma. Reston, VA: USGS.

Vaidyanathan, Gayathri. 2013. "Huge Opportunity" to Drive Down Drilling Usage through Management, Regulation—Report. *EnergyWire*, November 7.

Veil, J. A., and M. G. Puder. 2006. Potential Ground Water and Surface Water Impacts from Oil Shale and Tar Sands Energy-Production Operations. Oklahoma City: Argonne National Laboratory.

Vidic, R. D., S. L. Brantley, J. M. Vandenbossche, D. Yoxtheimer, and J. D. Abad. 2013. Impact of Shale Gas Development on Regional Water Quality. *Science* 340 (6134). doi:10.1126/science.1235009.

Unconventional natural gas resources offer an opportunity to access a relatively clean fossil fuel that could potentially lead to energy independence for some countries. Horizontal drilling and hydraulic fracturing make the extraction of tightly bound natural gas from shale formations economically feasible. These technologies are not free from environmental risks, however, especially those related to regional water quality, such as gas migration, contaminant transport through induced and natural fractures, wastewater discharge, and accidental spills. The authors review the current understanding of environmental issues associated with unconventional gas extraction. Improved understanding of the fate and transport of contaminants of concern and increased long-term monitoring and data dissemination will help manage these water quality risks today and in the future.

Waldner, C. L., C. S. Ribble, and E. D. Janzen. 1998. Evaluation of the Impact of a Natural Gas Leak from a Pipeline on Productivity of Beef Cattle. *Journal of the American Veterinary Medical Association* 212 (1): 41–48.

The objective of this study was to determine the association between a leak of sour natural gas (more than 30 percent hydrogen sulfide) from a pipeline in a river valley and the health of beef cattle in the intensively ranched surrounding area. It was designed as a prospective cohort study with a sample population of 13 herds of cattle within 4 kilometers (2.5 miles) of the leak and 10 herds outside this zone. The authors determined the distance of the herds from the leak site using geographic information system technology. They obtained information about speed and direction of winds from a local meteorologic station and an ambient air-quality monitoring trailer. Health and productivity data for surrounding beef herds, as well as exposure information, were collected and analyzed. Results show no association between total herd calf mortality and herd distance from the leak, wind-aided exposure, location in the river valley, signs of irritation consistent with exposure to the gas, or reports of odors of gas at the time of the leak. Management changes reported in response to the gas leak are identified as risk factors for total herd calf mortality. Other herd-level risk factors associated with increased calf mortality ratio include a median calving date in February and percentage of twin births for a herd.

Walsh, Bryan. 2013. Deep Disposal Wells from Oil and Gas Drilling Linked to Earthquakes. *Time*, July 12.

($) Warner, Nathaniel R., Cidney A. Christie, Robert B. Jackson, and Avner Vengosh. 2013. Impacts of Shale Gas Wastewater Disposal on Water Quality in Western Pennsylvania. *Environmental Science & Technology* 47 (20): 11849–57. doi:10.1021/es402165b.

The safe disposal of liquid wastes associated with oil and gas production in the United States is a major challenge given their large volumes and typically high levels of contaminants. In Pennsylvania, oil and gas wastewater is sometimes treated at brine treatment facilities and discharged to local streams. This study examines the water quality and isotopic compositions of discharged effluents, surface waters, and stream sediments associated with a treatment facility site in western Pennsylvania. The elevated levels of chloride and bromide, combined with the strontium, radium, oxygen, and hydrogen isotopic compositions of the effluents, reflect the composition of Marcellus Shale produced waters. The discharge of the effluent from the treatment facility increased downstream concentrations of chloride and bromide above background levels. Barium and radium were substantially (>90 percent) reduced in the treated effluents compared with concentrations in Marcellus Shale produced waters. Nonetheless, radium (226Ra) levels in stream sediments at the point of discharge were 200 times greater than upstream and background sediments and were above radioactive waste disposal threshold regulations, posing potential environmental risks of radium bioaccumulation in localized areas of shale gas wastewater disposal.

Warner, Nathaniel R., Robert B. Jackson, Thomas H. Darrah, Stephen G. Osborn, Adrian Down, Kaiguang Zhao, Alissa White, and Avner Vengosh. 2012. Geochemical Evidence for Possible Natural Migration of Marcellus Formation Brine to Shallow Aquifers in Pennsylvania. *Proceedings of the National Academy of Sciences* 109 (30): 11961–66. doi:10.1073/pnas.1121181109.

The debate surrounding the safety of shale gas development in the Appalachian Basin has generated increased awareness of drinking water quality in rural communities. Concerns include the potential for migration of stray gas, metal-rich formation brines, and hydraulic fracturing and/or flowback fluids to drinking water aquifers. A critical question common to these environmental risks is the hydraulic connectivity between the shale gas formations and the overlying shallow drinking water aquifers. This article presents geochemical evidence from northeastern Pennsylvania showing that pathways, unrelated to recent drilling activities, exist in some locations between deep underlying formations and shallow drinking water aquifers. Integration of chemical data and isotopic ratios from this and previous studies in 426 shallow groundwater samples and 83 northern Appalachian brine samples suggests that mixing relationships between shallow groundwater and a deep formation brine causes groundwater salinization in some locations. The strong geochemical fingerprint in the salinized groundwater sampled from the Alluvium, Catskill, and Lock Haven aquifers suggests possible migration of Marcellus brine through naturally occurring pathways. The occurrences of saline water do not correlate with the location of shale gas wells and are consistent with reported data before rapid shale gas development in the region; however, the presence of these fluids suggests conductive pathways and specific geostructural and/or hydrodynamic regimes in northeastern Pennsylvania that are at increased risk for contamination of shallow drinking water resources, particularly by fugitive gases, because of natural hydraulic connections to deeper formations.

Warner, Nathaniel R., Timothy M. Kresse, Phillip D. Hays, Adrian Down, Jonathan D. Karr, Robert B. Jackson, and Avner Vengosh. 2013. Geochemical and Isotopic Variations in Shallow Groundwater in Areas of the Fayetteville Shale Development, North-Central Arkansas. *Applied Geochemistry* 35: 207–20.

Exploration of unconventional natural gas reservoirs, such as impermeable shale basins, through the use of horizontal drilling and hydraulic fracturing has changed the energy landscape in the United States, providing a vast new energy source. The accelerated production of natural gas has triggered a debate concerning the safety and possible

environmental impacts of these operations. This study investigates one of the critical aspects of the environmental effects: the possible degradation of water quality in shallow aquifers overlying producing shale formations. The geochemistry of domestic groundwater wells was investigated in aquifers overlying the Fayetteville Shale in north-central Arkansas, where approximately 4,000 wells have been drilled since 2004 to extract unconventional natural gas. Monitoring was performed on 127 drinking water wells, and the geochemistry of major ions, trace metals, methane (CH_4) gas content and its carbon isotopes, and select isotope tracers was compared with the composition of flowback water samples directly from Fayetteville Shale gas wells. Dissolved CH_4 was detected in 63 percent of the drinking water wells (32 of 51 samples), but only six wells exceeded concentrations of 0.5 mg CH_4/L. The study finds no spatial relationship between CH_4 and salinity occurrences in shallow drinking water wells with proximity to shale gas drilling sites. The integration of multiple geochemical and isotopic proxies shows no direct evidence of contamination in shallow drinking water aquifers associated with natural gas extraction from the Fayetteville Shale.

($) Weston, R. Timothy, and Stephen J. Matzura. 2012. Acquisition of Water for Energy and Mineral Development in the Eastern United States. In *Rocky Mountain Mineral Law Institute*. Denver, Colorado: Rocky Mountain Mineral Law Foundation.

($) Weston, Timothy. 2008. Harmonizing Management of Ground and Surface Water Use under Eastern Water Law Regimes. *University of Denver Water Law Review* 11 (2): 239–92.

Wheeler, Tim. 2013. O'Malley Urged to Fight Gas Export Terminal on Bay. *Baltimore Sun*, September 17.

Witter, Roxanna, Lisa McKenzie, Meredith Towle, Kaylan Stinson, Kenneth Scott, Lee Newman, and John Adgate. 2010. Health Impact Assessment for Battlement Mesa, Garfield County Colorado. Aurora: Colorado School of Public Health.

Zielinkska, Barbara, Eric Fijita, and Dave Campbell. 2010. Monitoring of Emissions from Barnett Shale Natural Gas Production Facilities for Population Exposure Assessment. Houston, TX: Mickey Leland National Urban Air Toxics Research Center.

Zoback, Mark, Saya Kitasei, and Brad Copithorne. 2010. Addressing the Environmental Risks from Shale Gas Development. Washington, DC: Worldwatch Institute.

Climate

Allen, David T., Vincent M. Torres, James Thomas, David W. Sullivan, Matthew Harrison, Al Hendler, Scott C. Herndon, Charles E. Kolb, Matthew P. Fraser, A. Daniel Hill, Brian K. Lamb, Jennifer Miskimins, Robert F. Sawyer, and John H. Seinfeld. 2013. Measurements of Methane Emissions at Natural Gas Production Sites in the United States. *Proceedings of the National Academy of Science* 110 (44): 17768–73. doi:10.1073/pnas.1304880110.

Engineering estimates of methane emissions from natural gas production have led to varied projections of national emissions. This work reports direct measurements of methane emissions at 190 onshore natural gas sites in the United States (150 production sites, 27 well completion flowbacks, 9 well unloadings, and 4 workovers). For well completion flowbacks, which clear fractured wells of liquid to allow gas production, methane emissions ranged from 0.01 to 17 megagrams (Mg) (mean = 1.7 Mg; 95 percent confidence bounds of 0.67–3.3 Mg), compared with an average of 81 Mg per event in the 2011 EPA national emissions inventory from April 2013. Emissions factors for pneumatic pumps and controllers as well as equipment leaks were both comparable with and higher than estimates in the national inventory. Overall,

if emissions factors from this work for completion flowbacks, equipment leaks, and pneumatic pumps and controllers are assumed to be representative of national populations and are used to estimate national emissions, total annual emissions from these source categories are calculated to be 957 gigagrams (Gg) of methane (with sampling and measurement uncertainties estimated at ±200 Gg). The estimate for comparable source categories in the EPA national inventory is ~1,200 Gg. Additional measurements of unloadings and workovers are needed to produce national emissions estimates for these source categories. The 957 Gg in emissions for completion flowbacks, pneumatics, and equipment leaks, coupled with EPA national inventory estimates for other categories, leads to an estimated 2,300 Gg of methane emissions from natural gas production (0.42 percent of gross gas production).

Alvarez, Ramón A., Stephen W. Pacala, James J. Winebrake, William L. Chameides, and Steven P. Hamburg. 2012. Greater Focus Needed on Methane Leakage from Natural Gas Infrastructure. *Proceedings of the National Academy of Science* 109 (17): 6435–40. doi:10.1073/pnas.1202407109.

Natural gas is seen by many as the future of American energy, a fuel that can provide energy independence and reduce greenhouse gas emissions in the process. However, there has also been confusion about the climate implications of increased use of natural gas for electric power and transportation. The authors propose and illustrate the use of technology warming potentials as a robust and transparent way to compare the cumulative radiative forcing created by alternative technologies fueled by natural gas and oil or coal by using the best available estimates of greenhouse gas emissions from each fuel cycle (i.e., production, transportation, and use). They find that a shift to compressed natural gas vehicles from gasoline or diesel vehicles leads to greater radiative forcing of the climate for 80 or 280 years, respectively, before beginning to produce benefits. Compressed natural gas vehicles could produce climate benefits on all timeframes if the well-to-wheels methane (CH_4) leakage were capped at a level 45–70 percent below current estimates. By contrast, using natural gas instead of coal for electric power plants can reduce radiative forcing immediately, and reducing CH_4 losses from the production and transportation of natural gas would produce even greater benefits. There is a need for the natural gas industry and science community to help obtain better emissions data and for increased efforts to reduce methane leakage in order to minimize the climate footprint of natural gas.

Bradbury, James, Michael Obeiter, Laura Draucker, Wen Wang, and Amanda Stevens. 2013. Clearing the Air: Reducing Upstream Greenhouse Gas Emissions from U.S. Natural Gas Systems. Washington, DC: World Resources Institute.

Brandt, A.R., G.A. Heath, E. A. Kort, F.O'Sullivan, G. Pétron, S.M. Jordaan, P. Tans, J. Wilcox, A.M. Gopstein, D. Arent, S. Wofsy, N.J. Brown, R. Bradley, G.D. Stucky, D. Eardley, and R. Harriss. 2014. Methane Leaks from North American Natural Gas Systems. *Science* 343 (6172): 733–35. doi:10.1126/science.1247045.

Natural gas (NG) is a potential "bridge fuel" during transition to a decarbonized energy system: it emits less carbon dioxide during combustion than other fossil fuels and can be used in many industries. However, because of the high global warming potential of methane (CH_4, the major component of NG), climate benefits from NG use depend on system leakage rates. Some recent estimates of leakage have challenged the benefits of switching from coal to NG, a large near-term greenhouse gas (GHG) reduction opportunity. Also, global atmospheric CH_4 concentrations are on the rise, with the causes still poorly understood. To improve understanding of leakage rates for policymakers, investors, and other decisionmakers, this article reviews 20 years of technical literature on NG emissions in the United States and Canada. It finds that measurements at all scales show that official inventories consistently

underestimate actual CH_4 emissions, with the NG and oil sectors as important contributors; many independent experiments suggest that a small number of "superemitters" could be responsible for a large fraction of leakage; recent regional atmospheric studies with very high emissions rates are unlikely to be representative of typical NG system leakage rates; and assessments using 100-year impact indicators show that system-wide leakage is unlikely to be large enough to negate climate benefits of coal-to-NG substitution.

Brown, Stephen P. A., Alan J. Krupnick, and Margaret A. Walls. 2009. Natural Gas: A Bridge to a Low-Carbon Future? Washington, DC: Resources for the Future.

Over the next 20 years, the United States and other countries seem likely to take steps toward a low-carbon future. Looking beyond this timeframe, many analysts expect nuclear power and emergent energy technologies—such as carbon capture and sequestration, renewable power generation, and electric and plug-in hybrid vehicles—to hold the keys to achieving a sustainable reduction in carbon dioxide (CO_2) emissions. In the meantime, however, many are discussing greater use of natural gas to reduce CO_2 emissions. Recent assessments suggest that the United States has considerably more recoverable natural gas in shale formations than was previously thought, given new drilling technologies that dramatically lower recovery cost. Because natural gas use yields CO_2 emissions that are about 45 percent lower per Btu than coal and 30 percent lower than oil, its apparent abundance raises the possibility that natural gas could serve as a bridge fuel to a future with reduced CO_2 emissions. Such a transition would seem particularly attractive in the electric power sector if natural gas were to displace coal.

Burnham, Andrew, and Corrie Clark. 2012. Examining the Impacts of Methane Leakage on Life-Cycle Greenhouse Gas Emissions of Shale and Conventional Natural Gas. *EM: The Magazine for Environmental Managers* (June): 8–13.

C2ES (Center for Climate and Energy Solutions). 2013. Leveraging Natural Gas to Reduce Greenhouse Gas Emissions. Washington, DC: C2ES.

Cathles, Lawrence M., Larry Brown, Milton Taam, and Andrew Hunter. 2011. A Commentary on "The Greenhouse-Gas Footprint of Natural Gas in Shale Formations" by R. W. Howarth, R. Santoro, and Anthony Ingraffea. *Climatic Change* 113:525–35. doi:10.1007/s10584-011-0333-0.

Natural gas is widely considered to be an environmentally cleaner fuel than coal because it does not produce detrimental by-products such as sulfur, mercury, ash, and particulates and because it provides twice the energy per unit of weight with half the carbon footprint during combustion. These points are not in dispute. However, in their 2011 publication in *Climatic Change Letters*, Howarth et al. reported that their life cycle evaluation of shale gas drilling suggested that shale gas has a larger GHG footprint than coal and that this larger footprint "undercuts the logic of its use as a bridging fuel over the coming decades." In this article, the authors argue that the analysis by Howarth et al. is seriously flawed in that they significantly overestimated the fugitive emissions associated with unconventional gas extraction, undervalued the contribution of "green technologies" to reducing those emissions to a level approaching that of conventional gas, based their comparison between gas and coal on heat rather than electricity generation (almost the sole use of coal), and assumed a time interval over which to compute the relative climate impact of gas compared with coal that did not capture the contrast between the long residence time of CO_2 and the short residence time of methane in the atmosphere. High leakage rates, a short methane GWP, and comparison in terms of heat content are the inappropriate bases upon which Howarth et al. grounded their claim that gas could be twice as bad as coal in its greenhouse impact. The authors argue here that using more reasonable leakage rates and bases of comparison, shale gas has a GHG footprint that is half and perhaps a third that of coal.

($) Caulton, Dana R., Paul B. Shepson, Renee L. Santoro, Jed P. Sparks, Robert W. Howarth, Anthony R. Ingraffea, Maria O. L. Cambaliza, Colm Sweeney, Anna Karion, Kenneth J. Davis, Brian H. Stirm, Stephen A. Montzka, and Ben R. Miller. 2014. Toward a Better Understanding and Quantification of Methane Emissions from Shale Gas Development. *Proceedings of the National Academy of Sciences* 111 (17): 6237–42. doi:10.1073/pnas.1316546111.

The identification and quantification of methane emissions from natural gas production have become increasingly important owing to the increase in the natural gas component of the energy sector. An instrumented aircraft platform was used to identify large sources of methane and quantify emissions rates in southwestern Pennsylvania in June 2012. A large regional flux, 2.0–14 g CH_4 s^{-1} km^{-2}, was quantified for an ~2,800 km^2 area, which did not differ statistically from a bottom-up inventory, 2.3–4.6 g CH_4 s^{-1} km^{-2}. Large emissions averaging 34 g CH_4/s per well were observed from seven well pads determined to be in the drilling phase, two to three orders of magnitude greater than US Environmental Protection Agency estimates for this operational phase. The emissions from these well pads, representing ~1 percent of the total number of wells, account for 4 to 30 percent of the observed regional flux. More work is needed to determine all of the sources of methane emissions from natural gas production, to ascertain why these emissions occur, and to evaluate their climate and atmospheric chemistry impacts.

EDF (Environmental Defense Fund). 2014. Co-producing Wells as a Major Source of Methane Emissions: A Review of Recent Analyses. New York, NY: EDF.

Edmonds, Jae A., and Haewon McJeon. 2013. Implications of Abundant Natural Gas. Presented at the Global Technology Strategy Program: Abundant Gas Workshop, Cambridge, MD, April.

EPA (US Environmental Protection Agency). 2013. Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2011. Washington, DC: EPA.

EPA (US Environmental Protection Agency). 2014. Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012. Washington, DC: EPA.

EPA (US Environmental Protection Agency). 2014. White Papers on Methane and VOC Emissions. Washington, DC: EPA.

On April 15, 2014, EPA released for external peer review five technical white papers on potentially significant sources of emissions in the oil and gas sector. The white papers focus on technical issues covering emissions and mitigation techniques that target methane and volatile organic compounds (VOCs). As noted in the Obama administration's Strategy to Reduce Methane Emissions, EPA will use the papers, along with the input received from the peer reviewers and the public, to determine how best to pursue additional reductions from these sources.

Flannery, Brian, Leon Clarke, and Jae Edmonds. 2013. Perspectives from the Abundant Gas Workshop. College Park, MD: Joint Global Change Research Institute.

Howarth, Robert W., Renee Santoro, and Anthony Ingraffea. 2011. Methane and the Greenhouse Gas Footprint of Natural Gas from Shale Formations. *Climatic Change* 106 (4): 679–90. doi:10.1007/s10584-011-0061-5.

The authors evaluate the greenhouse gas footprint of natural gas obtained by high-volume hydraulic fracturing from shale formations, focusing on methane emissions. Natural gas is composed largely of methane, and 3.6 to 7.9 percent of the methane from shale gas production escapes into the atmosphere through venting and leaks over the lifetime of a well. These methane emissions are at least 30 percent greater than those from conventional gas, perhaps

more than twice as great. The higher emissions from shale gas occur when wells are hydraulically fractured—as methane escapes from flowback return fluids—and during drill-out following the fracturing. Methane is a powerful greenhouse gas, with a global warming potential far greater than that of carbon dioxide, particularly over the time horizon of the first few decades following emission. Methane contributes substantially to the greenhouse gas footprint of shale gas on shorter timescales, dominating it on a 20-year time horizon. The footprint for shale gas is greater than that for conventional gas or oil when viewed on any time horizon, but particularly so over 20 years. The footprint of shale gas is at least 20 percent greater than that of coal on the 20-year horizon, perhaps more than twice as great, and is comparable over 100 years.

Howarth, Robert W., Renee Santoro, and Anthony Ingraffea. 2012. Venting and Leaking of Methane from Shale Gas Development: Response to Cathles et al. *Climatic Change* 113 (2): 537–49.

In April 2011, the authors published the first comprehensive analysis of greenhouse gas (GHG) emissions from shale gas obtained by hydraulic fracturing, with a focus on methane emissions. Their analysis was challenged by Cathles et al. in January 2012. Here, they respond to those criticisms. The authors stand by their approach and findings, stating that the latest EPA estimate for methane emissions from shale gas falls within the range of their estimates but not those of Cathles et al., which are substantially lower. They note that whereas Cathles et al. believe that the focus should be just on electricity generation and the global warming potential of methane should be considered only on a 100-year timescale, their analysis covered both electricity (30 percent of US usage) and heat generation (the largest usage), and they evaluated both 20- and 100-year integrated timeframes for methane. They argue that both timeframes are important but the decadal scale is critical, given the urgent need to avoid climate system tipping points. Using all available information and the latest climate science, the authors conclude that for most uses, the GHG footprint of shale gas is greater than that of other fossil fuels on timescales of up to 100 years. When used to generate electricity, the shale gas footprint is still significantly greater than that of coal at decadal timescales but is less at the century scale. They reiterate their conclusion from their earlier paper that shale gas is not a suitable bridge fuel for the 21st century.

($) Karion, Anna, Colm Sweeney, Gabrielle Pétron, Gregory Frost, Michael Hardesty, Jonathan Kofler, Ben R. Miller, Tim Newberger, Sonja Wolter, Robert Bandta, Alan Brewer, Ed Dlugokencky, Patricia Lang, Stephen A. Montzka, Russell Schnell, Pieter Tans, Michael Trainer, Robert Zamora, and Stephen Conley. 2013. Methane Emissions Estimate from Airborne Measurements over a Western United States Natural Gas Field. *Geophysical Research Letters* 40 (16): 4393–97. doi:10.1002/grl.50811.

Methane emissions from natural gas production are not well quantified and have the potential to offset the climate benefits of natural gas over other fossil fuels. The authors use atmospheric measurements in a mass balance approach to estimate methane emissions from a natural gas and oil production field in Uintah County, Utah, on one day in February 2012. The emissions rate they find corresponds to 6.2 to 11.7 percent of average hourly natural gas production in Uintah County in February. This study demonstrates the mass balance technique as a valuable tool for estimating emissions from oil and gas production regions and illustrates the need for further atmospheric measurements to determine the representativeness of this single-day estimate and to better assess inventories of methane emissions.

($) Laurenzi, Ian J., and Gilbert R. Jersey. 2013. Life Cycle Greenhouse Gas Emissions and Freshwater Consumption of Marcellus Shale Gas. *Environmental Science & Technology* 47 (9): 4896–4903. doi:10.1021/es305162w.

This article presents the results of a life cycle assessment (LCA) of Marcellus Shale gas used for power generation. The analysis employs the most extensive dataset of any LCA of shale gas to date, encompassing data from actual gas production and power generation operations. Operations associated with hydraulic fracturing constitute only 1.2 percent of the life cycle GHG emissions and 6.2 percent of the life cycle freshwater consumption. These results are influenced most strongly by the estimated ultimate recovery of the well and the power plant efficiency: increase in either quantity will reduce both life cycle freshwater consumption and GHG emissions relative to power generated at the plant. The authors compare the life cycle impacts of Marcellus gas and US coal, finding that the carbon footprint of Marcellus gas is 53 percent lower than coal, and its freshwater consumption is about 50 percent of that of coal. They conclude that substantial GHG reductions and freshwater savings may result from the replacement of coal-fired with gas-fired power generation.

Lee, April, Owen Zinaman, and Jeffrey Logan. 2012. Opportunities for Synergy between Natural Gas and Renewable Energy in the Electric Power and Transportation Sectors. Washington, DC: NREL (National Renewable Energy Laboratory) and JISEA (Joint Institute for Strategic Energy Analysis).

Lee, April, Owen Zinaman, Jeffrey Logan, Morgan Bazilian, Douglas Arent, and Robin L. Newmark. 2012. Interactions, Complementarities and Tensions of the Nexus of Natural Gas and Renewable Energy. *Electricity Journal* 25 (10): 38–48. doi:10.1016/j.tej.2012.10.021.

Natural gas and renewable energy technologies enjoy many complementarities spanning economic, technical, environmental, and political considerations. The authors discuss how these complementarities arise from their similarities, which include improved environmental performance compared with coal and oil and their ability to contribute to a robust US economy, but note that it is from their dissimilarities that the biggest opportunities for mutually beneficial collaboration can be found.

($) Miller, Scot M., Steven C. Wofsy, Anna M. Michalak, Eric A. Kort, Arlyn E. Andrews, Sebastien C. Biraud, Edward J. Dlugokencky, Janusz Eluszkiewicz, Marc L. Fischer, Greet Janssens-Maenhout, Ben R. Miller, John B. Miller, Stephen A. Montzka, Thomas Nehrkorn, and Colm Sweeney. 2013. Anthropogenic Emissions of Methane in the United States. *Proceedings of the National Academy of Sciences* 110 (50): 20018–22. doi:10.1073/pnas.1314392110.

This study quantitatively estimates the spatial distribution of anthropogenic methane sources in the United States by combining comprehensive atmospheric methane observations, extensive spatial datasets, and a high-resolution atmospheric transport model. Results show that current inventories from the US Environmental Protection Agency (EPA) and the Emissions Database for Global Atmospheric Research underestimate methane emissions nationally by a factor of ~1.5 and ~1.7, respectively. This study indicates that emissions due to ruminants and manure are up to twice the magnitude of existing inventories. In addition, the discrepancy in methane source estimates is particularly pronounced in the south-central United States, where the authors find that total emissions are ~2.7 times greater than in most inventories and account for 24 ± 3 percent of national emissions. The spatial patterns of the authors' emissions fluxes and observed methane–propane correlations indicate that fossil fuel extraction and refining are major contributors (45 ± 13 percent) in the south-central United States. This result suggests that regional methane emissions due to fossil fuel extraction and processing could be 4.9 ± 2.6 times larger than in the Emission Database for Global Atmospheric Research (EDGAR), the most comprehensive global methane inventory. These results cast doubt on EPA's recent decision to downscale its estimate of national natural gas emissions by 25 to 30 percent. Overall, the authors conclude that methane emissions

associated with both the animal husbandry and fossil fuel industries have larger greenhouse gas impacts than indicated by existing inventories.

($) Pétron, Gabrielle, Gregory Frost, Benjamin R. Miller, Adam I. Hirsch, Stephen A. Montzka, Anna Karion, Michael Trainer, Colm Sweeney, Arlyn E. Andrews, Lloyd Miller, Jonathan Kofler, Amnon Bar-Ilan, Ed J. Dlugokencky, Laura Patrick, Charles T. Moore Jr., Thomas B. Ryerson, Carolina Siso, William Kolodzey, Patricia M. Lang, Thomas Conway, Paul Novelli, Kenneth Masarie, Bradley Hall, Douglas Guenther, Duane Kitzis, John Miller, David Welsh, Dan Wolfe, William Neff, and Pieter Tans. 2012. Hydrocarbon Emissions Characterization in the Colorado Front Range: A Pilot Study. *Journal of Geophysical Research* 117 (D4): D04304. doi:10.1029/2011JD016360.

The multispecies analysis of daily air samples collected at the NOAA Boulder Atmospheric Observatory (BAO) in Weld County in northeastern Colorado since 2007 shows highly correlated alkane enhancements caused by a regionally distributed mix of sources in the Denver-Julesburg Basin. To further characterize the emissions of methane and nonmethane hydrocarbons (propane, n-butane, i-pentane, n-pentane, and benzene) around BAO, a pilot study involving automobile-based surveys was done in 2008. A mix of venting emissions (leaks) of raw natural gas and flashing emissions from condensate storage tanks can explain the alkane ratios observed in air masses impacted by oil and gas operations in northeastern Colorado. Using the WRAP Phase III inventory of total volatile organic compound (VOC) emissions from oil and gas exploration, production, and processing, together with flashing and venting emission speciation profiles provided by state agencies or the oil and gas industry, the authors derive a range of bottom-up speciated emissions for Weld County in 2008. They use the observed ambient molar ratios and flashing and venting emissions data to calculate top-down scenarios for the amount of natural gas leaked to the atmosphere and the associated methane and nonmethane emissions. Their analysis suggests that the emissions of the species they measured are most likely underestimated in current inventories and that the uncertainties attached to these estimates can be as high as a factor of two.

Pétron, Gabrielle, Gregory J. Frost, Benjamin R. Miller, Jonathan Kolfer, Stephen A. Montzka, Anna Karion, Colm Sweeney, Arlyn E. Andrews, Ed Dlugokencky, Michael Trainer, and Pieter Tans. 2013. Estimation of Emissions from Oil and Natural Gas Operations in Northeastern Colorado. Boulder, CO: Earth System Research Laboratory, National Oceanic and Atmospheric Administration.

This article presents top-down VOC and CH_4 emissions evaluation results from a pilot study conducted in the Denver-Julesburg fossil fuel basin (DJB) in northeastern Colorado. The authors use in-situ and canister data collected from a 300-meter-tall tower located in the DJB and an instrumented vehicle. Their analysis suggests that the emissions of the measured species are most likely underestimated in current inventories.

Shires, Terri, and Miriam Lev-On. 2012. Characterizing Pivotal Sources of Methane Emissions from Unconventional Natural Gas Production. Washington, DC: American Petroleum Institute (API) and America's Natural Gas Alliance (ANGA).

Skone, Timothy J., James Littlefield, and Joe Marriott. 2011. Life Cycle Greenhouse Gas Inventory of Natural Gas Extraction, Delivery and Electricity Production. Morgantown, WV: National Energy Technology Laboratory.

Regulatory

ALA (American Lung Association), APHA (American Public Health Association), ATS (American Thoracic Society), AAFA (Asthma and Allergy Foundation of America), and TAH (Trust for America's Health). 2011. Comments on Oil and Natural Gas Sector: Reviews of New Source Performance Standards and National Emissions Standards for Hazardous Air Pollutants, Docket ID No. EPA-HQ-OAR-2010-0505.

Andrews, Anthony, Peter Folger, Marc Humphries, Claudia Copeland, Mary Tiemann, Robert Meltz, and Cynthia Brougher. 2009. Unconventional Gas Shales: Development, Technology, and Policy Issues. Washington, DC: Congressional Research Service.

API (American Petroleum Institute). 2009. Hydraulic Fracturing Operations—Well Construction and Integrity Guidelines. Washington, DC: API.

($) Bearer, Scott, Emily Nicholas, Tamara Gagnoleta, Michele DePhilipa, Tara Moberg, and Nels Johnson. 2012. Evaluating the Scientific Support of Conservation Best Management Practices for Shale Gas Extraction in the Appalachian Basin. *Environmental Practice* 14 (4): 308–19.

Extensive shale gas development is expected throughout the Appalachian Basin, and implementing effective avoidance and mitigation techniques to reduce ecosystem impacts is essential. Adoption of best management practices (BMPs) is an important approach for standardizing these techniques. For BMPs to be credible and effective, they need to be strongly supported by science. This study focuses on 28 BMPs related to surface impacts to habitat and wildlife and tests whether each practice is supported in the scientific literature. The quantitative assessment produced four general conclusions: (1) The vast majority of BMPs are broad in nature, which provides flexibility in implementation, but the lack of site-specific details may hamper effectiveness and potential for successful conservation outcomes. (2) Relatively low support scores were calculated for a number of BMPs, most notably those relating to noise and light pollution, due to existing research documenting effects on behavior rather than directly on species' survival and fitness—an indication that more research is needed. (3) The most commonly and strongly supported BMPs include landscape-level planning and shared infrastructure; avoidance of sensitive areas, aquatic habitats, and core forest areas; and road design, location, and maintenance. (4) Actions to enhance the development and implementation of BMPs should include public education, increased communication among scientists, improved data sharing, development of site-specific BMPs that focus on achieving ecological outcomes, and more industry collaboration.

BLM (Bureau of Land Management). 2012. Oil and Gas: Well Stimulation, Including Hydraulic Fracturing, on Federal and Indian Lands. 77 Fed. Reg. 27691 (May 11).

Bordoff, Jason. 2013. There Will Be Oil. *Democracy: A Journal of Ideas* 29 (Summer).

Brown, Stephen R. 2012. Montana. *Texas Wesleyan Law Review* 18:541–50.

The author presents a review of oil and gas legislative and regulatory action at the state and local levels in Montana.

Burger, Michael. 2013. Fracking and Federalism Choice (Response). *Pennsylvania Law Review Online* 161:150–63.

Christopherson, Susan, Clay Frickey, and Ned Rightor. 2013. A Vote of "No Confidence": Why Local Governments Take Action in Response to Shale Gas Development. Research and Policy Brief Series 54. Ithaca, NY: Community and Regional Development Institute.

A systematic study of local communities that have passed resolutions or statutes in response to high volume hydraulic fracturing (HVHF) shale gas development in Marcellus states (New York, Pennsylvania, Ohio, and West Virginia) indicates that local governments have taken action in response to complex risks and uncertain accountability. An analysis of the authors' database of 298 communities in all four states in which localities have taken legislative action shows that these Marcellus communities are not isolated rural areas but are connected to urban centers. The majority of communities taking action want to delay drilling operations or restrict specific shale gas–related activities, facilities, outputs, or land uses. Few communities have enacted outright bans. The structured interviews the authors conducted with a sample of local officials in two of these states indicate that a major impetus for action is a lack of trust in the capacity or willingness of the oil and gas industry or the state to take action to protect local communities from harm or to pay the costs of shale gas development.

Christopherson, Susan, and Ned Rightor. 2011. How Shale Gas Extraction Affects Drilling Localities: Lessons for Regional and City Policy Makers. *Journal of Town & City Management* 2 (4): 350–68.

In countries around the world, the public debate over the prospect of high volume hydraulic fracturing (HVHF) for shale gas has revolved around its environmental impacts, while taking as a given that exploitation of this newly available natural gas asset will produce significant economic benefits for local and regional economies. In this paper, the authors use multiple methods, including a case study of the Marcellus Shale gas play in the United States, to examine how the economic costs and benefits of HVHF have been assessed. They argue that the economic impact models, which have been used to project potential benefits and job creation, provide only a fraction of the information needed to understand the consequences of drilling for the regions in which it occurs. The paper also examines some of the challenges local communities face in responding to the costs posed by shale gas extraction. The authors' analysis indicates that, while shale gas development may increase jobs and tax revenues in the predominantly rural regions where drilling occurs, it can also impose significant short- and long-term costs. To fully assess the economic effects of hydraulic fracturing, local and regional policymakers need to understand the boom-bust cycle that characterizes natural gas development. This cycle has implications for local costs and benefits in the short term, and for the longer-term economic development prospects of localities in drilling regions.

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Feiden, Molly, Madeline Gottlieb, Alan Krupnick, and Nathan Richardson. 2013. Hydraulic Fracturing on Federal and Indian Lands. Discussion paper 13-26. Washington, DC: Resources for the Future.

The federal government controls 700 million acres of subsurface rights (plus 56 million subsurface acres of Indian mineral estate) across 24 states, making it the largest landowner in the nation, and therefore it is in a position to negotiate lease terms and shape regulations of oil and gas development. The federal Bureau of Land Management (BLM) rules on how drilling activity can take place on federal lands essentially dictate terms, making BLM the largest "regulator" of drilling activity in the country. BLM last revised its oil and gas regulations (the Onshore Orders) in the 1980s and early 1990s, well before the recent rapid expansion of shale gas development. As of the writing of this article, there were two rounds of proposed revisions, the first issued in 2012 and the second issued in May 2013, after BLM received 177,000 comments on the first round. This paper examines the 2013 proposal in several key respects, including the scope and requirements of the new proposal and the substantial changes from the 2012 proposal. It also compares BLM's proposed rules with rules in states with shale gas development and significant federal landholdings, based on earlier work. The authors find that BLM's proposal addresses some apparent gaps in state-level regulation, and that BLM rules generally do not appear to impose significant requirements beyond existing state regulations, at least across the regulatory elements the authors analyzed and in those states with large federal landholdings.

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The article focuses on local government regulation of hydraulic fracturing, also known as fracking. Topics include the environmental risks of fracking, the federal preemption of state and local laws, and the drop in carbon emissions in the United States between 2007 and 2012. The authors also provide information on the increase in petroleum and natural gas output in the United States in 2011.

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($) Kennedy, Michelle L. 2011. The Exercise of Local Control over Gas Extraction. *Fordham Environmental Law Review* 22: 375–92.

Town boards in upstate New York are confronting legal questions regarding the application of local land use and zoning laws to natural gas extraction operations. The process of natural gas extraction, including drilling operations, wastewater treatment, compressor stations, pipelines, and heavy truck traffic, has the potential to industrialize upstate New York's rural landscape. If towns are preempted under state law from enforcing zoning laws against the oil and gas industry, the character of residential and agricultural districts stands to be compromised. Existing economies that are heavily reliant on tourism and historic preservation risk devastation. This essay thus argues in favor of uniform enforcement of local zoning laws without special treatment for the oil and gas industry.

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($) Kramer, Bruce M. 2012. Texas: A Renaissance Year for Oil and Gas Jurisprudence: The Texas Supreme Court. *Texas Wesleyan Law Review* 18:627–60.

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As US shale play development for oil, natural gas, and natural gas liquids moves from appraisal to production phase, it is increasingly difficult for surface operations to avoid impacts to environmentally sensitive wetlands and streams. Many shale plays are in areas more visible to the general public than ever before, resulting in increased scrutiny by agencies. This paper examines the challenges faced by producers and operators, who must be more proactive in the siting of wells and associated field infrastructure and navigate complex regulatory regimes. Working under new rules since 2008, regulatory agencies require offsets for unavoidable impacts to wetlands and streams in the watershed where the impacts will occur. With limited mitigation acreage available in areas where surface rights are locked up by landowners and operators, and the increased visibility of environmental risk and liability from field operations, the need for proactive, creative wetland and stream mitigation solutions is evident. Only through proactive understanding of complex regulatory regimes in each shale play can operators, producers, and infrastructure providers plan for solutions early in their project life cycle to eliminate operational risk and control their own destiny with regard to managing risk and operational liability in environmentally sensitive areas.

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PBPC (Pennsylvania Budget and Policy Center). 2013. Pa.'s Marcellus Impact Fee Comes Up Short: Fee Revenue Fails to Keep Up with Rising Value of Gas Production. Harrisburg: PBPC.

Pifer, Ross H. 2011. What a Short, Strange Trip It's Been: Moving Forward after Five Years of Marcellus Shale Development. *University of Pittsburgh Law Review* 72 (4): 615–60.

This article reviews the background of Marcellus Shale development in Pennsylvania and discusses the many legal issues that have been raised in the short history of extraction of this resource. It also considers some of the legal questions that need to be examined as Pennsylvania law is modernized in accordance with the current realities of Marcellus Shale drilling. Finally, it offers thoughts on the overall manner in which state policymakers should approach this topic to properly manage drilling-related activities so that Pennsylvanians realize the maximum benefits offered by Marcellus Shale natural gas while any adverse impacts are minimized.

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The production of natural gas from formerly inaccessible shale formations through the use of hydraulic fracturing has expanded domestic energy supplies and lowered prices and is stimulating the replacement of dirtier fossil fuels with cleaner natural gas. At the same time, shale gas production has proven controversial, triggering intense opposition in some parts of the United States. State and local regulators have scrambled to adapt to the boom in natural gas production, raising the question of whether federal regulators should step in to supplant or supplement state regulation. This article takes a policy-neutral approach to the federalism questions at the center of that inquiry, asking which level of government ought to resolve these policy questions, rather than which level of government is likely to produce a particular favored policy outcome. Consequently, the analysis begins with four economic and political rationales typically used to justify federal regulation. Federal regulation is necessary (1) to address spillover effects that cross state boundaries, (2) to prevent economic forces at the state level from initiating a "race to the bottom" in environmental regulation, (3) to promote business efficiencies through uniform national standards, and (4) to respond to national interests in the development of natural resources through a federal licensing system. Applying these rationales to the regulation of fracking yields several important conclusions. First, while a few of the externalities of shale gas production cross state boundaries, most are experienced locally. Second, existing federal regulatory regimes offer ample authority to address those few interstate externalities. Third, the race-to-the-bottom rationale does not justify federal regulation of shale gas production, because shale gas states are not competing for quantity- or time-limited capital investment. Fourth, given that the impacts of fracking are still under study and the subject of considerable ongoing debate, there is currently no overriding national interest supporting the creation of a comprehensive federal licensing or regulatory regime for shale gas production.

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Task Force on Cooperative Strategies Regarding State and Local Regulation of Oil and Gas Development. 2012. Protocols Recommendations. Denver: Colorado Department of Natural Resources.

Turgeon, Elizabeth. 2011. "Goin' to Carolina in My Mind": Prospects and Perils for Natural Gas Drilling in North Carolina. *North Carolina Journal of Law & Technology* 13 (1): 147–82.

The hydraulic fracturing and horizontal drilling technologies used in the extraction of natural gas have proven controversial, particularly in states where the legal infrastructure is unprepared to accommodate the industry. In particular, a newly discovered natural gas reservoir in central North Carolina highlights deficiencies in the state's laws addressing the serious environmental and public health concerns regarding impacts on the water supply. Looking to other natural gas–producing states as models, the article recommends that North Carolina adopt statutory measures to protect its water in anticipation of a natural gas industry. Specifically, a severance tax on the production of natural gas in North Carolina should be collected to fund the acquisition of land. This, together with other precautionary measures, would alleviate the negative impacts to water quality and quantity, should natural gas development come to fruition.

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The United States is in the midst of a boom in natural gas and oil production, much of which has occurred in shale formations around the country, largely as a result of new horizontal drilling and hydraulic fracturing. Questions have arisen regarding the environmental risks of drilling and fracturing in shales and how laws, policies, and regulations address these risks. This paper explores, in a preliminary fashion, how regulations are applied. It briefly surveys complaints about shale gas and tight sands development (both of which typically require fracturing) lodged by citizens with state agencies, states' notation of environmental violations at shale gas and tight sands wells both in response to these complaints and as a result of independently instigated site visits or self-reported violations, and states' capacity to inspect sites and enforce violations noted. The objective of this "on-the-ground" review of shale gas development regulatory activities is to offer a preliminary picture of the environmental effects of shale gas development and how states address them through citations of violations and/or initiation of enforcement action. Regulations have little effect if they are rarely applied to regulated actors or only sporadically enforced. Looking to the content of regulations, violations of the regulations, and enforcement therefore provides a more complete regulatory picture.

International

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Shale gas resource potential in China is assessed to be large, and its development could have wide-ranging economic, environmental, and energy security implications. Although commercial-scale shale gas development has not yet begun in China, it holds the potential to change the global energy landscape. Chinese decisionmakers are wrestling with the challenges associated with bringing the potential to reality: geologic complexity; infrastructure and logistical difficulties; technological, institutional, social, and market development issues; and environmental impacts, including greenhouse gas emissions, impacts on water availability and quality, and air pollution. This paper briefly examines the current situation and outlook for shale gas in China and explores existing and potential avenues for international cooperation. The authors find that despite some barriers to large-scale development, Chinese shale gas production has the potential to grow rapidly over the medium term.

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